Relative bulk density as a measure of compaction and its influence on tree height

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Abstract: Soil compaction often limits conifer regeneration on sites degraded by landings and roads, but inadequate understanding of the relationship between compaction and tree growth could lead to inappropriate soil conservation and rehabilitation efforts. We tested liquid and plastic limits, oxidizable organic matter, total carbon, particle size distribution, and iron and aluminum oxides on soil samples collected from five forest experiments in interior British Columbia. These data were used to estimate soil maximum bulk density (MBD) and relative bulk density (RBD); our objective was to relate RBD to tree growth. Height of interior Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Bessin) Franco) was limited when RBD was >0.72. For lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) and hybrid white spruce (*Picea glauca* (Moench) Voss × *Picea engelmannii* Parry ex Engelm.), RBDs of 0.60–0.68 corresponded to maximum height, whereas RBDs of 0.78–0.87 appeared to limit height growth. The presence of surface organic material mitigated compaction and was often associated with lower RBD. Our results illustrate the usefulness of RBD to assess compaction and suggest that soil rehabilitation should be considered on disturbed sites where soil RBD is >0.80.

Résumé : La compaction du sol nuit souvent à la régénération des conifères sur les sites dégradés par les jetées et les chemins mais une compréhension inadéquate de la relation entre la compaction et la croissance des arbres pourrait se traduire par des mesures inappropriées de réhabilitation et de conservation du sol. Nous avons testé les limites liquide et plastique, la matière organique oxydable, le carbon total, la distribution de la dimension des particules et les oxydes de iron et d'aluminium sur des échantillons de sol prélevés dans cinq expériences établies en forêt dans la partie intérieure de la Colombie-Britannique. Ces données ont été utilisées pour estimer la densité apparente maximale et la densité apparente relative (DAR). Notre objectif consistait à relier la DAR à la croissance des arbres. La hauteur du douglas de Menzies bleu (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco) était réduite lorsque la DAR était > 0,72. Dans le cas du pin tordu latifolié (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) et de l'épinette blanche hybride (*Picea glauca* (Moench) Voss × *Picea engelmannii* Parry ex Engelm.), une DAR de 0,60 à 0,68 correspondait à la hauteur maximale tandis qu'une DAR de 0,78 à 0,87 semblait limiter la croissance en hauteur. La présence de matière organique en surface atténuait l'effet de la compaction et était souvent associée à une DAR plus faible. Nos résultats illustrent l'utilité de la DAR pour évaluer la compaction et indiquent que la réhabilitation du sol devrait être envisagée sur les sites perturbés où la DAR est > 0,80.

[Traduit par la Rédaction]

Introduction

The use of heavy machinery in forest management often leads to soil disturbance and compaction, which in turn affect ecosystem stability and site productivity (Froehlich 1979; Wronski and Murphy 1994; Kuan et al. 2007). Soil disturbance and compaction can be particularly severe on permanent and temporary access areas, such as forest roads and landings. These areas may be unproductive unless soil rehabilitation is carried out. Trees growing on compacted soil are generally characterized by reduced root elongation (Whalley et al. 1995) and, sometimes, by reduced height growth (Greacen and Sands 1980; Ares et al. 2007; Bulmer et al. 2007), but predictability varies. The variation in tree growth responses reported in different studies could have been caused by selection of compaction indicators that were not always successful in describing the relationship between soil compaction and tree growth or by the fact that compaction treatments did not reach growth-limiting levels in some studies. Because soil rehabilitation practices are expensive to apply, a compaction evaluation method to better understand soil compaction effects on tree growth is needed.

Soil bulk density (BD) has been traditionally used as the most common measure of soil compaction, but establishment of growth-limiting BD thresholds is not straightforward. Any threshold value of BD depends on soil properties (e.g., texture, quantity and quality of organic matter, and particle density), site characteristics (e.g., microclimate), and the criteria used to evaluate when growth is affected. A review by Daddow and Warrington (1983) showed that

Received 26 February 2009. Resubmitted 24 March 2010. Accepted 15 May 2010. Published on the NRC Research Press Web site at cjfr.nrc.ca on 13 August 2010.

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 doi:10.1139/X10-115

growth-limiting BD for sandy loams and loamy sands was near 1.75 Mg·m^{-3}, whereas clay, silty clay loam, silty clay, and silt soils had growth-limiting BD around 1.40 Mg·m^{-3}. Similarly, the root growth-limiting BD for Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) seedlings grown on sandy loam to loam soils varied from 1.70 to 1.80 Mg·m^{-3} (Heilman 1981). However, an artificially created BD of 1.59 Mg·m^{-3} for a sandy loam soil in pots stopped root penetration of 2-year-old Douglas-fir seedlings (Heninger et al. 2002). These variable results illustrate why a single growth-limiting BD threshold is unrealistic for all situations on all sites.

Efforts have been made to develop high-level integrated soil parameters that can combine several soil properties and relate them to plant growth. One of these parameters was the least limiting water range (LLWR) introduced by da Silva et al. (1994) based on earlier work by Letey (1985). The LLWR describes the range of soil water contents where water availability, soil mechanical resistance, and air-filled porosity do not exceed assigned values associated with growth limitation. The LLWR has been shown to be a useful indicator of soil physical quality (Zou et al. 2000; Lapen et al. 2004). However, relating LLWR to plant productivity requires monitoring of soil water dynamics and the testing of field capacity and permanent wilting point, which are difficult for fine-textured soils.

Other high-level integrating soil parameters that were found to correlate well with plant growth include relative bulk density (RBD) and degree of compactness (D). Both parameters represent the ratio of field BD to a reference BD, and they only vary in the method used to obtain the reference BD: the former method applies 600 kN-m·m^{-3} of compaction force through rammer blows, whereas the latter uses 200 kPa static pressure to compact the sample (Carter 1990; Håkansson and Lipiec 2000). Relative bulk density was strongly correlated (R^2 = 0.69) to the relative grain yield of spring barley (*Hordeum vulgare* L.) and spring wheat (*Triticum aestivum* L.) in a study by Carter (1990) carried out on a fine sandy loam Orthic Humo-Ferric Podzol on Prince Edward Island. An RBD range of 0.77–0.84 was associated with a relative grain yield ≥95%, whereas RBDs >0.89 corresponded to relative yields <80%, and aeration porosity at that point impeded growth. Degree of compactness was correlated to yield of spring barley grown on a wide range of soil types in Sweden with clay contents between 2% and 60% and organic matter contents between 1% and 11% (Håkansson 1990). The author found that the optimal degree of compactness (D_{opt}) was consistently at 0.87, and this value was independent of soil particle size distribution and organic matter content. Because the reference BD obtained by the uniaxial test in the study of Håkansson (1990) was 7%–17% lower than that obtained by the Proctor test in the study of Carter (1990), the D_{opt} of 0.87 corresponded to an optimal RBD of 0.74–0.81.

Although RBD has been used to relate soil compaction to growth of annual plant species, its usefulness has not yet been tested for assessment of tree growth in forest ecosystems. Development of such a high-level integrating parameter of soil compaction that can also be successfully related to tree growth will be helpful to guide operational practices and to assess the viability of rehabilitation to restore productivity to degraded areas (Richardson et al. 1999). The objectives of our study were to (*i*) determine RBD for soils on heavily disturbed tree-growing sites, such as landings and roads, and (*ii*) assess the relationship between RBD and tree height. We also evaluated the influence of presence of surface organic materials (i.e., wood waste mulches applied to disturbed sites or natural forest floors) on tree height.

Materials and methods

Site description

Five experiments (Table 1), including forest landings and roads, were selected throughout interior British Columbia (BC). When selecting experiments for this study, we focused on those with a broad range of soil mechanical disturbance and rehabilitation treatments (Table 2), which enabled us to include a range of compaction levels in our study. Experiments 1, 2, 4, and 5 were established to evaluate the effectiveness of tillage and biological inoculation on conifer seedlings, and experiment 3 was established to determine the effect of tillage and wood waste amendment on soil rehabilitation (Teste et al. 2004; Bulmer et al. 2007; Campbell et al. 2008). Each experiment was laid out as a randomized complete block design or randomized block split-plot design with three replicate blocks. One-year-old nursery-grown seedlings of interior Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Bessin) Franco), lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.), and hybrid white spruce (*Picea glauca* (Moench) Voss × *Picea engelmannii* Parry ex Engelm.) were planted. Species distribution on the experimental sites selected for this study, year of the site establishment, and tree age at the time of growth measurement are shown in Table 2. Planting densities ranged from 2000 to 5000 stems·ha^{-1} in experiments 2, 3, and 5. Seedlings were planted in rows on the roads at experiments 1 and 4, and row spacing was typically 2 m with an intraseedling distance of 0.5 m. At the time of measurement, interactions among neighbouring trees were not considered to be a factor affecting the results.

Field and laboratory methods

On the landings and plantations, three soil BD samples per plot were randomly collected to a depth of 20 cm from the surface of the mineral soil, whereas randomization was restricted to the middle of the row of trees on road sites. On sites with coarse fragment (diameter >2 mm) content <25%, BD samples were collected in 518 cm^3 cores using a slide hammer. On sites with coarse fragment content >25%, BD samples were collected by the excavation method (Grossman and Reinsch 2002) and water was used to determine the sample volume.

Maximum bulk density (MBD) was derived using four models developed by Zhao et al. (2008). These models related MBD obtained by the Proctor method (American Society for Testing and Materials 2000) to soil physical and chemical properties using a subset of samples (n = 144) from a wide range of sites in BC (Table 3). A nonplastic model was used for samples without plastic limit, a moderately plastic model was used for plastic samples with liquid limit <0.50 kg·kg^{-1}, and highly plastic and overall models were used for plastic samples with liquid limit >0.50 kg·kg^{-1}.

Table 1. Location of the five experiments in north-central British Columbia and associated elevation, mean annual precipitation (MAP), mean annual temperature (MAT), soil texture, and site indices of interior Douglas-fir (Fd), lodgepole pine (Pl), and hybrid white spruce (Sx).

Experiment No.	Location	Latitude (N)	Longitude (W)	Elevation (m a.s.l.)	MAP (mm)	MAT (°C)	Soil texture*	BEC unit†	Series	Site index Fd	Site index Pl	Site index Sx
1	Bear Lake	54°37′	123°13′	820	805	3.0	L, SL	SBSmk1	01	—‡	20.1	—
2	Miriam Creek	50°24′	118°57′	790–1050	601	4.7	SL	ICHmw2	03	21.0	—	—
3	OK Falls	49°18′	119°26′	1100	517	4.8	SL	IDFdm1	01	—	18.0	—
4	Fort St. James§	54°27′	124°15′	818–900	554	2.4	SL to SiCL	SBSdw3/mk1	01/06/07	18.0/21	21.0	15.0–21.4
5	Will Lake	50°27′	119°38′	1260	511	3.4	SL	IDFdk2	03	—	18.0	—

Note: Mean annual temperature and precipitation were estimated for all sites based on the Climate BC model and normal conditions from 1971 to 2000 (Wang et al. 2006).

*Texture was for the 0–20 cm depth of the mineral layer. Experiment 1 had two soil textures, and experiment 4 had soil textures ranging from sandy loam to silty clay loam. L, loam; S, sand; Si, silt; C, clay.

†BEC, biogeoclimatic ecosystem classification.

‡Not applicable.

§Mean annual temperature and precipitation for Fort St. James were calculated by averaging values for the three replicates.

Methods used to determine total carbon, oxidizable organic matter, oxides of aluminum and iron, particle size distribution, and plastic and liquid limits were described by Zhao et al. (2008). Relative bulk density was calculated as the ratio of field BD to the predicted MBD. Three nonplastic samples with very high liquid limit were excluded in the MBD estimation because the overall model and the specified model provided very different estimates of MBD. With few exceptions, three RBD values at each plot were averaged to represent the RBD of the plot. The highest RBD value (0.92) from an untreated landing of experiment 5 was not included in the analysis because of incomplete tree growth data for that plot.

The thickness of surface organic material was measured at each BD sampling location, and three measurements were averaged to represent thickness of surface organic material at each plot. Surface organic material thicker than 3 cm has been reported to substantially change soil water and heat regimes (Bhatti et al. 2000; Parent et al. 2006), which would alter the effects of soil compaction on tree growth. In our study, the presence of the surface organic material was used as a dummy variable and its value was set at one when thickness was >3 cm and zero when thickness was <3 cm.

Tree height was measured at the end of the growing season (late September – early October), which corresponded with the time of BD sampling. Tree heights were measured from ground level to the terminal bud for all the live trees present at the plot.

Data analysis

We used the SAS REG procedure (SAS Institute 1990) to carry out multiple regression analysis by experiment with RBD, presence of surface organic material, and variables derived from presence of surface organic material and RBD (e.g., RBD^{-1}, RBD^2, and presence of surface organic material × RBD) as independent variables and height as the dependent variable. A stepwise method was used to exclude any independent variables that may have overlapping effects on the dependent variable. The χ^2 significance level was set at 0.25 for entry of variables into the regression and 0.10 for retention of variables, respectively.

Simple regression analysis was used for the relationship between height and RBD for the three species. To derive the relationship between height and RBD, we used the curve-fitting functions in SigmaPlot (SYSTAT Inc. 2000). For one experiment with a poor relationship between height and RBD (i.e., spruce growth on experiment 4), studentized residuals were calculated to remove outliers (SAS Institute Inc. 1990). Height of Douglas-fir and lodgepole pine growing on experiment 4 was always lower than that on the other experiments, even when RBD was considered to be optimal. This experiment is located in north-central BC and is near the northern geographic limit for Douglas-fir and lodgepole pine (BC Ministry of Forests and Range 2006). The SAS GLM procedure (SAS Institute 1990) was used to carry out two-factor analysis of variance of treatment effects on tree height for this experiment, with RBD being set at three levels (low, RBD < 0.70; medium, RBD between 0.70 and 0.83; and high, RBD > 0.83) and presence of surface organic material at two levels (surface organic material ≥3 cm and <3 cm).

Table 2. Establishment time, treatments, number of soil samples, tree species, and year of tree height measurements for the experiments included in this study.

Experiment No.	Year established	Treatments*	No. of soil samples	Year of sampling	Species and no. of growing seasons at the time of measurement[†]
1	2000	B, DM, P, S, U	45	2001	Pl: 1, 2, 5[‡], 8
2	2000	P, DD, SD	27	2001	Fd: 1, 2, 5, 7
3	1998	D, DT, DSS, U	35	1998	Pl: 4, 5, 8
4	2001	B, P, U	81	2001	Fd: 4, 7; Pl: 4, 7; Sx: 4, 7
5	2000	P, D, DTBP, U	35	2001	Pl: 8[§]

*B, burn; D, decompact; DD, deep till; DM, deep till and mulch; DSS, decompact and sortyard waste on surface; DT, decompact and topsoil; DTBP, till and burnpile/topsoil; P, plantation adjacent to disturbance; S, scratch; SD, shallow till; U, untreated.

[†]Fd, interior Douglas-fir; Pl, lodgepole pine; Sx, hybrid white spruce.

[‡]There were no height data for this plantation.

[§]Tree data were only available for treatments D and DTBP.

Table 3. Four regression models used to derive maximum bulk density (MBD).

Name*	Model[†]	R^2	n
Overall	MBD = 2.02 – 1.35LL + 0.0005CL – 0.005oxOM – 0.16AlO + 0.0005VCS	0.92	144
Nonplastic	MBD = 1.98 – 1.61LL – 0.11AlO + 0.0006VCS – 0.003TC + 0.0006CL	0.98	29
Moderately plastic	MBD = 2.27 – 1.62PL – 0.003oxOM – 0.0005MSI – 0.003T – 0.0005FSI – 0.18AlO	0.92	99
Highly plastic	MBD = 1.72 – 0.004TC – 0.82PL	0.87	16

*Nonplastic, soils with no plastic limit; moderately plastic, soils with a plastic limit when the liquid limit <0.50 $kg \cdot kg^{-1}$; highly plastic, soils with a liquid limit >0.50 $kg \cdot kg^{-1}$.

[†]LL, liquid limit; PL, plastic limit ($kg \cdot kg^{-1}$); AlO, Al-oxide (%); oxOM, oxidizable organic matter; TC, total C ($g \cdot kg^{-1}$); CL, Clay; MSI, medium silt; FSI, fine silt; VCS, very coarse sand ($g \cdot kg^{-1}$).

Table 4. Relative bulk density (RBD) and bulk density (BD) by treatment and surface organic material thickness of the five experiments included in this study.

Experiment No.	RBD range*	BD range ($Mg \cdot m^{-3}$)*	Surface organic material thickness (cm)
1	0.54 (B) – 1.01 (U)	0.91 (B) – 1.85 (U)	0–10
2	0.48 (C) – 0.94 (SD)	0.65 (C) – 1.76 (SD)	0–5
3	0.50 (DSS) – 0.71 (D)	0.87 (DSS) – 1.46 (U)	0–11
4	0.54 (U) – 0.96 (U)	0.72 (U) – 1.63 (U)	0–16
5	0.63 (DTBP – 0.91 (D)	0.80 (P) – 1.45 (U)	0

*Treatment code for the respective RBD values are given in parentheses. See Table 2 for treatment codes.

Results

Relative bulk density, surface organic material, and tree height

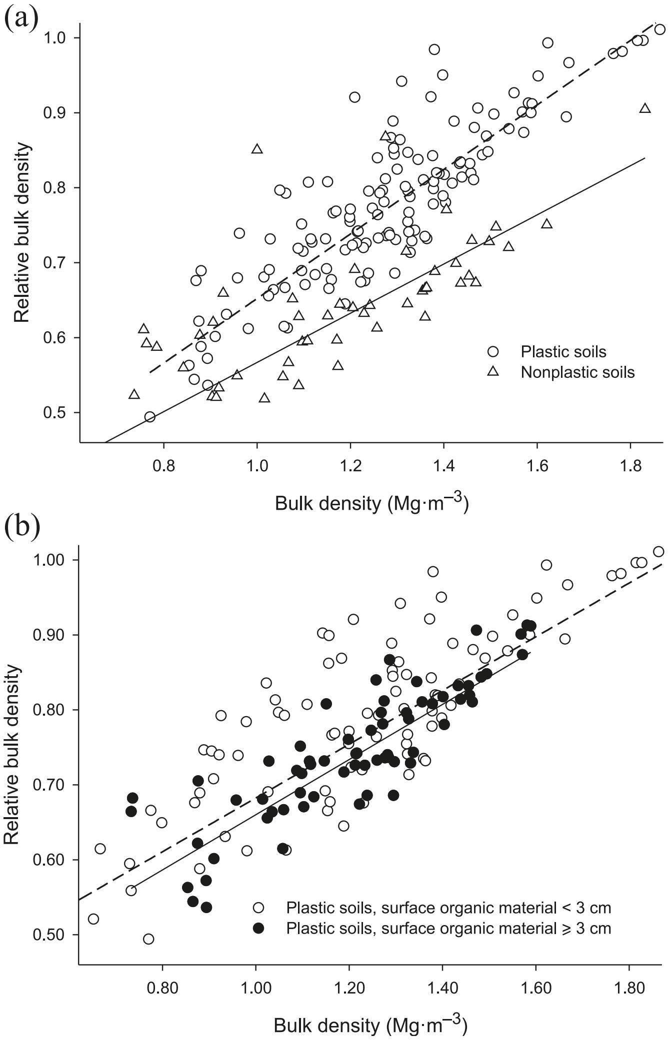
The RBD overall values ranged from 0.48 to 1.01 (Table 4), with the highest value obtained in disturbed plots without rehabilitation (e.g., experiments 1 and 4) and the lowest on rehabilitated sites (e.g., experiments 2, 3, and 5). The RBD values did not always match treatments as expected. For example, the unrehabilitated roads at experiment 4 had very low RBD value (0.54), whereas a shallow tillage treatment in experiment 2 yielded an RBD of 0.94, which was even higher than RBD of some unrehabilitated plots.

The overall thickness of surface organic material varied from 0 to 16 cm (Table 4). Surface organic material was not present on unrehabilitated plots, with the exception of several unrehabilitated roads and landings that had developed a thin (1–2 cm) layer of fan moss (*Rhizomnium glabrescens* (Kindb) T. Kop.) and juniper moss (*Polytrichium juniperinum* Hedw.).

Substantial variation in RBD was observed for soils with BD values below approximately 1.70 $Mg \cdot m^{-3}$ (Fig. 1*a*). The plastic soils had higher overall RBD than the nonplastic soils, and the very loose soils with both low RBD and low BD values tended to be nonplastic soils with no surface organic material (Fig. 1*a*; surface organic material data not shown). Among the plastic soils, a wider range of BD was observed for soils that had <3 cm of surface organic material, compared with those with thicker surface organic material (Fig. 1*b*). The subgroup with surface organic material <3 cm had significantly higher RBD values (P < 0.001) than the subgroup with thicker surface organic material (Fig. 1*b*), whereas no significant difference was observed for the nonplastic soils between the subgroups with surface organic material >3 cm and <3 cm (data not shown).

Presence of surface organic material was the first covariable used in the multiple regression analysis in the years immediately after planting for experiments 1, 2, and 3 (Table 5). For the experiments where presence of surface organic material was strongly correlated with tree height, the

Fig. 1. Relationship between relative bulk density and field bulk density for (*a*) plastic and nonplastic soils and (*b*) plastic soils with (≥3 cm) and without (<3 cm) surface organic material. Broken and solid lines are trend lines for plastic and nonplastic soils, respectively, in Fig. 1*a* and for plastic soils with surface organic material thickness <3 cm and ≥3 cm, respectively, in Fig. 1*b*.



amount of variation in height explained by the presence of surface organic material was generally found to decrease over successive growing seasons (Table 5). Experiment 3 had a narrow range of RBD, and surface organic material in combination with RBD or RBD^2 was positively related to tree growth. For experiments with a wider range of RBD values (i.e., experiments 1, 2, 4, and 5), surface organic material was usually the second variable or was excluded from the regression analysis in the older ages: RBD^2 was the main variable negatively related to height (Table 5). The ability of presence of surface organic material and RBD to explain height was not improved when soils were grouped according to the presence of surface organic material (data not shown) because grouping narrowed the RBD range and decreased the number of observations.

The presence of surface organic material generally did not affect growth of interior Douglas-fir or hybrid white spruce, whereas improved growth of lodgepole pine was associated with increased surface organic material at RBDs of 0.70–0.83 and >0.83 (Fig. 2). For sites lacking surface organic material, the height of interior Douglas-fir was greater at low RBDs (<0.70) than at higher RBD ranges (0.70–0.83 and >0.83) (Fig. 2*a*). Growth of lodgepole pine decreased with increasing RBD for trees growing in soils with surface organic material <3 cm ($P < 0.03$; Fig. 2*b*).

Relative bulk density and height: interior Douglas-fir

Height of interior Douglas-fir in experiment 2 did not vary with soil compaction during the first growing season (data not shown). After five growing seasons, 68% of variation in the height was explained by RBD. For the seventh growing season, about 70% of variation in height was associated with changes in RBD, implying that there was an increasing influence of compaction on growth (Fig. 3*a*). The best-fit (quadratic) regression lines showed that RBD values >0.72 were associated with height lower than the reference height (i.e., the estimated growth for average conditions on undisturbed soils of these site types) for these sites from the fifth growing season onward. Bulk density showed stronger relationships with height for both growing seasons, whereas the growth threshold BD increased from 1.10 $Mg{\cdot}m^{-3}$ in the fifth growing season to 1.20 $Mg{\cdot}m^{-3}$ in the seventh growing season (Fig. 3*b*).

Relative bulk density and height: lodgepole pine

The RBD values from experiment 1 were distributed over a wide range, and the relationships between lodgepole pine height and RBD were relatively strong (Fig. 4*a*). During the first growing season, height was not related to RBD (data not shown). From the second growing season onward, height varied with RBD, indicating that compaction affected growth of lodgepole pine. During the second growing season, a linear regression best described the relationship between height and RBD, and better height than in undisturbed conditions was obtained at RBDs <0.78. For the fifth and eighth growing seasons, a second-order regression best described the relationship, and height was better than reference height when RBDs were <0.80 (fifth growing season) and <0.87 (eighth growing season). Height was more closely related to BD than to RBD over these three growing seasons with threshold BD varying from 1.20 to 1.50 $Mg{\cdot}m^{-3}$ (Fig. 4*b*).

The RBDs of experiment 3 had a narrower range than experiment 1 with the highest RBD being 0.71. Over the RBD range in this experiment, heights in the fourth and eighth growing seasons were generally greater than in the reference condition (Fig. 4*c*). Although BD ranged from 0.75 to 1.52 $Mg{\cdot}m^{-3}$, height was not associated with BD, and a BD as high as 1.52 $Mg{\cdot}m^{-3}$ (associated with impeded tree growth in experiment 1) did not limit tree growth in this experiment (Fig. 4*d*).

Pooling lodgepole pine height–RBD data over experiments 1, 3, and 5 for the eighth growing season showed the same trends as experiment 1 (Fig. 4*e*). Less than reference height was associated approximately with an RBD of 0.87, and the best growth occurred at lower RBDs of 0.55–0.75. Height was weakly associated with BD ($R^2 = 0.30$) with a BD of 1.50 $Mg{\cdot}m^{-3}$ being the threshold that impeded growth for lodgepole pine (Fig. 4*f*).

Table 5. Regression analysis of relative bulk density (RBD) and presence of surface organic material (FF) on height.

Experiment No. and species*	No. of growing seasons	Intercept	Coefficient and variable	R^2	P
Experiment 1 (n = 15)					
Pl	1	19.8	$1.7FF \times RBD^2$	0.20	0.096
Pl	2	57.7	$-35.9RBD$	0.75	<0.001
Pl	5	216.8	$-168.3RBD^2$	0.74	<0.001
Pl	8	436.0	$-321.7RBD^2$	0.78	<0.001
Experiment 2 (n = 9)					
Fd	1	23.9	$3.1FF \times RBD^2$	0.69	0.005
Fd	2	32.5	$10.2FF - 9.4RBD$	0.98	0.001
Fd	5	93.7	$-87.2RBD^2 + 68.9FF \times RBD^2$	0.86	0.003
Fd	7	188.6	$-197.6RBD^2 + 132.8FF \times RBD^2$	0.83	0.005
Experiment 3 (n = 12)					
Pl	4	63.0	$44.7FF \times RBD$	0.62	0.002
Pl	5	93.8	$106.1FF \times RBD^2$	0.61	0.003
Pl	8	219.2	$137.6FF \times RBD^2$	0.33	0.052
Experiment 4 (n = 27)					
Fd	4	–16.0	$35.9RBD^{-1}$	0.30	0.006
Fd	7	–71.1	$91.4RBD^{-1}$	0.38	0.001
Pl	4	90.8	$-48.4RBD^2 - 81.7FF \times \log(RBD)$	0.43	0.002
Pl	7	213.4	$-127.5RBD^2 + 53.8FF \times \log(RBD)$	0.44	0.002
Sx	4	25.3	$-211.1\log(RBD)$	0.42	<0.001
Sx	7	262.9	$-231.1RBD$	0.41	<0.001
Experiment 5 (n = 6)					
Pl	8	347.6	$-274.1RBD^2$	0.83	0.011

*Fd, interior Douglas-fir; Pl, lodgepole pine; Sx, hybrid white spruce.

Relative bulk density and height: hybrid white spruce

Growth of hybrid white spruce decreased linearly (P < 0.001) with increasing RBD in the fourth and seventh growing seasons, but the linear relationships only explained 25%–27% of the variation (data not shown). For both growing seasons, there were nonlinear relationships between height and RBD at RBDs <0.75, whereas no substantial change in height was observed at RBDs >0.75 (Fig. 5a). For the fourth growing season, height over the observed RBD range was greater than the reference height. After the tree establishment (i.e., the seventh growing season), height was generally greater than the reference height when RBDs were <0.75; the peak model (SYSTAT Inc. 2000) best fit the data distribution (R^2 = 0.66), and the model indicated that the height peaked within a narrow RBD range of 0.60–0.68, and RBDs of approximately 0.78–0.80 were the threshold associated with less than the reference height (Fig. 5a). The peak growth was associated with a BD range of 0.90–1.10 $Mg \cdot m^{-3}$ for both ages, and a BD of 1.30–1.40 $Mg \cdot m^{-3}$ started to impede growth in the seventh growing season, whereas no substantial change in growth response was observed at BDs >1.25 $Mg \cdot m^{-3}$ for the fourth growing season (Fig. 5b).

Discussion

In our study, the RBD threshold at which compaction limited the height growth of both lodgepole pine and hybrid spruce was between 0.78 and 0.87, and maximum height of these two species occurred at RBDs of 0.60–0.68. In agricultural ecosystems, an RBD <0.80 was reported to support better yield or growth of annual species relative to undisturbed soil conditions (Carter 1990; Håkansson and Lipiec 2000), and the biological meaning of this value has been explained by the LLWR. For example, in a loamy sand soil in Ontario supporting alfalfa (*Medicago sativa* L.), an RBD of 0.80 was associated with high LLWR (corresponding with aeration ≥10%, maximum available water, and penetration resistance <2500 kPa); however, when RBD was >0.80 there was a sharp drop in LLWR (da Silva et al. 1994). Relative grain yield of spring barley and spring wheat started to decrease at RBDs >0.80, and RBDs >0.89 was associated with <80% relative grain yield (Carter 1990); in contrast, we found that tree growth was substantially impeded at the uppermost RBD value of 1.01 (i.e., lodgepole pine in experiment 1). On the other hand, the most common RBD values reported for continuously tilled soils were approximately 0.66 (Arvidsson and Håkansson 1991), and values as low as 0.63 obtained in our study were seldom reported in studies with annual plant species. We found that RBD influenced growth through the seventh (Douglas-fir) or eighth (lodgepole pine) growing season, and some research suggests that such effects may persist for many years or even decades. For example, Froehlich et al. (1985) reported that compaction was restricting growth of trees planted on compacted skid trails in west-central Idaho even 23 years after logging, and these trees were lagging behind in their growth relative to trees growing on adjacent uncompacted plantations.

Hybrid white spruce generally did not grow well when RBD was >0.80 and the trees were beyond the establishment period. Hybrid spruce is a shallow-rooted species, often forming >87% of its root mass in the top 15 cm of soil (in-

Fig. 2. Relationship between height and relative bulk density after 7 years growth of (*a*) interior Douglas-fir (Fd), (*b*) lodgepole pine (Pl), and (*c*) hybrid white spruce (Sx) in experiment 4. Error bars are standard errors. Height bars with the same letter are not significantly different at $P = 0.05$.

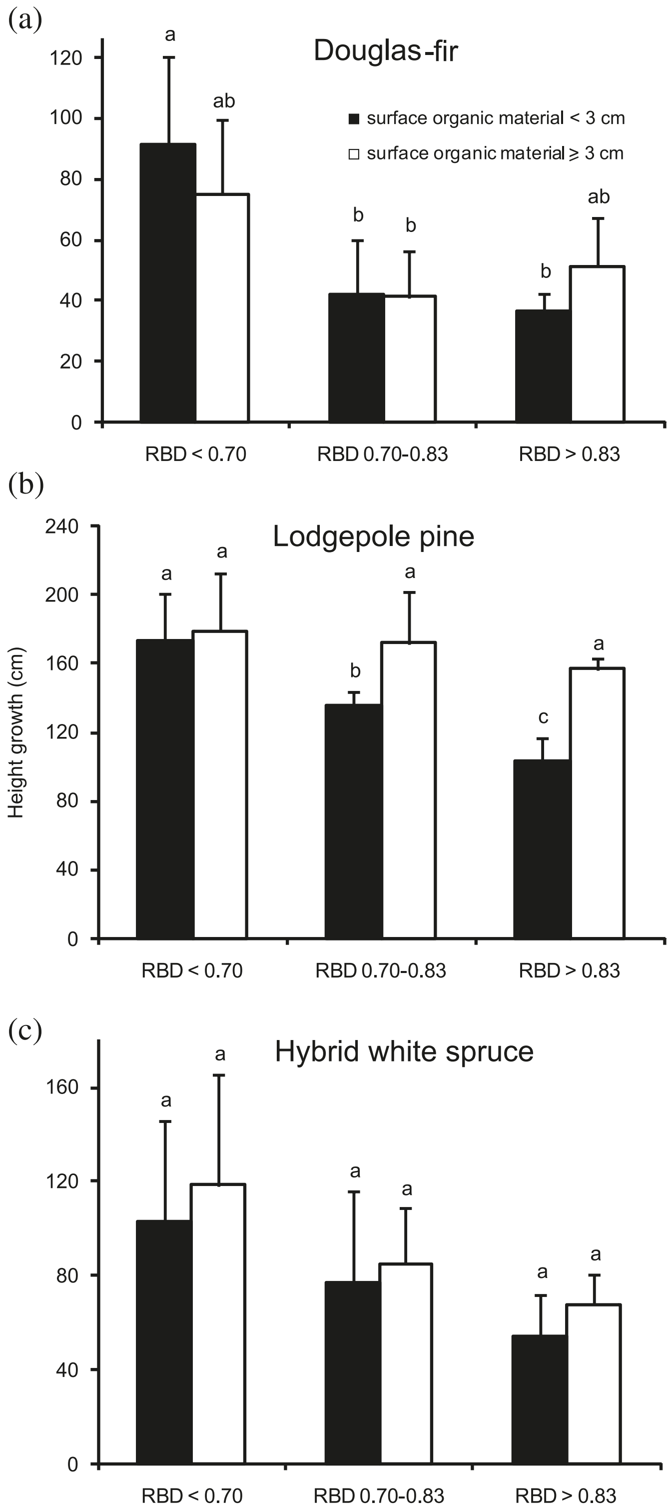
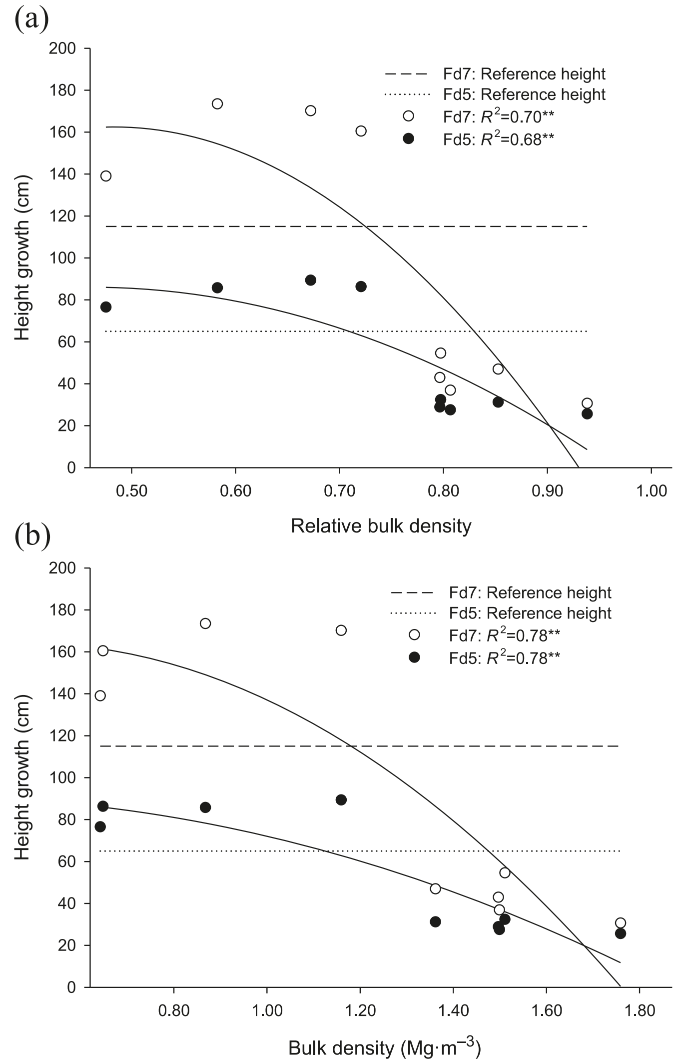


Fig. 3. Relationship between height of interior Douglas-fir (Fd) and (*a*) relative bulk density and (*b*) bulk density in experiment 2. The reference height was estimated from SiteTools (Research Branch, Ministry of Forests and RamSoft Systems 2004) using the model of Thrower and Goudie (1992), and data distributed above the lines indicate better growth than in predisturbed conditions. Fd5 and Fd7, five and seven growing seasons in the field, respectively. For the R^2 values, asterisks indicate significant differences: **, $P < 0.01$.



cluding both forest floor and an A horizon) (Safford and Bell 1972; Kimmins and Hawkes 1978), suggesting that this species is sensitive to surface soil compaction. The effect of compaction likely becomes more pronounced as spruce ages because of the greater density of surface roots. At RBDs >0.80, the fact that hybrid spruce attained height equivalent to undisturbed soils in some cases may be attributed to the presence of cracks and fissures along which roots could grow and the presence of lateral roots close to the surface of the roads.

Environmental conditions on the experimental sites located in north-central BC were not suitable for optimal growth of Douglas-fir and lodgepole pine. These sites were near the northern limit of the geographic distribution for Douglas-fir and were characterized by medium- and fine-textured soils. Those two conditions combined with the fact that these sites occurred in low-lying portions of the landscape with low aeration might restrict the growth of Douglas-fir and lodgepole pine. Despite this, the relative magnitude of the growth effects of these three species may

Fig. 4. Relationship between height of lodgepole pine (Pl) and (*a*) relative bulk density in experiment 1; (*b*) bulk density in experiment 1; (*c*) relative bulk density in experiment 3; (*d*) bulk density in experiment 3; (*e*) relative bulk density in experiments 1, 3, and 5; and (*f*) bulk density in experiments 1, 3, and 5. The reference height was estimated from SiteTools (Research Branch, Ministry of Forests and RamSoft Systems 2004) using the model of J.S. Thrower & Associates (1994), and data distributed above the lines indicate better growth than in predisturbed conditions. Pl2, Pl5, and Pl8, two, five, and eight growing seasons in the field, respectively. For the R^2 values, asterisks indicate significant differences: *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.

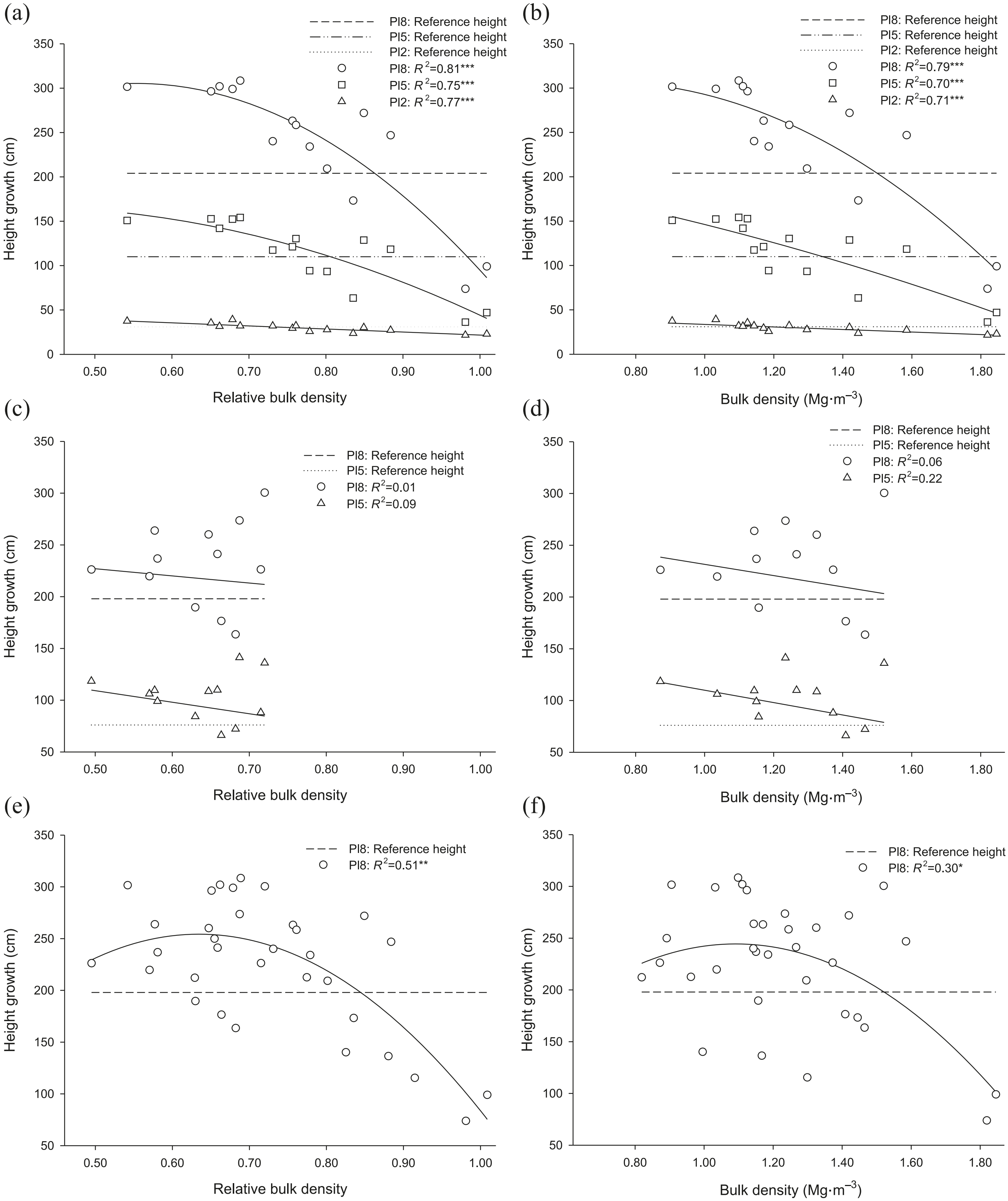
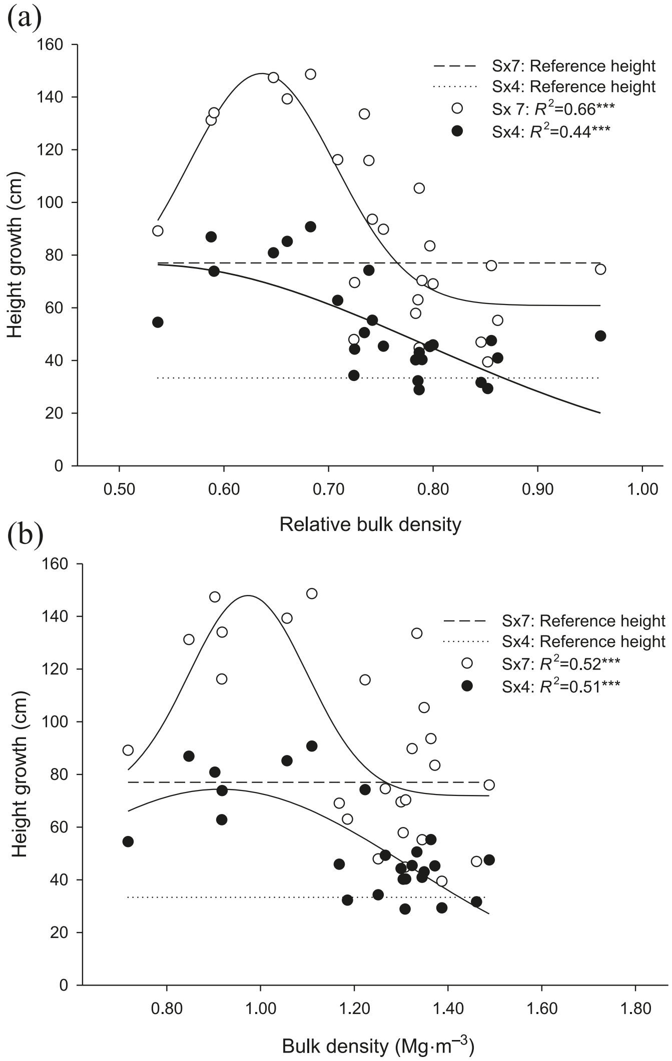


Fig. 5. Relationship between height of hybrid white spruce (Sx) and (*a*) relative bulk density and (*b*) bulk density in experiment 4. The reference height was estimated from SiteTools (Research Branch, Ministry of Forests and RamSoft Systems 2004) using the model of Goudie (1984), and data distributed above the lines indicate better growth than in predisturbed conditions. Sx4 and Sx7, four and seven growing seasons in the field, respectively. For the R^2 values, asterisks indicate significant differences: ***, $P < 0.001$.



provide insight into their relative susceptibility to compaction in north-central BC, particularly during the seedling establishment phase when the majority of roots are confined to surface soil layers. For Douglas-fir, the best performers were about 6.2 times as tall as the poorest performers, suggesting that this species is particularly vulnerable to compaction. The best performing spruce trees were 3.8 times as tall as the poorest whereas the magnitude of the height growth response was 2.6 times for pine.

In experiment 2, which is located in the middle of Douglas-fir's geographic range in BC, growth of seedlings appeared to be impeded at RBDs >0.72 during the fifth and seventh growing seasons. On the other hand, Douglas-fir in the north-central interior sites showed a continuous decrease in its growth over the RBD range, and height after 7 years was always less than in experiment 2 when RBDs were <0.72. Our results imply that climate or other site conditions may have reinforced the detrimental effect of compaction on early growth for interior Douglas-fir on these sites where the roads, landings, and trails were characterized by forest floor removal.

Lodgepole pine showed more resistance to compaction than spruce. Not only did lodgepole pine have increasing threshold RBD values over successive growing seasons (e.g., 0.87 in the eighth growing season), but its growth also declined more slowly than for hybrid spruce when RBD was >0.68. On blade-scarified sites with forest floor incorporation into the mineral soil, McMinn (1978) reported that lodgepole pine developed a root system larger than spruce by the second growing season, and this trend continued during the rest of the 5 year experiment. In compacted soils, lodgepole pine develops a dual root system with the lateral roots growing largely within the top 30–60 cm and with vertical roots extending to the rock layer at a depth of 100–120 cm (Berndt and Gibbons 1958; Bishop 1962). After seven growing seasons in our study, many of the lodgepole pine trees may have developed a root system that extended deeper than the level of our soil measurements. Although we did not measure rooting depth, our results are consistent with but do not prove the conclusion that the effect of surface soil compaction on growth was reduced as the trees could be deriving a greater proportion of their resources from relatively undisturbed soils at depth.

The presence of surface organic material on disturbed soils has been associated with lower bulk density and RBD, which may reflect redistribution of the compactive forces caused by machine traffic (Page-Dumroese 1993). In contrast, removal of surface organic material is associated with higher RBD because of increased disturbance of the mineral soil or slow recovery of soil physical properties. Kabzems and Haeussler (2005) showed that soils that were compacted without organic material present at the surface achieved higher bulk density values than those that were compacted in the presence of 7–8 cm of forest floor. The presence of surface organic material also substantially alters the tree rooting environment by reducing water evaporation and changing soil temperature (Bhatti et al. 2000). These changes were substantial on a site with 5–10 cm of forest floor but not when the surface organic was thinner. We considered that the presence of thin (i.e., <3 cm) surface organic material would not significantly protect the mineral soil from compaction or provide a significant improvement in the rooting environment.

Although the presence of surface organic material mitigated the negative influence of compaction on growth, our study showed that tree height was more strongly related to RBD than to presence of surface organic material. When soils were severely compacted, factors such as poor aeration and high mechanical resistance associated with high RBD were more likely to limit plant growth (da Silva et al. 1994). Therefore, it may be important to reduce soil compaction below a limiting level so that the presence of surface organic material can enhance tree growth.

Calculated as a ratio of field BD to the maximum BD of the same soil, RBD removes influences of intrinsic soil properties (i.e., particle density and texture) on BD that are not directly affected by compaction. Based on our study, an RBD of 0.80 appears to represent a growth-limiting threshold for lodgepole pine and hybrid spruce during their early growth stages regardless of soil texture and particle density. On the other hand, BD thresholds varied substantially with species and soil texture. For example, in our study, BD as high as 1.52 Mg·m^{-3} was not impeding lodgepole pine growth at experiment 3, and threshold BD ranges for interior Douglas-fir, lodgepole pine, and hybrid white spruce at other experiments were 1.10–1.20, 1.25–1.50, and 1.30–1.40 Mg·m^{-3}, respectively. Daddow and Warrington (1983) reported BD thresholds of 1.60–1.80 Mg·m^{-3} for sandy loam and 1.40 Mg·m^{-3} for silt loam.

Although closely related to BD, RBD did not always agree with BD. For example, at experiment 1 of our study, the burn and deep-till treatments at one plot had the same low BD value (0.74 Mg·m^{-3}), but the RBD (0.68) of the deep till treatment differed substantially from that of the burn treatment (0.42). Similarly, a deep-till treatment and a burn treatment from another plot had quite different BD values (1.03 and 1.26 Mg·m^{-3}, respectively), yet the RBD did not differ (0.73). Where machine traffic and soil disturbance lead to subtle differences in BD, expected compaction levels would not be reached because BD does not necessarily indicate level of compaction. As a result, determination of the RBD may provide additional insight into the factors affecting forest productivity on compacted soils compared with BD alone.

Our findings suggest that BD may not always be a good indicator of soil compaction, and it is especially beneficial to characterize compaction by RBD for forest soils, which are often characterized with heterogeneity of textures and complexity of site conditions. For example, Bulmer et al. (2007) studied the effects of tillage and wood waste amendment on lodgepole pine seedling growth in the same site as our experiment 3, and they found that rehabilitation methods did not result in an expected increase in growth. In this experimental plot, we found that the untreated plots already had a very low RBD (0.70), and growth was not reduced. This low RBD value implied that rehabilitation using tillage was not necessary; this finding could not be made based on BD values alone (Bulmer et al. 2007).

For lodgepole pine and spruce in their early growth stages, rehabilitation involving soil decompaction should be considered as a measure to improve productivity when RBD is >0.80. For Douglas-fir, a threshold RBD of 0.80 should be considered for decompaction, although further study is needed to confirm this. One reason for the poor performance of interior Douglas-fir at low RBDs (i.e., 0.72) in our study may be ascribed to its susceptibility to soil disturbance, which often disrupts the development of mycorrhizae (Danielson 1985; Perry et al. 1987; Simard et al. 2003); while compaction reinforces this influence (Skinner and Bowen 1974; Wert and Thomas 1981).

In studies focusing on compaction impacts, it would be more informative to quantify (i.e., determine RBD) rather than qualify the level of compaction (i.e., simply state a generic level of soil compaction, such as light, medium, or heavy). By stratifying soils into plasticity groups as we have done, such interpretations could be further refined. Our findings suggest that rehabilitation practices may benefit tree growth at sites where RBD is >0.80, and that compaction is not detrimental at lower RBD values.

Conclusions

Relative bulk density should be considered as an indicator of forest soil compaction with consequences for tree height growth and site productivity. Relative bulk density values observed in this study ranged from 0.48 to 1.01, and rehabilitated roads, landings, and undisturbed soils were often associated with low RBD values. Although soils with thin surface organic material had high BD and RBD values, unrehabilitated soils did not always have high RBD values and, thus, did not always require rehabilitation. The presence of surface organic material mitigated the severity of compaction and was associated with lower RBD values. When interior Douglas-fir was planted close to the northern limits of its geographic range in BC and where lodgepole pine was planted on low-lying areas and clay-rich soils, these species did not grow well, and RBD was weakly related to height. Height of interior Douglas-fir was limited when RBD was >0.72. Threshold RBD values associated with limited growth of lodgepole pine increased from 0.78 to 0.87 as the trees grew older. The threshold RBD associated with limited height for spruce was 0.80. An RBD of 0.60–0.68 corresponded to the maximum height of lodgepole pine and hybrid white spruce. To obtain good seedling establishment, rehabilitation involving soil decompaction should be considered as a measure to improve productivity when RBD is >0.80. The relationships found in our study have implications in assessing forest soil compaction and its effect on site productivity. The results will also help predict and monitor soil behaviour and associated tree growth in response to timber harvesting and site rehabilitation.

Acknowledgements

This work was supported by the Natural Sciences and Engineering Research Council of Canada and the Forest Investment Account – Forest Science Program. We thank Dr. Shannon Berch who provided the tree growth data before 2007. Technical assistance of George Franssen with soil sampling and tree measurement is greatly appreciated. We also greatly acknowledge two anonymous reviewers for their very constructive comments and suggestions.

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