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Soil Physical Changes Associated with Forest Harvesting Operations on an Organic Soil

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ABSTRACT

The influence of forest operations on forest soil and water continues to be an issue of concern in forest management. Research has focused on evaluating forest operation effects on numerous soil and water quality indicators. However, poorly drained forested watersheds with organic soil surface horizons have not been extensively investigated. A study was initiated in the Tidewater region of North Carolina to gain a better understanding of the impact of harvesting operations on poorly drained organic soils. Soils on the study site, having >80% organic matter (OM) content to a depth of 60 cm below the soil surface, were classified as shallow organic soils. Soil physical properties were examined by collecting soil cores from control and treatment watersheds in a nested design. Compaction caused by the harvest operation increased bulk density (D_b) from 0.22 to 0.27 g cm^{-3}, decreased saturated hydraulic conductivity (k_{sat}) from 397 to 82 cm h^{-1}, and decreased the drained volume for a given water table depth. However, D_b following the harvest remained low at 0.27 g cm^{-3}. The drained volume at equilibrium following the lowering of the water table from the soil surface to a depth of 200 cm was reduced by 10% from that of control watershed as a result of harvesting.

Increased demand for timber products has resulted in management practices to increase productivity of the current forestland base. The USA supplies 25% of the worldwide demand for timber products. Forests within the southern USA are some of the most productive forests in the world, supplying 60% of all timber products in the nation (Prestemon and Abt, 2002). Increased productivity of southern forest can be attributed largely to the increased utilization of intensive forest management practices over the past 25 yr. Site preparation, thinning, harvesting, and fertilization are forest operations typically associated with intensive management. Commonly, these forest operations involve large mechanized equipment to perform management activities.

Previous soil investigations on forest operations have focused on effects of varying operational procedures on site disturbance from forest lands (Burger et al., 1989; McDonald et al., 1995; Seixas et al., 1996) and impacts of operations in upland systems (Allen et al., 1999; Miller and Sirois, 1986; Stuart and Carr, 1991). Past research on soil impacts (Burger et al., 1995; Gent et al., 1984; King, 1979; King and Haines, 1979) has shown that soil moisture content influences the extent and magnitude of soil disturbance. Forest operations in wetland or poorly drained sites have increased potential for negative impacts due to the wet nature of these areas. Poorly drained sites are susceptible to degrading changes in D_b, k_{sat}, soil mechanical resistance, and porosity (Aust et al., 1991a, 1991b, 1993a, 1993b; Blanton et al., 1998; Gent et al., 1983).

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Forest operations, as with any intervention to natural systems, can impact future conditions. In the past 20 yr, increased concern has arisen regarding the implications of forest management on the environment (specifically soils and water quality) (Gent et al., 1983; Grace, 2005; Grace et al., 1998). It is this increased sensitivity to environmental impacts that has resulted in investigations to address impacts of forest operations. The majority of the previous investigations to quantify the impact of operations on forest soil concentrated on mineral soils, specifically focusing on forest floor disturbance and D_b impacts. Soil property changes initiated by agricultural land development on Belhaven soils in the Tidewater region has been shown to increase water yield, peak flows, and raise water tables (Skaggs et al., 1980). However, the influence of forest operations on organic soils has received little consideration. Changes in soil hydraulic properties could be significant on these lands.

Organic soils can present difficulties in both laboratory- and field-based physical property and soil water property tests, due to their inherent characteristics and complex material (chemical) properties. The high OM content, high water contents, and low bulk density exhibited by these soils, including the Belhaven soil in this investigation, make soil water characteristics complicated. Organic soils are primarily composed of a negatively charged colloidal matter, humus, characterized by carboxyl groups (COOH) and a high cation exchange capacity (CEC). Shrinkage and hysteresis similar to that exhibited by mineral colloidal matter, clay, exists in organic soils due to their chemical properties. Draining and drying an organic soil results in shrinkage, hysteresis, and irreversible drying from the loss of water molecules and alterations in pore structure. The interaction of these phenomena can present challenges in defining the moisture release properties of organic soils. The soil water characteristic behavior is dependent on the method of determination, that is, sorption or desorption (Dane and Wierenga, 1975; Hillel, 1998; Phillip, 1964; Topp, 1969). The hysteresis phenomenon has been presented as a function of geometric nonuniformity of pores and different suctions due to contact angles during sorption and desorption (Hillel, 1998) and the wetting and drying history of the soil (Hillel and Mottes, 1966).

Knowledge of the impacts of forest operations on soil properties of poorly drained organic soils is required for

Abbreviations: CEC, cation exchange capacity; D_b, bulk density; k_{sat}, saturated hydraulic conductivity; OM, organic matter; SOM, soil organic matter.

further development of models, as planning tools, to manage these resources. A study was initiated to investigate the impact of forest operations on soil and water from poorly drained forested watersheds in eastern North Carolina. This paper reports the initial phase and had the specific objectives of (i) defining physical properties of drained forested organic soils in the Tidewater region and (ii) assessing the impact of mechanical harvesting of hardwoods on physical properties of the poorly drained organic soils.

MATERIALS AND METHODS

Site Description

The study area is located in the Tidewater region of North Carolina at approximately 35° latitude and 76° longitude in Washington County near Plymouth, NC (Fig. 1). Characteristic of the area, the site is poorly drained and has a shallow water table in its natural condition. Soils are hydric, primarily Belhaven muck series (loamy, mixed, dysic, thermic Terric Medisaprists), which is characterized by extremely acid shallow organic horizons ranging from 40 to 130 cm below the surface (Soil Conservation Service, 1981). The soil organic matter (SOM) content is 80% or greater and total porosity is 0.80 $cm^3\ cm^{-3}$ in the 60-cm surface horizon (O_a horizon). Average soil surface elevation ranges from 4.1 to 4.5 m above sea level with an average slope of <0.02%. The site is drained by lateral parallel ditches, which are 1.0 to 1.2 m deep and spaced approximately 100-m apart. In 1999, the 44-ha primarily hardwood study watershed was divided into two subwatersheds, hereafter referred to as the WS3 and WS6 watersheds (Fig. 2).

Study Design

The experimental design for determining soil physical property (soil water characteristic, D_b, and k_{sat}) impacts was set up as a nested experiment due to restrictions on the number of sites available (Keppel, 1982; Montgomery, 1991). The treated watershed (WS3) had a companion untreated (control) watershed (WS6). The stated hypothesis for soil analysis was that treatments effects are equal to zero. The model for this design is given by:

$$Y_{ijk} = u.. + T_i + S_{j(i)} + E_{ijk} \quad [1]$$

where Y_{ijk} = predicted response; $u..$ = overall mean; T_i = treatment effects; $S_{j(i)}$ = plot location effect nested within treatments; E_{ijk} = error in observations.

WS3 received a 23-ha clearcut harvest treatment in June 2001 and the remaining 21-ha watershed (WS6) served as the unharvested control. Felling was accomplished with a tracked feller buncher. Skidding was conducted with two grapple skidders with dual tires, a tracked shovel loader, and a rubber-tired clambunk skidder. Approximately half of the timber was skidded to each of the two decks located on each side of the harvested area (on the east and west watershed boundaries) (Fig. 2). The volume of timber removed from the WS3 watershed was 6800 Mg; hardwood accounted for 5800 Mg of that total.

Soil Sampling and Methods

Soil properties for the profiles in each individual watershed were initially determined based on observations and soil cores (7.6 cm in diameter and 7.6 cm in length) taken during the period between August 1999–April 2000 (before harvest of WS3, June 2001). The soil cores were taken from three randomly located soil pits in each watershed (Fig. 2). Textural classification and layer depth of the four horizons (O_a, A, B, and C horizons) were determined in the soil pits identified. A total of eighteen cores from the O_a horizon, eleven cores from the A horizon, six cores from the B horizon, and eight cores from the C horizon were collected from the soil pits and used to develop soil water characteristics for the control (WS6) and the preharvested condition on WS3. Soil water characteristics for the postharvest condition were determined from soil cores taken from three pits in WS3 during the summer of 2001 (denoted as postharvest pits in Fig. 2). A total of six cores were taken from each of the top three horizons (O_a, A, and B) in WS3 for the postharvest condition. It was not possible to extract cores from the C horizon (213 to 250 cm depth) postharvest because of a high water table.

A second set of intact soil core samples for determining harvesting effects on D_b, k_{sat}, and soil water characteristic were collected postharvest during the summer of 2001 from each watershed using a core method (Blake and Hartge, 1986; Uhland, 1950). Bulk density and k_{sat} were determined on eight randomly located soil cores (7.6 cm in diameter by 7.6 cm in length) at 5- and 30-cm depths in four randomly located 10 by 20-m plots nested within each watershed (Fig. 2) for a total of 64 cores per watershed.

Collected samples were trimmed in the field, sealed with plastic caps, and sealed in plastic bags to maintain original moisture. Pressure increments of 0, 3.8, 10, 20, 30, 40, 60, 80, 100, 140, 200, 300, and 500 cm were used to develop soil water characteristics for the control, preharvest, and postharvest condition based on soil cores taken from randomly located soil pits on each watershed. The relationship between volume

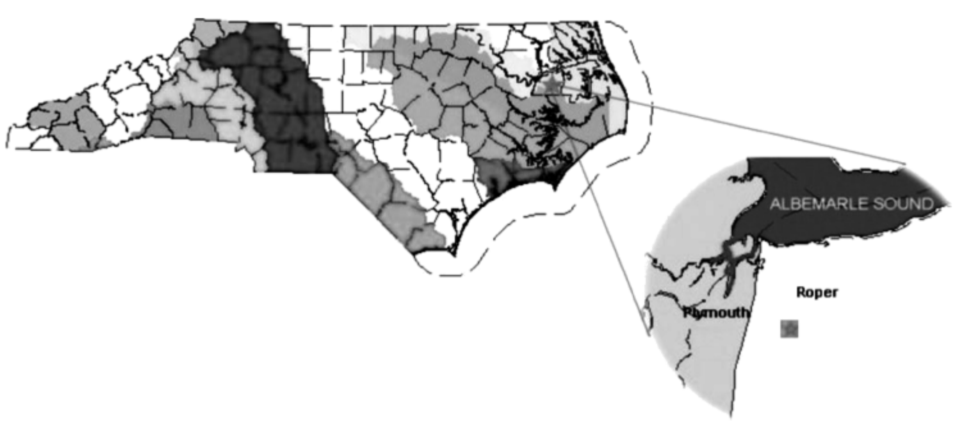

Fig. 1. Location of the study watershed in the Tidewater region of North Carolina near Plymouth, NC.

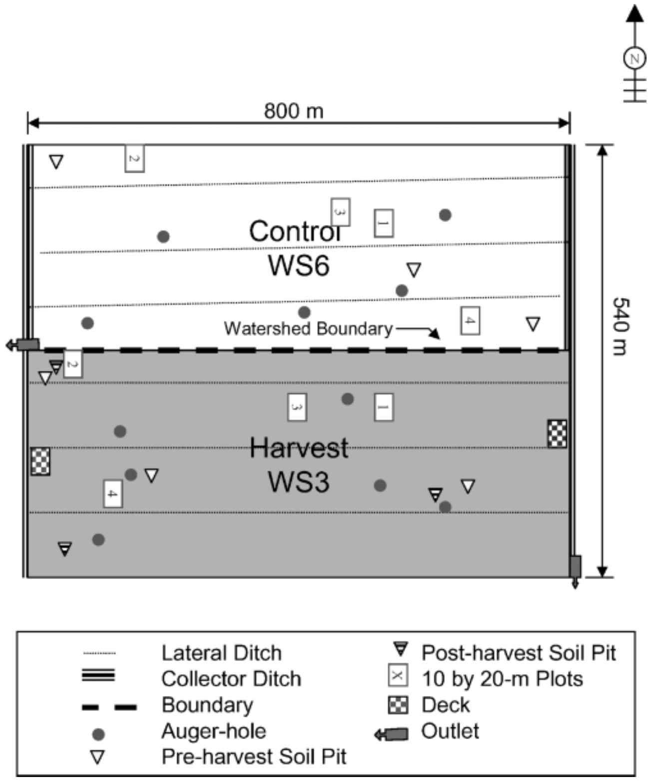

Fig. 2. Paired watersheds, WS3 and WS6, defined in the study for the evaluation of harvesting effects. Schematic shows locations of randomly located 10 by 20 m plots, decks, watershed outlets, and soil pits.

drained and water table depth was determined from the soil water characteristics by procedures described by Skaggs et al. (1978) and drainable porosity was determined from that relationship using methods described in the same reference. Volume drained at a given water table depth is defined as the volume of water (in depth units, cm^3 per cm^2 of surface area) drained when the water table is lowered from the surface to the given depth and the profile above the water table is drained to equilibrium (hydrostatic). Thus defined, the volume drained for a given water table depth is equal to the volume of water free pore space in the profile above the water table, assuming drained to equilibrium conditions.

Organic content of the surface soil horizon was determined by collecting 0.5-kg soil samples from 0- to 30- and 30- to 60-cm depths from four randomly located plots within WS3 and WS6. Soil organic matter content was quantified by determining C content in the soil samples using the loss on ignition method described by Rabenhorst (1988). Saturated hydraulic conductivity was determined using the constant head method (Klute, 1965; Klute and Dirksen, 1986) with a constant hydraulic gradient of 1.7 cm cm^{-1}. The auger-hole method (van Beers, 1958) was used to make in-field determinations of k_{sat} in the two upper soil profile layers (O_a and A horizons) at random locations in each watershed (Fig. 2).

Volumetric water content response to pressure steps in the soil water characteristics developed for the watersheds were tested for treatment effects using SAS GLM procedures (SAS Institute, 2004). In the nested design, D_b and k_{sat} data collected from the four randomly located plots nested within each watershed were tested using SAS NESTED procedures (SAS Institute, 2004). Individual treatment mean values were tested for significance at the 0.05 probability level where the nested ANOVA indicated significant differences.

RESULTS AND DISCUSSION

The soil profile data (horizon designation, layer depth, and soil textural classification) were collected from three randomly located soil pits for each horizon in the WS3 and WS6 watersheds. Horizon designations, layer depths, and soil textural classifications were similar for the watersheds before harvesting WS3. Saturated hydraulic conductivity and bulk density, compared by horizon between the two watersheds, were not significantly different. These data were combined and represent the preharvest soil profile for the watersheds (Table 1). The preharvest soil profile characteristics found in this investigation are consistent with that reported for the Belhaven muck series (Soil Conservation Service, 1981).

The effect of harvest on bulk density, D_b, is shown in Table 2. Bulk density distributions deviated from normality and were normalized using a logarithmic transformation before performing the nested ANOVA. Postharvest D_b for the 0 to 60 cm O_a horizon was greater than D_b for the control watershed based on ANOVA ($\alpha = 0.05$) (Table 2). Typical of organic sites, D_b values for the organic surface horizon were low for the control and postharvest condition. Control D_b ranged from 0.16 to 0.31 g cm^{-3} and had a standard deviation of 0.030. Following harvest operations, D_b standard deviation increased considerably to 0.095 with a range from 0.17 to 0.85 g cm^{-3}. The increase in variability in D_b indicates that the harvest operation affected the soil surface. But it did not affect soils on the entire watershed uniformly. This spatial variability is one of the difficulties in assessing the impact of operations on soil properties. Compaction varies in intensity over a watershed and even within a square meter. Variability in soil property data following any mechanical operations should be expected due to the characteristics of these operations. For example, the majority of disturbance occurs under the machine tires, which typically affect <20% of a watershed (Miller and Sirois, 1986; Seixas et al., 1996; Stuart and Carr, 1991). At the same time, a large portion of a harvested watershed is only minimally disturbed (even on a clearcut). This difference in disturbance levels on a watershed following operations can explain the increased variability in D_b of the O_a horizon. The harvest operation did not appear to affect the A and B horizons as there was no significant difference in D_b between the control and postharvest watersheds (Table 2).

Table 1. Soil textural classification, D_b, and k_{sat} for each horizon in the preharvest soil profile defined from cores collected from randomly located soil pits.

Horizon	Layer depth	Sample depth	Classification	D_b	k_{sat}
	cm	cm		g cm^{-3}	cm h^{-1}
O_a	0–60	40	Black, organic, loam	0.21 (0.03) †	354 (264)
A	60–107	90	Dark brown, Clay loam	1.42 (0.17)	14 (6)
B	107–213	160	Light brown, Sandy clay loam	1.50 (0.49)	4 (3)
C	213–250	230	Gray, loamy sand	1.31 (0.09)	1 (2)

† Standard deviations are given in parenthesis.

Table 2. Effect of harvest on bulk density, D_b.

Horizon (depth, cm)	N	D_b, g cm^{-3}† Control	Postharvest	P-value
O_a (0–60)	64	0.22 (0.030)	0.27 (0.095)	0.0477*
A (60–107)	6	1.37 (0.220)	1.25 (0.106)	0.3730
B (107–213)	6	1.52 (0.007)	1.40 (0.135)	0.2690

* Significant at the 0.05 probability level.
† Standard deviations are given in parenthesis.

Soil water characteristic curves were developed for each horizon in the soil profile and analyzed using SAS GLM procedures (Fig. 3). There was no significant difference between soil water characteristics from the control (WS6) and the preharvested condition in WS3 (data not shown), so the data were combined and are plotted in Fig. 3 for each horizon. These curves represent the soil water characteristics for the preharvested condition. The shape of the surface horizon soil water characteristic curve for preharvest conditions (Fig. 3) was similar to those previously reported for shallow organic soils in the Tidewater region (Skaggs et al., 1980). The soil water content in the organic O_a horizon was 0.8 cm^3 cm^{-3} at saturation (pressure head = 0) and decreased to about 0.4 cm^3 cm^{-3} at a pressure head of −500 cm. The response of the volumetric water content to changes in pressure head was much less for the underlying mineral soil horizons (A, B, and C horizons) with changes in water content of about 0.2 cm^3 cm^{-3} as the pressure head is lowered from 0 to −500 cm (Fig. 3). That is, much more water is removed from the organic surface horizon than from the underlying horizons for a given change in pressure head.

The effect of harvest on the soil water characteristic of the surface O_a horizon is shown in Table 3 and Fig. 4. Soil water contents were not detected as different for the preharvest and postharvest conditions at saturation (P = 0.053) and a pressure head of −3.8 cm (P = 0.071) based on analysis of variance (ANOVA) (Table 3). However, soil water contents were detected as significantly greater for the postharvest than for the preharvest condition for pressure heads of −10 cm or less at the 0.05 probability level (Table 3). The soil water characteristics for

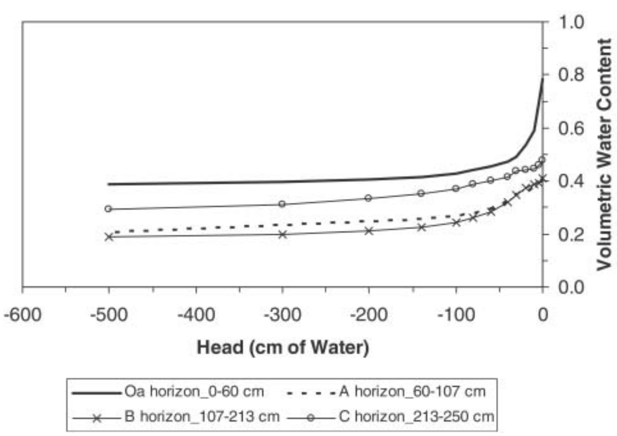

Fig. 3. Average soil water characteristic for each horizon in the preharvest condition soil profile.

Table 3. ANOVA results for tests on mean volumetric water contents for each pressure step in the O_a horizon soil water characteristic curves.

Pressure head (cm of water)	Preharvest† (cm^3 cm^{-3}) N = 10	Post-harvest (cm^3 cm^{-3}) N = 6	Standard error	P-value
Saturation	0.783	0.835	0.019	0.053
−3.8	0.696	0.728	0.017	0.071
−10	0.586	0.677	0.019	0.006*
−20	0.530	0.643	0.022	0.005*
−30	0.484	0.594	0.050	0.047*
−40	0.467	0.585	0.050	0.047*
−60	0.452	0.574	0.048	0.040*
−80	0.438	0.563	0.047	0.039*
−100	0.426	0.555	0.046	0.037*
−140	0.413	0.545	0.044	0.033*
−200	0.403	0.536	0.043	0.032*
−300	0.395	0.528	0.043	0.033*
−500	0.385	0.514	0.042	0.035*

* Significant at the 0.05 probability level.
† Mean volumetric water contents for preharvest WS3 and control samples.

the A and B horizons, postharvest (data not shown), were not significantly different from those given in Fig. 3 for preharvest. Harvest operations primarily affected soil water characteristics of the surface 60-cm thick organic O_a horizon.

Volume drained-water table depth relationships were developed for the pre and postharvest conditions from soil water characteristics and are plotted in Fig. 5. Differences in volume drained for a given water table depth were detected in the ANOVA. Volume drained, or the water free pore space under drained to equilibrium conditions, was less for WS3 postharvest than for the preharvest condition (preharvest WS3 and control). For example, the volume drained for a water table depth of 90-cm preharvest was 21 cm (cm^3 per cm^2 surface area) compared with 17 cm for the postharvest condition, a difference of 4 cm. The difference between the preharvest and postharvest conditions was significant at the 0.05 probability level ($P < 0.0001$) and the difference in volume drained remained relatively constant with increasing water table depth for depths greater than 90 cm. For a 200-cm water table depth, the drained volume was 34 cm for postharvest, which was 4 cm less than the pre-

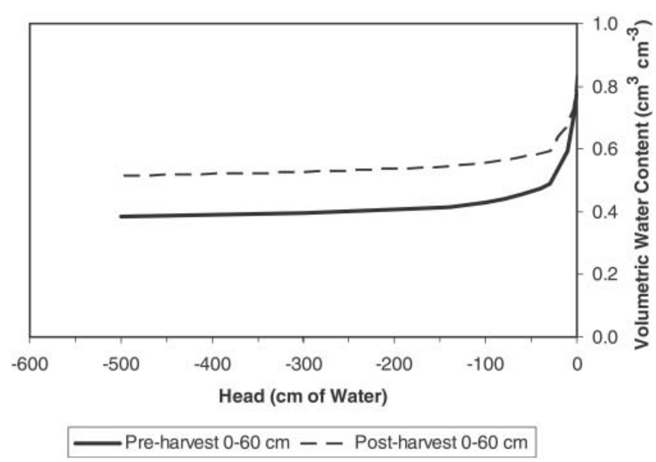

Fig. 4. Surface soil water characteristic curves developed for the preharvest condition (preharvest WS3 and control) and postharvest WS3 for the shallow organic (Belhaven series) soil in this investigation.

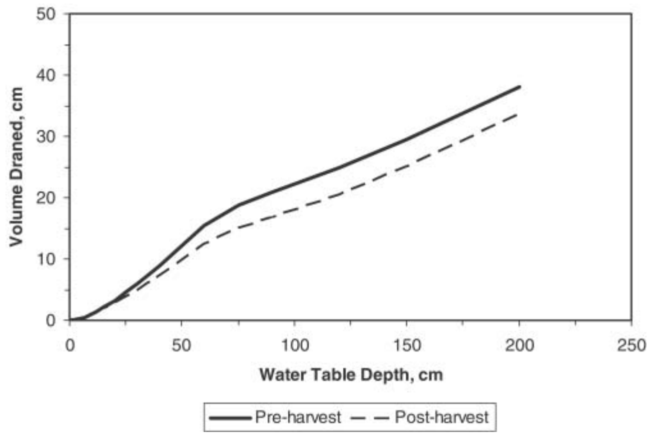

Fig. 5. Drained volume relationships developed for the preharvest condition (preharvest WS3 and control) and postharvest WS3 for the shallow organic (Belhaven series) soil in this investigation.

harvest conditions with a drainage volume of 38 cm (P = 0.0001). This effect can be attributed to compaction of the O_a horizon resulting from harvesting operations, which reduced drainable pore space. This hypothesis is supported by the results of the D_b analysis presented in the previous section.

Drainable porosities for water tables <90 cm deep, determined as the average slope of the volume drained versus water table depth relationship, were 0.28 and 0.23 for the control and harvested watershed, respectively. At water table depths greater than 120 cm, the drainable porosity was 0.15 and 0.16 for the control and harvested watershed, respectively. These results indicate that compaction primarily affected the larger pore spaces that drain easily for water table depths <90 cm. The drainage properties for the smaller pores that are not as easily drained, pores that drain at water table depths between 90 and 200 cm, were less affected by compaction from the harvest operation.

Similar reductions in volume drained following agricultural land development for Belhaven soils in this region were reported in previous research (Skaggs et al., 1980). These investigators reported a 35% reduction in drained volumes for developed shallow organic soils at a water table depth of 150 cm. The similarities in reductions in drained volumes for the harvested condition in this investigation and the agricultural land development investigation seem to support the hypothesis that harvesting primarily affected the larger, easily drained pores. However, the drained volumes for a given water table depth reported here are much greater than those reported in the agricultural land development investigation for developed and undeveloped organic soils. The difference in the drained volume relationships can be attributed to the fact that the soils considered herein had dried out or irreversibly cured to a depth of 60 cm. Whereas, the authors of the previous study indicated that the surface layer was cured to a depth of <25 cm. Water held in the cured 60-cm deep surface horizon of the soil in the current study is released from large pores under lower pressures than that of a soil that has not dried irreversibly.

The soil water behavior of these Belhaven soils related to moisture state or previous drying history was also observed in laboratory determinations of soil water characteristics and bulk density. Based on the organic content of the soils, shrinkage was expected under high suctions (pressure heads <−500 cm of water), but soil water characteristic information below −500 cm was not needed for developing volume drained-water table depth relationships and was not measured. Shrinkage was minor in the range of pressure heads investigated (0 to −500 cm of water). The lack of shrinkage during drainage was attributed to the soil retaining enough water to prevent irreversible deformation. Shrinkage would likely have been a concern at suctions much >500 cm of water due to the loss of water held in smaller pores and by colloidal matter. This is evident by shrinkage observed during the drying process for the determination of bulk density. Oven drying the soil at 105°C resulted in irreversible drying with shrinkage as great as 50%.

Results for saturated hydraulic conductivity are summarized in Table 4. As with bulk density, distributions deviated from normality and were normalized using a logarithmic transformation before performing the nested ANOVA. Mean k_{sat} in the O_a horizon, as determined on cores by the constant-head method, was significantly less for the harvested watershed than for the control watershed based on ANOVA (α = 0.05) (Table 4). Treatment explained >60% of the total variance in the nested ANOVA model. The difference in k_{sat} between the harvested and control watersheds was highly significant with a p-value equal to 0.0003. Conductivities for both harvested and control watersheds were highly variable with ranges that spanned greater than 1200 cm h^{-1}.

A total of 11 tests were run on the harvested and control watersheds to determine k_{sat} by the auger-hole method. The field tests were randomly distributed over the watersheds. These tests were conducted with an auger-hole depth of 90 cm and water table depths ranging from 30 to 40 cm. Thus the values of k_{sat} obtained represent a composite of the O_a and A horizons. As expected, analysis of k_{sat} values determined in the field using the auger-hole method was not as definitive as the analysis of k_{sat} determined in the laboratory. The harvested and control watersheds had statistically similar k_{sat} values based on the ANOVA of auger-hole data

Table 4. Saturated hydraulic conductivity for the O_a horizon in the harvested and control watersheds.

Treatment	N	Mean†	P-value
	Constant-head–k_{sat}, cm h^{-1}‡		
Control	64	397 (261)	
Harvested	64	82 (184)	0.0003*
	Auger-hole–k_{sat}, cm h^{-1}§		
Control	5	63 (55)	
Harvested	6	50 (25)	0.616

* Significant at the 0.05 probability level.
† Standard deviations are given in parenthesis.
‡ k_{sat} (saturated hydraulic conductivity) determined by the constant-head method.
§ k_{sat} (composite for O_a and A horizons) determined by the auger-hole method with a hole depth of 0.9 m.

(Table 4). The inability to detect differences in auger-hole determined k_{sat} from the two watersheds likely was due to the small sample size, compared with the larger number of k_{sat} measurements in the laboratory. Another factor was the variability in the water table depths at the time of tests, which further affected the variability of the composite k values obtained. The high spatial variability of soils would require larger sample sizes to increase confidence in the true mean k_{sat} for each watershed.

Mean k_{sat} in the surface soil layer for the watersheds based on the constant-head method were extremely high, especially for the control watershed. The mean k_{sat} was 397 cm h^{-1} for the control watershed and ranged from 6.0 to 1300 cm h^{-1} using the constant-head method. Conductivities from the control watershed were greater than the k_{sat} value (70 cm h^{-1}) previously reported for an organic soil in the Tidewater region (Broadhead and Skaggs, 1989). However, k_{sat} values measured using the auger-hole method are consistent with the conductivities reported in the previous investigation. The high k_{sat} for the control in this study is likely due to irreversible drying and curing of the entire 60 cm thick organic surface horizon, compared with similar drying of a much shallower surface layer in the Broadhead and Skaggs (1989) study. The irreversible drying likely resulted in a substantial change in soil structure, with more aggregation, larger pores and, hence, increased hydraulic conductivity.

CONCLUSIONS

The effect of clearcut harvest operations on soil water characteristics, drainable porosity, D_b, and k_{sat} was studied in a forested shallow organic (Belhaven series) soil watershed in the Tidewater region. Saturated soil water contents in the O_a horizon for both the preharvested and control watersheds were near 0.80 cm^3 cm^{-3}. Results of the analysis of variance revealed that harvesting a hardwood watershed significantly influenced the soil physical properties of the 60-cm thick surface O_a horizon of this soil. Soil water contents were significantly greater for the postharvest condition than for the preharvest condition for pressure heads less than −10 cm. Compaction caused by the harvest operation, and documented through the analysis of D_b data, altered the hydraulic properties of the poorly drained shallow organic soil. This compaction by harvesting resulted in the reductions in k_{sat} although k_{sat} remained high on the postharvest watershed. The reduction in water-filled pore volume resulted in a decrease in volume drained on the postharvest watershed.

Previous investigations on both upland and bottomland systems have found that disturbance activities, such as agricultural land development and forest operations, can influence soil physical properties. Forest operations that disturb the forest floor can alter soil physical properties, particularly soil hydraulic properties, as a result of compaction. The changes in soil hydraulic properties documented in this study, coupled with reduced evapotranspiration as a result of vegetation removal, can influence watershed hydrology. Reductions in k_{sat}, drained volumes, and drainable porosity are expected to result in shallower water tables and an increased duration of flow periods.

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