INTERACTION AMONG MACHINE TRAFFIC, SOIL PHYSICAL PROPERTIES AND LOBLOLLY PINE ROOT PROLIFERATION IN A PIEDMONT SOIL

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Abstract-The impact of forwarder traffic on soil physical properties was evaluated on a Gwinnett sandy loam, a commonly found soil of the Piedmont. Soil strength and saturated hydraulic conductivity were significantly altered by forwarder traffic, but reductions in air-filled porosity also occurred. Bulk density did not increase significantly in trafficked treatments. The greatest impacts to soil physical properties occurred in the surface layer. Loblolly pine root proliferation increased in both trafficked and untrafficked treatments but differed in the soil depth at which this occurred. Further investigations are necessary to understand the response of roots to machine traffic.

INTRODUCTION

The impact of forest machinery on harvested sites traditionally has been gauged by changes in soil physical properties including bulk density, soil strength, macroporosity, saturated hydraulic conductivity, and water infiltration (Gent and Ballard 1984, Greacen and Sands 1980, Lenhard 1986, Reisinger and others 1988, Wronski 1984). Soil physical properties are negatively impacted during trafficking; the results can persist for many years and limit tree productivity (Greacen and Sands 1980, Tuttle and others 1988). Low productivity of selected pine species is correlated with impaired root growth and development in compacted soils. Compaction restricts the volume of soil that can be exploited for available moisture and nutrients (Mitchell and others 1982, Sands and Bowen 1978, Tuttle and others 1988). The relationship among machinery, root systems, and soil physical properties has been extensively investigated in agricultural systems and linked to numerical values of soil physical properties that are considered to be root limiting (Unger and Kaspar 1994). An understanding of this relationship for tree species is limited, and future productivity would be aided by an understanding of soil physical changes and their role in root growth.

The objective of the study was an evaluation of the impact of forwarder traffic on selected soil physical properties of a Piedmont soil, and determination of a response by loblolly pine roots to forwarder traffic.

METHODS

The study was established in June 1996 on experimental sites managed by the School of Forestry, Auburn University, and cultivated for agricultural use prior to its conversion to a loblolly pine (*Pinus taeda*) stand. The study site supported a 15-year-old loblolly pine stand with an average diameter at breast height (d.b.h.) of 21 centimeters in a 2.7- by 1.8-meter spacing. The soil series within the study site was identified as a Gwinnett sandy loam, a member of the clayey, kaolinitic, thermic family of Typic Rhodudults. The experimental design consisted of a randomized complete block with two treatments: untrafficked (UNT) and trafficked by a loaded forwarder (TR), and replicated twice. Each replication encompassed an area approximately 3,700 square meters, subdivided into two treatment areas each approximately 1,350 square meters in size and separated by a buffer strip measuring approximately 9 by 45 meters. Each treatment plot contained approximately 12 rows of loblolly pines with 15 trees per row.

Pretreatment site preparation was necessary to permit movement of the forwarder through the stand. This consisted of hand-felling every other row of trees, limbing and topping of trees on site, winching boles to the edge of each treatment block, and removal from treatment areas. Similar pretreatment site preparation was applied to the UNT treatment areas to ensure uniform site conditions for consistency in comparisons. Trafficked treatments consisted of 10 passes of a loaded Franklin 710 forwarder weighing approximately 13 tons and driven at a rate of 3 miles per hour after removal of slash from traffic lanes.

Soil sampling was conducted in three phases: (1) bulk soil sample collection in June 1996 after pretreatment site preparation; (2) collection of soil core after pretreatment and again after installation of traffic treatments in June 1996 in one replication to assess impact of traffic; and (3) collection of soil cores in fall 1996 from each treatment in both replications to compare soil physical properties of UNT and TR treatments. Bulk soil samples were collected at 12 locations in each block with a hand-held auger, in increments of 15 centimeters to a depth of 90 centimeters. The samples were then air-dried, ground, and passed through a 2 millimeter sieve for soil chemical and physical analyses. Sixteen soil cores, 5 centimeters in diameter and 5 centimeters in length, were collected from the soil surface layer (0 to 10 centimeters) at random locations along traffic lanes in one replication of TR prior to and at the conclusion of traffic treatments. Soil cores of similar dimension were collected along traffic lanes at regular intervals (approximately 10 meters) in UNT and TR in each replication to compare treatments; the number of cores collected was dependent on the type of soil physical analysis and the number of soil depths.

Bulk soil samples were analyzed for particle size by the hydrometer method according to Klute (1986). Soil cores

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collected from pre- and post-traffic treatments were analyzed for bulk density, gravimetric water content; saturated hydraulic conductivity; soil moisture retention characteristics at potentials of -l/l 0, -1/3, -1, and -5 bar; and porosity (total and microporosity) according to Klute (1986). Air-filled porosity was measured in each core according to Carter (1990). A total of 72 soil cores was collected from the UNT and TR treatment areas of each replication from three locations per track (or row) at three depths: 0 to 10, 10 to 20, and 20 to 30 centimeters. The cores were analyzed for bulk density and gravimetric water content according to methods previously cited. Additional cores were collected in each row at one location in each treatment, at two depths (0 to 10 and 10 to 20 centimeters) for a total of 20 soil cores per replication. These were analyzed for saturated hydraulic conductivity, soil moisture retention characteristics, and air-filled porosity.

Soil strength was determined with a Rimik CP 20 cone penetrometer with a base cone diameter of 113 square millimeters, manually inserted to a depth of 300 millimeters, and recorded in 25 millimeter increments. Soil strength is expressed indirectly as cone index (Cl), or the force required divided by the cross-sectional area of the base of the cone and measured in units of pressure (megapascals). Soil strength is reported for fall 1996 only.

Root samples were collected prior to installation of traffic treatments in June 1996 and in traffic lanes in fall 1996. Root samples were collected in June 1996 by manually driving polyvinyl chloride (PVC) cores, 7.6 centimeters in diameter and 60 centimeters in length, in 12 random locations in each block. The PVC cores were removed, subdivided into 10 centimeter increments, and roots and soil separated in a Gillison Root Washer. Root length (centimeters) was estimated utilizing a Comair Root Length Scanner and root length densities were calculated by dividing total root length (centimeters) by soil core volume (cubic centimeters). Root length densities were estimated for trafficked and untrafficked sites in one block in Fall 1996 through the collection of five soil cores, 5 centimeters in diameter and 30 centimeters in length, as a transect across one traffic lane (outside track, in track, and between tracks) in three locations along the length of one traffic lane; a total of 15 cores per treatment was collected. Preparation of root samples and root length density calculations were performed as previously described.

Statistical analyses were performed utilizing the Statistical Analysis System (SAS) (SAS 1988). Data collected for soil physical properties were analyzed in an analysis of variance (ANOVA), and means were analyzed by paired t tests. Comparisons of soil physical data from pre- and post-traffic sites was performed by paired t tests.

RESULTSANDDISCUSSION

Soil Physical Characterization

Soil texture and bulk density of the study site are typical for soils of the Piedmont physiographic region (tables 1 and 2). Particle size analysis indicated the presence of subsoil layers with a high percentage of clay. This is indicative of the presence of an argillic horizon (B2t), a defining characteristic of the Ultisol soil order of which the Gwinnett soil series is a member. Bulk density values of 1.3 megagrams per cubic meter of the surface soil layer were higher than expected for forest soils of the Piedmont. The high soil porosity, both total and air-filled, high hydraulic conductivity, and low percentage of gravimetric water content at field capacity (-1/10 bar) is a consequence of the sandy nature of the surface soil layer and the positive influence of undisturbed tree growth (table 1 and fig. 1).

Soil physical characteristics determined for soil samples of the study site are similar to properties reported for a Gwinnett sandy loam (SCS 1981). The Gwinnett soil series is a highly weathered, Piedmont soil of low moisture capacity in surface horizons underlain by a B2t, or argillic, subsoil horizon. Bulk density reported for an undisturbed Piedmont forest soil was 1 .16 megagrams per cubic meter

Table l-Impact of forwarder traffic on selected soil physical properties of a Gwinnett sandy loam soil

	Physical Property					
				Porosity		
Soil status	Bulk density	Moisture content	Saturated hydraulic conductivity[a]	Air-filled	Microporosity	Total
	Mg/m^{-3}	Percent	Cm/hr^{1}	Percent		
Pretraff ic	1.30	21.4	2.43	32.5	20.3	52.7
Posttraff ic	1.56	19.7	0.177	22.7	18.4	41.2

[a] Means of soil physical parameters were significantly different at the P = 0.05 level.

Table 2-Particle size analysis of a Gwinnett sandy loam soil

Depth	Sand	Silt	Clay	Classification
---Cm---	Percent			
O-10	72	6	23	Sandy clay loam
IO-20	47	18	35	Sandy clay
20-35	30	28	43	Clay
35-45	30	25	43	Clay

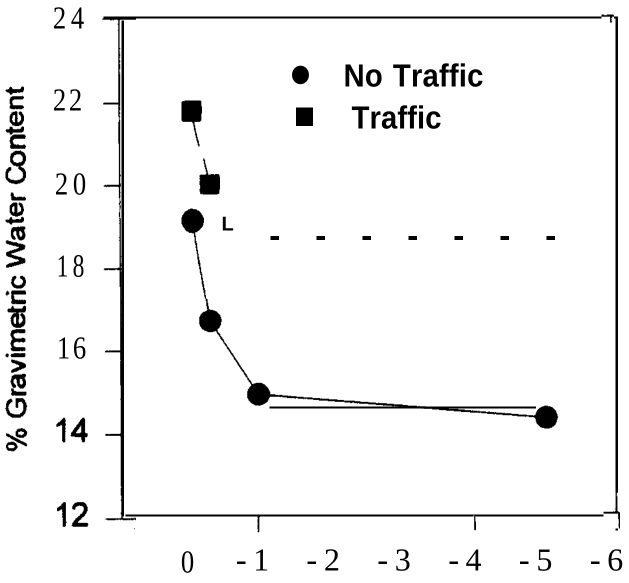

Figure I-Soil moisture retention characteristics of the surface layer of a Gwinnett sandy loam subjected to no traffic (UNT) and traffic (TR).

(Gent and Ballard 1984). In spite of elevated bulk density values, saturated hydraulic conductivity of 2.34 centimeters per hour and macroporosity in the vicinity of 33 percent are typical of forest soils that remain undisturbed for extended periods of time (Reisinger and others 1988).

Impact of Forwarder Traffic

Bulk density, soil moisture retention, hydraulic conductivity, and porosity of the soil surface layer responded negatively to forwarder traffic (table 1 and fig. 1). Soil compaction as a result of forwarder traffic increased in the study site as indicated by increased bulk density and decreased air-filled porosity. Total porosity was reduced at the expense of the large, air-filled pores in the surface layers after trafficking, which converted soil macropores to micropores. This change in pore size reduced the ability of the soil to transmit water and increased the soil moisture retention rate at each soil moisture potential. An indication of the alteration of pore size from trafficking is the shift in moisture retention characteristics in TR compared to UNT (fig. 1).

The changes in soil physical properties reported in this study are typical of the impact of machine traffic on bulk density, macroporosity, and saturated hydraulic conductivity of forest soils (Incerti and others 1987, Lenhard 1986, Wronski 1984). Bulk density increased to 1.56 megagrams per cubic meter in the surface layer of TR, matching bulk density values reported for heavily trafficked (in skid trails) sandy loam soils in North Carolina (Gent and others 1984). Air-filled porosity decreased from 33 to 23 percent in traffic lanes but the post-traffic air-filled porosity of 22 percent exceeds the minimum air filled percentage of 10, which is considered to be the lower limit for proper oxygen diffusion (Incerti and others 1987). Saturated hydraulic conductivity reductions from 2.34 to 0.177 centimeters per hour were typical of sandy loam (or finer) soils subject to compaction (Akram and Kemper 1979).

Subsoil Response to Forwarder Traffic

Soil response to forwarder traffic was detectable in subsurface (greater than 10 centimeters) as well as surface (0 to 10 centimeters) layers (table 3 and fig. 2). Bulk density was lower in UNT compared to TF? at comparable depths, and may indicate a response, however slight, to forwarder traffic. An ANOVA determined that neither the treatment, the depth, nor their interaction was significant for bulk density. Cone index (Cl) values were consistently and significantly higher in TR than in UNT at all sampled depths ($P > 0.001$). Although significant differences were detected at every depth, the impacts associated with trafficking may be limited to the upper 15 centimeters where the greatest differences occurred. A 10 percent difference in air-filled porosity and a tenfold reduction in saturated hydraulic conductivity were detected between TR and UNT in the surface layer, and little difference was discerned in the

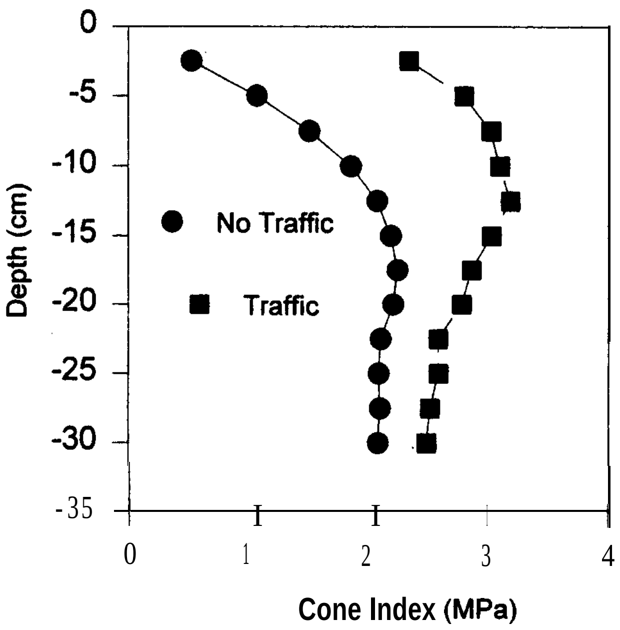

Figure 2-Cone index (MPa) measurements of a Gwinnett sandy loam subjected to no traffic (UNT) and traffic (TR). All depths are significantly different between treatments ($P > 0.001$).

Table 3-Comparison of soil physical properties at selected depths of a Gwinnett sandy loam subjected to two levels of trafficking

Treatment	Bulk density	Gravimetric water content	Air-filled porosity	Saturated conductivity
	Mg/m-3	*--------------Percent*	*————*	*Cm/hr 1*
Traffic				
o- 10	1.57	21 .o	27.7	0.27
10-20	1.70	15.2	21.1	0.186
20 - 30	1.77	17.4	ND	ND
No Traffic				
o- 10	1.51	22.1	37.3	3.12
10-20	1.69	16.5	18.7	0.078
20 - 30	1.66	18.9	ND	ND

ND = no samples analyzed.

subsoil layer. Treatment alone did not significantly affect air-filled porosity but was significantly lower in subsoil layers than in surface layers. Saturated hydraulic conductivity of TR slightly exceeded UNT in the 10 to 20 Centimeter layer and is potentially explained by the higher porosity of this layer. Treatment, depth, and their interaction were significant sources of variation for saturated hydraulic conductivity. Saturated hydraulic conductivity in surface layers was significantly higher than in subsoil layers for both treatments, and conductivity was reduced significantly in the surface layer in trafficked soils.

Natural differences in soil physical properties between surface and subsurface layers may be present in highly weathered soils and potentially explained in terms of soil texture. Bulk density and soil strength increases with depth, under undisturbed conditions (UNT), occurred simultaneously with clay content increases and sand fraction decreases. Bulk density and soil strength are known to vary under the influence of particle size distributions in a soil layer (Carter 1990, Tuttle and others 1988). The presence of clay and very fine sand correlated well with higher bulk density and soil strength values in undisturbed profiles in North Carolina (Vepraskas 1988).

Machine traffic exacerbates natural conditions by packing soil particles closer together regardless of texture, and increasing bulk density and soil strength at the expense Of porosity (Greacen and Sands 1980). The impact of such activities is often limited to the near-surface soil environment, although changes in soil properties can be induced below 40 centimeters by increasing loads (Burger and others 1985, Greacen and Sands 1980). Soil strength data may corroborate this observation as the extent of impact from machine traffic was greatest in the upper 15 centimeters. Significant differences in Cl between treatments at every depth may reflect the influence Of varying moisture conditions at the time of measurement. Cone index was determined in one replication under low moisture conditions rather than field capacity, which is necessary to minimize the influence of related soil factors on penetration resistance (O'Sullivan and others 1987). This may have overestimated soil strength when Cl values were averaged for each treatment.

Loblolly Pine Root Proliferation

Root length proliferation within the soil profile was highest in the surface layer and tapered with depth. Root length densities were less than 4 centimeters per cubic centimeter at each depth interval, with a high standard deviation (table 4). The high standard deviations indicate a high degree of variability for root densities, which is typical of this type of data. Root proliferation increased in trafficked treatments (UNT vs. TR) from the pretraffic levels and appeared to be influenced by forwarder traffic. However, significant increase in root biomass in UNT also occurred. Regardless of the reason for these differences, total root biomass accumulation in the sampled profile in UNT and TR were similar, but distribution differences were evident. The

Table 4-Root length densities and standard deviations of a 15-year-old loblolly pine stand under pretraffic and trafficked conditions in a Gwinnett sandy loam

Depth	Root length density		
		Posttraffic	
	Pretraffic	Traffic	No traffic
Cm	————	*Cm/cm -3*	*-----------*
o- 10	3.72 (1.58)	17.87 (9.46)	6.39 (0.66)
10-20	1.99 (1.52)	3.57 (2.13)	20.07 (21.46)
20 - 30	1.72 (0.76)	2.50 (1.54)	1.92 (0.09)

majority of root mass accumulation in UNT occurred in the intermediate depth of 10 to 20 centimeters as opposed to TR, which experienced root proliferation in the surface layer.

Root length distribution under undisturbed conditions (pretreatment) was similar to root distributions reported for *Pinus elliottii* Engelm. and *P. radiata* (Davis and others 1983, Escamilla and others 1991). The natural decline in root length density with depth may reflect subsoil conditions that limited root growth and proliferation. The limited number of studies on the influence of soil physical properties on pine root growth have found root growth to be limited at bulk densities of 1.4 and 1.6 megagrams per cubic meter in a sandy clay loam and sandy soil, respectively, and at cone index values in excess of 3.0 MPa (Sands and Bowen 1978, Sands and others 1979, Tuttle and others 1988). Root response after trafficking may be the result of soil physical properties that changed in surface layers. This may have induced a large degree of proliferation due to its inability to penetrate below 10 centimeters. A similar situation had the potential to occur in UNT as naturally occurring limits were encountered at the 20 centimeter depth. The impact of traffic on root proliferation requires more indepth evaluation.

CONCLUSION

Forwarder traffic had a negative impact on the soil physical properties of a Gwinnett sandy loam. Significant changes occurred in soil strength and saturated hydraulic conductivity as a result of forwarder traffic. The impacts were greatest in the surface layer and, to a lesser degree, in subsoil layers. Root distribution within undisturbed profiles was relatively uniform but forwarder traffic appeared to induce root proliferation. The change in soil properties was consistent with other studies but root performance in trafficked plots did not agree with results reported by others.

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