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SOIL COMPACTION BY LOGGING AND SITE PREPARATION EQUIPMENT: EFFECTS ON SEEDLING GROWTH ON FOUR SOIL TYPES IN WEST-CENTRAL ALBERTA, CANADA

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INTRODUCTION

Intensified interest in site classification and land evaluation for optimizing resource expenditure and allocation has led to a desire to characterize and quantify site properties, potentials, and responses to management in managed forest ecosystems. Incidental side effects on soils from the use of heavy forestry equipment can be serious. In particular, the problem of soil compaction and its influence on tree growth has been widely recognized (cf. Lull 1959, Froehlich 1978, 1982, Greacen and Sands 1980, Froehlich and McNabb 1984). However, few quantitative data have been published on the effects of soil compaction on tree growth in the Canadian boreal forest.

This paper reports the effects of heavy (summer logging and site preparation) equipment on the bulk densities of four soil types differing widely in physical properties. The influence of soil compaction on the growth of white spruce (*Picea glauca* [Moench] Voss) and lodgepole pine (*Pinus contorta* Loudon var. *latifolia* Engelm.) seedlings in the greenhouse is also reported.

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Study area

The study area is located between 116° and 118°W and 53° and 54°N within the St. Regis (Alberta) Forest Management Agreement area in west-central Alberta, Canada. The towns of Edson and Hinton lie within the study area. The climate is humid continental, with cold winters and cool summers. Freezing temperatures can occur in any month. The mean annual temperature at Edson is 1.7°C; mean monthly temperatures are above freezing from April through October (the highest is 14.9°C in July and the lowest is -14°C in January); annual precipitation averages 55 cm, half of which falls as rain in June, July, and August (Anon. 1975). Annual potential evapotranspiration ranges from 45 to 50 cm (Anon. 1969).

Surficial geology and soils

Ice covered parts of the study area during the Cordilleran and Keewatin glacial periods. The Cordilleran ice affected terrain that includes about two-thirds of the study area in the south and west (Roed 1968). The rest of the study area was covered by Keewatin ice in at least two ice advances. Surficial deposits include Keewatin and Cordilleran ground moraines, Tertiary glaciolacustrine silts, clays with bedding, coarse glaciofluvial gravels forming terraces and benchlands, aeolian sands, and recent alluvial deposits. Small outcrops of shale, sandstone, coal, and conglomerate occur in the more mountainous southwestern areas.

Soils of the Luvisolic, Brunisolic, Gleysolic, Regosolic, Podzolic, and Organic orders of the Canadian Soil Classification System (Can. Soil Survey Comm. 1978) are present in the Edson area. The dominant soil subgroups ranked in order of decreasing abundance are Brunisolic Gray Luvisols, Mesisols, Orthic Gray Luvisols, and Orthic Gleysols (Dumanski et al. 1972). Sample plots were located on soils of the Marlboro, Hinton, Lendrum, and Summit soil associations described by Dumanski et al. (1972).

Vegetation

The study area lies within the Lower Foothills (B19a) and Upper Foothills (B19c) Sections of the Boreal Forest Region (Rowe 1972). The forests are dominated by lodgepole pine, but black spruce (*Picea mariana* [Mill.] B.S.P), white spruce, trembling aspen (*Populus tremuloides* Michx.), balsam poplar (*P. balsamifera* L.), and alpine fir (*Abies lasiocarpa* [Hook] Nutt.) also occur.

EXPERIMENTAL METHODS

Field

Each study area was selected to provide a chronosequence of clearcutting and site preparation of at least 20 years on a predominantly single soil association (Dumanski et al. 1972). The soils of the four areas selected differed widely in physical properties, especially texture:

- Lendrum: moderately well to imperfectly drained Orthic Gray Luvisol on stone-free lacustrine silty clay

- Marlboro: moderately well to well drained Brunisolic Gray Luvisol on cobbly clay loam till overlain by silt loam fluvio-aeolian veneer

- Summit: well to rapidly drained Brunisolic Gray Luvisols and Eluviated Eutric Brunisols on sandy loam to clay loam cobbly Tertiary glacio-fluvial deposits

- Hinton: well to imperfectly drained Cumulic Regosols on aeolian silt loam to loam.

These soils encompass most of the variability encountered in soil physical properties in the Edson area.

Summer-clearcut stands of three or four age classes (depending on the availability of current-year clearcuts) were selected on each soil type, and three sample plots were established in each age class. Control plots were established, two each on the Lendrum and Marlboro soils, one each on the Hinton and Summit soils.

In each sampled stand, a 50-m baseline was run through the cleared block on a compass bearing that avoided obvious trails, landings, wet depressions, standing trees, and steep topography. Soil moisture and bulk density determinations were made at 5-m intervals along the line at 1- to 10-m randomly assigned distances from the line, for a total of 10 measurements on each transect within a 0.1-ha area. At each measurement point, moisture and density counts were taken at the surface and at depths of 10, 20, and 30 cm with a Troxler model 3401B density/moisture gauge with 30.5-cm probe. The ground surface was prepared for the gauge by removing the organic layer from a 20 x 35 cm area and driving a transmission hole for the gauge probe with a Campbell Pacific Nuclear slide hammer. The thickness of the organic layer was recorded. The moisture and density counts were converted to the corresponding percent moisture and bulk density (g/cm^3) estimates with the aid of tables and algorithms provided with the gauge. The means, standard deviations, and standard errors of the mean, for moisture content and bulk density, were calculated for each depth and age class ($n = 30$) on each soil type. The results were graphed.

In the second (1985) field season, soil bulk density was determined gravimetrically from soil cores and bulk density estimates were made once more with the Troxler moisture/density gauge. Direct and indirect estimates of soil bulk density were examined by regression analysis. Regressions of bulk density determined directly from soil cores on bulk density estimated from nuclear gauge determinations were used to calibrate the gauge for each soil type[2]. Such calibration was recommended by Steele et al. (1983), who found that the relationship between nuclear gauge and gravimetric determinations varied with soil type and condition. At a representative location near each plot center, a soil pit was excavated and a soil profile was described. In one control plot per soil type, soil samples were taken from each horizon for laboratory analysis.

Greenhouse

To evaluate the effect of soil compaction on seedling growth, lodgepole pine and white spruce seedlings were grown in each of the four soils compacted to bulk densities representative of

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[2] For further discussion of this method, see Corns, I.G.W., Can. J. For. Res. 18:75-84. 1988.

various field conditions. Mineral soil from the top 20 cm of undisturbed soil profiles in uncut mature stands was air dried on greenhouse benches, and clod size was reduced gently to a diameter of 2 cm or less. The moisture content of the air-dried soil was estimated on the basis of oven-dried subsamples. and the weight of oven-dried soil of each soil association necessary to obtain predetermined bulk densities in cylindrical pots 15 cm in diameter and 20 cm high was calculated. A plastic cap on the pot base, drilled with holes and lined with filter paper, retained the soil and provided drainage. The pots were filled within 2.5 cm of the top with soil compressed incrementally by means of a Carver laboratory press (11,000 kg capacity) equipped with a piston 15 cm in diameter. The three bulk densities used (Table 1) approximate those found in the following field conditions: 1) clearcut block roads immediately after logging and site preparation; 2) clearcut block roads 5-10 years later; and 3) undisturbed control. Ten replicates were prepared for each bulk density treatment per soil. Seeds of lodgepole pine or white spruce were sown on the surface of each pot and covered with grit to prevent splashing. The pots were placed on polyethylene-lined benches under high pressure sodium vapor lighting for 18 h/day at 20°C and were watered from below. Fungicide was applied to the soil surface. Fertilizer was applied weekly in the irrigation water at concentrations of 125, 60, 159, and 5.5 ppm for N, P, K, and Fe, respectively. Seedlings were thinned to five per pot at 4 weeks and to three at eight weeks. The latter were healthy and well spaced. At 15 weeks the lodgepole pine seedlings were removed and washed free of soil over a 5-mm mesh screen to prevent loss of roots and foliage. At 24 weeks, the white spruce seedlings were similarly treated. Root depth, total oven-dried biomass per pot, and seedling top height and stem diameter were measured. Root systems of individual seedlings were not measured separately because of the difficulty of separating them.

Table 1. Soil bulk density levels used in growing lodgepole pine and white spruce seedlings in greenhouse culture.

	Bulk density (g/cm^3)		
Soil	Group 1	Group 2	Group 3
Lendrum	1.2	1.35	1.5
Marlboro	1.3	1.4	1.5
Summit	1.3	1.4	1.5
Hinton	0.7	0.8	0.9

One-way analysis of variance was used to evaluate differences in seedling growth among bulk densities within each soil type. A two-tailed t-test was undertaken to detect differences significant at P 0.05.

RESULTS

Field bulk density

Soil bulk densities on clearcuts of various ages on three of the four soil types examined in the Edson map area tend to be greatest on the most recent clearcuts and least on the oldest clearcuts (Fig. 1). Contributing to this trend is the increasing size and weight of harvesting equipment used since harvesting began in the study area in the late 1950s. The effect is evident to at least 30 cm, the greatest depth sampled. In all cases, bulk densities recorded under the mature forest were slightly greater than those on the oldest clearcuts, perhaps because of pressure exerted on the soil by root growth and tree weight (Greacen and Sands 1980). Bulk densities tended to increase with soil depth. They were greatest (0.8 to 1.65 g/cm^3) on the Marlboro soil (Fig, 1a), least on the Hinton soil (0.5 to 0.8 g/cm^3) (Fig. 1d), and intermediate on the Lendrum (Fig. 1b) and Summit (Fig. 1c) soils.

On all soils except the Hinton association, the range in bulk density between the surface and 30-cm depth was narrower on the most recent clearcuts than on the uncut controls (Table 2). Increases in bulk density with depth are greater near the surface than farther down (Table 3). Marlboro soils show the greatest increases in bulk density with depth (28 to 48% under a recent trail) in comparison with the uncut control; Summit soils showed no differences, and Lendrum and Hinton soils were intermediate. The bulk density of the Lendrum soil would probably have shown a higher maximum had a more recent block road been available for sampling; the road sampled was 19 years old. Recovery from compaction to preharvest bulk densities is estimated to require 20-21 years for the Marlboro soil, 13-15 years for Lendrum, and < 6 years for Hinton. The Summit soil was unaffected. The assumption underlying these estimates is that recovery is linear over time. On the Lendrum soil, the 19-year-old block road yielded the highest bulk densities (< 1.48 g/cm^3); this illustrates the prolonged persistence of severe compaction on this soil.

Seedling Growth

Differences in seedling growth among the three bulk density levels on the four soils were generally greater in lodgepole pine than in white spruce (Table 4), even though the spruce seedlings were 9 weeks older than the pine. The differences were most evident on the Lendrum (lacustrine) and Summit (glaciofluvial) soils. Growth was poor and mortality high on the Marlboro soil. Seedling growth was also poor on the highly calcareous Hinton soil.

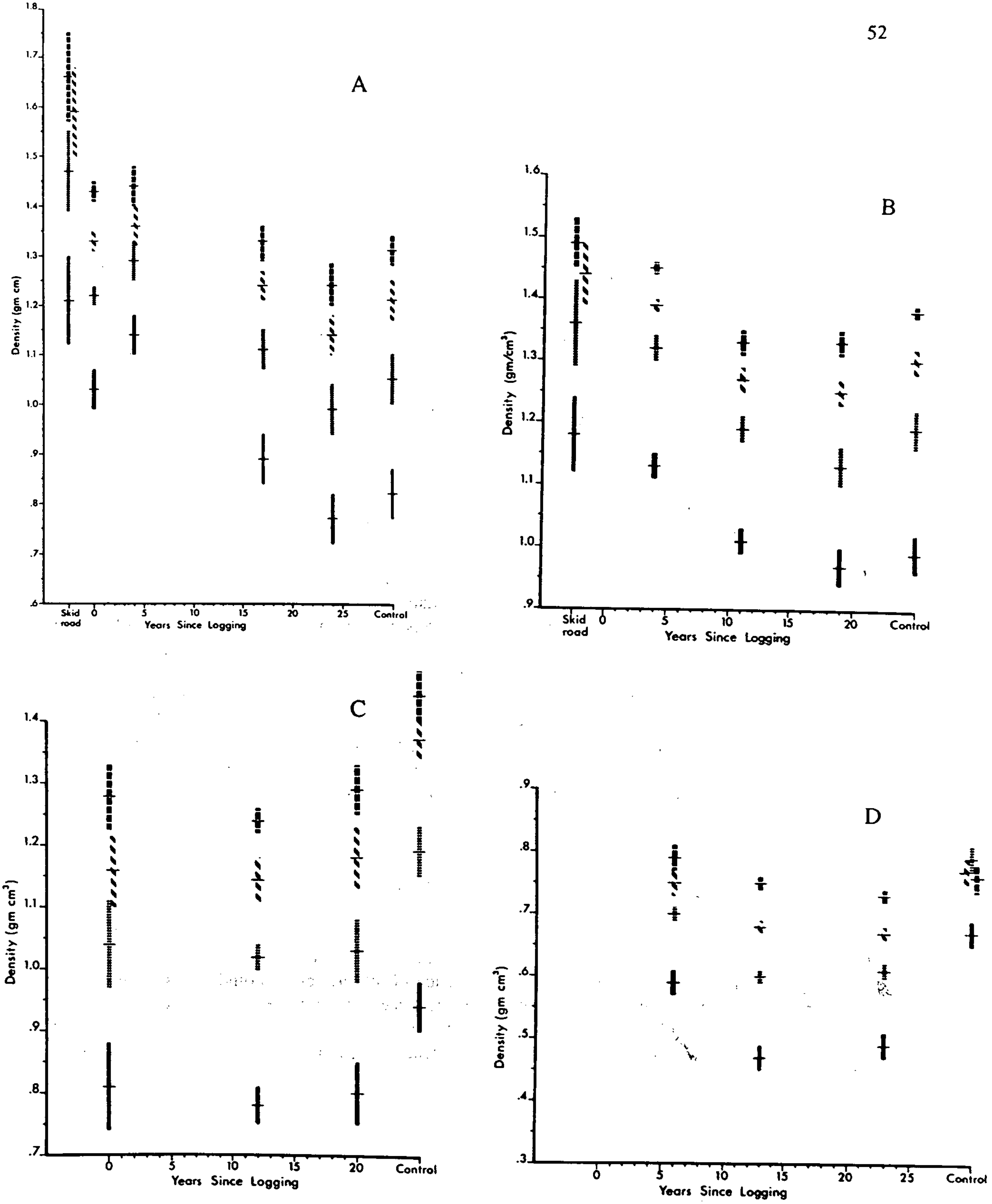

Figure 1. Mean and standard error of mean for soil bulk densities on clearcuts and uncut controls on four soil associations in west-central Alberta: (a) Marlboro, (b) Lendrum, (c) Summit, and (d) Hinton. Surface and 10-, 20-, and 30-cm depths sampled.

Table 2. Soil bulk density (g/cm^3) at the surface and the 30-cm depth on the most recent clearcuts and uncut controls.

	Most recent clearcut			Uncut forest control		
Soil	Surface	30 cm	Range	Surface	30 cm	Range
Lendrum	1.13	1.45	0.32	0.95	1.38	0.43
Marlboro	1.09	1.50	0.41	0.82	1.30	0.48
Summit	0.81	1.28	0.47	0.94	1.44	0.54
Hinton	0.59	0.79	0.20	0.65	0.75	0.10

Table 3. Soil bulk densities immediately after summer logging and an estimate of the time (years) required for them to recover from the compaction experienced during logging.

Depth (cm)	BDC[a]	BDM[b]	Increase[c]	Recovery[d]	BDC	BDM	Increase	Recovery
		<u>Lendrum</u>				<u>Marlboro</u>		
0	0.95	1.18	24	14	0.82	1.21	48	21
10	1.19	1.36	14	15	1.05	1.47	4	21
20	1.30	1.44	11	14	1.21	1.59	31	20
30	1.38	1.48	7	13	1.30	1.66	28	20
		<u>Hinton</u>				<u>Summit</u>		
0	0.65			<6	0.94	0.81	0	0
10	0.79			<6	1.19	1.04	0	0
20	0.77			<6	1.37	1.16	0	0
30	0.75	0.79	5	14	1.44	1.28	0	0

[a] Mean bulk density, uncut control.

[b] Mean maximum bulk density recorded either on recent block road or on recent clearcut.

[c] Percentage increase in bulk density from control to mean maximum rocorded.

[d] Recovery time (years since logging) to revert to control (presumed original) bulk density, if linear reversion is assumed; the recovery time corresponds to the intercept opposite control bulk density at a given depth when a line is drawn between mean maximum and mean minimum bulk densities recorded at the same depth.

Table 4. Results of analyses of variance (AV) and t–tests (t) between group means for lodgepole pine (LP) and white spruce (WS) growth measurements on four soils of three bulk densities.

Soil	Species	Maximum root depth		Maximum root depth within soil		Total weight		Stem weight		Root weight		Stem diameter		Stem height	
		AV[a]	t[b]	AV	t	AV	t	AV	t	AV	t	AV	t	AV	t
Lendrum	LP	**	1–3 2–3	**	1–3 2–3	**	1–3 2–3	**	1–3 2–3	**	1–3 2–3	**	1–3 2–3	**	1–3 2–3
	WS	**	1–3 2–3	**	1–3 2–3	**	1–3 2–3	**	1–3 2–3	**	1–3 2–3	**	1–3 2–3	**	1–3 2–3
Marlboro	LP	**	2–3	**	1–3 2–3	NS		*		NS		*		**	1–3
	WS	NS		NS		*		NS		**		NS		*	
Summit	LP	NS		**	1–3	**	1–2 1–3	**	1–2 1–3	**	1–2 1–3	**	1–2 1–3	**	1–2 1–3
	WS	NS		NS		NS		NS		NS		NS		NS	
Hinton	LP	**	1–3	**	1–3			**	1–3	**		NS		**	1–2
	WS	**	1–2 1–3	**	1–2 1–3	**	1–3	*		NS		NS		**	1–2

[a] NS = not significant at P 0.05; * and ** = significant at P 0.05 and 0.01 levels, respectively.

[b] t–test between group means; e.g., 1–3 indicates significance (P 0.05) of difference between means of groups 1 and 3. See Table 1 for group mean bulk density values.

For the Lendrum soil, t-tests showed that the mean growth differences tended to be significant between bulk density groups 1 and 3 and groups 2 and 3 (Tables 1 and 4).

This implies that in neither species is seedling growth impaired significantly until bulk density exceeds 1.35 g/cm^3, the bulk density for group 2. Bulk densities > 1.35 g/cm^3 occurred at the 10-cm depth in soil that had been compacted 4, but not 11, years earlier (Fig. 3). In soils compacted 11 years earlier, bulk densities > 1.35 g/cm^3 occurred at the 30-cm depth.

On the Marlboro soil, a similar trend is less evident because of unaccountable and extensive seedling mortality. However, differences in maximum rooting depth between groups 2 and 3, as determined by t-test, were significant (P 0.01), as were differences between groups 1 and 3 and groups 2 and 3 for maximum root depth inside the soil core, and between groups 1 and 3 for stem height (Table 4). This suggests that lodgepole pine seedling growth on Marlboro soil may not be impaired until bulk density exceeds 1.4 g/cm^3. Such densities at the 10-cm depth were recorded only on recent block roads (Fig. 1). The thick (often > 20 cm) organic layer on many Marlboro sites has likely helped to reduce compaction.

On the Summit soil, most measures of lodgepole pine seedling growth differed significantly among the three bulk density treatments (Table 4). This indicates that bulk densities > 1.3 g/cm³ depress the growth of pine seedlings on the Summit soil. Such densities in the field were encountered only at the 20-cm depth in the control and at the 30-cm depth on a recent clearcut (Fig. 4). There were no significant growth differences among the white spruce seedlings on the Summit soil.

On the Hinton soil, mean growth differences in the lodgepole pine seedling group were, with the exception of stem diameter, highly significantly different between 0.7 g/cm³ and 0.9 g/cm³ (Table 4). Several measures of white spruce growth on the Hinton soil differed significantly among bulk densities (Table 3); root weight and stem diameter did not differ significantly between group means.

DISCUSSION

Soil compaction

It is apparent from Figure 1 that the soils under investigation in the west-central Alberta study area, with the apparent exception of the Summit soil association, have been compacted during logging and subsequent site preparation operations. The effect of forestry machinery on the physical properties of soil, especially bulk density, and on subsequent tree growth have been well documented. Lull (1959), Greacen and Sands (1980), and Froehlich (1973) have drawn attention to this widespread problem.

Compaction increases soil strength and reduces total porosity at the expense of large voids. Tree growth is reduced because of reduced water supply, restricted root space, and poor aeration (Taylor et al. 1966; Froehlich 1978, 1982; Greacen and Sands 1980; Froehlich and McNabb 1984). The trend evident for the Lendrum, Marlboro, and Hinton soil associations is for compaction (i.e., increased bulk densities) to be greater on the more recent cutovers and least on the oldest cutovers. This suggests that damage by compaction diminishes with the passage of time, likely as a result of dry/wet and freeze/thaw cycles, which depend heavily on soil texture (Greacen and Sands 1980). In the present study, estimates of recovery times for soils range from 20-21 years on the clay loam Marlboro soil (Table 3) to zero (i.e., no compaction) on the coarse-textured Summit soil. These findings agree with those of Hatchell et al. (1970) and Hatchell and Ralston (1971), who observed no recovery in a loblolly pine forest one year after compaction, but slow recovery on soils that had been logged 19 years earlier. These workers estimated that soil compacted in areas used for log decks would need 18 years to recover. Perry (1964) estimated that 40 years would be required for full recovery of infiltration capacity on an old forest road with 40% clay soil. Froehlich (1979) observed in Oregon that soil compaction from logging equipment remained readily detectable in a sandy clay loam 16 years after cutting, with bulk densities 9-18% higher than in undisturbed soils. Greacen and Sands (1980) have observed compaction of sandy soil on logging trails under radiata pine (*Pinus radiata* D. Don) 50 years after the trails were last used.

Dickerson (1976) reported that bulk density increases averaged 20%, to 1.55 g/cm^3, on wheel-rutted loamy sand to silty clay loam in northern Mississippi. In the present study, the 28-48% increases in bulk density of the Marlboro soil on the logging trail are higher than those reported elsewhere.

Effects on tree growth

Especially in field experiments, the myriad factors responsible for tree growth compromise attempts to attribute growth reductions to any one factor such as soil compaction. The environmental control possible in greenhouse experiments allows the investigator to monitor some effects of treatment more closely, e.g., the effect of soil bulk densities on seedling growth. However, some questions remain as to the applicability of the results to field situations.

In the present greenhouse experiment, the range of bulk density treatments, simulating soil bulk densities from those found immediately after logging to those found under undisturbed forest, gave significant seedling growth differences for most growth attributes measured for the four soil types (Table 4). The most significant differences in growth occurred at the highest bulk density levels on the Lendrum and Marlboro soils. Such densities in the field are restricted to recent block roads and at the 20- to 30-cm depth on the clearcuts. This suggests that the direct effects of compaction on tree growth may not become evident until the roots exploit soil at the 20- to 30-cm depth. The soil bulk densities at 30 cm in the Lendrum and Marlboro controls (Fig. 1a, 1b) approach the 1.5 g/cm^3 density that showed significant (P 0.01) growth reduction in the greenhouse (Table 4) and may in part account for the observed paucity of root penetration below 30 cm in undisturbed conditions.

It is apparent that summer logging by power saw and rubber-tired skidder, followed by some kind of mechanized site preparation, can increase soil bulk densities in the rooting zone. The effects of compaction on root growth appear to result from a complex interaction among soil strength, water and nutrient availability, and aeration. A root must overcome the strength of the soil to penetrate a pore smaller than the diameter of the root. Because compaction both increases soil strength and decreases the number of macropores, the rate of root elongation, and therefore root length, is reduced (Greacen and Sands 1980). In a greenhouse experiment, Minore et al. (1969) grew seedlings of several Pacific coast tree species in soil compacted to three bulk density levels. They found that roots of lodgepole pine, Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), and red alder (*Alnus rubra* Bong.) can penetrate soil, the bulk density of which inhibited root growth of Sitka spruce (*Picea sitchensis* [Bong.] Carr.), western red cedar (*Thuja plicata* Donn), and western hemlock (*Tsuga heterophylla* [Raf.] Sarg.). The ability of lodgepole pine to survive on heavily compacted soils is noteworthy and may account for the fact that a soil compaction problem has not been apparent in the predominantly lodgepole pine forest of the Hinton-Edson area. It seems likely, however, that bulk density levels exceeding those that limit seedling growth in the greenhouse (where moisture, nutrient, and temperature regimes are favorable) will also limit tree growth in the field (where growing conditions are usually less favorable).

Prevention and amelioration of compaction

Measures to prevent or ameliorate soil compaction are unlikely to be taken by the forest manager unless he is convinced that they are economically justified. Unfortunately, long-term data on the effects of soil compaction on tree growth in the field are scarce. Froehlich (1982) attributed to tractor logging a reduction of 48% in volume yield in a 17-year-old ponderosa pine (*Pinus ponderosa* Laws.) plantation in the Pacific Northwest of the United States. Ameliorative methods such as ripping or deep tillage are expensive; over large areas, economic justification may be difficult, but, in conjunction with site preparation, such treatment may be cost-effective locally on heavily compacted areas, such as trails and landings. The Craig-Simpson ripper plow is an example of a tool used locally for the dual purpose of loosening the soil and exposing a mineral-soil microsite for seeding or planting. Broader application of such tools to areas of soils known to be susceptible to damage by compaction should be considered.

Preventive measures are preferable to, and usually less costly than, the cures and may have other benefits. Greacen and Sands (1980) have outlined some of these. The maintenance of organic matter (as a source of nutrients and for exchange capacity, water retention, and resistance to compaction) can be achieved, in part, by avoiding severe slash burns, windrowing, and severe scarification. The encouragement of soil fauna, including earthworms in soils that support them, is desirable and can be accomplished, in part, by incorporating organic matter into mineral soil at depth. As a separate operation, this would probably be too expensive, but it could be combined with site preparation. Deep-rooted legumes, after introduction by seeding, can ameliorate compaction, fix nitrogen, and incorporate organic matter at depth (Greacen and Sands 1980).

Traffic control can also be important in minimizing compaction and erosion. This can be accomplished by using vehicles with low ground pressure (Lull 1959, Froehlich 1978) and trails designed to minimize the area of disturbance (Rothwell 1978, Greacen and Sands 1980). Wetness increases the susceptibility of soils to compaction, and highly compactable soils should be avoided during spring thaw and after heavy rains. The most susceptible soils should be logged in winter when the soil is frozen. Soil surveys, available for much of the commercial forest land in Canada, should be used for identifying areas of wet and easily compactable soils.

SUMMARY AND CONCLUSIONS

A 19- to 24-year chronosequence of logging and subsequent mechanized site preparation was examined on four west-central Alberta soil types differing widely in texture for the purpose of evaluating residual effects of heavy equipment on soil bulk density. Compaction, evident on three soils, was greatest on soils of the Marlboro association. It was estimated that Marlboro soil bulk densities would need 20-21 years to recover to their preharvest levels. Soils of the Summit association were free of compaction.

Lodgepole pine and white spruce seedlings were grown on the four soils compacted in the laboratory to three bulk densities approximating the range of those occurring in the field. Significant differences in seven measures of seedling growth were observed among treatments.

Damage to forest soil through compaction by heavy equipment, though often hidden, has been found to reduce forest productivity in many parts of the world. On the basis of field determinations of soil bulk density and greenhouse determinations of growth responses of seedlings of local tree species to field-simulating levels of bulk density, losses of productivity in the Canadian boreal forest are probably similar in magnitude to those recorded elsewhere. In some soils in the boreal forests of Alberta, compaction appears to persist for several decades in spite of annual freeze-thaw cycles.

Recognition by forest resource managers of the potential for productivity losses after vehicular compaction of soil should lead to logging designs and schedules for minimizing the adverse impact of heavy equipment. Soil surveys, available for many forest leases, should be used for this purpose.

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