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TIMBER HARVESTING EFFECTS ON SPATIAL VARIABILITY OF SOUTHEASTERN U.S. PIEDMONT SOIL PROPERTIES

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Site-specific forestry requires detailed characterization of the spatial distribution of forest soil properties and the magnitude of harvesting impacts in order to prescribe appropriate management schemes. Furthermore, evaluation of the effects of timber harvesting on soil properties conducted on a landscape scale improves the interpretive value of soil survey data. Questions exist regarding the extent and spatial distribution of the effects of timber harvesting on eroded soils of the Alabama Piedmont. We evaluated the impacts of clear-cut harvesting on the temporal and spatial variability of bulk density (ρ_b), soil strength, and water content (θ_g) at three sites in the Alabama Piedmont where timber was predominantly mature plantation stands of loblolly pine (*Pinus taeda* L.). Preharvest spatial variability of texture, surface horizon thickness, and soil organic carbon (SOC) within single soil mapping delineations was also evaluated. Soils were moderately to severely eroded and classified in fine, kaolinitic, thermic Typic and Rhodic Kanhapludult and Kandiudult families. Although significant increases ($P < 0.05$) in ρ_b were observed after timber harvesting for some of the trafficking class-depth interval combinations at all sites, the largest increases were observed at the moderately eroded site. Harvesting timber increased soil strength by 25.1% on the moderately eroded site, with increases occurring to a 40-cm depth in skid trails. Results suggested the degree of harvesting impacts were erosion phase dependent, with greater impacts on moderately versus severely eroded soils. Geostatistical analyses indicated that pre-harvest % clay and surface thickness were more highly spatially correlated than pre-harvest SOC, which may be related to erosion processes. Analyses also suggested harvesting slightly increased the overall spatial variablity of ρ_b, soil strength, and θ_g. These results suggest that the establishment of site-specific forest tillage zones to ameliorate compaction may be impractical to implement because of the increases in spatial variability of these properties. (Soil Science 2002;167:288–302)

Key words: Geostatistics, Piedmont, timber harvesting, Ultisols, soil survey.

THE southeastern United States produces approximately 40% of U.S. timber annually, and Alabama ranks third in the region in total volume production (Nix, 1998). Extensive timber production occurs in the Piedmont portion of Alabama, with loblolly pine (*Pinus taeda* L.) th predominant species both in plantation and na ural stands. The Piedmont region exists as a dissected peneplain, with uplands dominated primarily by highly weathered residual soils. Several studies have established general relationships between parent material, soil development, and soil survey in this region (Cady, 1950; Calvert et al., 1980; Rice et al., 1985; Ogg and Smith, 1993). Because of prior land use patterns, which included a period of more than 100 years of inten-

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sive monoculture cotton cultivation, soils of the Piedmont are generally moderately to severely eroded (Hendrix et al., 1992).

Soil compaction is often the result of trafficking during conventional timber harvesting (Munns, 1947; Johnson et al., 1991; Cullen et al., 1991). Amelioration of compaction has been a primary regeneration focus of the timber industry as a result of both decreases in soil aeration and permeability and increasing mechanical resistance to root growth (Foil and Ralston, 1967; Lockaby and Vidrine, 1984; Reisinger et al., 1988). Soil compaction has also been shown to lead to increased erodibility (Roy and Jarrett, 1991), although some investigators have found minimal erosion losses in Piedmont soils following timber harvesting (Grace and Carter, 2000). Greacen and Sands (1980) suggested that because forests are subjected to more highly spatially variable mechanical stresses than agronomic settings, the degree and extent of compaction is relatively more heterogeneous in forest soils. Some of these stresses are induced by trees and tree roots and others by anthropogenic effects resulting from planting, felling, and skidding processes. Estimates indicate a 10 to 30% increase in surface bulk density (ρ_b) during timber harvesting (van der Weert, 1974; Dickerson, 1976), with the largest increases in skid trails and loading decks (Sidle and Drlica, 1981; Incerti et al., 1987).

Past studies have evaluated the effects of timber harvesting on soil physical properties of upland soils of the Piedmont. Gent et al. (1984) estimated that harvesting caused increases in ρ_b and decreases in hydraulic conductivity (Ks) within the upper 0.20 m. Although disking reduced ρ_b in the upper 0.07 to 0.12 m, these authors suggested the effects of site-preparation traffic below this depth may result in reduced root growth. Burger et al. (1985) found increases in ρ_b caused by trafficking in the top 0.06 m; however, no effects were seen below this depth. Thus, it is apparent that the depths affected by harvesting traffic vary within the Piedmont, and this is likely due to differences in surface soil properties and soil water content during harvesting operations.

Questions have been raised regarding the impacts of harvesting practices and subsequent site preparation techniques on near-surface soil properties and site productivity in the Southeastern U.S. Piedmont area. The timber industry and the Natural Resource Conservation Service-National Cooperative Soil Survey have invested significant resources in the creation of soil surveys of timber lands. Although these surveys are used for many timber management applications, they are underutilized for guiding harvesting strategies for minimization of harvesting impacts. This underutilization may be the result, in part, of a lack of data evaluating both the extent of timber harvesting impacts and the susceptibility to impacts per soil map unit. Because of the problems caused by soil compaction, data relating site susceptibility to compaction from harvesting (at a standard soil water content) would be beneficial to forest soil survey programs and forest management.

Soil surveys group soil properties into mapping units on the landscape. However, many near-surface dynamic properties, sometimes referred to as *use-dependent* properties, are often more spatially variable than subsurface properties within soil mapping units (Wilding and Drees, 1983). Spatial evaluation of near-surface soil properties has been studied extensively in row-crop lands [e.g., thickness of surface horizon (Kachanoski et al., 1985); soil organic carbon (SOC) and ρ_b (Cambardella et al., 1994)], but relatively few studies have evaluated the spatial variability of near-surface soil properties in forested systems of the Piedmont (Carter et al., 2000). These relatively dynamic near-surface properties largely determine harvesting impacts; however, they are not typically addressed within the soil taxonomic system. For example, surface horizon depth, % SOC, and erosion class, which typically do not separate soil taxa in Piedmont upland soils, may have more of an effect on trafficking response than differentiating characteristics used as criteria within Soil Taxonomy. As inputs into timber production become more site-specific, improved spatial characterization of soil properties within and between soil mapping units becomes necessary.

Thus, our objectives in this study were to: (i) characterize timber harvesting effects on selected soil properties for certain eroded soils of the Southeastern U.S. Piedmont; (ii) characterize the spatial variability of these soil properties as affected by timber harvesting; and (iii) relate harvesting effects to near surface soil properties.

MATERIALS AND METHODS

Site Description

Three sites representative of upland soils in the Alabama Piedmont region were evaluated (Fig. 1): Site 1 was 0.88 ha, site 2, 0.73 ha, and site 3, 0.37 ha. Timber stands were predominantly loblolly pine (*Pinus taeda* L.) with small inclusions of hardwoods. Site 1 was established in 1954 and sites 2 and 3 in 1951. Tracts averaged 725 trees

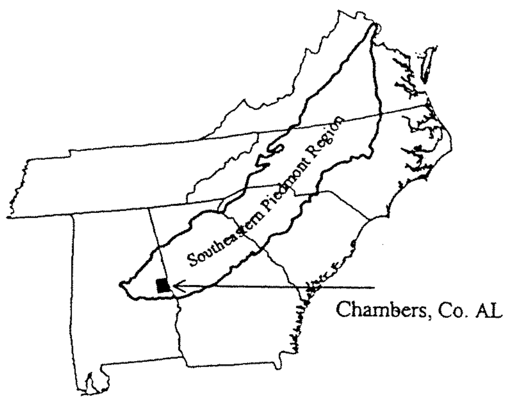

Fig. 1. Location of Chambers Co., AL, within the Piedmont physiographic region of Alabama. Study sites are located within Chambers Co.

ha^{-1}, with an estimated average green tonnage of 108 tons ha^{-1}. All sites were clear-cut using one feller-buncher and two rubber tire skidders.

Sites were selected to ensure that plots were located within a single soil mapping delineation. Soils at these sites are common to the Alabama Piedmont, and representative pedons were classified in fine, kaolinitic, thermic Typic and Rhodic Kanhapludult and Kandiudult families(Table 1). All soils are considered to be in similar taxa in regard to National Cooperative Soil Survey standards. Most of these soils formed from felsic parent materials; however, the Rhodic soils found on site 1 have most likely been influenced by the weathering of amphibolite containing substantial ferromagnesian minerals. These Rhodic soils are often mapped together with the Typic soils in associations or complexes or are mapped as consociations if separable on the landscape.

Pedon Characterization

Representative pedons (2 at each site) were sampled by horizon as per standard Soil Survey techniques (Table 1) (Soil Survey Investigations Staff, 1996). Samples were air-dried, crushed, and coarse fragments (>2 mm) were removed. Particle size determination (PSD) was conducted by the pipette method (Kilmer and Alexander, 1949). Base cations (Ca, Mg, K, and Na) were extracted with 1 *M* NH_4OAC (pH 7), Al was extracted with 1 *M* KCl, and both base cations and Al were measured with atomic absorption spectroscopy (AAS) (Soil Survey Investigations Staff, 1996). Cation exchange capacity (CEC) was measured using the NH_4OAC (pH 7) method (Soil Survey Investigations Staff, 1996).

Location of Sampling Areas and Site Disturbance Classes

Before harvesting, regularly spaced grids (≈7-m intervals) were established at each site. Differentially corrected GPS (DGPS) was used to georeference sampling areas (established at each sampling point) for geostatistical analyses and for navigating back for postharvest sampling. Limitations in DGPS accuracy resulted in sampling areas averaging ≤1 m^2 in size. The number of sampling areas at each site for each measured parameter before and after whole-tree harvesting are given in Table 2. None of the sampling areas within these sites were located within loading decks, but primary and secondary skid trails were present. In addition, site 3 was raked prior to postharvest sampling. In order to assess the degree of trafficking, sampling areas were classified into site disturbance classes derived from Dyrness (1965) and modified for local conditions (Lanford and Stokes, 1995). These trafficking classes were grouped further into no traffic (NT), traffic (T), and primary and secondary skid trails (ST).

Field Measurements within Sampling Areas

At both pre- and postharvest, the soils within sampling areas were described and sampled by horizon down to 40 cm as per standard Soil Survey techniques (Soil Survey Investigations Staff, 1996). The 40 cm depth was chosen because previous studies in similar soils suggested timber harvesting impacts do not occur below this depth (Gent et al., 1984; Carter et al., 2000). In each sampling area, a recording cone penetrometer was used to measure soil strength at 2.5-cm increments down to a 40-cm depth. During preharvest sampling, six insertions were made randomly within sampling areas, whereas nine insertions were made postharvest. Concurrent with soil strength measurements, gravimetric water content (θ_g) was measured by horizon in each sampling area (gravimetric-oven drying technique: Gardner, 1986). Pre-harvest (and harvesting) and post-harvest soil strength measurements were conducted at θ_g shown in Table 3 (averaged θ_g for all sampling areas within a site). The ρ_b was determined within all sampling areas at the 0–5-cm (3 reps) and 5–20-cm (2 reps) depths using the core method of Blake and Hartge (1986).

Samples were air-dried, crushed, and passed through a 2-mm sieve, and particle size determination of the top three horizons was conducted on randomly selected pre-harvest samples using the pipette method (Kilmer and Alexander, 1949). Soils were crushed using a ball mill grinder,

TABLE 1

Soil characterization data for representative pedons from the three Alabama Piedmont sites†

Site	Horizon	Depth	sand	silt	clay	Ca	Mg	K	Na	Al	ECEC	CEC	BS	pH‡
		cm	%			cmol$_c$ kg^{-1}							%	
					fine, kaolinitic, thermic Rhodic Kandiudult									
Site 1-1	A	4	29.1	43.2	27.7	3.5	1.1	0.4	0.1	0.0	5.0	14.5	34.5	5.39
Site 1-1	Bt1	15	22.0	34.2	43.8	2.2	0.9	0.3	0.1	0.0	3.4	8.5	40.4	5.50
Site 1-1	Bt2	50	18.6	24.0	57.4	1.7	0.8	0.2	0.1	0.0	2.8	6.9	40.2	5.44
Site 1-1	Bt3	74	19.4	19.2	61.3	1.2	1.0	0.2	0.0	0.1	2.5	7.1	34.2	5.24
Site 1-1	Bt4	105	18.7	24.2	57.2	0.5	0.9	0.1	0.1	0.1	1.7	6.3	25.5	5.31
Site 1-1	Bt5	150	43.6	3.3	53.1	0.3	0.9	0.1	0.1	0.7	2.1	6.9	19.6	5.19
					fine, kaolinitic, thermic Rhodic Kanhapludult									
Site 1-2	A	4	38.8	31.5	29.7	3.6	1.6	0.4	0.1	0.2	5.8	11.9	47.6	5.35
Site 1-2	BA	18	20.9	46.1	33.0	1.7	1.0	0.4	0.1	0.3	3.4	8.0	38.8	5.44
Site 1-2	Bt1	39	17.1	30.7	52.2	1.4	0.9	0.2	0.1	0.3	2.9	7.6	34.3	5.16
Site 1-2	Bt2	65	30.6	13.2	56.1	1.4	0.9	0.2	0.1	0.5	3.1	7.3	36.3	5.14
Site 1-2	Bt3	101	40.3	13.9	45.7	0.3	0.4	0.1	0.0	1.6	2.4	5.3	14.7	5.00
Site 1-2	Bt4	140	38.5	20.8	40.8	0.5	0.7	0.1	0.1	1.7	3.0	6.3	21.6	5.11
Site 1-2	Bt5	150	41.8	15.6	42.7	0.6	0.8	0.2	0.1	1.6	3.2	7.2	22.9	4.98
					fine, kaolinitic, thermic Typic Kanhapludult									
Site 2-1	A	2	55.9	28.1	15.9	0.3	0.2	0.2	0.1	2.1	2.9	6.9	11.3	—
Site 2-1	Bt1	24	35.3	27.3	37.4	0.2	0.1	0.0	0.0	2.2	2.6	6.5	6.5	—
Site 2-1	Bt2	54	24.5	26.0	49.5	0.5	0.3	0.0	0.0	2.7	3.5	8.5	10.2	4.49
Site 2-1	Bt3	83	20.8	37.5	41.6	0.1	0.2	0.0	0.0	3.1	3.5	6.1	6.1	4.93
Site 2-1	Bt4	126	26.0	36.1	37.9	0.0	0.1	0.0	0.0	2.9	3.1	8.0	2.7	4.83
					fine, kaolinitic, thermic Typic Kanhapludult									
Site 2-2	A	2	47.5	24.7	27.8	1.7	0.7	0.3	0.1	1.0	3.8	19.1	15.0	—
Site 2-2	Bt1	76	41.4	21.7	36.9	0.2	0.2	0.0	0.0	1.6	2.0	4.7	8.1	4.58
Site 2-2	Bt2	85	19.8	40.9	39.3	0.1	0.2	0.0	0.0	2.2	2.6	5.7	6.6	4.81
Site 2-2	Bt3	119	22.2	41.5	36.4	0.0	0.1	0.0	0.0	2.3	2.4	5.9	2.5	4.86
Site 2-2	Bt4	136	16.5	52.9	30.6	0.0	0.1	0.0	0.0	1.6	1.7	4.6	2.6	5.00
					fine, kaolinitic, thermic Typic Kanhapludult									
Site 3-1	A	2	39.4	39.2	21.4	1.3	0.6	0.2	0.0	0.1	2.2	7.4	29.0	4.47
Site 3-1	Bt1	29	32.0	30.7	37.2	0.5	0.4	0.1	0.0	0.4	1.4	5.1	19.2	4.63
Site 3-1	Bt2	50	15.0	25.2	59.8	0.5	0.9	0.0	0.0	0.6	2.1	10.0	14.9	4.97
Site 3-1	Bt3	92	21.0	27.2	51.8	0.2	0.7	0.0	0.0	1.0	1.9	6.4	13.8	4.98
Site 3-1	BC	150	24.4	36.0	39.6	0.0	0.4	0.1	0.0	1.4	1.9	5.4	9.8	4.82

Continued

TABLE 1—*Continued*

Soil characterization data for representative pedons from the three Alabama Piedmont sites†

Site	Horizon	Depth	sand	silt	clay	Ca	Mg	K	Na	Al	ECEC	CEC	BS	pH‡
		cm	%			$cmol_c\ kg^{-1}$							%	
					fine, kaolinitic, thermic Typic Kandiudult									
Site 3-2	A	6	50.0	23.1	26.9	0.8	0.7	0.2	0.0	0.1	1.9	5.4	31.9	4.95
Site 3-2	Bt1	33	34.4	20.1	45.5	0.4	0.7	0.1	0.0	0.2	1.4	5.2	23.1	4.90
Site 3-2	Bt2	52	31.5	15.4	53.1	0.4	0.8	0.1	0.0	0.2	1.5	4.8	26.5	5.12
Site 3-2	Bt3	80	30.8	22.1	47.1	0.3	0.6	0.0	0.0	0.9	1.9	7.6	13.5	4.91
Site 3-2	BC1	116	29.1	26.1	44.8	0.2	0.4	0.0	0.0	3.5	4.2	9.7	7.4	4.73
Site 3-2	BC2	150	22.3	34.1	43.6	0.2	0.3	0.0	0.1	4.6	5.2	8.2	7.4	4.70

†Ca, Mg, Na, K are exchangeable bases by NH_4OAC method; CEC is cation exchange capacity; ECEC is effective cation exchange capacity; BS is base saturation.
‡-indicates insufficient soil for analyses.

and soil organic carbon (SOC) was measured by horizon on pre-harvest samples using dry combustion (Yeomans and Bremner, 1991).

Spatial Statistics

Geostatistical analyses were conducted on the data. Pre- and post-harvest ρ_b at the 0–5- and 5–20-cm depth intervals, θ_g (weighted average to 40 cm), and soil strength values averaged from the 0–10-, 10–20-, 20–30-, and 30–40-cm depth intervals were analyzed. Percent sand, % silt, % clay, % SOC, and surface thickness (including A, AB, and BA horizons) were analyzed only pre-harvest because of the perceived minor effects timber harvesting has on these soil properties. Data for which log-transformation resulted in a skewness closer to 0 compared with nontransformed data were log-transformed before semivariogram analyses (25 of 54 data sets). Semivariograms were calculated in GS+®[1] (Robertson, 1998) using the formula:

$$\gamma(h) = \frac{1}{2|N(h)|}\sum_{N(h)}[Z(S_i) - Z(S_j)]^2 \quad (1)$$

where:
γ(h) = semivariogram value separated by effective distance (h)
Z(s) = data value at point s
N(h) = number of distinct pairs that are separated by the distance (h).

Lag distances averaged 68.3 m (± 8.5 m) for site 1, 65.6 m (± 7.0 m) for site 2, and 58.2 m (± 10.6 m) for site 3. Models were fit to isotropic semivariograms. Although the presence of anisotropy in the data are likely evident for some of these data (particularly post-harvest measurements), this was not evaluated in this study. Lag class distance intervals (step sizes) ranged between 5 and 10 m. Models that exhibited the highest r^2 as evaluated in GS+® (Robertson, 1998) were utilized for parameter estimation. Spherical models were fit to the majority of the isotropic semivariograms (Sadler et al., 1998):

Spherical model:

$$\gamma(0) = 0$$

$$\gamma(h) = C_o + C\left\{\frac{3h}{2a} - \frac{1h^3}{2a^3}\right\} \text{ when } 0 < h < a \quad (2)$$

$$\gamma(h) = C_o + C \text{ when } h > a$$

where:
γ(h) = as defined above
h = distance between two points

C_o = nugget-random variance caused by either micro-variability of the property or sampling and measurement error (Trangmar et al., 1985)
C = sill (approximates sample variance)
a = range of spatial dependence.

Exponential models were used in two cases (Sadler et al., 1998):

Exponential model:

$$\gamma(h) = C_o + C\{1 - \exp\left(\frac{-h}{a_0}\right)\} \quad (3)$$

where:
a_o = range parameter, range estimated as $3a_o$.

RESULTS AND DISCUSSION

Soils

The gridding of the site allowed for a relatively close-interval landscape-scale evaluation of near surface (0–40 cm) soil morphological properties. Soils at site 3 had thicker, loamier surface horizons, suggesting relatively less erosion than at sites 1 and 2, which had thinner, clayier (for site 1) surfaces (Table 3). Utilizing soil erosion class criteria currently employed by the National Cooperative Soil Survey Southeastern Piedmont Region (NRCS File Code no. 430–15–1) (uses a combination of surface horizon thickness, color, and texture), the majority of soils at sites 1 and 2 were severely eroded, whereas soils at site 3 were moderately eroded.

Trafficking effects

The timber at all sites was harvested at similar θ_g (23–26%)(Table 3). Similar to observations from other trafficking studies (Gent et al.,1984; Burger et al., 1985), significant ($P < 0.05$) increases in ρ_b were observed between pre- and post-harvest samples for many of the depth interval-trafficking class combinations at all three sites (Table 4). Similar to other studies (Morris and Campbell, 1991), we observed that ρ_b increased not only in skid trails but also within relatively less trafficked areas (Table 4). However, relative changes in ρ_b differed among sites.

The largest changes in ρ_b were observed on the moderately eroded site 3. Significant increases ($P < 0.05$) in ρ_b were observed in all traffic classes for both depths for site 3, with the exception of the no traffic class for the 5–20-cm depth interval (Table 4). Averaged for all traffic classes for site 3, a 36.6% increase in ρ_b was observed at the 0–5-cm depth interval, whereas an 11.3% increase in ρ_b was observed at the 5–20-cm depth interval, with an overall increase of 22.8%. When both depth intervals (0–5 and 5–20 cm) were averaged for the severely eroded sites, site 1 had a 5.0% increase in ρ_b whereas site 2 had a 9.7% increase (Table 4). For sites 1 and 2, the average ρ_b (for all traffic classes) for the trafficked and skid trail disturbance classes increased 6.9% at the 0–5-cm depth interval compared with a 12.4% increase at the 5–20-cm depth interval. The aggregate of data suggest that harvesting induced a greater degree of compaction on the moderately eroded site (site 3) compared with the severely eroded sites (sites 1 and 2). The nonsignificant decrease after harvesting of ρ_b at site 1 was suggestive of limitations in our site trafficking class groupings.

The highest average postharvest ρ_b was observed in skid trails for site 3 (1.55 and 1.53 g cm^{-3} for the 0–5- and 5–20-cm depth intervals, respectively) (Table 4). The highest ρ_bs for site 1 and site 2 occurred within the 5–20-cm depth intervals in skid trails (1.45 and 1.46 g cm^{-3}, respectively). However, few of the averaged postharvest ρ_bs observed in this study are considered to be root restrictive for the textures found at these sites (>1.45 g cm^{-3}) (Daddow and War-

TABLE 2

Number of sampling areas analyzed for each property at each site†

	sites					
	Site 1		Site 2		Site 3	
	pre	post	pre	post	pre	post
Bulk density (ρ_b)	74	74	122	118	71	71
Soil strength	73	73	122	118	71	66
Gravimetric water content (θ_g)	74	74	122	118	71	66
Particle size determination (PSD)	25	na	42	na	20	na
Soil organic carbon (SOC)	25	na	104	na	66	na

†na indicates not analyzed.

TABLE 3

Select soil properties averaged for all sampling areas within each of the three AL Piedmont sites†

Site		Depth	psd Sand	Silt	Clay	Text class	SOC‡ (10 cm)	θ_g§ pre	θ_g post
		cm	%				%	cm³ cm⁻³	
Site 1	Surf¶	8.1 ± 6.7	35.0 ± 4.8	29.7 ± 3.5	35.3 ± 5.1	c/cl	2.0 ± 0.7	0.26 ± 0.03	0.22 ± 0.04
	SS		30.8 ± 6.6	26.4 ± 4.8	42.8 ± 7.7	c			
Site 2	Surf	5.0 ± 8.3	53.9 ± 12.3	22.9 ± 7.2	23.2 ± 6.7	scl	1.0 ± 0.4	0.23 ± 0.04	0.26 ± 0.04
	SS		44.1 ± 8.1	22.6 ± 4.9	33.3 ± 7.4	cl			
Site 3	Surf	14.5 ± 9.3	47.3 ± 6.7	29.2 ± 4.3	23.5 ± 6.0	l	1.4 ± 0.4	0.26 ± 0.04	0.26 ± 0.06
	SS		31.3 ± 6.9	30.6 ± 6.4	38.0 ± 5.5	cl			

†± Values are standard deviations of means.
‡SOC represents Soil Organic Carbon.
§θ_g - weighted mean to 40 cm (for site 1, post-20 cm).
¶Surf indicates surface (A and corresponding transitional horizons); SS indicates subsurface (Bt horizons down to 40 cm).

rington, 1983). This may be because sites were harvested at water contents near field capacity, and, therefore, the degree of compaction (as evaluated by changes in ρ_b) was not as great as if they had been harvested at higher water contents.

Soil strength measurements are highly soil water content dependent (Busscher et al., 1997). Because of this, these measurements are often taken in late winter to ensure similar water contents between sites. Our measurements were taken at different times of the year as a result of harvesting schedules, making comparison between pre- and post-harvest values problematic. However, pre- and post-harvest soil strength measurements were taken at similar θ_g for site 3; these values are compared here. For site 3, when all sampling areas were averaged, increases in soil strength resulting from timber harvesting were observed down to 40 cm. A nonlinear response (R^2=0.98) existed for the percent increase in soil strength with depth after harvesting for site 3, with relatively larger increases at shallow depth intervals (58.6% increase in soil strength after harvesting at 10 cm) and smaller increases with depth (9.4% increase at 40 cm) (Fig. 2). When analyzed by disturbance class, significant increases ($P < 0.05$) in soil strength were observed for the moderately eroded site 3, with the largest increases on skid trails (Fig. 3). At the 10-, 20-, and 30-cm depths for site 3, significant soil strength increases ($P < 0.05$) occurred for both trafficked and skid trail areas (Fig. 3).

Spatial Statistics

We evaluated the degree of spatial variability of both pre- and post-harvest soil properties by assessing correlation ranges, nugget semivariance values, and the appearance of "all nugget" patterns in the semivariograms. Correlation ranges are used as a relative assessment of the distance that soil properties are correlated at a site (Clark and Harper, 2000). Nugget semivariance, or the percentage of the nugget compared with the total semivariance (nugget + sill), is used to describe the degree of spatial dependence exhibited for a particular soil property (Table 5) (Cam-

TABLE 4

Pre- and post-harvest bulk densities averaged for all sampling areas for the three sites†

Parameter	Grouping‡	Site 1 Pre-harvest	Site 1 Post-harvest	Site 2 Pre-harvest	Site 2 Post-harvest	Site 3 Pre-harvest	Site 3 Post-harvest
		g cm⁻³					
ρ_b (0–5 cm)	NT	1.25a	1.28a	1.32a	1.39a	1.08a	1.28b
ρ_b (0–5 cm)	T	1.20a	1.30b	1.27a	1.40b	1.10a	1.51b
ρ_b (0–5 cm)	ST	1.35a	1.31a	1.25a	1.42b	1.13a	1.55b
ρ_b (5–20 cm)	NT	1.31a	1.29a	1.31a	1.38a	1.19a	1.27a
ρ_b (5–20 cm)	T	1.24a	1.39b	1.26a	1.39b	1.32a	1.45b
ρ_b (5–20 cm)	ST	1.29a	1.45b	1.28a	1.46b	1.35a	1.53b

†Means followed by the same letter are not significantly different ($p<0.05$ level) between pre- and post-harvest samples.
‡NT-no traffic; T-trafficked; ST-primary and secondary skid trails.

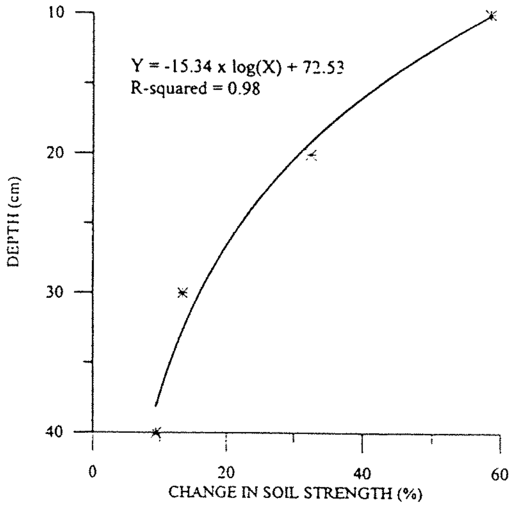

Fig. 2. Percent (%) increase between pre- and post-harvest soil strength values for site 3.

bardella et al., 1994). The rationale is that if the nugget (micro-scale or experimental variability; nonspatial variance) constitutes a high proportion of the total semivariance, the soil property possesses a weaker spatial dependence. Cambardella et al., (1994) proposed limits for strong spatial dependence at nugget semivariance values ≤25%, moderate spatial dependence at nugget semivariance values between 25 and 75%, and weak spatial dependence at nugget semivariance values >75%. We used these guidelines for interpreting spatial characteristics of these data.

Pre-harvest Samples

Comparison of correlation ranges for pre-harvest soil properties from this study compared with values from past studies are given here. Overall, the range of spatial correlation tended to be largest for pre-harvest % clay (weighted average to 20 cm) (104.7 m for site 1, 48.7 m for site 2, 31.4 m for site 3), suggesting a systematic distribution of surface texture across these sites within these mapping delineations (Table 5). For sites 2 and 3, the range of correlation for pre-harvest % sand was 30.6 m and 33.8 m, respectively (Table 5), which is similar to results obtained by Campbell (1978) on Kansas Mollisols (30 m) and by Vauclin et al., (1983) on sandy Tunisian soils (35 m). The correlation ranges found for pre-harvest ρ_b in this study (8.5 to 73.3 m) were smaller than values found in cultivated Midwestern settings (129 m) (Cambardella et al., 1994) but were greater than values found for an Arizona fluvial soil with heterogeneous parent material (6 m) (Gajem et al., 1981). For sites 1 and 3, pre-harvest depth of surface correlation range averaged only 16.6 m, suggesting some spatial variability in erosion class within this mapping delineation. Pre-harvest θ_g values had correlation ranges from 14.2 m (site 1) to 32.5 m (site 3).

The distances of most of the correlation ranges for soil properties evaluated in this study are substantially smaller than the size of the soil map unit polygons encompassing these sites. Thus, similar to other findings (Wilding and Drees, 1983), the near-surface properties evaluated exhibit a certain degree of spatial independence within

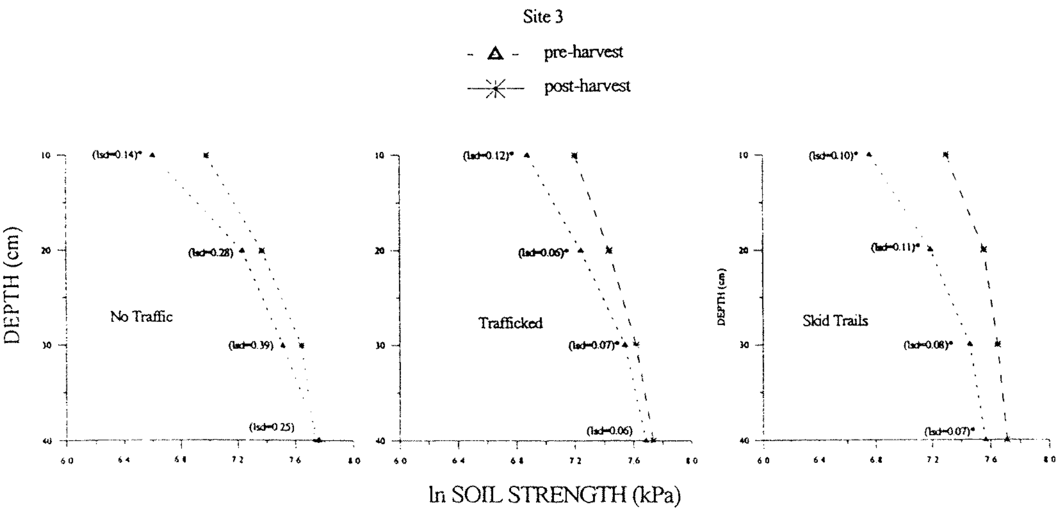

Fig. 3. Pre- and post-harvest soil strength (ln transformed) values for site 3 in no-traffic areas, trafficked areas, and skid trails. LSD = least significant difference. * indicates values different at the $P < 0.05$ level.

TABLE 5

Semivariogram parameters for selected soil properties before and after timber harvesting†

Site	Parameter‡	Pre-harvest Model§	r^2	Nugget semi.	Range (m)	Post-harvest Model§	r^2	Nugget semi.	Range (m)
Site 1	ρ_b (0–5 cm)	sph	0.69	6.3	14.0	ns			
	ρ_b (5–20 cm)	sph	0.90	45.5	73.3	sph	0.88	5.3	18.7
	θ_g (40 cm)	sph	0.67	0.0	14.2	sph	0.64	9.8	19.7
	depth-surface	sph	0.83	0.1	15.6	na			
	% clay (20 cm)	sph	0.55	0.2	104.7	na			
	% sand (20 cm)	ns				na			
	% SOC (10 cm)	ns				na			
	SS-10 cm¶	ns				sph	0.63	20.0	13.7
	SS-20 cm	ns				sph	0.78	49.5	29.3
	SS-30 cm	exp	0.31	27.5	8.1	sph	0.87	39.3	18.0
	SS-40 cm	sph	0.91	50.0	30.2	sph	0.83	7.0	14.4
Site 2	ρ_b (0–5 cm)	sph	0.51	16.7	8.5	sph	0.80	17.4	11.4
	ρ_b (5–20 cm)	sph	0.88	0.0	14.1	ns			
	θ_g (40 cm)	exp	0.67	50.0	17.7	ns			
	depth-surface	ns				na			
	% clay (20 cm)	sph	0.84	40.1	48.7	na			
	% sand (20 cm)	sph	0.63	23.8	30.6	na			
	% SOC (10 cm)	ns							
	SS-10 cm	sph	0.66	17.6	8.1	ns			
	SS-20 cm	ns				ns			
	SS-30 cm	sph	0.74	22.7	10.4	sph	0.73	12.3	15.7
	SS-40 cm	sph	0.85	48.0	26.8	sph	0.92	43.5	57.5
Site 3	ρ_b (0–5 cm)	sph	0.64	9.6	12.2	ns			
	ρ_b (5–20 cm)	sph	0.75	37.5	22.8	sph	0.94	14.8	39.0
	θ_g (40 cm)	sph	0.59	50.0	32.5	ns			
	depth-surface	sph	0.78	0.1	17.6	na			
	% clay (20 cm)	sph	0.64	0.2	31.4	na			
	% sand (20 cm)	sph	0.49	0.8	33.8	na			
	% SOC (10 cm)	sph	0.83	16.1	13.2	na			
	SS-10 cm	sph	0.96	27.0	135.3	ns			
	SS-20 cm	ns				ns			
	SS-30 cm	sph	0.94	43.2	33.9	sph	0.62	19.5	8.4
	SS-40 cm	sph	0.61	44.0	61.1	sph	0.86	0.2	13.3

†Geostatistical parameters: model = semivariogram model where sph = spherical and exp = exponential; nugget semi. = nugget semivariance = % of nugget/total semivariance; r^2 = coefficient of determination for model-semivariance fit; range = range of correlation (m).

‡Non-normally distributed parameters log-normal transformed before analyses.

§ns = non-significant spatial correlation, "all nugget", na = not analyzed.

¶SS-10 cm indicates soil strength averaged to 10 cm, etc.

the soil mapping units. Although soil survey is our most effective method for grouping soil variability at the landscape level, results suggest that some near-surface properties exhibit substantial spatial variability within the mapping units at the scale of conventional survey (1:12 000 to 1:24 000).

Nugget semivariance (NS) values for pre-harvest ρ_b (all sites), pre-harvest θ_g (all sites), % clay (all sites), and depth of surface (for sites 1 and 3) all indicated a strong to moderate degree of spatial correlation over the range of correlation distance. However, % SOC exhibited no spatial dependence on the severely eroded sites 1 and 2, with strong spatial dependence on the moderately eroded site 3. This could be attributable to past erosion effects on SOC distribution at these sites, although further studies are warranted in this.

Comparison between Pre- and Post-Harvest Samples

Our first spatial dependence assessment between pre- and post-harvest data compared the structure of the semivariograms. There were sev-

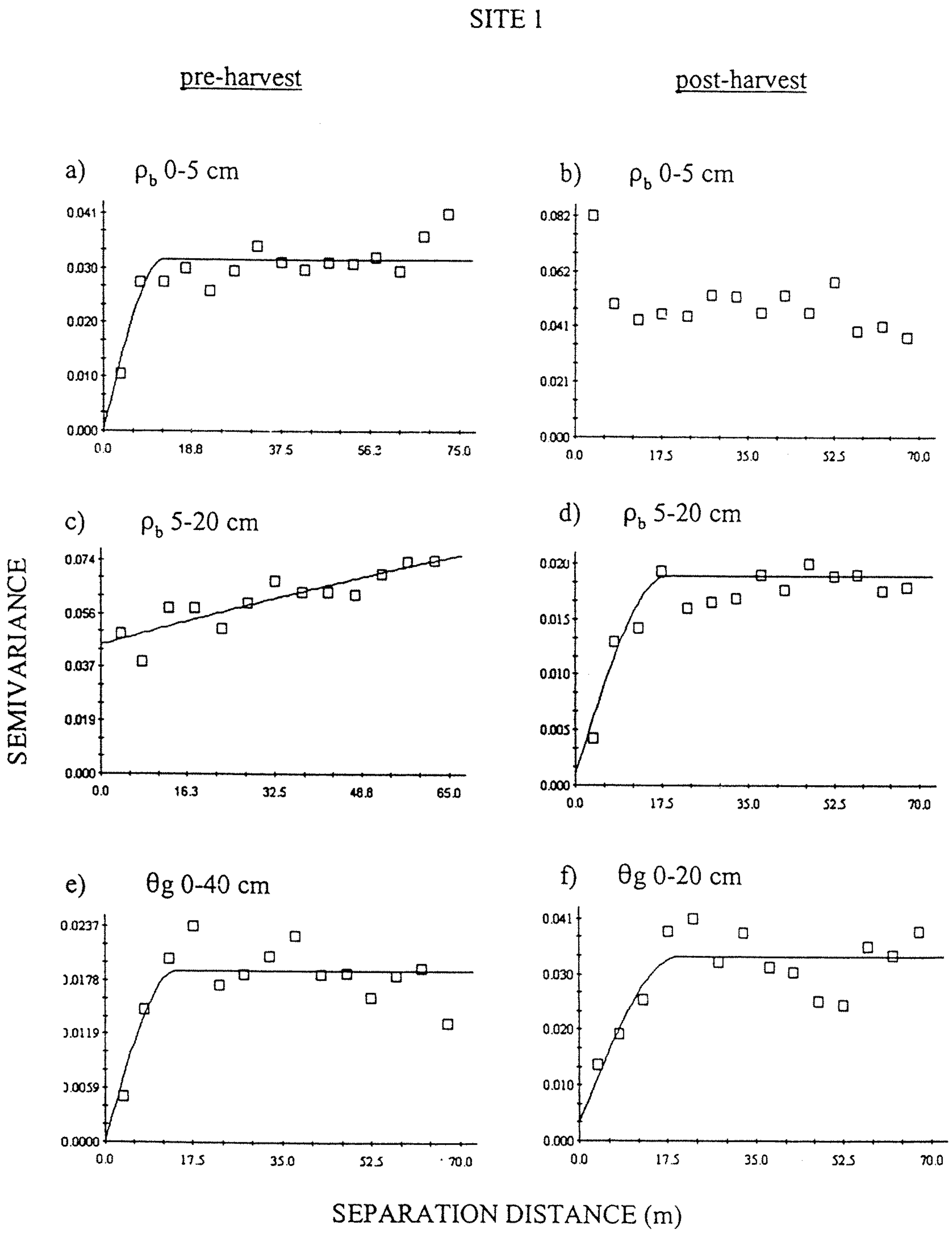

Fig. 4. Semivariograms for site 1: a) Pre-harvest ρ_b for 0–5 cm depth, b) Postharvest ρ_b for 0–5 cm depth, c) Pre-harvest ρ_b for 5–20 cm depth, d) Postharvest ρ_b for 5–20 cm depth, e) Pre-harvest θ_g for 0–40 cm depth, f) Post-harvest θ_g for 0–20 cm depth.

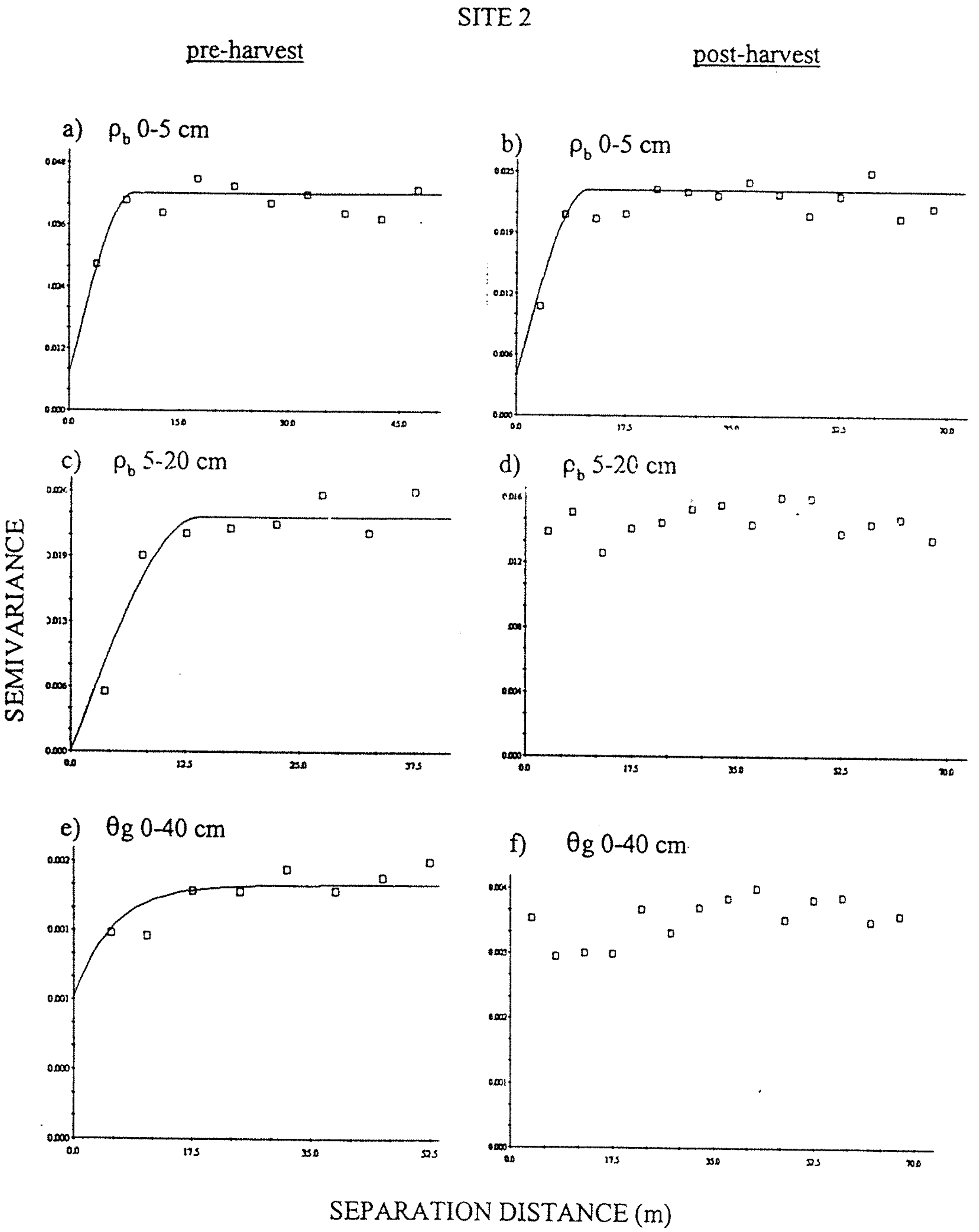

Fig. 5. Semivariograms for site 2: a) Pre-harvest ρ_b for 0–5-cm depth; b) Postharvest ρ_b for 0–5-cm depth; c) Pre-harvest ρ_b for 5–20-cm depth; d) Postharvest ρ_b for 5–20-cm depth; e) Pre-harvest θ_g for 0–40-cm depth; f) Post-harvest θ_g for 0–40-cm depth.

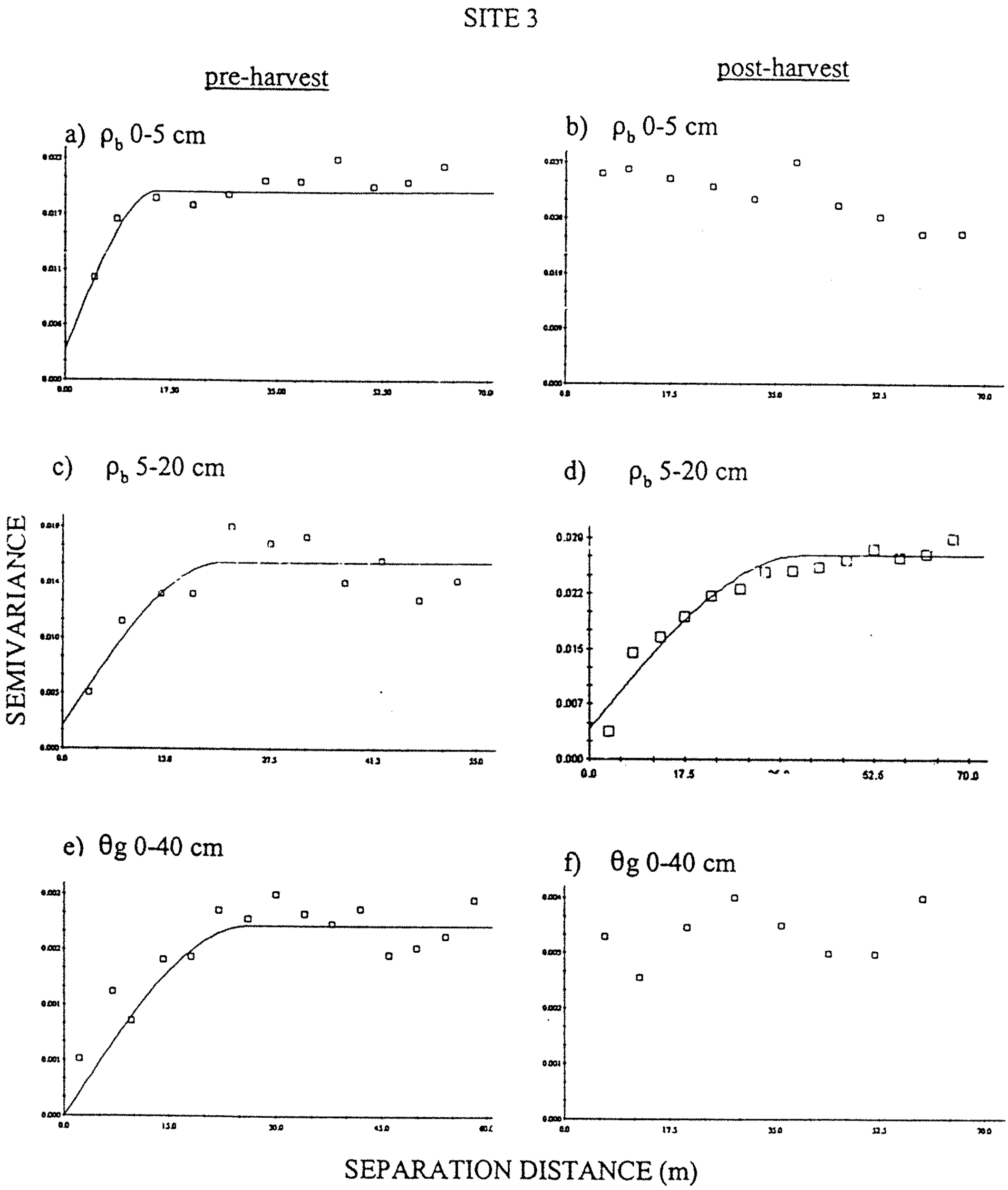

Fig. 6. Semivariograms for site 3: a) Pre-harvest ρ_b for 0–5-cm depth; b) Postharvest ρ_b for 0–5-cm depth; c) Pre-harvest ρ_b for 5–20-cm depth; d) Postharvest ρ_b for 5–20-cm depth; e) Pre-harvest θ_g for 0–40-cm depth; f) Postharvest θ_g for 0–40-cm depth.

eral soil properties that possessed postharvest semivariograms that displayed no structure (termed all nugget), whereas pre-harvest semivariograms displayed a higher degree of spatial correlation (Table 5). We interpreted semivariograms that exhibited an all nugget appearance as indicative of a very low degree of spatial dependence for the sampling scale used. Representative semivariograms are given in Fig. 4 (a–f) (site 1), Fig. 5 (a–f) (site 2), and Fig. 6 (a-f) (site 3). A comparison of ρ_b (0–5 cm) for site 1 (Fig. 4a vs 4b), ρ_b (5–20 cm) and θ_g (0–40 cm) for site 2 (5c vs d and 5e vs f; respectively), and ρ_b (0–5 cm) and θ_g (0–40 cm) for site 3 (6a vs b and 6e vs f; respectively), illustrates our point. For these soil properties, the post-harvest semivariograms indicate minimal spatial dependence. Using this evaluation, there were few cases where spatial correlation existed for post-harvest samples that did not exist for pre-harvest samples (soil strength measurements for site 1 at the 10-cm and 20-cm depths were the exceptions). However, all semivariograms for pre-harvest ρ_b values exhibited some degree of spatial correlation (as illustrated by semivariogram structure), whereas after harvesting, 50% of the ρ_b semivariograms had an all nugget appearance (Table 5). In addition, θ_g values, which displayed strong spatial correlation pre-harvest, displayed a low degree of spatial correlation post-harvest (Table 5 and Fig. 5 e,f and 6 e,f). We interpret these data to suggest a general increase in spatial variability for ρ_b and θ_g after harvesting.

A comparison of semivariogram parameters for pre- and post-harvest ρ_b, θ_g, and soil strength displays few trends with regard to spatial variability. Depending on the parameter, both increases and decreases in nugget semivariance values were observed (Table 5). However, if semivariograms that exhibited an all nugget appearance are given nugget semivariance values of 100% (total semivariance= nugget), the nugget semivariance values averaged overall for ρ_b, θ_g, and soil strength increased between pre-harvest (42.3%) and post-harvest (54.2%) samples. The range of correlation, averaged for pre-harvest versus postharvest sampling, showed a general decrease with harvesting (30.8 m pre-harvest vs 21.6 m post-harvest). Similar to findings above, these data are suggestive of an increase in spatial variablity upon harvesting.

Soil strength values for the 30- and 40-cm depths at all sites displayed well structured semivariograms for both pre- and post-harvest, with a corresponding high to strong spatial dependence as indicated by nugget semivariance values (Table 5). It is suggested that these values are associated with the depth to the clayiest portion of the argillic horizon, which appears to be fairly systematic across the site. Similarly, the depth of surface exhibited strong spatial correlations for sites 1 and 3, which would be consistent with observations for soil strength.

CONCLUSIONS

Harvesting increased ρ_b for these eroded Piedmont soils. Our data indicates increases were greater for the moderately eroded site, where increases in soil strength were also found. Our findings indicate that inclusion of an erosion phase in timber soil inventories of the Southeastern U.S. Piedmont would benefit forest managers when assessing a site's susceptibility to harvesting impacts.

Overall, our results suggest only mildly that harvesting operations increase the spatial variability of soil properties. Decreases in semivariogram structure were observed for some soil properties. Averaged pre- and post-harvest nugget semivariance values and correlation ranges indicated a slight increase in spatial variability of ρ_b, θ_g, and soil strength. Although evidence is not conclusive, the ramifications of increasing variability can be quite large, especially with regard to site-specific forestry. Site-specific forest tillage has been proposed as a way of reducing site-preparation costs while increasing environmental stewardship by applying tillage only where needed. Although obvious portions of a site might warrant this approach (e.g. loading decks, skid trails), other moderate to slightly trafficked portions often constitute the majority of a site (McDonald et al., 1998). It is these areas that questions related to soil classification, near-surface properties, and susceptibility to compaction exist. An increase in variability renders it difficult to develop zones of compacted areas for these Piedmont soils. Future work is needed to evaluate the spatial dynamics of near-surface soil properties for other typical soils of major timber-producing regions.

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