

# Soil compaction induced by careful logging in the claybelt region of northwestern Quebec (Canada)

S. Brais<sup>1,2</sup> and C. Camiré<sup>3</sup>

<sup>1</sup>Unité de recherche et développement forestiers de l'Abitibi-Témiscamingue, Université du Québec en Abitibi-Témiscamingue, Rouyn-Noranda, Québec, Canada J9X 5E4; <sup>2</sup>Centre de recherche en biologie forestière, Faculté de foresterie et de géomatique, Université Laval, Ste-Foy, Québec, Canada G1K 7P4. Received 30 April 1997, accepted 18 August 1997.

Brais, S. and Camiré, C. 1998. Soil compaction induced by careful logging in the claybelt region of northwestern Quebec (Canada). *Can. J. Soil Sci.* 78: 197–206. Soil compaction induced by forest harvesting operations can reduce site productivity. Intensity, extent and persistence of soil compaction were assessed on fine- to medium- and coarse-textured soils. Severe compaction took place in the wheel track section of the skid trails. On fine- to medium-textured soils, half of the effects on the 0- to 10-cm and 10- to 20-cm mineral soil bulk densities (+11 and +8%) and half of the changes in the 10-cm depth soil strength (+69%) occurred in the course of the first two skidding cycles (cycle of half impact). On coarse soils, half of the effect on the 0- to 10-cm bulk density (+11%) occurred during the first three passes. Cycles of half impact for soil strength were 9, 14, 7 and 6 for the 2.5-, 5-, 10-, and 20-cm depths and corresponded to increases of 235, 402, 157 and 103% respectively. Compaction was more limited between track sections of trails. Six to twelve years following clearcutting on fine- to medium-textured soils, 0- to 10-cm soil bulk density was less in the skid trails than on the undisturbed sections of cutovers. Careful logging on moist, fine- to medium-textured soils is the safest way to limit the extent of soil compaction. On coarse-textured soils, spreading the traffic remains a valid option.

**Key words:** Soil compaction, bulk density, soil strength, forest harvesting, careful logging

Brais, S. et Camiré, C. 1998. Compactage du sol engendré par les opérations de récolte dans la ceinture d'argile du nord-ouest québécois. *Can. J. Soil Sci.* 78: 197–206. Le compactage engendré par la récolte forestière peut réduire la productivité des sols. L'étendue, la sévérité et la persistance du compactage ont été évaluées pour des sols de texture fine à moyenne et de texture grossière. Le sol directement sous le passage des roues était fortement compacté. Sur les sols de texture fine à moyenne, plus de la moitié des changements de la masse volumique apparente entre 0–10 et 10–20 cm de profondeur (+ 11 et + 8 %) et de la résistance à 10 cm (+ 69 %) prenaient place au cours des deux premiers passages. Sur les sols de texture grossière, la moitié des effets sur la masse volumique apparente entre 0–10 cm (+ 11 %) prenaient place au cours des trois premiers passages. La moitié des impacts sur la résistance à 2,5, 5, 10 et 20 cm de profondeur (+ 235, 402, 157 et 103 %) n'étaient apparents qu'après les 9e, 14e, 7e et 6e passages respectivement. À l'intérieur des sentiers, entre les traces de roues, le compactage était moins sévère. Six à douze ans après coupe à blanc, le compactage résiduel affectait les ornières entre 10 et 40 cm de profondeur. Sur les sols de texture fine à moyenne la CPRS constitue le meilleur moyen de limiter l'étendue du compactage. Sur les sols de texture grossière, étendre le trafic à l'ensemble du parterre demeure une option valable.

**Mots clés:** Compactage, masse volumique, résistance, opérations forestières, CPRS

Soil compaction as well as puddling and rutting caused by forest operations have received considerable attention in the literature (Lull 1959; Greacen and Sands 1980; Froehlich and McNabb 1984). Seedling growth reductions due to artificially induced compaction have been reported for numerous species including *Pinus contorta* (Dougl.) (Corns 1988; Conlin and van den Driessche 1996), *Pinus rigida* (Mill.) (Zisa et al. 1980), *Pinus nigra* (Arnold) (Zisa et al. 1980), *Pinus sylvestris* (L.) (Wasterlund 1985), *Picea glauca* ([Moench] Voss) (Corns 1988), *Picea mariana* ([Mill.] B.S.P.) (Prévost and Bolghari 1990) and *Picea abies* ([L.] Karst) (Wasterlund 1985). Growth reductions on primary skid trails have been reported as well for *Tsuga heterophylla*

([Raf.] Sarg) (Miller et al. 1996), *Pinus ponderosa* (Laws.) (Froehlich et al. 1986), *Pinus taeda* (L.) (Lockaby and Vidrine 1984) and *Pseudotsuga menziesii* ([Mirb] Franco) (Wert and Thomas 1981).

Lack of commitment of management agencies toward soil protection is partly rooted in the widespread belief that traffic-induced perturbations are of short duration and that natural weathering forces will alleviate compaction (e.g. Zelazny et al. 1989), especially in fine-textured soils. Yet persistence of compaction below the plough layer has been reported for agricultural soils subjected to freeze-thaw cycles (Blake et al. 1976; Voorhees et al. 1978; Voorhees 1983). Residual soil compaction caused by logging operations has been reported for periods ranging from 15 to 55 years (Power 1974; Wert and Thomas 1981; Froehlich et al. 1986; Corns 1988).

Soil susceptibility to compaction is dependent on several inherent properties such as texture (Bodman and Constantin

<sup>1</sup>To whom correspondence should be addressed: Suzanne Brais, URDFAT-UQAT, 445 boulevard de l'Université, Rouyn-Noranda, Québec, Canada J9X 5E4.

1965), parent material (Wasterlund 1985; McNabb and Boersma 1996) and moisture retention properties (Williams and Shaykewich 1970; Vepraskas 1984). Prediction of compaction based on soil properties remains a difficult exercise (Butt and Rollerson 1988) as degree and extent of compaction in the field will depend on effective soil moisture (Moehring and Rawls 1970), number of passes (Steinbrenner 1955; Miles et al. 1981; Sidle and Drlica 1981), harvest season (Holman et al. 1978), direction of skidding relative to slope (Sidle and Drlica 1981), and pattern of skid trails (Froehlich et al. 1981).

Designated skid trails are promoted as an approach for restricting soil compaction (Froehlich and McNabb 1984). This approach is supported by the fact that most damage to soil structure is caused by the first passes of machinery (Steinbrenner 1955; Jakobsen and Moore 1981; Miles et al. 1981). However, spreading the traffic evenly over the clearcut area remains an option when the initial passes cause only minor changes in soil structural properties (Jakobsen and Moore 1981). In Quebec, careful logging has gradually replaced arbitrary use of skid trails as a means of protecting natural regeneration and limiting soil disturbance, and is now mandatory on all clearcut operations (Ministère des Ressources Naturelles du Québec 1994). Careful logging creates an alternating pattern of protection strips, where no traffic is allowed, and trails in which feller bunchers and skidders or forwarders are restricted. With commonly used equipment, skid trails cover approximately 33% of clearcuts area. Given that this system was partly designed for soil protection, a thorough investigation of its impacts on soils should be carried out. Questions concerning the degree, distribution and extent of soil compaction and rutting need to be addressed and the effectiveness of careful logging techniques should be evaluated for soil types with different characteristics.

Results presented here originated from three different studies conducted within the framework of a Forest Ecosystem Classification (FEC) for the southern part of the claybelt area of northwestern Quebec (Cartier et al. 1996; Harvey et al. 1996). These studies aimed at evaluating the impacts of forest harvesting on soil physical properties of the most common site types. Their primary focus was growth conditions in the years following harvesting rather than soil behavior in the course of harvesting. Objectives were 1) to establish the relationship between number of passes and degree of soil compaction for fine- to medium- and coarse-textured glaciolacustrine surface deposits, 2) to compare soil physical properties between skid trails and protection strips following careful logging on these fine- to medium- and coarse-textured soils and assess the extent and severity of compaction following careful logging and 3) to assess the extent, degree, and persistence of soil compaction on old clearcuts (6 to 12 yr) on fine- to medium-textured soils. Although methodologies differed among the studies, integration of these results has allowed us to answer the following questions: How do bulk density and soil strength change with increasing number of passes? Is the rate of change different for the fine- to medium- and coarse-textured soils? What is the extent of compaction over a carefully logged cutover? Is compaction limited to the wheel track or

does it affect the inner part of the trail and the protection strips? How does the extent following careful logging compare with that where movement of machinery is unrestricted (unplanned)? How persistent is compaction on fine- to medium-textured soils? Is careful logging the best way to minimise site damage on all soils?

## MATERIAL AND METHODS

### Study Area

The study area was located between 47°45' and 48°30' N and 78°40' and 79°30' W, just east of the Quebec-Ontario border in the southern part of the claybelt. The climate is continental with mean annual temperature of 0.6 to 1.7°C and precipitation of 823 to 937 mm, falling mainly as rain (Environment Canada 1982). The region is part of the Precambrian Shield and the topography is generally gentle with short slopes. Most of the bedrock is covered with Quaternary deposits. Because of their dimensions, eskers are important features of the landscape. The clay plain (fine- to medium-textured glaciolacustrine deposits) formed by sedimentation in the bottom of glacial Lake Barlow-Ojibway lies between the eskers (Allard 1974). The transition zone between the eskers and the clay plain is often covered with reworked glaciofluvial material overlaying the bottom of the lake (coarse-textured glaciolacustrine deposits). The region is situated at the southern fringe of the boreal forest and is characterized by forests of balsam fir (*Abies balsamea* [L.] Mill.), white birch (*Betula papyrifera* Marsh.), and white spruce (*Picea glauca*) stands on mesic sites. The soils in the study have evolved from fine clayey to fine loamy and sandy textured glaciolacustrine deposits under dry to moist moisture regimes (Brais and Camiré 1992). Gray Luvisol soils evolved on finer material and humo-ferric Podzols are found on coarse-textured deposits (Canada Soil Survey Committee 1987).

### Experimental and Sampling Designs

#### *Study 1: Relationship between number of skidding cycles and the intensity and extent of soil compaction*

In order to assess the relationship between number of skidder passes and changes in soil physical conditions for two contrasting soil types, two experimental studies were conducted, one on silty clay to clay loam soils and one on loamy sand to sandy soils. Moisture regime for both types of soil ranged from fresh to moist. These experiments were set up as a factorial design with three blocks, seven levels of skidding cycles (main treatment) randomly assigned within each block and three position levels (subtreatment) within passes. Position relative to skid trails (**wheel track [WT]**, skid trail in **between tracks [BT]** and adjacent **undisturbed area [UD]**) could not be assigned randomly. The study was treated as a split-block design.

Prior to treatments, seven 15 × 50 m strips in each block were cleared of all trees over 10 cm diameter at breast height. No machinery entered into the strips during this preparatory operation. At time of treatments, five soil samples were taken in each strip for mineral soil water content determination at 25–30 cm. Treatments were similar to

Table 1. Study 1: Skidder, load and soil characteristics

	Fine- to medium-textured site	Coarse-textured site
<i>Soils</i>		
Moisture content (g kg <sup>-1</sup> )	268–450	7–9
Organic content (g kg <sup>-1</sup> )	377–513	123–183
Mineral content (g kg <sup>-1</sup> )	23–355	810–867
Bulk density 0–10 cm (Mg m <sup>-3</sup> )	1.14	1.06
Bulk density 10–20 cm (Mg m <sup>-3</sup> )	1.31	1.19
Bulk density 20–30 cm (Mg m <sup>-3</sup> )	1.55	1.31
Moisture content (kg kg <sup>-1</sup> )	0.25–0.41	0.25–0.32
Minimum water content	0.23–0.31	0.14–0.15
Soil compaction (kg kg <sup>-1</sup> )		
Plasticity limit (kg kg <sup>-1</sup> )	0.26–0.38	
<i>Skidders and loads</i>		
Skidder	Clark 667C	Tree-Farmer C8E
Capacity (Mg)	9.50	12.95
Length	30.5L × 32	30.5L × 32
Weight (Mg)	2.5	2.6

as described by Jakobsen and Moore (1981). Each treatment consisted of a given number of skidding cycles (0, 1, 5, 7, 11, 15 cycles), all of which were carried out in the same manner. The skidder was driven over the strip pulling a load of logs. Past the end of the strip, the load was hooked and the skidder was turned around and driven back over the strip. It then returned, via a detour, to pick up the load, and finally returned to its starting point via a second detour. Skidder, load and soil characteristics are given in Table 1.

Sampling was done within a year following treatments; this corresponds to the period when reforestation of cutovers or skid trails takes place. In each strip and for each position (WT, BT and UD), three sample locations were equally spaced along the strip. Undisturbed soil samples were taken from the 0- to 10-cm, 10- to 20-cm and 20- to 30-cm mineral soil depths in the WT and the BT portions of the strip for bulk density measurements. No measurements were taken in the UD portion since the 0 cycle strip acted as a control treatment. All positions were surveyed for soil strength but only in two of the three blocks for the sandy soils, and in all three blocks but only for the 0, 1, 5 and 15 cycles for the fine to medium soils. At each sampling location, three penetrometer readings (see Soil analyses) were taken for the 0- to 10-cm mineral depth and one soil sample was collected within the same depth for soil moisture determination.

#### Study 2: Soil conditions in skid trails and protection strips following careful logging on fine- to medium- and coarse-textured soils.

This study was situated within the limits of Normick Perron Inc.'s summer logging area. All cutovers were carefully logged 1 yr prior to sampling. Wood extraction was done using cable skidders similar to those described in Table 1. Careful logging created an alternating pattern of 10 m wide protection strips and 4 to 5 m wide skid trails.

Four cutovers were located on fresh to moist fine clayey and fine loamy soils (clay and sandy clay loam) and three on dry to fresh sandy soils (sand to loamy sand). Two 0.25-ha

Table 2. Study 3: Average number of soil samples taken in each stand for different locations and soil depths

Location	Depth (cm)		
	0–10	10–20	20–40
Wheel track	56	14	13
Between track	52	16	13
Undisturbed	23	16	16
Uncut stands	16	16	15

blocks on fine- to medium-textured soils and three on coarse-textured soils were located within each cutover, so as to ensure appropriate coverage of cutover area and uniform soil moisture conditions. Within each block, at three equally spaced locations, samples and measurements were taken: 1) within the trails, between the wheel tracks (BT); 2) in the outer portion of the protection strip next to the wheel track (UD-O); and 3) in the central portion of the protection strip (UD-C). Wheel tracks were not sampled. Hence, six sampling locations per cutover were surveyed for fine-textured sites and nine for coarse-textured sites. The sampling design was treated as a randomized complete block design, where the cutovers constituted the blocks and the position relative to the trails constituted the treatments. Procedures for soil sampling and measurements were the same as in Study 1. Data from fine- to medium- and coarse-textured sites were analyzed separately.

#### Study 3: Residual soil compaction on fine-textured soils

The third study was located within the limits of a balsam fir–white birch–white spruce forest mosaic that contained stands that were harvested 6 to 12 yr prior to sampling. All stands were summer harvested using cable skidders. Skid trails were distributed arbitrarily over the cutover area. Skidder characteristics were not available.

Visible skid trails were located and sampled in three cutovers. Sampling was done in the wheel tracks, in the center of the trails (between the tracks), and outside visible trails, in the undisturbed area. Undisturbed soil cores were taken from the center of the 0- to 10-cm, 10- to 20-cm and 20- to 40-cm mineral soil depths for bulk density measurements. To ensure adequate coverage of cutovers, sampling locations (Table 2) were distributed along at least two trails in each cutover at distances ranging from 10 to over 200 m from roadside. Half the sampling locations were on dry to fresh soil and half on moist soil. Since a preliminary sampling had indicated that the variability in soil bulk density was greater in the surface layer and in the skid trails, more samples were taken in these locations (Table 2). The sampling design was treated as a randomized complete block design, where the three cutovers constituted the blocks and the positions relative to the trails constituted the treatments. Data for dry to fresh and moist soil moisture regimes were first treated separately. As no difference could be found between moisture regime, data were pooled.

In order to verify that no significant residual soil compaction was present between detectable skid trails, soil conditions of the undisturbed areas of cutovers were compared with those of undisturbed stands. Three uncut stands of similar

pre-harvest forest cover and soil conditions were sampled for bulk density determination (Table 2). This design was treated as a completely random design with two treatments (uncut and cut-undisturbed) and where each stand and cutover constituted a replication.

Areal extent of residual skid trails was estimated. Transect lines were extended across three cutovers and sampling locations were located every 10 or 20 m depending on transect length. At each point, moisture regime was determined and presence or absence of skid trail features was noted. Between 48 and 61 locations were sampled in each cutover.

### Soil Analyses

Sampling for bulk density was done with a double cylinder soil sampler. Undisturbed soil samples (5 cm diameter, 100 cm<sup>3</sup>) were oven dried (105°C) for 48 h prior to weighing. Soil strength (penetration resistance) was assessed with a mechanical recording penetrometer (Eijkelkamp Agrisearch Equipment, P.O. Box 4, 6987 ZG Giesbeek, The Netherlands). Sixty degree cones were used. Cone surface area used was 1 cm<sup>2</sup> on fine-textured soils and 2 cm<sup>2</sup> on coarse-textured soils. Soil moisture was determined on a weight/weight basis on oven dried soils. Soil texture was determined by the Bouyoucos hydrometer method (McKeague 1976). In order to characterize soil material, standard Proctor tests (Head 1992) were conducted on five samples covering the range of texture classes encountered in Study 1. Plastic limit of fine material was determined according to the ASTM D424-59 procedure (McKeague 1976) on three of the five samples.

### Statistical Analyses

All statistical analyses were done using the GLM, FREQ, REG and NLIN procedures of SAS Institute, Institute (1988). Homogeneity of variance was tested using Bartlett's procedure. Variables that did not meet the requirement were log-transformed. Data were treated according to their respective sampling design. For Study 1, different analyses were undertaken for each soil depth. For Studies 2 and 3, depth was considered as a factor and the data were treated according to a split block in space design which took into account the non randomization of depths (Steel and Torrie 1980). Significance ( $P < 0.100$ ) of effect of number of cycles (linear, quadratic), depth (linear), position relative to skid trails and, of interaction between those factors was tested by means of contrasts (Steel and Torrie 1980). Although part of the relationships between skidding cycles and soil parameters could often be described as linear and quadratic, the relationships over the whole range of cycles were best described as exponential. Whenever a significant linear relationship was found, an exponential model (Ratkowsky 1983) was fitted to the curve and the "cycle of half impact ( $t_{1/2}$ )" — the equivalent of the half-life of a decaying population or of radioactive decay (Edelstein-Keshet 1988) — was used to further describe and compare the relationships.

Soil water content at time of sampling was used as a covariate for soil strength (Yasin et al. 1993) when it was not affected by treatments (Lison 1968). Soil strength at 20 and 30 cm in fine- to medium-textured soils and at 30 cm in

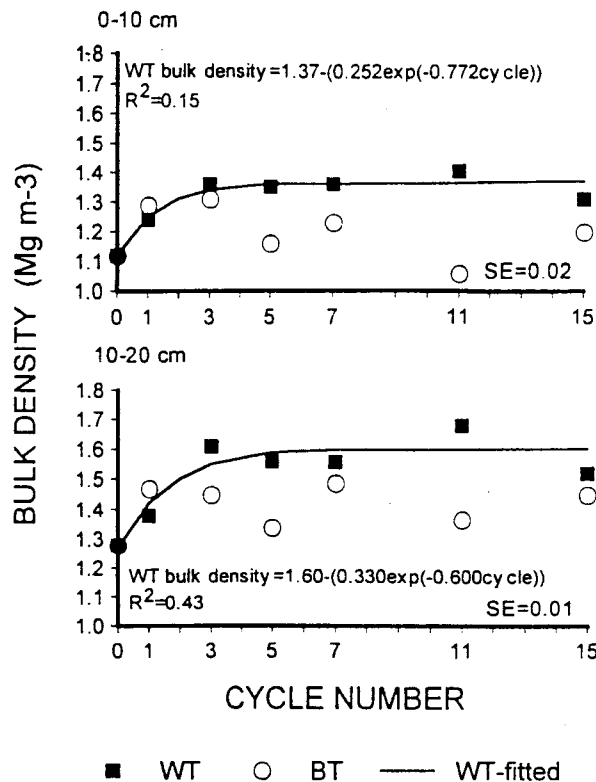


Fig. 1. Soil bulk density ( $\text{Mg m}^{-3}$ ) as affected by number of skidding cycles and position relative to skid trail on fine- to medium-textured sites (WT = wheel track, BT = between tracks).

coarse-textured soils was often higher than the applicable ranges of the penetrometer (respectively 500 and 250 N  $\text{cm}^{-2}$ ). The strength values were divided into classes and the relationship between soil strength and position relative to skid trail was tested by means of the  $\chi^2$  criterion (Steel and Torrie 1980) for each depth.

## RESULTS

### Study 1: Relationship between Number of Skidding Cycles and the Intensity and Extent of Soil Compaction on Fine- to Medium-textured Soils

The 0- to 10-cm mineral soil bulk density of the WT section increased with number of cycles relative to that of the BT section (Fig. 1) as shown by the significant linear component of the interaction between positions (Table 3). In the course of the first cycle ( $t_1 = 0.9$ ), bulk density increased by 11% of control values (no cycle). Bulk density in the BT section fluctuated randomly. In the 10- to 20-cm layer, bulk densities increased linearly with number of cycles but behaved differently depending on position (Table 3). In the WT, bulk density increased by 8% of control values in the course of the first cycle ( $t_1 = 1.2$ ) and remained constant after seven cycles (Fig. 1). No exponential model could be fitted to BT values. After 15 cycles, BT observed value were 13% higher than control values. Treatments had effect on 20- to 30-cm bulk densities (average 1.57 Mg m<sup>-3</sup>

Table 3. Effects of number of logging cycles and position relative to skid trail on physical characteristics of fine to medium textured soils. Probability levels of factors, interactions, and contrasts

Characteristic	Bulk density		Strength	
	0-10	10-20	5	10
Depth (cm)	df	P>F	df	P>F
Position				
WT vs. BT	1	0.126	2	0.080
BT vs. UD	1	0.126	1	0.038
Cycle				
Linear	6	0.846	3	0.776
Quadratic	1	0.556	1	0.480
Position × cycle				
WT vs. BT × linear	1	0.017	1	0.754
BT vs. UD × linear	1	0.072	1	0.844
WT vs. BT × quad.	1	0.212	1	0.727
BT vs. UD × quad.	1	0.048	1	0.818

Soil strength at the 2.5-cm depth was not affected by treatments. At the 5 cm depth, strength was higher in the BT section ( $76 \text{ N cm}^{-2}$ ) than in the UD section ( $60 \text{ N cm}^{-2}$ ,  $SE = 3 \text{ N cm}^{-2}$ ). WT strength ( $72 \text{ N cm}^{-2}$ ) was not different from BT strength (Table 3). At the 10-cm depth, WT strength (Fig. 2) increased with cycles. Following the first two cycles ( $t_1 = 2.1$ ), predicted values were 69% higher than control values (no cycle). The BT values were not significantly different from the UD values. At the 20-cm depth, 57% of WT values were over  $500 \text{ N cm}^{-2}$  (the upper limit of the penetograph range), compared with 22 and 19% for the BT and UD sections respectively ( $\chi^2 = 23$ ,  $P = 0.021$ ,  $n = 162$ ). At the 30-cm depth, values were 72, 54, and 50% for the WT, BT and UD sections, respectively ( $\chi^2 = 8$ ,  $P = 0.091$ ,  $n = 162$ ).

#### Study 1: Relationship between Number of Skidding Cycles and the Intensity and Extent of Soil Compaction on Coarse-textured Soils

Wheel track bulk density increased with the number of cycles in the 0- to 10-cm soil depth (Fig. 3; Table 4). WT bulk density was 11% higher than control values after three cycles ( $t_1 = 2.64$ ). Between track values fluctuated in an irregular fashion. Treatments had no significant effect on the 10- to 20-cm bulk density. The linear component of the interaction between position and cycle was significant for the 20- to 30-cm depth (Table 4), but no satisfactory model could be fitted to WT values. Averaged over all cycles, the 20- to 30-cm bulk density was 3% higher in the WT than in the BT section (Fig. 3).

Wheel track soil strength increased with cycles for all sampled depths (Table 4, Fig. 4). Cycles of half impact ( $t_1$ ) were 9, 14, 7 and 6 for the 2.5-cm, 5-cm, 10-cm, and 20-cm depths, respectively, and corresponded to increases in strength of 235, 402, 157 and 103% of control values (no cycle). According to the models, values would continue to increase after 15 cycles. At the 10-cm depth, BT values ( $81 \text{ N cm}^{-2}$ ) were higher than UD values ( $67 \text{ N cm}^{-2}$ ,  $SE = 4 \text{ N cm}^{-2}$ ). This difference was not related to number of cycles

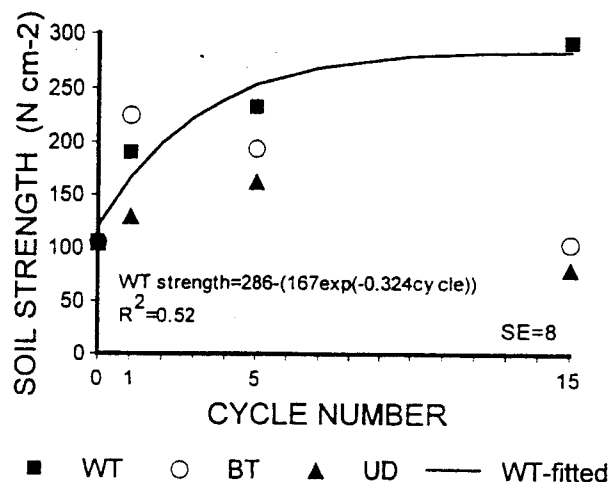


Fig. 2. Soil strength ( $\text{N cm}^{-2}$ ) as affected by number of skidding cycles and position relative to skid trail on fine- to medium-textured sites (WT = wheel track, BT = between tracks, UD = undisturbed).

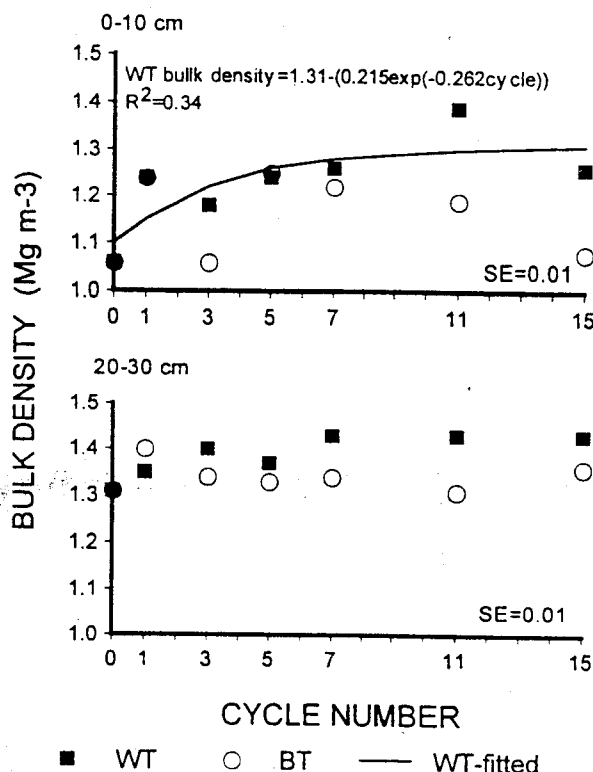


Fig. 3. Soil bulk density ( $\text{Mg m}^{-3}$ ) as affected by number of skidding cycles and position relative to skid trail on coarse-textured sites (WT = wheel track, BT = between tracks).

(Table 4). At the 30-cm depth, 37% of WT values were higher than  $250 \text{ N cm}^{-2}$  (the upper limit of the instrument range) compared with 18 and 13% for the BT and UD sections, respectively, ( $\chi^2 = 13$ ,  $P = 0.009$ ,  $n = 114$ ). Ten percent of the 30-cm strength values were higher than  $250 \text{ N cm}^{-2}$  after 3 cycles, compared with 22% after 7 cycles, and 39% after 15 cycles ( $\chi^2 = 10$ ,  $P = 0.040$ ,  $n = 114$ ).

Table 4. Effects of number of logging cycles and position relative to skid trail on physical characteristics of coarse textured soils. Probability levels of factors, interactions, and contrasts

Characteristic	Bulk density			Strength				
	Depth (cm)	0-10	20-30	2.5	5	10	20	
Effect	df	P>F		df	P>F			
Position	1	0.102	0.046	2	0.087	0.016	0.003	0.007
WT vs. BT	1	0.102	0.046	1	0.049	0.010	0.003	0.006
BT vs. UD	1			1	0.441	0.935	0.029	0.110
Cycle	6	0.048	0.872	6	0.273	0.070	0.085	0.100
Linear	1	0.100	0.345	1	0.050	0.004	0.006	0.012
Quadratic	1	0.026	0.753	1	0.695	0.451	0.409	0.270
Position × cycle	6	0.184	0.374	12	0.007	0.014	0.092	0.217
WT vs. BT × linear	1	0.021	0.088	1	<0.001	<0.001	0.003	0.008
BT vs. UD × linear	1			1	0.781	0.728	0.484	0.666
WT vs. BT × quad.	1	0.775	0.196	1	0.098	0.531	0.360	0.828
BT vs. UD × quad	1			1	0.666	0.777	0.987	0.463

### Study 2: Soil Conditions in Skid Trails and Protection Strips Following Careful Logging on Fine- to Medium- and Coarse-textured Soils

On fine- to medium-textured soils, comparisons between skid trails (between tracks - BT) and protection strips (UD\_C and UD\_O combined) and between the central portion (UD\_C) and outer portion (UD\_O) of the protection strip did not reveal any significant differences in bulk density or soil strength. Soil bulk density and strength increased with depth ( $P < 0.001$ ) but were not affected by position relative to skid trails. Averaged bulk densities were 1.20, 1.45, and 1.49  $\text{Mg m}^{-3}$  for the 10-cm, 20-cm and 30-cm depths respectively ( $SE = 0.01 \text{ Mg m}^{-3}$ ). Averaged soil strength values were 14, 29, 85  $\text{N cm}^{-2}$  for the 2.5-, 5-, and 10-cm depths ( $SE = 1 \text{ N cm}^{-2}$ ). No significant effect of skid trail position was found for soil strength at the 20 ( $\chi^2 = 7$ ,  $P = 0.146$ ,  $n = 69$ ) and 30 cm ( $\chi^2 = 2$ ,  $P = 0.657$ ,  $n = 69$ ) depths.

On coarse-textured soils, bulk density was not affected by position relative to skid trails ( $p = 0.459$ ). Values increased with depth ( $P < 0.001$ ). Averages were 1.17, 1.28, and 1.37  $\text{Mg m}^{-3}$  for the 10-, 20-, and 30-cm depths respectively ( $SE = 0.01 \text{ Mg m}^{-3}$ ). Soil strength values were adjusted for soil water content at time of sampling (Lison 1968). Soil strength was higher ( $P = 0.036$ ) in the UD\_O portion than in the UD\_C portion of protection strips (Fig. 5). Increases in soil strength were 26, 8, 9, and 18% of control values (UD\_C) for the 2.5-, 5-, 10-, and 20-cm depths, respectively. The outer portion of the protection strip showed a somewhat steeper increase in strength with depth than the central portion ( $P = 0.073$ ). The BT values were higher than the UD\_C values, but the planned comparisons did not allow for direct comparison between BT and UD\_C. Position had no effect on strength at the 30 cm depth ( $\chi^2 = 2$ ,  $P = 0.784$ ,  $n = 81$ ).

### Study 3: Residual Soil Compaction on Fine-textured Soils

Bulk density values obtained from the UD area were higher than BT and WT values at the 0- to 10-cm depth and similar to the BT values at the 10- to 20-cm and 20- to 40-cm depths (Fig. 6), resulting in a greater increase in bulk density with

depth for the BT section ( $P = 0.001$ ). Wheel track (WT) bulk densities were higher at all depths than BT values ( $P = 0.006$ ) and were 8 and 11% higher than control values (UD) at the 10- to 20-cm and 20- to 40-cm depths, respectively. No difference in bulk density was found between the undisturbed section of cutovers and uncut stands. Averaged values for uncut stands were 0.94, 1.18, and 1.26  $\text{Mg m}^{-3}$  for the 0- to 10-cm, 10- to 20-cm, and 20- to 40-cm depths ( $SE = 0.03 \text{ Mg m}^{-3}$ ). Areal extent of skid trails (WT + BT) within three 6- to 12-yr-old cutovers represented 5, 12, and 37% of cutover area (average 18%).

## DISCUSSION

Relationships between number of cycles and increase in soil bulk density and strength were only apparent in the wheel track section of the skid trail. Differences between the two soil types were found in the rate of change in soil physical properties with number of passes (cycle of half impact). On fine- to medium-textured soils, more than half of the effect on bulk density and strength occurred in the course of the first two passes. On coarse soils, half of the effect on bulk density occurred in the course of the first three passes and changes in soil strength took place very gradually and, at the 5-cm depth which was the most affected, only half of the impacts had occurred before the 14th pass. Some other studies have attempted to quantify the relationships between the number of passes and changes in soil properties (Steinbrenner 1955; Jackobsen and Moore 1981; Sidle and Drlica 1981). Jackobsen and Moore (1981) conducted a similar study but soil measurements were taken from the center of the track where compaction is minimal. Steinbrenner's study (1955) did not provide details on soil characteristics and his treatments were not replicated. Sidle and Drlica (1981) developed a regression model for mountainous conditions which involved skidding direction relative to slope and the logarithm of number of cycles.

Increases in bulk density in the wheel tracks were in the same range as those reported by Holman et al. (1978) and Lockaby and Vidrine (1984) for primary skid trails, but much lower than those reported by Gent et al. (1983) (38%),

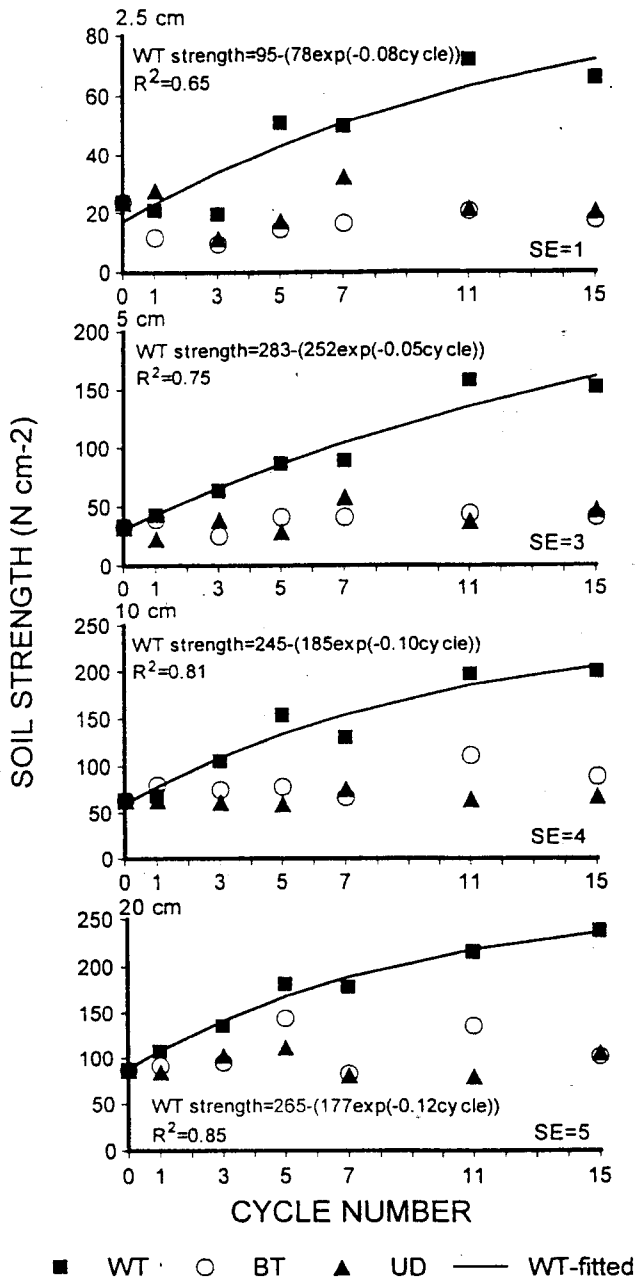


Fig. 4. Soil strength ( $N\ cm^{-2}$ ) as affected by number of skidding cycles and position relative to skid trail on coarse-textured sites (WT = wheel track, BT = between tracks, UD = undisturbed).

Hatchell et al. (1970) (44%) and Steinbrenner and Gessel (1955) (60%). Compaction was as severe on coarse-textured soils as it was on fine- to medium-textured soils in terms of percent increase in bulk density but increases in soil strength were more pronounced on coarse-textured soils.

On fine- to medium-textured soils, water content at the time of treatments was within the range of the plasticity limits for these soils but higher than the optimum for compaction in two of the three experimental blocks. These conditions were more conducive to soil displacement than to compaction. Rutting, which was measured in a concomitant

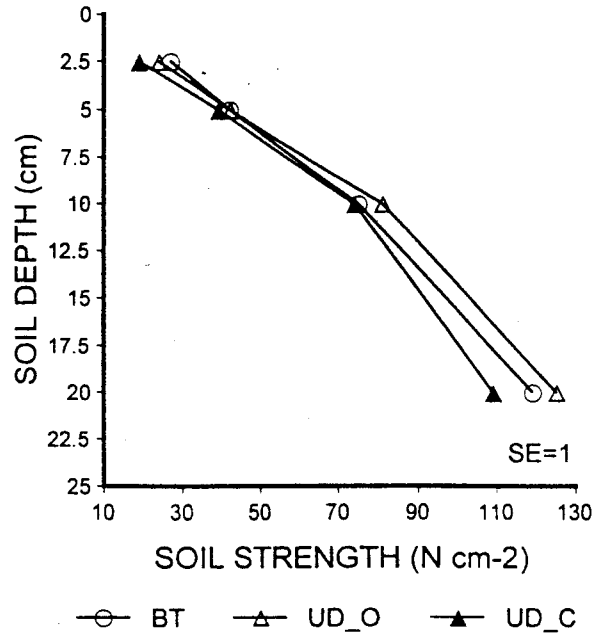


Fig. 5. Soil strength ( $N\ cm^{-2}$ ) as affected by position relative to skid trail on coarse-textured sites (BT = between tracks, UD\_O = outer portion of undisturbed strip, UD\_C = central portion of undisturbed strip).

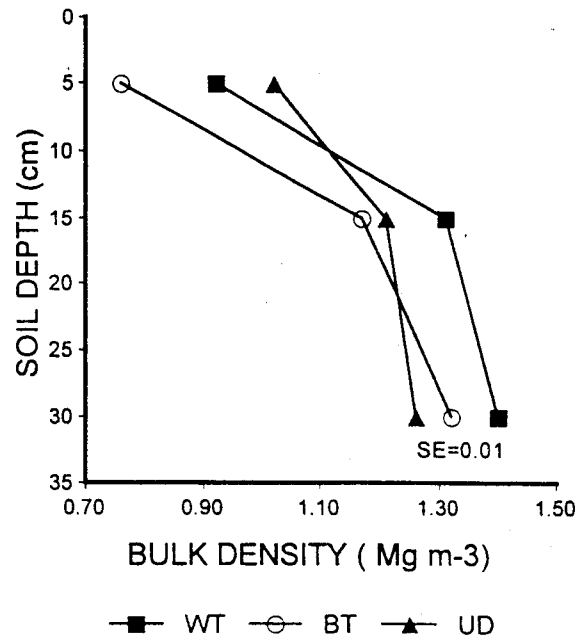


Fig. 6. Soil bulk density ( $Mg\ m^{-3}$ ) as affected by position relative to skid trail on fine-textured soils, 6 to 12 yr after logging (WT = wheel track, BT = between tracks, UD = undisturbed).

study, increased regularly with number of passes (Meek 1994). Hence, changes in soil properties observed in the wheel tracks arose as much from exposure of deeper soil layers as from compaction. Comparisons were made between similar post-disturbance depths and will allow for a more realistic assessment of the impacts of logging on

growth conditions than comparison based on pre-disturbance soil depths. On coarse soils, water content at time of treatments was higher than optimal content for compaction. Higher bulk density values could be expected with drier conditions.

Compaction between the wheel tracks took place on both types of soil. Compaction was limited in depth and intensity and took place mostly during the initial cycle. Results obtained in Study 2 showed that for coarse soils, the outer portion of the protection strip was also lightly compacted. Wronski (1984) attributed similar results to "the lateral movement of soil beneath the zone of maximum compression".

Residual compaction was observed in 6- to 12-yr-old cutovers. Differences between undisturbed and wheel track values were similar to those found in recent cutovers for the 10- to 20-cm soil layer but compaction affected deeper layers in these old cutovers. No compaction was detected in the between-track section of the trails or in the 0- to 10-cm soil layer of wheel tracks, indicating that surface soil structure has improved. This may be a result of trail occupation by perennial grasses following logging (Brais et al. 1996). Thick root mats produced by these species may have improved soil structure in the 0- to 10-cm layer. However, differences in results between recent and older cutovers could be related to differences in skidder characteristics such as tire width. The lower bulk densities obtained in Study 3 on undisturbed soils ( $1.26 \text{ Mg m}^{-3}$  at the 30-cm depth compared with  $1.52 \text{ Mg m}^{-3}$  in Study 2 and  $1.47 \text{ Mg m}^{-3}$  in Study 1) also suggested differences in parent material.

Fine- to medium-textured glaciolacustrine deposits of this area are naturally dense, as shown by the 20- to 30-cm depth bulk density. Pedogenic processes, such as clay eluviation and pedoturbation, have improved the surface mineral soil structure. The 0- to 10-cm layer is characterized by a fine granular structure and a high macroporosity as pores  $>60 \mu\text{m}$  can occupy up to 25% of the soil volume (average of 15% for Study 1, unpublished data). Macroporosity decreases rapidly with depth (average 8% in the 10- to 20-cm layer) as structure changes to subangular blocky. Soil compaction could destroy the porous surface layer of an otherwise dense material.

In Study 1, wheel track and between track bulk density values of the 10- to 20-cm layer were in the range of growth-limiting bulk densities ( $1.40$  to  $1.55 \text{ Mg m}^{-3}$ ) reported by Daddow and Warrington (1983) and Jones (1983) for soils of similar texture. Root and shoot growth of white spruce seedlings have been shown to decrease when the bulk density of soils of similar origin and texture was raised from  $1.35$  to  $1.50 \text{ Mg m}^{-3}$  (Corns 1988). Similar results have been reported for *Pinus taeda* (Tuttle et al. 1988), *Picea abies*, *Pinus nigra* and *Pinus rigida* (Zisa et al. 1980) on medium-textured soils. Moreover, ruts on fine- to medium-textured sites collected run-off waters and were unsuitable for planting.

Bulk density of coarse-textured soils was in the same range as that of fine- to medium-textured soils, but growth-limiting bulk density for these soils has been estimated at  $1.75 \text{ Mg m}^{-3}$  (Daddow and Warrington 1983; Jones 1983). Even after 15 skidding cycles, wheel track densities were under these critical values at all depths. Nevertheless, studies

conducted on coarse-textured soils have shown that a bulk density of  $1.45 \text{ Mg m}^{-3}$  severely limited the growth of seedlings of *Picea mariana* (Prévost and Bolghari 1990) and that root growth of *Picea abies*, *Pinus nigra*, *Pinus rigida* (Zisa et al. 1980) and *Pinus taeda* (Tuttle et al. 1988) decreased rapidly when bulk densities exceeded  $1.6 \text{ Mg m}^{-3}$ . On the other hand, in coarse-textured soils, growth is more limited by soil strength than by soil aeration (Sands et al. 1979; Wasterlund 1985).

In carefully logged cutovers, protection strip width was 10 m and wheel tracks occupied 2 m of the 5 m skid trails. The outer portion of the protection strip (UD\_O) has been defined as the 1.6-m band next to the trails on each side of the protection strip. Thus, careful logging severely affected 13% of cutover area (WT) for both soil types. For fine- to medium-textured soils an additional 20% of cutover area (BT) was lightly compacted, although this light compaction may not always be detected or be present as shown by the results obtained in Study 2. For coarse-textured soils, light compaction was detected on 41% of cutover area (BT + UD\_O).

Areal extent of soil compaction following unplanned use of skid trails on these soils was highly variable. Age of cutovers could not explain this variability as the highest value was obtained from the oldest cutover. Differences in the extent of compaction may have been related to difference in soil moisture at time of logging, stand density and skidding equipment (skidder weight and tire width) and technique. Contrary to Study 1, which was conducted on fresh to moist soils, soil moisture regime ranged from dry to moist in Study 3. On the other hand, bulk density is a less sensitive measure of soil compaction as shown by the magnitude of the increases in strength compared with those of bulk density. Compaction in the undisturbed sections of old cutovers may have gone undetected. This variability precludes any solid conclusion concerning the effectiveness of careful logging compared with unplanned use of skid trails in limiting soil compaction. This study indicates the difficulty in drawing strong conclusions from retrospective studies when operating conditions are not known and may influence the outcome. Pairing field trials with retrospective studies may correct this short-coming, but extension of results from field trials requires a good characterization of soil physical properties.

Despite the number of studies showing traffic-induced compaction on forest soils, forecasting compaction intensity and extent for given soil conditions and under a given logging system remains difficult. Variations in logging systems, sampling locations, and soil characteristics (texture, organic matter content, stoniness, moisture) combined with the fact that many studies lack valid statistical controls (Powers 1989), preclude extrapolation of results from one region to another. Use of homogeneous FEC soil or site types, combined with empirical data, can provide a valuable framework for minimizing site degradation.

Considering that 1) on fresh to moist fine- to medium-textured soils, more than half of the effect on soil properties took place in the course of the two first passes, 2) in old cutovers compaction is still apparent in the wheel tracks,

3) these materials are naturally dense, careful logging is to be the most operational method of limiting the effect of wheel tracks and soil compaction and its potential mental effect on future stand growth. Distance between trails should be increased as much as possible.

On coarse-textured soils, management implications of these results depend on the relationship between the observed degree of compaction and growth reductions. If compaction is of no consequence to growth, spreading traffic over the cutover evenly over the entire cutover remains a sound option. These sites are frequently occupied by jack pine (*Pinus banksiana* Lamb.). Natural regeneration is often sparse and planting is required. Restricted movement of machinery in a tree-length harvesting operation could provide adequate surface-layer disturbance for natural pine seeding.

### CONCLUSION

The extent and intensity of compaction following careful logging have been assessed for two contrasting site types. Fine- to medium-textured sites, compaction in the wheel tracks took place in the course of the first two cycles, while on coarse-textured sites compaction took place more gradually.

For both soil types, compaction severity and depth were more limited in the zone between skid trail tracks. Gradual compaction was observed in the wheel tracks of 6- to 2-yr-old cutovers on fine- to medium-textured soils. Careful logging on moist, fine- to medium-textured soils is the most operational method of limiting the extent of soil compaction. On coarse-textured soils, spreading the traffic over the cutover area remains a valid option. Field trials are being conducted to assess the relationships between soil compaction and seedling growth and the tolerance of different species to trail conditions.

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