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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 inappropri-

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

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

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

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 × 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×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 × RBD^2	0.86	0.003
Fd	7	188.6	–197.6RBD^2 + 132.8FF × RBD^2	0.83	0.005
Experiment 3 (n = 12)					
Pl	4	63.0	44.7FF × RBD	0.62	0.002
Pl	5	93.8	106.1FF × RBD^2	0.61	0.003
Pl	8	219.2	137.6FF × 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 × log(RBD)	0.43	0.002
Pl	7	213.4	–127.5RBD^2 + 53.8FF × log(RBD)	0.44	0.002
Sx	4	25.3	–211.1log(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

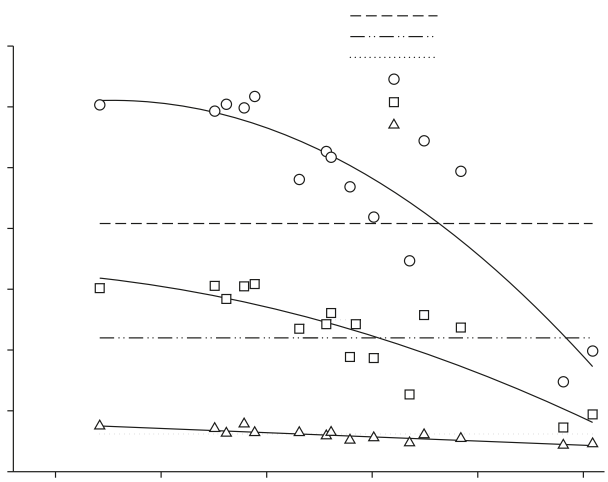
*Fd, interior Douglas-fir; Pl, lodgepole pine; Sx, hybrid white spruce.

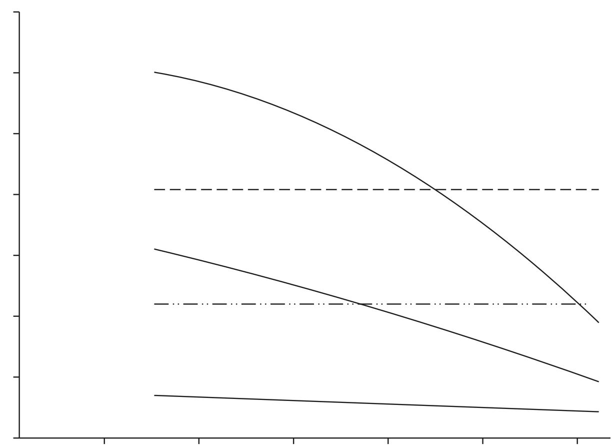
Relative bulk density and height: hybrid white spruce

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. 5*a*). 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. 5*a*). The peak growth was associated with a BD range of 0.90–1.10 Mg·m^{-3} for both ages, and a BD of 1.30–1.40 Mg·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·m^{-3} for the fourth growing season (Fig. 5*b*).

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-





old 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 $Mg\cdot m^{-3}$ 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 $Mg\cdot m^{-3}$, respectively. Daddow and Warrington (1983) reported BD thresholds of 1.60–1.80 $Mg\cdot m^{-3}$ for sandy loam and 1.40 $Mg\cdot m^{-3}$ 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 $Mg\cdot m^{-3}$), 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 $Mg\cdot m^{-3}$, 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

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