CORRELATIONS AND SPATIAL VARIABILITY OF SOIL PHYSICAL PROPERTIES IN HARVESTED PIEDMONT FORESTS

E.A. Carter

USDA Forest Service
Auburn, Alabama

J.N. Shaw

Department of Agronomy and Soils
Auburn University
Auburn, Alabama

ABSTRACT

Soil response to timber harvest trafficking was similar for eroded soils in two locations of the Piedmont of Alabama. Pre-harvest and post-harvest data indicated compaction to be present to a depth of 40 cm as indicated by cone index measurements, with the most significant changes occurring in the upper 20 cm. The degree of spatial dependence differed among soil properties and varied by the site and the specific soil property. Significant correlations existed between individual properties (different properties for each plot) and supported previous research results in regards to the relationship between soil properties and compaction. Coregionalization was present in each site as indicated by the results for co-kriging of correlated properties and indicated that more intensively sampled properties may provide the means to predict the spatial distribution of more difficultly measured soil properties. However, it is unclear which specific conditions promote the greatest degree of compaction, and which site-soil property combinations should be evaluated to provide a better understanding of soil compaction in Piedmont soils.

Keywords: bulk density, cone index, soil strength, spatial variability, correlations, co-kriging, Piedmont

INTRODUCTION

Soil compaction is an inevitable consequence of forest harvest operations that can vary in intensity and distribution. Machine movements are highly dispersed throughout the forest tract in the course of felling and skidding operations with the highest degree of trafficking likely to occur on skid trails and landings. A recent investigation tracked machine movements in a conventional harvest operation and estimated the percentage of area subjected to trafficking to be approximately 70% (McDonald et al., 1998). As a consequence of the interaction among trafficking patterns, machine parameters, and site characteristics, the final soil compaction status as indicated by changes in soil bulk density, soil moisture content, and soil strength, can vary in intensity and spatial variability (Carter et al., 2000a; Carter et al. 2000b; Shaw and Carter, 2002). An assessment of soil physical response to harvest trafficking and their distribution would be beneficial for providing a basis for management decisions related to site preparation and regeneration.

The change in soil volume expressed as bulk density and, to a lesser degree, soil compaction expressed as soil strength, are common measures of soil compaction. The collection of soil cores for bulk density estimations is a time consuming task while soil strength measurements expressed as cone index values are simple and rapid, providing an opportunity to collect more data in a shorter period of time. A better understanding of the relationship among soil bulk density, soil moisture content and soil strength in timber harvested landscapes might permit the use of cone penetrometers for rapid assessment of soil response to forest operations. Previous investigations have noted the influence of bulk density and soil moisture content on cone index measurements and have adjusted cone indices for local site conditions in agricultural settings (O'Sullivan et al., 1987; Christensen et al., 1989; Busscher, 1990; Mielke et al., 1994). This relationship among soil physical variables as a response to trafficking has not been well defined for forestry applications. In addition to the information on soil response, specific information on spatial characteristics of soil properties in harvested landscapes and the correlations between properties and the presence of coregionalization could be examined. This has the potential to permit the prediction of soil physical properties that has been sampled less intensely from a more intensively sampled soil parameter. Ideally, bulk density and/or soil moisture content could be predicted from more intensively sampled cone penetrometer data.

The objectives of the study were an evaluation of the spatial dependence of correlated soil properties subjected to harvesting disturbances and determination of the extent of co-regionalization between soil variables; especially the use of cone index measurements to predict bulk density or soil moisture content.

MATERIALS AND METHODS

Site Characteristics

Two study sites managed as loblolly pine (*Pinus taeda* L.) plantations were located within the Piedmont region of Alabama. Site 1 was located in Lee

County, AL and supported a 20 year old pine plantation with a yield of 202 Mg (green) ha $^{-1}$. Site 2 was located in Chambers County, AL and supported a loblolly pine stand with a yield estimated to be 91 Mg (green) ha^{-1}. The sites were clear-cut harvested in 1998 and 1999, respectively, utilizing one feller-buncher and two skidders pulling wood to a centralized landing. Soils within the harvest tracts were classified as fine, kaolinitic, thermic Typic and Rhodic Kanhapludults.

Soil Physical Response

Soil response to harvest trafficking selected for examination in this study have been previously reported (Carter et al., 2000a; Carter et al., 2000b; Shaw and Carter, 2002). Three plots from the previously cited studies were selected for this paper and are identified as plots A and B as reported in Carter et al. (2000a; 2000b) and plot C from Shaw and Carter (2002). Plot sizes were estimated to be approximately 0.4 ha for A and C and 0.6 ha for plot B. A point grid system was established on each plot with spacings of 3 x 6 (A), 6 x 6 (B) and 7 x 7 (C) m and soil physical response assessed in the post harvest condition for all sites as well as pre-harvest condition in plot C. Geo-referenced (using differential GPS) soil physical properties measured in each site included bulk density, soil water content, and soil strength according to standard protocols (Klute, 1986; ASAE 2000). Soil bulk density and gravimetric moisture contents were measured by the collection of soil cores, approximately 20 cm in length and 5 cm in diameter, that were subdivided into 5, 10 or 20 cm increments. Soil cores were dried at 105 $^{\circ}$ C and the dry weights recorded for each sample. Soil strength, expressed as cone index/unit area, was estimated by the use of a Rimik CP20 recording soil penetrometer inserted to approximately 40 cm and data recorded in 2.5 cm increments. Nine insertions were made in the post harvest locations and 6 made in pre-harvest sites. Mean values of each soil property, coefficients of variability (CV) (%) and Pierson linear correlation coefficients were computed by the Statistical Analysis System (SAS Institute, Cary, NC).

Spatial Variability

Evaluation of the spatial structure associated with select soil physical properties was conducted using the GS+ Geostatistics package (Gamma Design Software, Plainwell, MI). Relevant spatial parameters were computed and punctual kriging and co-kriging were performed on soil physical properties.

RESULTS AND DISCUSSION

Soil Response to Harvesting

Soil physical response to harvesting disturbances in the three sites selected for evaluation is included in Table 1. Soil response to machine trafficking is evident from a comparison of data from plot C. Soil bulk density and cone index levels increased in surface and subsurface layers of post-harvest locations from pre-harvest levels. Soil bulk density and cone index measurements of plots A and

Table 1. Means and coefficients of variation (% CV) of select post-harvest (sites A, B, C) and pre-harvest (site C) soil physical properties in soils of the Alabama Piedmont.

Site	Depth (cm)	Bulk Density ($Mg\ m^{-3}$)	Gravimetric Water Content (%)	Depth (cm)	Cone Index (MPa)
Plot A	*fine, kaolinitic, thermic Rhodic Kanhapludult*				
	0 – 10	1.06 (20.0)	0.23 (27.3)	0 - 10	1.46 (44.1)
	10 – 20	1.30 (12.1)	0.23 (17.9)	10 - 20	2.19 (27.3)
	20 – 30	1.27 (10.4)	0.25 (23.7)	20 - 30	2.44 (23.5)
	30 – 40	1.20 (10.2)	0.27 (16.1)	30 - 40	2.50 (22.6)
Plot B	*fine, kaolinitic, thermic Rhodic Kanhapludult*				
	0 – 10	1.34 (22.0)	0.28 (48.5)	0 - 10	1.66 (33.2)
	10 – 20			10 - 20	2.27 (22.5)
	20 – 30			20 - 30	2.44 (21.5)
	30 – 40			30 - 40	2.44 (21.9)
Plot C	*fine, kaolinitic, thermic Typic Kanhapludult*				
postharvest					
	0 – 5	1.38 (13.1)	0.26 (23.0)	0 - 10	1.43 (30.4)
	5 – 20	1.36 (11.2)		10 - 20	1.78 (19.3)
				20 – 30	2.08 (14.1)
				30 – 40	2.29 (13.4)
preharvest					
	0 – 5	1.02 (13.9)	0.26 (17.3)	0 – 10	0.93 (22.5)
	5 – 20	1.23 (10.2)		10 – 20	1.40 (18.1)
				20 – 30	1.88 (20.6)
				30 – 40	2.15 (20.4)

B were similar to post-harvest results for site C, and suggest soil layers were compacted in this location.

Previous results reported for these sites indicated differences in trafficking patterns, soil surface disturbances, the number of machine passes, and the spatial variability of inherent soil properties resulted in differences in soil response (Carter et al., 2000a; 2000b; Shaw and Carter, 2002). This is consistent with results previously reported for soil response to compactive forces, on the influence of soil properties on compaction, and the spatial variability of soil properties in natural and managed landscapes (Ayers and Perumpral, 1980; Greacen and Sands, 1980; Riha et al., 1986).

Correlation Among Soil Physical Properties

Correlation coefficients computed for soil physical parameters of plots A and B are included in Table 2. Significant ($p \leq 0.001$) negative correlations were indicated for the relationship between bulk density and soil moisture content in all depth increments to 30 cm of plot A. Negative correlation between bulk density and soil moisture content suggested a potential decrease in soil moisture at higher bulk densities presumably due to compaction. This is consistent with studies that have examined bulk density and soil moisture content (Hill and Sumner 1967; Greacen and Sands 1980). Weaker correlations were detected between cone index and soil moisture in the upper 20 cm of plot A. A similar significant trend was indicated in plot B between bulk density and soil moisture as well as between cone index and soil moisture. In addition, bulk density and soil strength were strongly positively correlated. All were highly significant. It would be expected that bulk density and soil strength would increase simultaneously, but lower soil moisture contents would be associated with higher bulk densities and cone index values.

Table 2. Pearson linear correlation coefficients between select soil physical properties in response to harvesting disturbances in two harvested tracts of the Piedmont of Alabama.

	Plot A			Plot B		
Soil † Property	**BD**	**GMC**	**CI**	**BD**	**GMC**	**CI**
BD10	**1.000**	***-0.422*** §	0.115	**1.000**	***-0.601***	***0.537***
GMC10		**1.000**	***-0.336***		**1.000**	***-0.349***
CI10			**1.000**			**1.000**
BD20	**1.000**	***-0.489***	0.058			
GMC20		**1.000**	***-0.325***		No Data ‡	
CI20			**1.000**			
BD30	**1.000**	***-0.547***	0.04			
GMC30		**1.000**	-0.189		No Data	
CI30			**1.000**			
BD40	**1.000**	-0.268	0.195			
GMC40		**1.000**	-0.065		No Data	
CI40			**1.000**			

† BD=bulk density; GMC=gravimetric water content; CI=cone index; numbers associated with soil property refer to 10 cm depth increments.
‡ No Samples were collected from these depths.
§ Correlations in bold italics were significant at the $p \leq 0.001$ level.

Correlation coefficients were determined for soil physical properties in plot C for three cases: relationship between properties in pre-harvest condition, between properties in post-harvest condition, and between soil properties in pre-harvest condition and post-harvest response (Table 3). The strongest correlations existed between soil moisture and subsurface bulk density (r=-0.636) in the pre-harvest condition; between surface bulk density and subsurface bulk density in post-harvest phase (r=0.544); between the pre-harvest and post-harvest subsurface bulk density (r=0.531); and pre-harvest soil moisture content and post-harvest bulk density (r=–0.543). All were significant at the p≤ 0.001 level. Weaker correlations were detected between cone index and bulk densities in pre-harvest and post-harvest conditions as well as between pre-harvest moisture and cone index in the upper 20 cm. These were not emphasized in the discussion but have the potential to be more significant as indicated by results for plots B (cone index and bulk density) as well as the influence of soil moisture on cone index measurements.

A highly significant negative correlation was detected between pre-harvest soil moisture and subsurface bulk density and may suggest soil moisture contents were low as a result of less pore space available for water infiltration and retention at elevated bulk density levels. Soil moisture content was averaged over surface and subsurface soil layers and reflects soil moisture throughout the profile. Post-harvest soil surface bulk density was positively correlated with subsurface bulk density, indicative of an increase in soil bulk density in response to trafficking. Soil compaction is known to extend into subsurface layers and the correlation suggests soil depths to 20 cm were compacted during harvest operations. Post–harvest subsurface bulk density was positively correlated to pre-harvest subsurface bulk density and negatively correlated with pre-harvest soil moisture. The positive correlation between pre-harvest and post-harvest subsurface bulk densities may reflect a relative change in bulk density after trafficking, that is, higher bulk densities in subsurface layers are typically higher after trafficking. The negative correlation between soil moisture and bulk density may suggest two possibilities: that soil moisture contents declined as bulk density increased due to less storage space or that soil moisture content was sufficient for the soil to resist compaction. Investigations on the relationship between soil moisture and bulk density have reported lower bulk densities at higher moisture contents due to soil water occupying a majority of soil pore space (Ayers and Perumpral, 1980; Greacen and Sands, 1980).

A number of strong correlations were detected between cone index levels at different soil depths. For example, post-harvest cone index in the 0-10 cm and the 10-20 cm layer were highly correlated (r=0.769). This trend was repeated for many combinations of adjacent cone index levels. A significant relationship between cone index of an overlying and underlying depth might be due to the effects of the soil penetrometer on the final soil strength of underlying horizons as it is inserted into the ground (O'Sullivan et al., 1987). For this reason, the relationships between cone index of adjacent soil depth increments are not discussed.

Table 3. Pierson linear correlation coefficients for preharvest and postharvest response of select soil physical properties to harvesting disturbances for eroded Piedmont soils, Alabama.

Plot C							
Soil MOIST Property †	**BD-SH**	**BD-DE**	**CI10**	**CI20**	**CI30**	**CI40**	
			PreHarvest				
BD-SH	**1.000**	0.321	-0.065	0.058	0.051	0.068	-0.233
BD-DE		**1.000**	-0.344	-0.025	0.044	0.115	***-0.636***
§							
CI10			**1.000**	0.436	0.214	0.231	0.089
CI20				**1.000**	0.765	0.515	-0.007
CI30					**1.000**	0.729	-0.057
CI40						**1.000**	-0.031
MOIST							**1.000**
			PostHarvest				
BD-SH	**1.000**	***0.544***	0.355	0.226	0.055	-0.048	ND ‡
BD-DE		**1.000**	0.201	0.262	0.164	0.037	ND
CI10			**1.000**	0.769	0.543	0.382	ND
CI20				**1.000**	0.808	0.551	ND
CI30					**1.000**	0.813	ND
CI40						**1.000**	ND
PreHarvest			**PostHarvest**				
BD-SH	0.286	0.124	-0.010	0.141	0.061	0.068	ND
BD-DE	0.296	***0.531***	0.298	0.287	0.205	0.254	ND
CI10	-0.035	-0.173	0.263	0.309	0.319	0.271	ND
CI20	-0.201	-0.261	0.256	0.278	0.288	0.339	ND
CI30	-0.261	-0.270	0.285	0.238	0.357	0.441	ND
CI40	-0.068	-0.116	0.220	0.217	0.396	0.271	ND
MOIST	-0.350	***-0.543***	-0.311	-0.303	-0.198	-0.250	ND

† BD-SH=bulk density shallow (0-5 cm); BD-DE=bulk density deep (5–20 cm); CI10=cone index of 0 – 10 cm layer, etc.; MOIST=soil moisture content of soil profile between 0 and 40 cm.

‡ ND=no comparisons possible

§ Correlations in bold italics are significant at the $p \leq 0.001$ level.

Spatial Variability of Soil Properties

Soil properties for which correlations existed were analyzed for spatial dependence using isotropic semivariogram analysis. An appropriate model was fit to the semivariograms, and estimates of the nugget (C_o), sill ($C + C_o$), range (Ao), and coefficient of determination (r^2) were calculated (Table 4). In addition, nugget semivariance, or the percentage of the nugget compared with the total semivariance (nugget + sill), was calculated for each soil physical property and used to interpret the degree of spatial dependence associated with each property (Cambardella et al., 1994).

Table 4. Semivariogram parameters for select soil physical properties before and after harvesting disturbances in eroded piedmont soils in Alabama.

		Semivariance Parameters †			
Soil Properties	**Trans**	**Model**	**Range (m)**	**Nugget Semivariogram**	r^2
Plot A					
BD10 ‡	no	EXP	91.0	52	0.44
GMC10	nlog	EXP	91.0	50	0.12
CI10	nlog	EXP	5.3	6	0.92
BD20	no	SPH	3.9	28	0.00
GMC20	sqrt	EXP	14.7	0	0.925
CI20	no	SPH	168.2	42	0.73
BD30	no	SPH	183.8	50	0.16
GMC30	nlog	EXP	11.7	2	0.74
Plot B					
BD10	no	EXP	6.5	21	0.83
GMC10	sqrt	EXP	118.6	42	0.45
CI10	no	EXP	6.4	16	0.84
Plot C					
PreHarvest					
BD-SH	no	SPH	102.2	31	0.62
BD-DE	no	SPH	151.6	50	0.54
MOIST	nlog	EXP	47.5	23	0.84
PostHarvest					
BD-DE	sqrt	EXP	18.2	1	0.91

† Geostatistical Parameters:Trans=Transformation where sqrt = square root; nlog = natural log; Model: SPH = spherical; EXP = Exponential; Range = range of correlation; Nugget Semivariance - % of nugget/total semivariance; r^2 = coefficient of determination for model semivariance fit;
‡ Soil Properties: BD10 refers to bulk density in 0 – 10 cm layer, etc.; GMC10 refers to gravimetric water content in 0 – 10 cm layer, etc.; CI10 refers to cone index in 0 – 10 cm layer; BD-SH refers to bulk density shallow (0-5 cm); BD-DE refers to bulk density deep (5 – 20 cm); MOIST refers to soil moisture of 0 – 40 cm layer.

A discussion of the spatial structure of soil properties in general and spatial dependence associated with properties of the sites under evaluation in this paper has been previously reported (Carter et al., 2000a; Carter et al., 2000b; Shaw and Carter, 2002).

A major emphasis of this study was an evaluation of the data using co-kriging, or the computation of cross-semivariograms to predict the spatial distribution of correlated properties. Spatial parameters were computed for correlated soil properties and results of the co-kriging are included in Table 5. The soil property identified as 'z' indicates the primary variable for which a related and ideally more intensely sampled variable ('z2') was evaluated. Nugget semivariance values suggested a high degree of spatial dependence for all combinations in each plot with the exception of BD10 x GMC10 in plot B and PREBD-DE x PRE-MOIST in plot C; these properties exhibited a moderate degree of spatial dependence.

The mean square error (MSE) values computed by cross validation procedures for individual soil properties and for co-kriged pairs are included in Table 6. A comparison of MSE values of auto-semivariograms of single soil parameters and the resulting pairs gives an indication of the potential for co-kriging a primary variable from a secondary, more easily measured, variable. The data suggests that GMC10 and GMC20 can be estimated from measurements of CI10 and CI20, respectively, as well as CI20 from GMC20 in plot A. Pre-harvest surface soil bulk density in plot C has the potential to be estimated from moisture content, while estimating post-harvest subsurface bulk density from pre-harvest subsurface bulk density and surface soil moisture were not possible under the conditions of the study with these data. No improvement in MSE was noted for variables evaluated in plot B.

SUMMARY

Soil compaction resulted from harvest trafficking in eroded soils of the Piedmont of Alabama. The degree of spatial dependence differed among soil properties and a high degree of spatial dependence existed for CI10 and GMC20 for plot A, and post-harvest subsurface bulk density for plot C. Significant correlations existed between individual properties for each plot typically between soil moisture and bulk density. Co-regionalization was evident in select correlated properties and suggests the possibility of predicting a set of variables from a more intensively sampled related property.

Table 5. Cross-semivariogram parameters of correlated soil physical properties subjected to harvesting disturbances in eroded soils of the Piedmont, Alabama.

	Semivariance Parameters †			
Soil Property	**Model**	**Range (m)**	**Nugget Semivariance**	**r^2**
Plot A				
GMC10 (z) ‡ CI10 (z2)	EXP	14.3	1	0.50
BD20 (z) GMC20 (z2)	EXP	104.3	7	0.81
GMC20 (z) CI20 (z2)	SPH	35.5	11	0.51
Plot B				
BD10 (z) GMC10 (z2)	SPH	12.5	34	0.75
BD10 (z) CI10(z2)	SPH	21.0	1	0.88
CI10 (z) BD10 (z2)	SPH	22.9	1	0.98
Plot C				
PREBD-DE (z) PRE-MOIST (z2)	SPH	91.0	35	0.48
POSTBD-DE (z) PREBD-DE (z2)	SPH	90.2	10	0.73
POSTBD-DE (z) PRE-MOIST (z2)	EXP	40.8	6	0.91

† Geostatistical Parameters: Model refers to semivariogram model where SPH=spherical; EXP=exponential. Range refers to range of spatial dependence; Nugget Semivatiance = % nugget of total semivariance; r^2 refers to coefficient of determination for model fit.

‡ Soil parameters: BD10 refers to bulk density in the 0 – 10 cm layer, etc.; GMC10 refers to gravimetric water content of 0 – 10 cm layer, etc.; CI10 refers to cone index of 0 – 10 cm layer; PREBD-DE refers to preharvest shallow bulk density (0 – 5 cm); PRE-MOIST refers to preharvest moisture content (0 – 40 cm); POSTBD-DE refers to postharvest deep bulk density (5 – 20 cm).

Table 6. Mean square errors (MSE) of spatially dependent and correlated soil physical properties subjected to cross- validation procedures.

Soil Property	Auto Semivariogram	Cross Semivariogram
Plot A		
GMC10 †	0.21	0.075 (GMC10 x CI10)
CI10	602.2	NC ‡ (CI10 x GMC10)
BD20	0.14	0.14 (BD20xGMC20)
GMC20	0.34	0.106 (GMC20 x CI20)
CI20	670.6	540.6 (CI20 x GMC20)
Plot B		
BD10	0.2	0.22 (BD10xGMC10)
GMC10		0.29 (BD10xCI10)
CI10	0.48	0.46 (CI10xBD10)
Plot C		
PREBD-SH	0.15	0.098 (PREBD-DE X PREMOIST)
PREBD-DE	0.083	0.10 (POSTBD-DE X PREBD-DE)
PREMOIST	0.10	0.10 (POSTBD-DE X PREMOIST)
POSTBD-DE	0.10	

† Soil Parameters: GMC10 refers to gravimetric water content in the 0 – 10 cm layer; CI10 refers to cone index of 0 – 10 cm layer, etc.; PREBD-SH & PREBD-DE refers to preharvest bulk density of shallow and deep layers; PREMOIST refers to preharvest soil moisture content; POSTBD-DE refers to postharvest deep bulk density.
‡ NC = no change in MSE.

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