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Influence of Thinning Loblolly Pine (*Pinus taeda L.*) on Hydraulic Properties of an Organic Soil

J. McFero Grace III, Research Engineer

USDA Forest Service, Southern Research Station, G.W. Andrews Forestry Sciences Laboratory, 520 Devall Drive, Auburn, AL 36849, jmgrace@fs.fed.us.

R. W. Skaggs, William Neal Reynolds Professor and Distinguished University Professor

Biological and Agricultural Engineering Department, North Carolina State University, Raleigh, North Carolina.

D. Keith Cassel, Professor

Soil Science Department, North Carolina State University, Raleigh, North Carolina.

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Abstract. *The impact of forest operations on soil properties has been a concern in forest management over the past 30 years. The objective of this study was to evaluate the impact of forest thinning operations on soil hydraulic properties of a shallow organic (Belhaven series) soil in the Tidewater region of North Carolina. Soil physical properties were evaluated in a nested design by collecting soil cores from an unthinned control and following a 40-ha fifth-row thinning with selection performed on a 14-year-old loblolly pine plantation in April 2001. Thinning decreased saturated hydraulic conductivity and drained volumes for a given water table depth; however, bulk density was not influenced. Saturated hydraulic conductivity determined by the constant head method before thinning was 100 cm hr^{-1}. Thinning resulted in a 3-fold decrease (from 100 to 32 cm hr^{-1}) in saturated hydraulic conductivity. The thinned watershed had less drainage at low pressures and greater retained water contents under increased soil water tensions in comparison with the control. Drained volume on the thinned watershed for a water table depth of 200 cm under drained to equilibrium conditions was reduced by 60 percent in comparison to drained volume for the control watershed.*

Keywords. Soils Properties, Forest Operations, Thinning, Compaction, Bulk Density, Drainage

Introduction

Site preparation, thinning, harvesting, and fertilization operations are typically associated with intensive forest management practices needed to meet timber product demands. Intensive management practices are often necessary to meet the goal of maintaining or improving productivity while sustaining or improving resource quality. Commonly, these forest operations are highly mechanized and require the movement of large machinery through forest stands. Increased ground pressures under the machinery may result in compaction and rutting, which can alter soil physical properties. The extent and magnitude of mechanized forest operations on soil properties are related to soil moisture content at the time the operations are performed (King and Haines, 1979; King, 1979; Burger et al., 1995). Forest operations on wet and poorly drained sites have had degrading impacts on bulk density, saturated hydraulic conductivity (k_{sat}), soil mechanical resistance, and porosity (Aust et al., 1991a, 1991b, 1993a, 1993b; Blanton et al., 1998; Grace et al., 2006).

Previous research in coastal areas on mineral soil and/or upland sites has shown that forest operations affect soil properties. For example, Gent et al. (1983) investigated the effect of harvesting and site preparation on soil physical properties of a 25-year-old loblolly pine plantation with Onslow (Spodic Paleudult, fine loamy, siliceous, thermic) and Rains (Typic Paleaquult, fine loamy, siliceous, thermic) soil series in the Lower Coastal Plain. Harvesting and site preparation were found to increase bulk density and decrease total porosity and saturated hydraulic conductivity (k_{sat}) in the first 8-cm below the soil surface and in the first 15-cm of depth in skid trails. Similar impacts associated with timber harvesting were observed on poorly drained soils in coastal South Carolina (Aust et al., 1991a). Post-harvest bulk density and mechanical resistance were significantly higher on the harvest areas than baseline samples. In addition, total porosity and $k_{\mathbf{sat}}$ decreased following harvest. In another study by Blanton et al. (1998), reductions in drainable porosity of nearly 50 percent resulted from harvesting on poorly drained soils in Carteret County, North Carolina. Soil water contents were significantly higher for the undisturbed areas than for the harvested areas for soil water pressure heads greater than –100-cm.

Most of the investigations cited above quantified the impact of forest operations on mineral soils and focused on forest floor disturbance and concomitant changes in bulk density. Organic soil behavior might be different from that of mineral soils subjected to the same conditions. Hydraulic properties of organic soils can be complex due to their composition (colloidal matter, humus, carboxyl groups (COOH)) and high cation exchange capacities (CEC) (Grace et al., 2006). The organic soil (Belhaven series) evaluated in this investigation is characterized by high saturated water contents that drain at relatively low negative soil water pressures. Previous investigations focusing on soil property changes resulting from agricultural development on organic soils have shown increased water yield, peak flows, and higher water tables (Skaggs et al., 1980).

Disturbance from mechanized equipment potentially can alter the drainage characteristics by decreasing porosity of these soils. However, the impact of forest operations on physical and hydraulic properties of organic soils has been given little consideration in previous research. Knowledge of the impacts of forest operations on these sensitive soils is needed to evaluate effects of harvesting alternatives. This study was initiated to (i) define soil physical properties of drained forested organic soils in the Tidewater region for use in model development, and (ii) assess the impact of thinning on soil physical properties from plantation pine watersheds.

Methods

Site Description

The study area is located in the Tidewater region of North Carolina at approximately 35^o 50' N latitude and 76^o 40' W longitude in Washington County near Plymouth, North Carolina (Figure 1). Soils in this poorly drained area have shallow water tables (<0.40 m the majority of the year) in their natural condition. The study was located on artificially drained experimental watershed units owned and managed by Weyerhaeuser Company, Inc. An established 14-year-old 56-ha loblolly pine (*Pinus taeda L.*) plantation was isolated by a network of forest roads and a series of drainage ditches. The watershed is drained by parallel lateral ditches 0.9 to 1.3-m deep spaced 100 m apart. The isolated watershed is surrounded by various age loblolly pine plantations on three sides (eastern, western, and southern boundaries) and a mature hardwood stand on the northern side. In 1999, the watershed was divided into a 40- and a 16-ha sub-watershed using earthen plugs in the collector canals. The larger 40-ha watershed served as the treatment watershed and the 16-ha watershed served as the control watershed, hereafter referred to as WS5 and WS2, respectively (Figure 2).

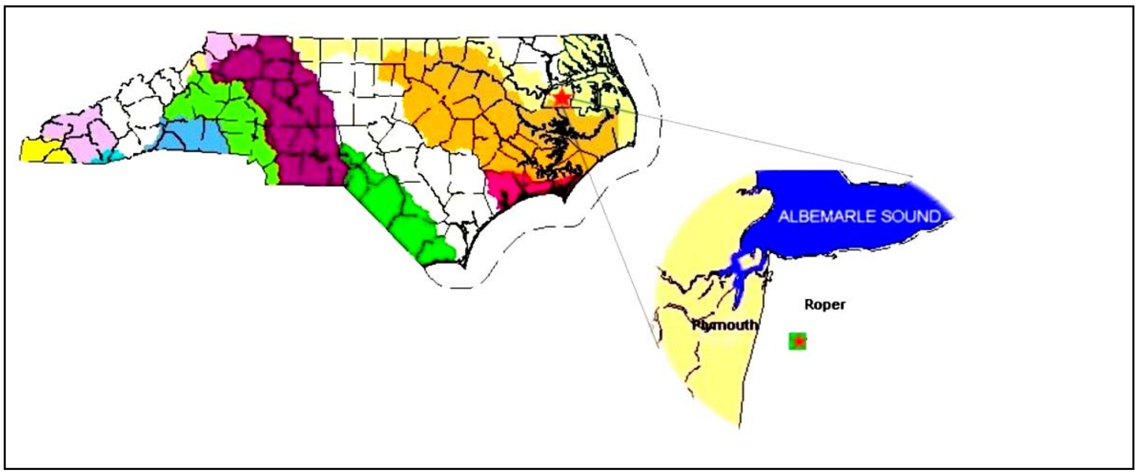

Figure 1. Location of the study watershed in the Tidewater region of North Carolina near Plymouth, NC.

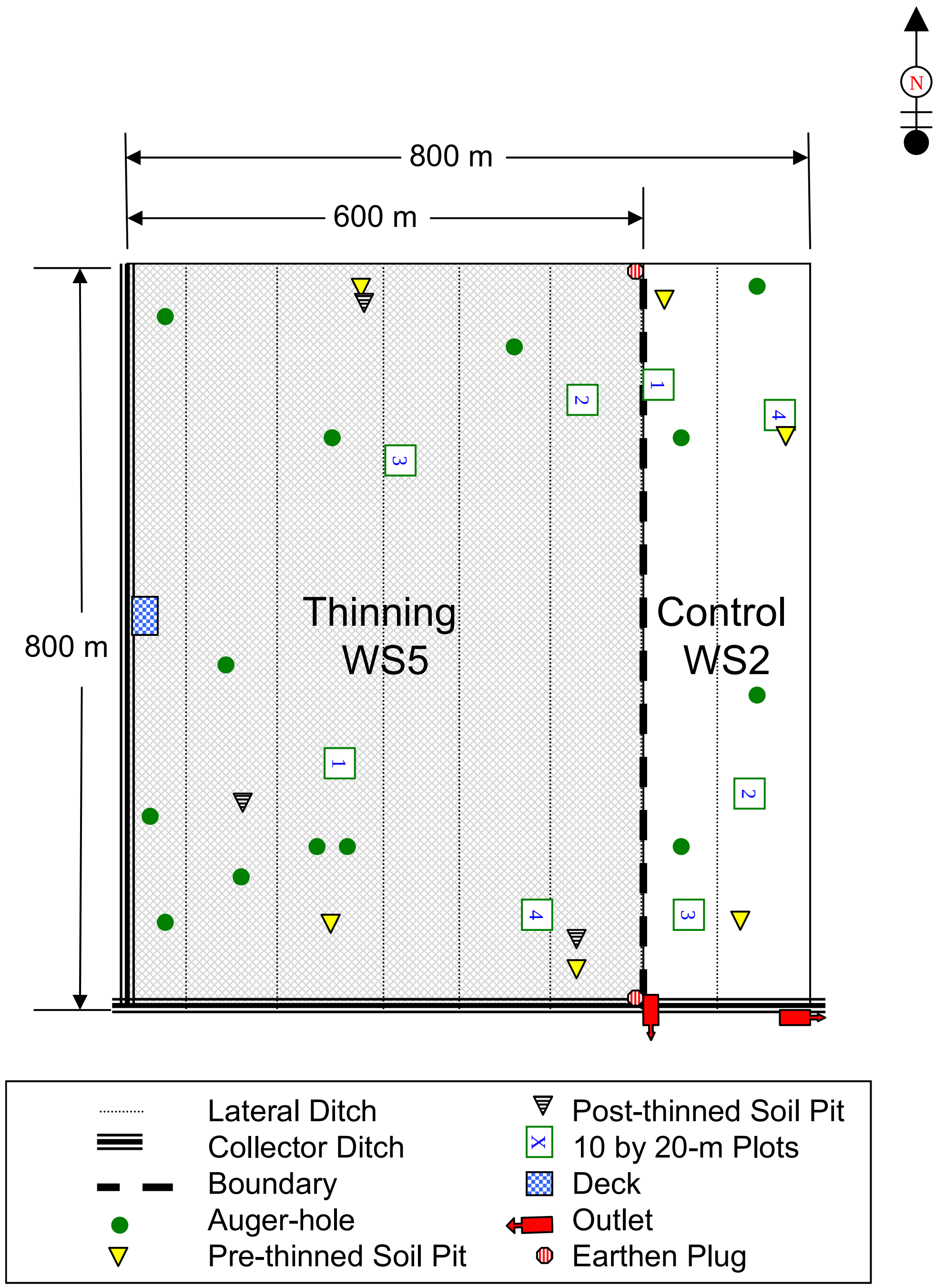

Figure 2. Paired watersheds, WS2 and WS5, defined in the study to evaluate thinning effects on soil properties. Locations of drainage ditches, earthen plugs, watershed outlets, soil pits, and auger-holes are shown.

The soil series is predominantly Belhaven muck (loamy, mixed, dysic, thermic Terric Medisaprists) characterized by extremely acid shallow organic horizons with thickness ranging from 41 to 130 cm (SCS, 1981). The soil organic matter (SOM) content was 80 percent or greater and total porosity was 0.75 cm^3 cm^{-3} in the upper 60-cm of the soil profile (Table 1). Average ground surface elevation is 4.1 to 4.5 m above sea level with an average slope of less than 0.1 percent.

Table 1. Organic matter content and total porosity of top soil layer for study watersheds prior to thinning WS5.

Watershed	Depth (cm)	Organic Matter (%)†	Total Porosity ($cm^3\ cm^{-3}$) *†
WS2	0-60	93 (9)	0.77 (0.14)
WS5	0-60	92 (4)	0.80 (0.05)

* Total porosity taken as equal to the measured saturated volumetric water content.

† ( ) standard deviations are given in parenthesis.

Treatment and Study Design

A 40-ha fifth-row thinning with selection treatment (days 93-115) was conducted on WS5 in April 2001; the remaining 16-ha (WS2) served as the un-thinned control. The fifth-row with selection thinning method consists of the removal of every fifth tree row thereby creating a corridor for mechanized equipment access (Figure 3). In addition, selected trees are removed from the remaining four rows between corridors. The thinning operation was completed with a feller buncher, two grapple skidders, and a loader. The entire thinning was serviced by a deck located at the western watershed boundary (Figure 2). A primary skid trail the length of the watershed (east to west) serviced intermediate skid trails between lateral ditches. The stand was thinned from an estimated 1060 trees per hectare with basal area of 39 $m^2\ ha^{-1}$ to 320 trees per hectare with basal area of 12 $m^2\ ha^{-1}$.

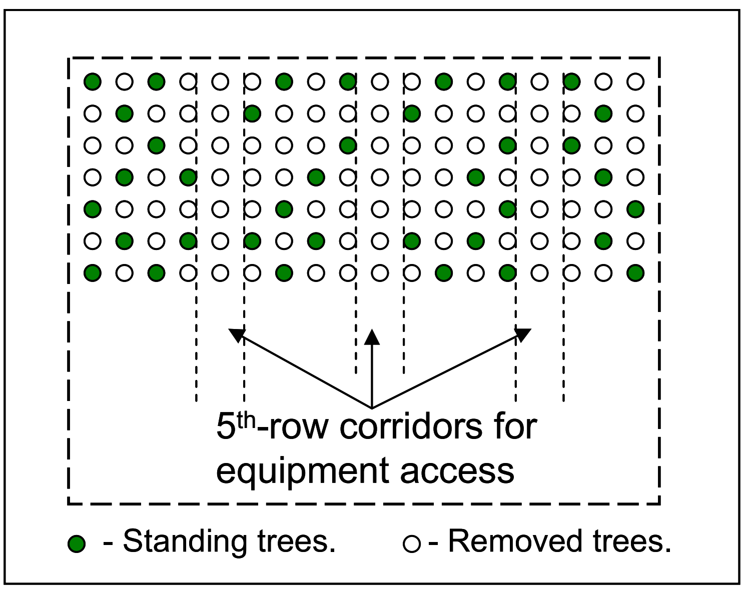

Figure 3. Illustration of fifth-row thinning with selection treatment conducted on the WS5 watershed.

A nested experimental design to evaluate soil physical property impacts was utilized (Keppel, 1982; Montgomery, 1991). The thinned watershed had a companion unthinned (control) watershed. The model for this design is given by:

$$Y_{ijk} = u.. + T_i + S_{j(i)} + O_k (E_{ijk}) \qquad (1)$$

Where:

Y_{ijk} = predicted response

u.. = overall mean

T_i = Treatment effects

$S_{j(i)}$ = Plot location effect nested within watersheds

O_k = Observation effects taken as error in this experiment

The stated hypothesis for the analysis of variance (ANOVA) is that treatments effects are equal to zero.

Soil Sampling

Prior to thinning WS5 soil properties for each individual watershed were initially measured on soil cores removed from three randomly located soil pits. This was done between August 1999 and April 2000. Soil pits were used for textural classifications and the measurement of horizon boundaries for each of the four identified horizons (O_a, A, B, and C horizons). Soil cores (7.6 cm in diameter and 7.6 cm in length) (Blake and Hartge, 1986) collected from each horizon of the soil profile were used to determine the soil water characteristic and volume drained relationships. Soil water characteristics for the control (WS2) and the pre-thinned condition on WS5 were developed based on a total of eighteen cores from the O_a horizon, nine cores from the A horizon, eight cores from the B horizon, and seven cores from the C horizon. Soil water characteristics for the thinned condition were developed based on six soil cores from each of the top three horizons (O_a, A, and B horizons) taken from soil pits (denoted as post-thinned soil pits in Figure 2) during the spring and summer of 2001. The C horizon was not sampled following thinning because the layer (163-250 cm depth) was below the water table.

Assessment of the thinning effect on D_b, k_{sat}, and soil water characteristic was made possible by the collection of a second set of intact soil cores during the spring of 2001 after thinning. Eight randomly located soil cores (7.6 cm in diameter by 7.6 cm in length) were collected at 5- and 30-cm depths from four randomly located 10- by 20-m plots nested within each watershed representing a total of 64 cores per watershed. Core samples were trimmed in the field, sealed with plastic caps, sealed in plastic bags, placed on ice, and transported to the laboratory for analysis.

Soil water characteristics were developed for the control, pre-thinned, and post-thinned condition based on cores taken from randomly located soil pits (Figure 2). The volume drained versus water table depth and drainable porosity relationships were determined from soil water characteristics using procedures described by Skaggs et al. (1978). The volume drained for a given water table depth, or volume of water free pore space in the profile above the water table, represents the volume of water (in depth units, cm^3 per cm^2 of surface area) that drains when the water table is lowered from the surface to the given depth with the soil profile above the water table drained to equilibrium.

Organic matter content of the surface soil horizon was determined by analysis of 0.5 kg soil samples collected from the O_a horizon from four randomly located plots within each watershed. SOM content was measured by determining soil sample carbon content using the loss on ignition method (Rabenhorst, 1988). Saturated hydraulic conductivity was determined using both the constant head method (Klute and Dirksen, 1986) and the auger-hole method (van Beers, 1958). A constant hydraulic gradient of 1.7 cm cm^{-1} was used to determine saturated hydraulic conductivity by the constant head method. Saturated hydraulic conductivities of the two upper soil profile layers (O_a and A horizons) were determined using the auger-hole method. A total of thirteen tests were randomly distributed over the thinned and control watersheds and used to determine k_{sat} by the auger-hole method. The field tests were conducted with an auger-hole depth of 90 cm and water table depths ranging from 25-35 cm.

Volumetric water content for each pressure step in the soil water characteristic (0, 3.8, 10, 20, 30, 40, 60, 80, 100, 140, 200, 300, and 500 cm of water) for the watersheds was tested for treatment effects using SAS GLM procedures (SAS, 2004). D_b and k_{sat} data collected from the four randomly located plots nested within each watershed were tested using SAS NESTED procedures (SAS, 2004). Individual treatment mean values were tested for significance at the 0.05 probability level where the nested analysis of variance indicated significant differences.

Results and Discussion

Soil profiles, based on profile descriptions prior to thinning, were similar for watersheds WS2 and WS5 and were consistent with the Belhaven muck series (SCS, 1981). Soil water characteristics, k_{sat}, and D_b were not significantly different based on comparisons by horizon between the control (WS2) and pre-thinned condition in WS5. Consequently, data for these watersheds were combined to represent the pre-thinned condition and are presented in Table 2 and Figure 4. Bulk density and saturated hydraulic conductivity for the O_a horizon was significantly different from all other horizons for the pre-thinned condition (Table 2).

Saturated water contents of 0.777 and 0.734 cm^3/cm^3 for the thinned and pre-thinned condition, respectively, were not significantly different (p=0.256). Volumetric water contents were consistent with the behavior of organic soils, that is, volumetric water contents for both watersheds initially decreased significantly for low pressure heads (less than -10 cm). The effect of thinning on the soil water characteristic of the O_a horizon is shown in Table 3 and Figure 5. Volumetric water contents for the pre- and post-thinned condition were not detected as different at soil water pressures greater than -20 cm, however; the thinned watershed had higher water contents at all pressure heads ≤ -20 cm at the 0.05 probability level (Table 3). The shape of the two soil water characteristic curves was similar and parallel for water pressures < -20 cm (Figure 5). Soil in the thinned watershed retained 70 percent of its saturated water content at a pressure head of -500 cm of water (0.5 bar) in contrast to 50 percent for the control watershed. That is, the water content at -500 cm of water was 0.53 for the thinned site compared to 0.38 for the control. Apparently, the thinning operation reduced the number of large pores which empty under relatively small tensions thereby increasing the water content.

Table 2. Soil textural classification, D_b, and k_{sat} for each horizon in the pre-thinned organic soil profile determined on cores collected from randomly located soil pits.

Horizon	Layer Depth cm	Sample Depth cm	Classification	D_b g cm^{-3} †	k_{sat} cm hr^{-1} †
O_a	0-60	40	Black, organic, loam	0.47 (0.35)b	124 (115)a
A	60-114	80	Reddish brown, clay loam	1.10 (0.48)a	24 (17)b
B	114-163	140	Light brown, sandy clay loam	1.37 (0.16)a	6 (10)b
C	163-250	200	Gray, loamy sand	1.52 (0.03)a	15 (20)b

† ( ) standard deviations are given in parenthesis.

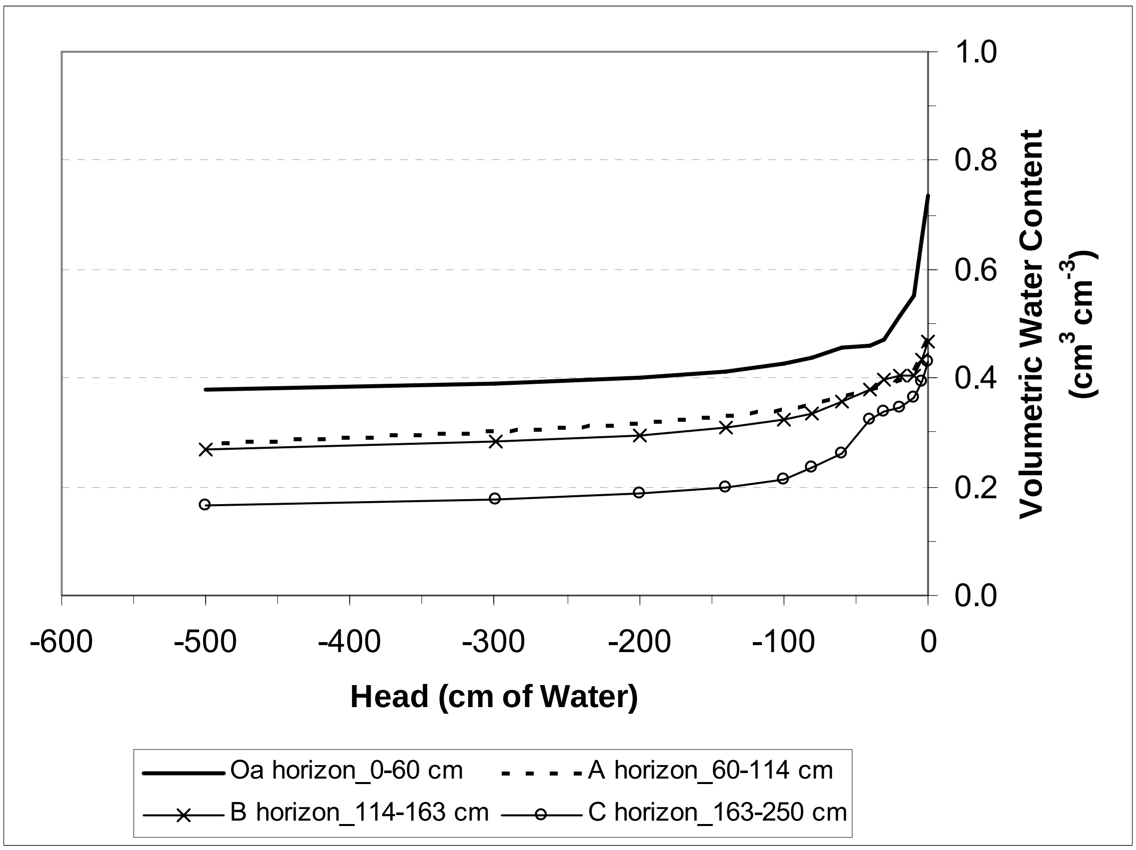

Figure 4. Soil water characteristic for each horizon in the soil profile for the pre-thinned condition.

Table 3. ANOVA results for tests on mean volumetric water contents for each pressure step in the soil water characteristic for the O_a horizon on pre- and post-thinned conditions.

Pressure Head (cm of Water)	Pre-thinned † (cm^3 cm^{-3}) N = 10	Post-thinned (cm^3 cm^{-3}) N = 6	Standard Error	P-value
Saturation	0.734	0.777	0.0502	0.256
-3.8	0.657	0.707	0.0456	0.334
-10	0.551	0.654	0.0499	0.114
-20	0.514	0.636	0.0481	0.032*
-30	0.461	0.623	0.0469	0.018*
-40	0.472	0.614	0.0488	0.014*
-60	0.454	0.601	0.0477	0.011*
-80	0.437	0.588	0.0490	0.011*
-100	0.425	0.578	0.0493	0.010*
-140	0.412	0.564	0.0524	0.012*
-200	0.400	0.552	0.0542	0.014*
-300	0.391	0.544	0.0567	0.016*
-500	0.378	0.529	0.0640	0.026*

* Significant at the 0.05 probability level.

† Mean volumetric water contents for pre-thinned WS5 and control samples.

Volume drained relationships were developed and plotted (Figure 6) for the pre- and post-thinned conditions based on soil water characteristics. Based on ANOVA, volume drained or water free pore space under drained to equilibrium conditions was less for the post-thinned condition than for the pre-thinned condition (P = 0.087). Volume drained was 18 cm (cm^3 per cm^2 of surface area) for the pre-thinned condition and 10 cm for the post-thinned condition at a water table depth of 90 cm. The difference of 8 cm was significant at the 0.10 probability level. The difference between pre- and post- thinning increased with increasing water table depth. For example, the volume drained at a water table depth of 200 cm was 36 cm (cm^3 per cm^2 of surface area) for the pre-thinned condition compared to 21 cm for the post-thinned condition. Average drainable porosities for the pre-thinned condition for water table depths less than 75 cm and greater than 75 cm were 0.25 and 0.16, respectively. The thinned watershed had an average drainable porosity of 0.14 for water table depths less than 75 cm and 0.10 for water table depths greater than 75 cm. Similar results from previous investigations were attributed to compaction that primarily affected larger pore spaces that drain under relatively small tensions (Grace et al., 2006).

The saturated water contents for both the pre-thinned and post-thinned watersheds (Table 3) fall within the range values found for Belhaven series soils in the Tidewater region following agricultural land development (Skaggs et al., 1980) and following clearcut harvesting operations (Grace et al., 2006). Both of the previous investigations in the Tidewater region reported a 35 percent or greater reduction in drained volumes following operations when the water table depth was 150 cm. The reductions in drained volume for a given water table depth and drainable porosity reported in this investigation (<50 percent) are greater than reported for Skaggs et al. (1980), but similar to those reported in Grace et al. (2006).

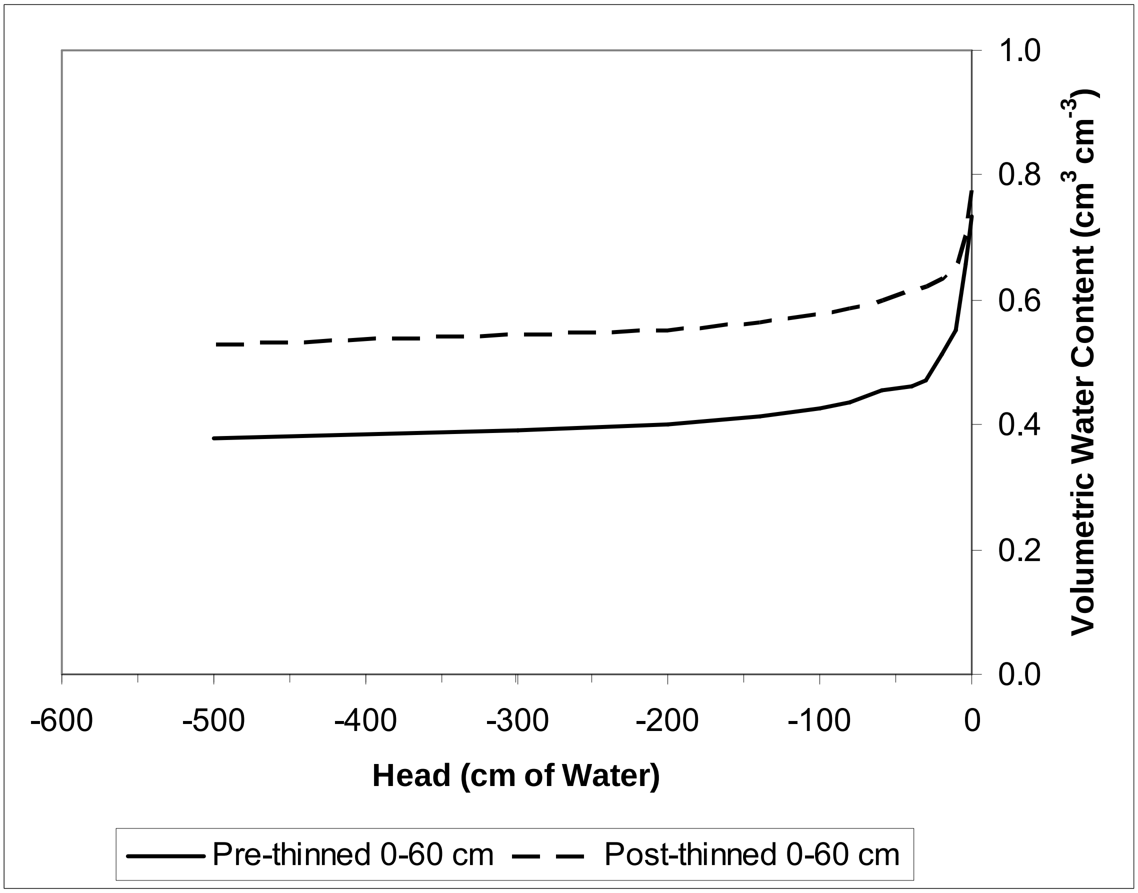

Figure 5. Surface soil water characteristic developed for the pre-thinned condition (control and pre-thinned WS5) and post-thinned WS5 for the Belhaven series soil in this investigation.

Bulk density and k_{sat} data for the O_a horizon (0-60 cm) deviated from normality and were normalized using a logarithmic transformation before performing the nested ANOVA. Post-thinned D_b was not different from D_b for the control watershed (α= 0.05) (Table 4). The standard deviation of D_b for the thinned and control was 0.32 and 0.38, respectively. The variability in the soil property data can be expected due to spatial variability in soils and operations seldom affect soils on a watershed uniformly. That is, traffic intensity is variable over a watershed following mechanical operations. The random location of plots in this investigation assessed the overall effect of the thinning operation by accounting for variability across the watersheds (beds, rows, inter-rows, and skid trails). Thinning (treatment) explained less than 1 percent of the total variance in the nested model for bulk density. However, k_{sat} measured by the constant head method decreased significantly as a result of thinning (p-value = 0.040) (Table 4). The control watershed had a k_{sat} of 100 cm hr^{-1} which was three times greater than k_{sat} on the thinned watershed (32 cm hr^{-1}). This result is consistent with those reported above for the soil water characteristic and volume drained relationships which suggest compaction occurred as a result of the thinning operation. However, analysis did not detect significant differences in bulk density resulting from the thinning operation.

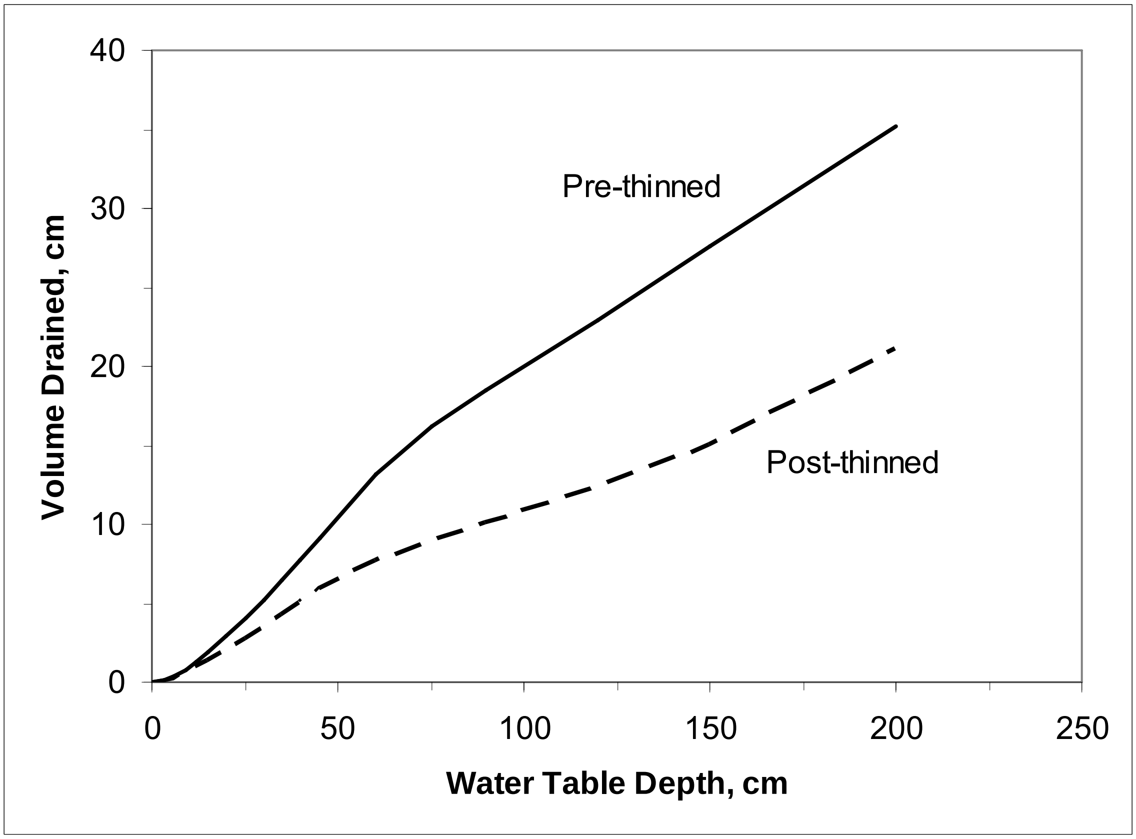

Figure 6. Drained volume relationships for the pre-thinned condition (control and pre-thinned WS5) and post-thinned WS5 for the Belhaven series soil in this investigation.

Table 4. The effect of thinning on soil D_b and k_{sat} for the Belhaven series.

Treatment	N	Mean †	P-value*
Bulk Density (g cm^{-3})			
Control	64	0.59 (0.38)	
Thinned	64	0.60 (0.32)	0.6508
Constant Head - k_{sat} (cm hr^{-1}) ‡			
Control	64	100 (58)	
Thinned	64	32 (29)	0.0400*
Auger-Hole - k_{sat} (cm hr^{-1})§			
Control	4	80 (60)	
Thinned	9	17 (18)	0.071**

*Indicates significance of the difference between mean values for the thinned and control watersheds at the 0.05 level.

** Indicates significance of the difference between mean values for the thinned and control watersheds at the 0.10 level.

† ( ) standard deviations given in parenthesis.

‡ k_{sat} determined by the constant head method.

§ k_{sat} determined in the field using the auger-hole method.

Results of k_{sat} measured by the auger-hole method were similar to those for k_{sat} measured using the constant head method (Table 4). Analysis of variance of the auger-hole k_{sat} data detected treatment effects on auger-hole determined k_{sat} values for the thinned and control watersheds. As expected, analysis of k_{sat} values determined in the field using the auger-hole method was not as significant as the analysis of k_{sat} determined in the laboratory by the constant head method. Mean k_{sat} for the control watershed was 100 and 80 cm hr^{-1} for the constant head method and auger-hole method, respectively. Surprisingly, the k_{sat} values determined using both methods were consistent with the 70 cm hr^{-1} value reported in earlier work by Broadhead and Skaggs (1989). k_{sat} values reported here for both methods were variable with ranges from 4 to 500 and 2 to 170 cm hr^{-1} for the constant head and auger-hole methods, respectively. However, the ranges of the k_{sat} values were not as wide as seen in previous research on primarily hardwood watersheds on Belhaven series soils (Grace et al., 2006).

Conclusions

Soil physical properties are impacted by forest operations such as thinning. In this study, thinning a pine plantation watershed had no influence on D_b of the 60-cm thick surface O_a horizon compared with the control watershed. In fact, analysis showed that treatments explained less than 1 percent of the total variance in the D_b model. Thinning, conversely, significantly decreased k_{sat} in the 60-cm thick O_a horizon as determined by both the constant head and auger-hole methods. Soil water characteristic relationships for the control watershed showed that water drained at high pressures (greater than -10 cm of water). Soils on the thinned watershed, on the other hand, had less drainage at high pressure heads and retained a greater percentage of its saturated water content under low soil water pressures. This behavior translated to a 14 cm difference (40 percent reduction) in volume drained for the thinned watershed soil at a water table depth of 200 cm.

These changes in soil hydraulic properties, coupled with reduced evapotranspiration as a result of vegetation removal, likely will influence hydrology on plantation watersheds. Reductions in k_{sat}, drained volumes, and drainable porosity are expected to result in shallower water tables and increased flow, peak flow rates, and duration of flow periods. Additionally, findings from this research provide much needed soil property information required to model the hydrology of the organic soil (Belhaven series) plantation pine sites.

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