Paper 3 (draft)

EFFECTS OF SKIDDER TRAFFIC ON WATER RETENTION AND PORE SIZE DISTRIBUTION OF MEDIUM-TEXTURED SOILS IN BOREAL FOREST OF ALBERTA

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Abstract

Effects of skidder traffic on soil water retention were studied on medium-textured Gray Luvisols and Brunisols at 14 sites in Alberta foothill and boreal forests. Treatments included 3, 7, and 12 cycles by mostly skidders with wide tires and non-trafficked soil. Soil cores were collected at four random points of each treatment at 5 and 10 cm depths. . Soil water content of each core was measured at six potentials. Tempe cells were used to measure water retention at potentials > -30 kPa; a conventional pressure plate was used in the range of -30 to -1500 kPa. The four-parameter equation developed by van Genuchten (1980) was fitted to the data. The macro-pore space of trafficked soil was not significantly affected when water content was drier than field capacity. At higher soil water contents, the first few skidding cycles caused a decrease in θ_s and α parameters, which reflected flattening of water retention curve in the high potential range and a simultaneous shift of steepest part of the slope to a lower potential. the result of compaction by skidders on these soils was decreased air-filled porosity without changing field capacity or available water holding capacity of the soils. Most modifications of pore size distribution in these soils can be avoided by operating wide-tired skidders when the soil is drier than a water potential of field capacity.

INTRODUCTION

Vehicular compaction affects pore-size distribution and water retention because the decrease in soil volume can only occur as a result of the compression of pore space. Most of the decreases in water retention occur at high potential where changes in different groups of macropores affect air-filled porosity and water availability to plants (Warkentin 1971, Dickerson 1976, Froehlich and McNabb 1984, Allbrook 1986, Bruand and Cousin 1995). Soil water retention at lower potentials may not be affected or may increase due to an increase in smaller pores at the expense of larger pores that are compressed during compaction (Hill and Sumner 1967).

The relationship between soil compaction and water content is usually included in models predicting soil compaction (Amir et al. 1976, Raghavan et al. 1977, McNabb and Boersma 1996). However, the dependence of compaction-induced changes in soil water retention and pore-size distribution on the water content are not well documented.

Most soil modifications, such as compaction, puddling or rutting, occur during the first few trips of a skidder (Hatchell et al. 1970, Froehlich and McNabb 1984, Greene and Stuart 1985, Rollerson 1990, Meek 1994). Further trafficking causes a progressively smaller decrease in soil volume and, consequently, a smaller decrease in total pore space. The optimal conditions for compaction often occur at a water content near field capacity (Akram and Kemper 1979, Soane et al. 1981, Gent, Jr. and Morris 1986). Forest machine trafficking may have little affect on drier soils (Greene and Stuart 1985). Little known on the associated changes in water retention and pore-size distribution.

Analysis of effects of compaction on water retention of forest soils is often limited to comparing water contents at specific levels of pressure or differences between them, e.g. the macropores, micropores, field capacity, air-filled porosity and available water holding capacity. A parameterization of the curve allows more integrated understanding of changes in pore size distribution. Lenhard (1985) related the pore-size distribution index of Brooks and Corey (1966) function to the number of vehicular passes on volcanic ash soil. Jorge et al. (1992) found significant difference between linearized water content - potential relationships for compacted and control sandy loam soil using covariance analyses. The objective of this study was to determine changes in soil water retention and pore size distribution functions that result from trafficking a medium-textured soil by skidders.

MATERIALS AND METHODS

Fourteen study sites were selected in mature conifer stands across west-central Alberta where forest harvesting and silvicultural operations in summer are most common. The area is part of the Southern Alberta Uplands ecodistricts of the Lower and Upper Boreal Cordilleran ecoregions (Strong 1992). The sites are dominated by lodgepole pine or white spruce with a small component of black spruce or aspen depending on soil wetness. Aspen is more typical of the Lower Cordilleran ecoregion (Corns and Annas 1986).

At each site, a skidding machine or forwarder made 3, 7, or 12 cycles (one empty and one loaded pass) in a designated skidding corridor that was marked in felled timber prior to skidding (Table 1). Each corridor was 40 m long and 6 m wide and was separated by a 10 m wide untrafficked control area. This treatment block was replicated 4 times at each site. All blocks were skidded as part of normal harvesting operation.

Immediately after skidding, four sampling points were randomly selected within each treatment. Soil cores, 3 cm in height and 7.6 cm in diameter, were collected at the midpoint of the 5, 10, and 20 cm depths at each point in the four treatment blocks for determination of bulk density (McNabb et al. 1998). The block with the most representative soil, was selected at each site for sampling soil for measurement of water retention. In this block, undisturbed soil cores, 3 cm in height and 5.2 cm in diameter, were collected at each sampling point from the midpoint of the 5 and 10 cm depths. All core samples were collected in thin-walled metal rings that were pressed into the soil by hand (McNabb and Boersma 1993). Cores for water retention were sealed in plastic wrap and stored at 4°C to reduce fungal and bacterial growth, and to maintain soil water content until analyzed.

Water retention was measured on these cores at -2, -5, -10, -30, -100, and -1500 kPa. Tempe pressure cells (Soil Moisture Equip. Co., Santa Barbara, USA) were used for water potentials between -2 and -30 kPa to reduce swelling (Reginato and van Bavel 1962). The pressure in the Tempe cells was maintained within ±0.02 kPa using a pressure transducer and solenoid valve connected to a 7X datalogger (Campbell Scientific). A pressure plate extractor was used at higher pressures (Klute 1986).

A four-parameter equation (van Genuchten 1980) was used to fit the soil water retention data using the Marquardt (1963) algorithm. Volumetric soil water content (θ, $m^3\ m^{-3}$) as a function of pressure (h, kPa) is given by

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\alpha \cdot -h)^n\right]^{1-\frac{1}{n}}} \quad (1)$$

where θ_r ($m^3\ m^{-3}$) is the residual water content and θ_s ($m^3\ m^{-3}$) is the saturated water content; α and n are empiric parameters. The residual water content is defined as the water content in the range of low potentials for which the $d\theta/dh$ becomes indefinitely small. In practice, it is sufficient to define θ_r as the water content at a low water potential, e.g. -1500 kPa, that is measured (van Genuchten 1980). Values of α and n are obtained for each individual core during fitting procedure.

The differentiation of Eq. [1] provides a quantitative measure of the change in the slope of the soil water retention curve that is otherwise difficult to assess because of the scale over which data are collected. Differentiation of Eq [1] gives

$$\frac{d\theta}{dh} = -\frac{\theta_s - \theta_r}{\left[1 + (\alpha \cdot -h)^n\right]^{1-\frac{1}{n}}} \cdot \frac{1-\frac{1}{n}}{\left[1 + (\alpha \cdot -h)^n\right]} \cdot (\alpha \cdot -h)^n \cdot \frac{n}{-h} \quad (2)$$

The α parameter is inversely related to the maximum value of $d\theta/dh$ (Wosten and van Genuchten 1988).

The largest effective diameter D (m) of pores retaining water at suction h (m) was calculated by the capillary equation of Vomocil (1965)

$$D = -\frac{4 \cdot \sigma \cdot \cos\gamma}{\rho \cdot g \cdot h} = -\frac{C}{h} \quad (3)$$

where σ ($kg\ s^{-2}$) is the surface tension of water, γ (degrees) is the contact angle between pore wall and water, ρ ($kg\ m^{-3}$) is the density of water, g is acceleration due to gravity ($m\ s^{-2}$), and C is a constant which equals $\frac{4 \cdot \sigma \cdot \cos\gamma}{\rho \cdot g}$.

The volumetric water content of soil at -10 kPa was assumed to be field capacity. Available water holding capacity and air-filled porosity were calculated as differences between water contents at -10 kPa and -1500 kPa and between saturation and -10 kPa, respectively (Vomocil 1965).

Effects of skidding traffic on bulk density, the four parameters of the water retention function, field capacity, available water holding capacity and air-filled porosity were analyzed using ANOVA with depth as a repeated factor.

RESULTS

Most sites were skidded with rubber tired grapple skidders (John Deer 648E, 748E, or Timberjack 480B, 450C), but two sites were skidded with 3-axle forwarders (Valmet 540 or Timberjack 520A) and one site was skidded with a tracked crawler (CAT D4H TSK) (Table 1). Most grapple skidders were equipped with tires 1.1 m wide, at least on the rear axle.

Soils were predominantly Gray Luvisols that vary in degree of gleying and depth to mottles. Soils at the two southern sites were Brunisols. Soils were relatively uniform in texture due to their formation in similar till materials (Strong 1992).

Soil wetness, as indicated by soil water potential, varied widely across the sites at the time of skidding (Table 1), was the dominant factor determining whether bulk density increased significantly during skidding (McNabb and Startsev, unpublished data). The values of bulk density are for cores collected from all four replications of the control. A significant increase in bulk density occurred after 3 skidding cycles at eight sites where water potential was higher than about -15 kPa. The seven sites, where the soil was at a water potential less than -15 kPa, were not significantly compacted after 12 skidding cycles.

Site had a significant effect on all four parameters in Equation 1 (Table 3). The number of skidding cycles only had a highly significant effect on the α parameter. Depth had a significant effect on two of the four parameters but its interaction with treatment was not significant, indicating that the effect of compaction on the soil was similar at the depths measured (McNabb et al. 1998).

Site accounted for about half of the variation in the ANOVA when all sites were combined. The sites were then coded for whether they were significantly compacted or not for subsequent analyses (Table 1); compaction accounted for about two-thirds of the variation due to the effect of site. Compaction had a significant effect on three water retention parameters; only the effect on θ_r which is related to the water content at the lowest water potential which did not change (Table 3). The number of skidding cycles only had a significant effect on α. The main and interactive effects of depth did not change from the previous, ANOVA of all sites because depth was the same repeated factor.

Reanalysis of data for sites classified as significantly compacted from those that were not found that site remained significant for θ_r for both groups (Table 3). The θ_s and α parameters were both significant for the group of sites that were significantly compacted, but only the α parameter for the nonsignificantly compacted sites maintained the same level of significance as the original analysis. The significance of θ_r for water retention as the lowest water potentials reflects the dominant influence that soil texture has on this parameter (reference) which is similar for our two groups of sites (Table 1).

The α parameter remains significant for the noncompacted group of sites because the level of statistical nonsignificance increases with decreasing water potential (Table 1, McNabb and Startsev 19xx). For example, Site 9 was significant at $p< 0.07$ in the original ANOVA and is barely significantly different from Sites 5 and 12 which are the driest soils in the nonsignificantly compacted groups of sites (Tables 1 and 3).

Data were combined by whether the site was significantly compacted or not and by depth and the data used to develop a common set of parameters for the two groups of sites (Table 4). The differences in the parameters of the water retention function for sites with significantly compacted soil and the other group is apparent in the generalized water retention curve for the two groups of sites (Fig. 1). The differences in the slope of the water retention curve as a result of skidding is even more apparent in the slope of the derivative function curve [Eq. 1] (Fig. 2).

Little change in the shape of either curve with increasing level of traffic on the nonsignificantly compacted soil confirms the lack of significant increase in bulk density at these sites (Fig. 1). The soil water retention of significantly compacted soil decreased between saturation and approximately field capacity (-10 kPa). The greatest change occurred in pores at a water potential -5 to -6 kPa; this corresponds to an effective diameters 48-58 μm (Equation 3). The peak of the derivative curve is the steepest part of the slope of the water retention curve and is sensitive to minor changes, which is not evident when the data is plotted on a logarithmic scale. Soil compaction compressed the peak of the derivative curve and shifted the peak to a lower water potential. The shift in the peak is associated with the significant difference in the α parameter between the control and 3 skidding cycles, and between 3 and 7 skidding cycles (Table 4). The control peak is somewhat higher and the peak potential is lower at the sites where compaction was not significant, but could not be attributed to any specific differences in soil among sites.

The dθ/dh peak corresponds to the part of pore size distribution curve where the pore volume starts to increase sharply with decrease in pore diameter (Fig. 2). This is the point where most of changes occur during compaction. The decrease in the slope of water retention curve and shift of its steepest part reflected a pore volume reduction in the range between 20 μm and 200 μm with maximum reduction in the 30-60 μm pores. Smaller pores were filled with water, according to the water potentials measured at the sites at the time of skidding. There was no reduction in pores larger than 200 μm because few pores of this size are present in undisturbed soils.

Most of changes in the shapes of water retention curve and pore size distribution occurred at a water potential higher than field capacity. Therefore, trafficking did not change field capacity or available water holding capacity of these soils (Table 5). Air-filled porosity decreased significantly after the first 3 cycles at the sites where the soil was significantly compacted. The differences in air-filled porosity between 3, 7, and 12 skidding cycles were not significant.

DISCUSSION

The effective pore diameters and pore volumes of soil calculated from water retention curves are often used to subdivide soil porosity into classes such as macro-, meso-, and micropores that are indicative of the soil hydrologic and biological environments (Luxmoore 1981). In our boreal forest soils, few macropores occur naturally as evident by the flat slope of the water retention curve between saturation and –0.3kPa, water potential (Fig. 1). The presence of few macropores in these soils is considered to be consistent with their genesis and other soil properties. The soil in the region are young, developing in tills that were deposited during the last glaciation less than 10,000 years ago (Mayewski et al. 1981). Soil biological activity is suppressed because of the cold northern climate (Startsev et al. 1998); and organic matter content of mineral surface soils is commonly less than 0.02 kg/kg (McNabb 1994, McNabb et al 1998). As a consequence, aggregates formed in these soils are generally small and weak (McNabb, unpublished data), suggesting that physical and mechanical processes dominate their development rather than biological and chemical processes (McNabb 1994).

Essentially all of the air-filled porosity of the significantly compacted soils were in the mesopore size class, pores drained of water between -10 to –0.3 kPa water potential (Table 1). Soil compaction at these sites caused a significant increase in bulk density reduced mesopore space by over one-third after 3-skidding cycles and two-thirds after 7- and 12-cycles (Table 5). The reduction in mesopore space occurred because the pores were destroyed rather than compressed into smaller pores which would have cause a noticeable change in the shape of the water retention curve and its deriviative function at water potentials <-10kPa. Compaction of wet soil is much more likely to cause a deformation of soil aggregates that causes the collapse of larger pores than will occur when the soil is drier (Hodek and Lovell 1979). The air-filled porosity remaining in these soils after compaction is attributed to air being trapped in the soil that could not escape during trafficking (Xu et al. 1992).

Soil compaction has a variable effect on the water holding capacity of forest soils (Froehlich and McNabb 1984). A significant increase in bulk density did not affect the parameters of field capacity, permanent wilting point, and available water holding capacity in these soils (Table 5) because the changes in soil porosity were essentially confined to the mesopore space while the micropore space remained unaffected (Fig.1). The stresses transferred to soil by the equipment used in this study were insufficient to cause significant compaction or a change in the water retention curve of these soils when the water potential was less than about –10 kPa. The resistance to compaction is due to an increase in soil strength as a result of partial drying (McNabb and Boersma 1996). If the loading stresses had been higher as a result of using equipment with narrower tires or higher tire inflation pressure (Greene and Stuart 1985), significant soil compaction could be anticipated at a yet to be determined, lower water potential than found in our study. Such compaction would either have resulted in a reduction of micropore space because part of the micropore space would have been filled with air, or a fracturing of larger soil aggregates that may have increased micropore space (Hodek and Lovell 1979). Both consequences of soil compaction under higher loading stresses would change the shape of the water retention curve at water potentials less than –10 kPa. Therefore, whether soil compaction affects soil water holding capacity is largely dependent on how the loading stresses causing soil deformation at different water potentials, and the shape of the water retention curve around the water potential of field capacity.

The analyses of water retention curves of noncompacted and compacted soil provide a more detailed interpretation of how soil changes as a result of compaction than evident from measuring bulk density (McNabb et al. 1998). Some information can be gained from studying the water retention curve, particularly the effect on the macro- and mesopore space (Fig. 1). But much of the change in the water retention curve as a result of compaction occurs at the steepest point on the curve of undisturbed soil that makes simple analyses difficult. A more quantitative analysis of water retention data and associated changes in pore size distribution is possible if parameters of models fit to the data or the deriviatives of the model are analyzed (van Genuchten 1980, Kosugi 1996). In our study, the α parameter in Eqn. 1 was the most sensitive to the effects of soil compaction, and the derivative of the water retention function was particularly sensitive to where the treatments changed the shape of the curve. Both analyses are powerful tools for analyzing the effects of soil compaction on porosity and soil structure.

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Table 1. Characteristics of soil and types of equipment

Site	Soil type	Texture	Initial bulk density^{z}		Water potential^{y}		Machine	Tire (track) width (m)
			5 cm	10 cm	5 cm	10 cm		
			Mg m^{-3}		kPa			
1	Orthic/Gleyed Gray Luvisol	Loam	1.13 ± 0.02^{x}	1.34 ± 0.04	-14	-15	Skidder	$0.8/1.1^{w}$
2	Gleyed Gray Luvisol	Silt Loam	1.29 ± 0.04^{x}	1.37 ± 0.07^{x}	-15	-7	Forwarder	0.7
3	Orthic Gray Luvisol	Silt Loam	1.19 ± 0.07^{x}	1.31 ± 0.03^{x}	-6	-7	Skidder	1.1
4	Orthic Gray Luvisol	Loam	1.21 ± 0.04^{x}	1.39 ± 0.03^{x}	-9	-6	Skidder	0.8/1.1
5	Brunisolic Gray Luvisol	Loam	1.09 ± 0.06	1.16 ± 0.03	-56	-105	Crawler	0.6
6	Brunisolic Gray Luvisol	Loam	1.08 ± 0.04	1.22 ± 0.02	-29	-29	Skidder	1.1
7	Eluviated Dystric Brunisol	Silt Loam	1.00 ± 0.06^{x}	1.25 ± 0.08^{x}	-7	-13	Skidder	0.8
8	Orthic/Gleyed Gray Luvisol	Clay Loam	1.15 ± 0.05	1.33 ± 0.07	-41	-37	Skidder	1.1
9	Orthic Gray Luvisol	Silt Loam	1.18 ± 0.09	1.33 ± 0.07	-13	-16	Skidder	1.1
10	Orthic/Gleyed Gray Luvisol	Silt Loam	1.09 ± 0.02^{x}	1.17 ± 0.02^{x}	-7	-11	Skidder	0.8/1.1
11	Eluviated Dystric Brunisol	Loam	1.01 ± 0.03^{x}	1.22 ± 0.06^{x}	-7	-9	Skidder	0.8
12	Orthic/Brunisolic Gray Luvisol	Clay Loam	1.07 ± 0.06	1.13 ± 0.07	-90	-19	Skidder	1.1/1.2
13	Gleyed Gray Luvisol	Clay Loam	1.06 ± 0.05	1.24 ± 0.05^{x}	-16	-13	Forwarder	1.1
14	Orthic Gray Luvisol	Silt Loam	0.93 ± 0.03	1.12 ± 0.07	-14	-13	Skidder	1.1

^{z}Means are followed by standard error of the mean, n=16.

^{y}Mean values, n=16 in most cases.

^{x}The first 3 skidding cycles caused significant ($P<0.05$) increase in bulk density.

^{w}Front/rear if tires are different.

Table 2. **Parameters of water retention function fitted to Equation 1**

Site #	Parameter	Treatment							
		Control		3 cycles		7 cycles		12 cycles	
		5 cm	10 cm	5 cm	10 cm	5 cm	10 cm	5 cm	10 cm
1	θ_s	0.62	0.55	0.53	0.45	0.56	0.43	0.52	0.47
	θ_r	0.18	0.16	0.24	0.24	0.20	0.19	0.26	0.23
	α	0.13	0.13	0.17	0.10	0.09	0.04	0.08	0.08
	n	1.88	1.78	1.83	1.85	2.49	2.07	2.33	2.69
2	θ_s	0.53	0.42	0.58	0.50	0.44	0.48	0.48	0.48
	θ_r	0.28	0.30	0.32	0.33	0.39	0.32	0.33	0.30
	α	0.10	0.11	0.09	0.08	0.09	0.05	0.06	0.05
	n	1.72	1.99	1.67	1.70	1.56	2.05	1.79	1.80
3	θ_s	0.50	0.49	0.50	0.45	0.44	0.50	0.47	0.43
	θ_r	0.23	0.20	0.25	0.22	0.21	0.14	0.23	0.19
	α	0.06	0.06	0.07	0.06	0.07	0.05	0.06	0.07
	n	2.59	2.20	1.99	2.11	2.72	4.07	2.31	2.48
4	θ_s	0.59	0.54	0.51	0.54	0.44	0.45	0.47	0.43
	θ_r	0.21	0.26	0.24	0.22	0.21	0.27	0.27	0.25
	α	0.18	0.12	0.09	0.10	0.07	0.03	0.10	0.07
	n	1.68	2.03	2.20	1.75	3.35	2.91	2.00	2.34
5	θ_s	0.62	0.58	0.57	0.58	0.55	0.51	0.60	0.56
	θ_r	0.18	0.16	0.19	0.17	0.21	0.16	0.22	0.17
	α	0.20	0.19	0.20	0.18	0.15	0.17	0.13	0.15
	n	1.72	1.70	1.92	1.80	1.81	1.70	1.88	1.84
6	θ_s	0.67	0.63	0.58	0.53	0.58	0.66	0.61	0.56
	θ_r	0.26	0.20	0.26	0.19	0.24	0.20	0.22	0.17
	α	0.17	0.17	0.08	0.08	0.14	0.14	0.12	0.12
	n	1.90	1.77	2.31	1.80	1.79	1.72	1.97	1.79
7	θ_s	0.57	0.48	0.57	0.47	0.54	0.49	0.57	0.47
	θ_r	0.32	0.28	0.30	0.21	0.30	0.29	0.34	0.28
	α	0.14	0.08	0.11	0.03	0.04	0.07	0.06	0.04
	n	1.75	1.79	1.70	1.92	2.22	1.72	2.22	2.16

Table 2. **(Continued)**

Site #	Parameter	Treatment							
		Control		3 cycles		7 cycles		12 cycles	
		5 cm	10 cm	5 cm	10 cm	5 cm	10 cm	5 cm	10 cm
8	θ_s	0.53	0.50	0.70	0.52	0.53	0.43	0.56	0.51
	θ_r	0.21	0.23	0.27	0.23	0.25	0.25	0.26	0.25
	α	0.18	0.13	0.15	0.11	0.17	0.13	0.17	0.14
	n	1.54	1.62	1.91	1.73	1.72	1.69	1.76	1.65
9	θ_s	0.49	0.50	0.53	0.54	0.49	0.47	0.49	0.50
	θ_r	0.29	0.25	0.25	0.22	0.21	0.24	0.26	0.23
	α	0.12	0.13	0.11	0.12	0.06	0.08	0.08	0.06
	n	1.79	1.67	1.87	1.98	1.90	2.09	1.83	1.92
10	θ_s	0.65	0.64	0.61	0.55	0.56	0.52	0.52	0.48
	θ_r	0.23	0.25	0.32	0.26	0.28	0.26	0.23	0.33
	α	0.13	0.16	0.08	0.05	0.05	0.07	0.06	0.06
	n	2.03	1.60	1.65	1.63	1.76	1.79	5.18	2.36
11	θ_s	0.59	0.55	0.57	0.43	0.45	0.39	0.47	0.38
	θ_r	0.24	0.19	0.27	0.32	0.23	0.20	0.27	0.22
	α	0.11	0.15	0.08	0.06	0.04	0.03	0.03	0.14
	n	2.30	1.76	2.28	2.70	1.99	1.96	2.72	5.22
12	θ_s	0.53	0.52	0.60	0.53	0.60	0.60	0.67	0.65
	θ_r	0.28	0.27	0.25	0.19	0.27	0.26	0.14	0.24
	α	0.17	0.11	0.13	0.09	0.16	0.13	0.14	0.17
	n	1.60	2.51	1.71	2.92	1.83	1.79	1.62	1.62
13	θ_s	0.54	0.50	0.54	0.50	0.66	0.66	0.50	0.52
	θ_r	0.30	0.21	0.32	0.24	0.42	0.37	0.32	0.27
	α	0.09	0.11	0.07	0.05	0.09	0.04	0.03	0.06
	n	2.77	1.87	1.76	1.91	2.14	2.11	2.60	2.41
14	θ_s	0.66	0.55	0.62	0.54	0.67	0.60	0.62	0.56
	θ_r	0.34	0.28	0.34	0.29	0.26	0.34	0.28	0.33
	α	0.17	0.14	0.14	0.16	0.10	0.12	0.11	0.16
	n	2.53	2.10	1.79	1.79	1.90	2.19	1.88	2.12

Table 3. Summary of ANOVA for parameters θ_s, θ_r, α, and n using depth as repeated factor

Source of variation	NDF[z]	DDF[z]	Parameters							
			θ_s		θ_r		α		n	
			F	Pr>F	F	Pr>F	F	Pr>F	F	Pr>F
All sites										
Site	13	39	4.98	0.000	8.35	0.000	10.75	0.000	2.85	0.006
Treatment	3	39	2.06	0.121	0.61	0.612	12.32	0.000	1.44	0.246
Depth	1	52	42.58	0.000	12.99	0.001	3.89	0.054	0.12	0.735
Trt. x Depth	3	52	1.38	0.260	0.85	0.475	2.41	0.078	0.57	0.635
Sites are coded for whether compaction was significant (Table 1)										
Compaction	1	51	20.01	0.000	0.24	0.624	26.71	0.000	4.31	0.043
Treatment	3	51	1.53	0.219	0.21	0.886	5.81	0.002	1.07	0.369
Depth	1	52	42.58	0.000	12.99	0.001	3.89	0.054	0.12	0.735
Trt. x Depth	3	52	1.38	0.260	0.85	0.475	2.41	0.078	0.57	0.635
Compacted sites (1-4, 7, 10, 11, 13)										
Site	6	18	4.88	0.004	11.64	0.000	2.40	0.070	2.99	0.033
Treatment	3	18	8.27	0.001	2.01	0.149	12.37	0.001	2.86	0.065
Depth	1	24	29.37	0.000	4.25	0.050	2.15	0.155	0.18	0.674
Trt. x Depth	3	24	0.95	0.434	0.15	0.927	1.34	0.284	0.45	0.718
Uncompacted sites (5, 6, 8, 12, 14)										
Site	6	18	2.43	0.068	10.65	0.000	11.77	0.000	2.48	0.063
Treatment	3	18	0.04	0.990	0.73	0.550	3.25	0.048	0.11	0.953
Depth	1	24	13.15	0.001	9.27	0.006	1.55	0.225	0.00	0.979
Trt. x Depth	3	24	0.47	0.707	1.92	0.154	1.38	0.273	0.26	0.851

[z] NDF and DDF are numerator and denominator degrees of freedom in the SAS 6.11 PROC MIXED output.

Table 4. **Effects of skidding on parameters of water retention function**

Number of skidding cycles	Parameters[z]			
	θs	θr	α	n
Compacted sites (1-4, 7, 10, 11, 13)				
0	0.55±0.02 a[y]	0.24±0.02 a	0.12±0.01 a	1.94±0.15 a
3	0.52±0.02 ab	0.27±0.02 a	0.08±0.01 b	1.93±0.15 a
7	0.48±0.02 b	0.25±0.02 a	0.06±0.01 c	2.33±0.15 a
12	0.47±0.02 b	0.27±0.02 a	0.07±0.01 c	2.24±0.15 a
Uncompacted sites (5, 6, 8, 12,14)				
0	0.56±0.02 a	0.25±0.02 a	0.15±0.01 a	1.93±0.09 a
3	0.56±0.02 a	0.24±0.02 a	0.12±0.01 a	1.94±0.09 a
7	0.57±0.02 a	0.26±0.02 a	0.12±0.01 a	1.88±0.09 a
12	0.56±0.02 a	0.24±0.02 a	0.12±0.01 a	1.92±0.09 a

[z] Least squares means and standard errors.

[y] Different letters indicate significant differences among treatments ($P< 0.05$).

Table 5. **Effects of skidding on field capacity, available water holding capacity, and air-filled porosity of soil**

Number of skidding cycles	Water content at field capacity	Available water holding capacity	Air-filled porosity
	$m^3\ m^{-3}$		
Compacted sites (1-4, 7, 10, 11, 13)			
0	0.40±0.02[z] a[y]	0.17±0.02 a	0.15±0.02 a
3	0.43±0.02 a	0.17±0.02 a	0.09±0.02 ab
7	0.43±0.02 a	0.18±0.02 a	0.05±0.02 b
12	0.43±0.02 a	0.16±0.02 a	0.05±0.02 b
Uncompacted sites (5, 6, 8, 12,14)			
0	0.39±0.02 a	0.14±0.01 a	0.17±0.03 a
3	0.40±0.02 a	0.15±0.01 a	0.17±0.03 a
7	0.42±0.02 a	0.16±0.01 a	0.15±0.03 a
12	0.39±0.02 a	0.15±0.01 a	0.17±0.03 a

[z] Least squares means and standard errors.

[y] Different letters indicate significant differences among treatments ($P < 0.05$).

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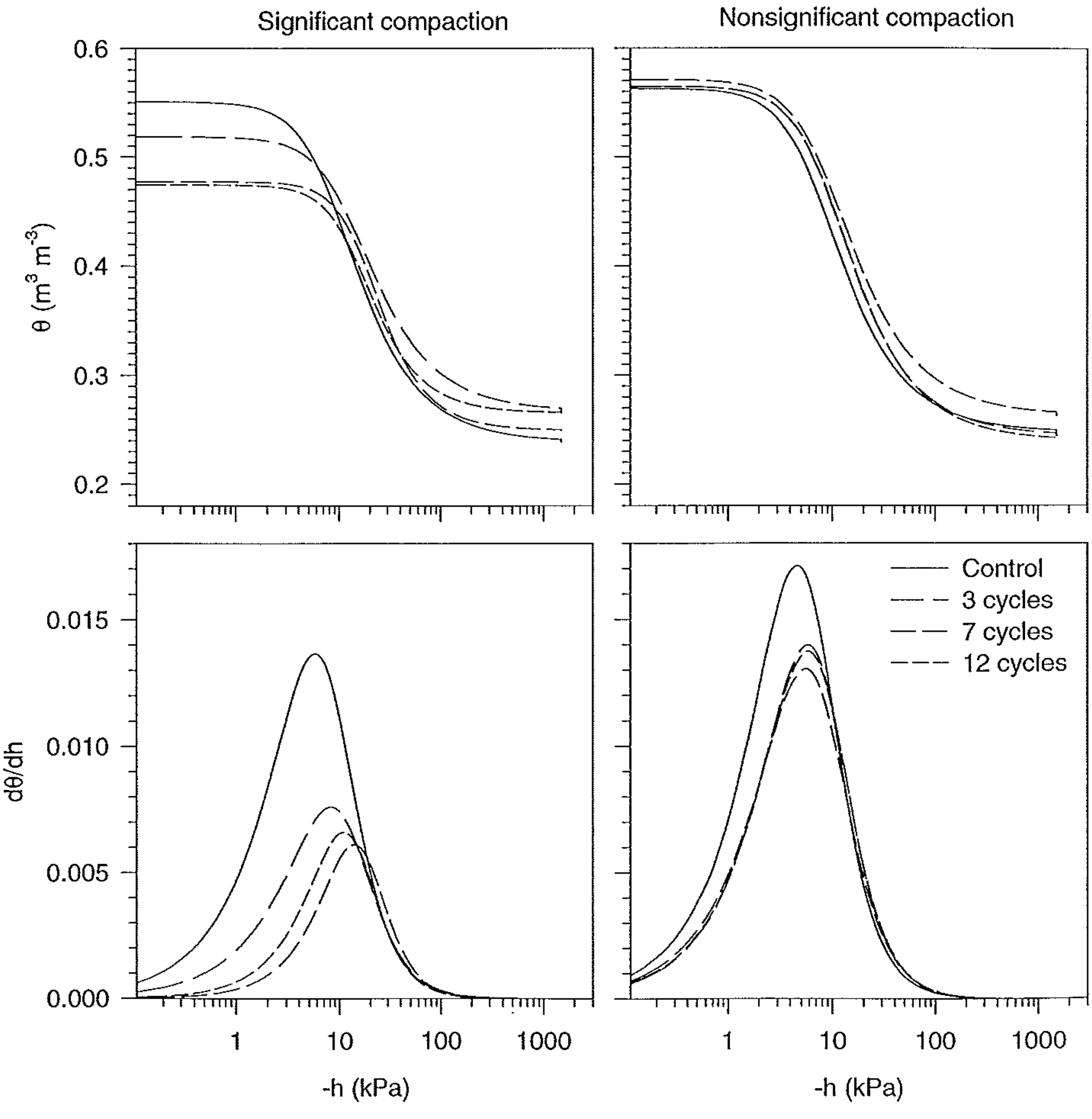
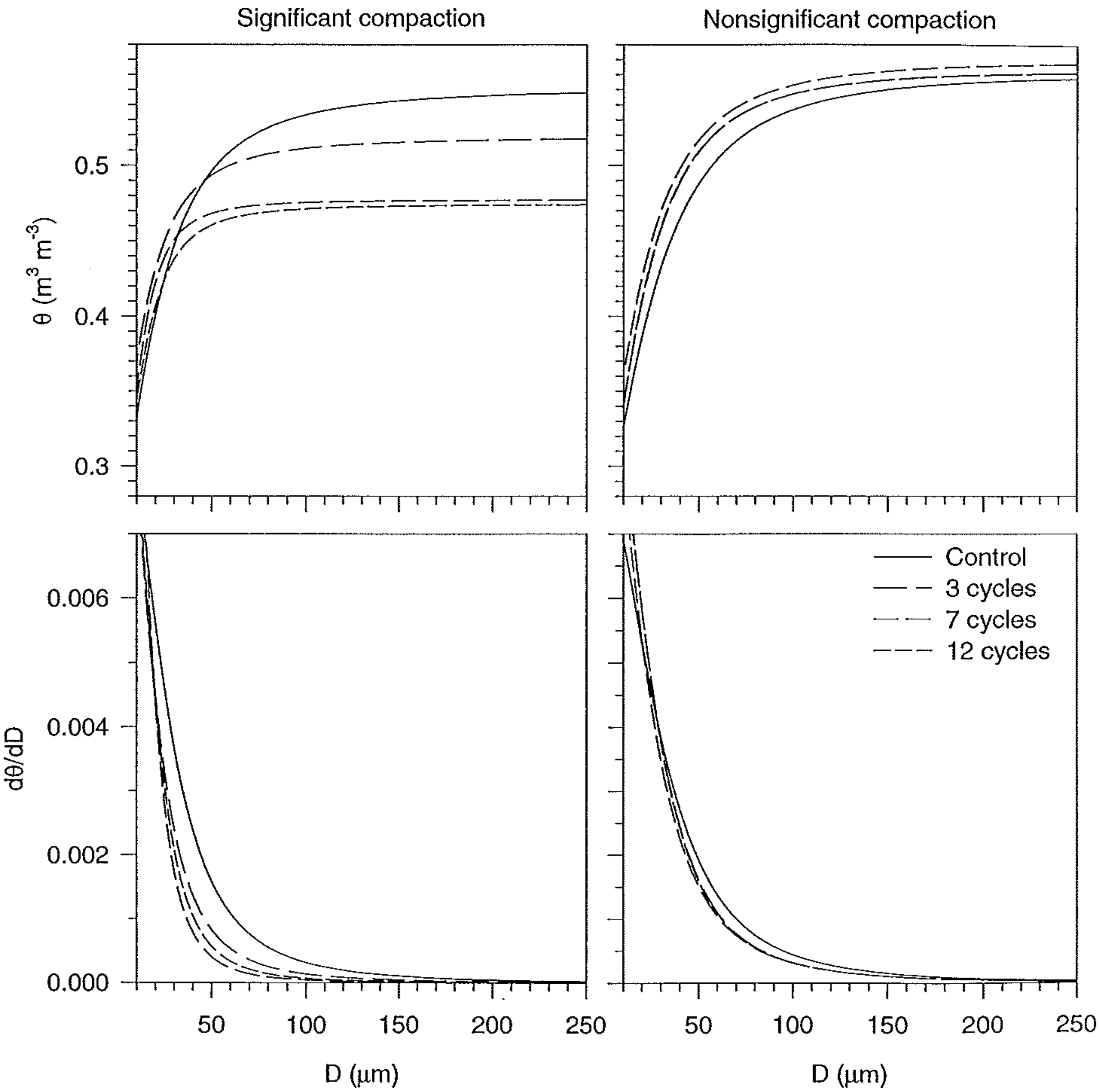


Significant compaction
Nonsignificant compaction
θ (m³ m⁻³)
0.6
0.5
0.4
0.3
0.2
dθ/dh
0.015
0.010
0.005
0.000
1
10
100
1000
-h (kPa)
Control
3 cycles
7 cycles
12 cycles


Significant compaction
Nonsignificant compaction
θ (m3 m-3)
0.3
0.4
0.5
dθ/dD
0.000
0.002
0.004
0.006
Control
3 cycles
7 cycles
12 cycles
50
100
150
200
250
D (μm)
D (μm)