Maximum Bulk Density of British Columbia Forest Soils from the Proctor Test: Relationships with Selected Physical and Chemical Properties

Yihai Zhao
Maja Krzic*
Faculty of Forestry
Univ. of British Columbia
Vancouver, BC V6T 1Z4
Canada

Chuck E. Bulmer
British Columbia Ministry of Forests and Range
Research Branch
Vernon, BC V1B 2C7
Canada

Margaret G. Schmidt
Dep. of Geography
Simon Fraser Univ.
Burnaby, BC V5A 1S6
Canada

The widespread use of heavy equipment during timber harvesting and site preparation can lead to reduced soil productivity and warrants development of new methods to assess compaction. We evaluated the effects of soil particle density, organic matter, particle size distribution, extractable oxides, and plastic and liquid limits on the maximum bulk density (MBD) of forest soils in British Columbia. Soil samples were collected from 33 sites throughout British Columbia, covering the major forest and soil types of the province. The standard Proctor test was used to determine MBD and related parameters, including the gravimetric water content (W_{MBD}) and porosity (f_{MBD}) at which MBD was achieved. The significance levels of single soil properties in predicting MBD were in the order plastic and liquid limits, organic matter, oxalate-extractable oxides, and particle size distribution. For all samples, liquid limit and clay were most closely related to MBD (R^2 = 0.83). Addition of organic matter to the model increased the regression coefficients, and oxidizable organic matter caused a greater increase than did total C. Stratification of the sample set into groups based on plasticity led to higher R^2 values in multiple regressions, and different soil properties were important for nonplastic soils than for those with high, moderate, and low plasticity. Prediction with multiple regression explained the most variation in MBD for nonplastic soils, while properties of highly plastic soils explained the least variation in MBD and moderately plastic soils were intermediate. Based on our findings, we propose an approach for using MBD to help better interpret bulk density data in forest soil compaction studies.

Abbreviations: BWBS, Boreal White and Black Spruce biogeoclimatic zone; CDF, Coastal Douglas-fir biogeoclimatic zone; CWH, Coastal Western Hemlock biogeoclimatic zone; f, porosity; f_{MBD}, porosity at MBD; ICH, Interior Cedar–Hemlock biogeoclimatic zone; IDF, Interior Douglas-fir biogeoclimatic zone; LTSP, Long-Term Soil Productivity Study; MBD, maximum bulk density; PCA, principal component analysis; SBS, Sub-Boreal Spruce biogeoclimatic zone; gravimetric water content at which MBD was achieved.

Mechanized forest harvesting operations apply heavy weights to soil, which often leads to compaction. Reduced tree volume and height growth caused by compaction have been reported in various parts of North America (Wert and Thomas, 1981; Page-Dumroese et al., 1998), and it can take decades (as long as 70 yr) for compacted soils to naturally recover to their predisturbance conditions (Froehlich et al., 1985; Miller et al., 1996). Compaction is a process of increasing the soil bulk density (and decreasing porosity) by application of mechanical forces to the soil. Successful planning to minimize compaction depends on knowledge of the distribution of soil types in a given area, coupled with a knowledge of the behavior of the soils in response to compactive effort. Many regions of North America and elsewhere have extensive soil resource inventories, but work on the site-specific effects of compaction needs to be better developed.

To maintain sustainable soil productivity, it is necessary to assess the ability of a soil to support plant growth after machines have traveled over it. Soil scientists studying sustainability have traditionally measured bulk density as an indicator of compaction, and this measurement is also made because bulk density is a key soil property for determining site nutrient contents. Despite this, limiting values for bulk density have not been defined for the wide range of soil conditions typical in forests, primarily because such limiting values are different for soils with varying texture, organic matter content, and other properties. Establishment of limiting values would be beneficial for soil scientists and land managers.

One approach to better evaluate the state of soil compaction among soil types involves expressing the actual bulk density as a percentage of some reference compaction state (Lipiec et al., 1991; Topp et al., 1997; Lipiec and Hatano, 2003). The idea of comparing soil physical conditions at field sites to a reference state was also proposed by Joosse and McBride (2003), who proposed comparisons based on the void ratio to evaluate the soil quality of agricultural sites. Such comparisons would allow conditions from a wide range of soil types to be evaluated using a single threshold limit, much as the critical limits of soil mechanical resistance and air-filled porosity appear to be relatively independent of soil type (Hakansson and Lipiec, 2000;

Soil Sci. Soc. Am. J. 72:442-452
doi:10.2136/sssaj2007.0075
Received 21 Feb. 2007.
*Corresponding author (krzic@interchange.ubc.ca).

677 S. Segoe Rd. Madison WI 53711 USA

Zou et al., 2001). Therefore, use of a reference state could potentially enhance interpretations in soil compaction studies.

Various parameters for a reference compaction state have been proposed (Carter, 1990; da Silva et al., 1994; Hakansson and Lipiec, 2000), but the maximum bulk density (MBD) determined by the standard Proctor compaction test (ASTM, 2000) is rigorously defined, is readily determined with standard test equipment, and has been used in several studies (Carter, 1990; Smith et al., 1997; Aragon et al., 2000). The potential advantages of using MBD as a reference compaction state can only be realized if the soil samples used to determine it reliably represent site conditions, and this can create challenges in forest soils. Unlike agricultural soils, where soil type is often relatively consistent within a particular field, the properties of forest soils are known to vary widely across short distances (Courtin et al., 1983) on many forested sites in response to more variable topography and the absence of tillage to mix and homogenize surface layers. Such variation would require a large number of samples to be taken to determine MBD, and some alternative method to predict MBD would be beneficial.

The standard Proctor method (ASTM, 2000) evolved from studies by civil engineers (Proctor, 1933) on the compaction of soils for dam and road foundations. Two parameters are obtained from this method: MBD and the critical water content at which MBD is achieved for a given amount of energy (W_{MBD}). The compactive force applied in the Proctor test as it is used in engineering studies has evolved over the years to make it more applicable to changing needs. Despite this, no information is currently available to determine whether different levels of applied force would improve interpretations of compaction effects on growth (Hakansson and Lipiec, 2000). Therefore the standard Proctor test is commonly used in productivity studies (Carter, 1990).

The variation in MBD as determined by the standard Proctor test for a range of soils has been attributed to changes in soil organic matter, particle size distribution, Fe and Al oxides, or plastic and liquid limits. For example, quantity as well as quality of organic matter has been determined to have effects on MBD (Soane, 1990; Aragon et al., 2000), and both organic C (Donkin, 1991; Smith et al., 1997; Krzic et al., 2004) and readily oxidizable organic matter (Ball et al., 2000) have been used to predict MBD. Cementing agents, such as Fe, Al, or Mn oxides (in acidic soils) and carbonates (in calcareous soils) enhance aggregate stability, contributing to high soil shear strength (Yee and Harr, 1977). Dorel et al. (2000) reported that Caribbean Andosols and Nitisols (FAO, 1998) or Andisols and Alfisols (according to Soil Survey Staff, 2006) were more resistant to compaction because of the presence of stable microaggregates containing halloysite and Fe oxide. Larson et al. (1980) found that among 36 agricultural soils from around the world, soils with predominantly kaolinite or Fe oxide in the clay fraction had lower MBD than soils with predominantly 2:1 type clays.

The MBD was significantly correlated with clay, fine silt, coarse silt, medium sand, and fine sand, and the clay + silt fraction had the strongest (inverse) correlation with MBD ($R = 0.79$) on 26 South African forest soils (Smith et al., 1997), while Nhantumbo and Cambule (2006) also showed a relationship between clay content and MBD. Peakedness (kurtosis) and symmetry (skewness) of the particle size distribution curve have also been suggested as parameters in predicting MBD (Webster and Oliver, 1990). Well-graded soils, as indicated by a low coefficient of kurtosis, tend to have a higher MBD. A linear relationship between MBD and kurtosis ($R^2 = 0.82$) was reported by Moolman (1981), while Smith et al. (1997) showed that MBD decreased as the degree of kurtosis increased, but the relationship was not strong ($R = -0.48$).

Particle density of mineral soils dominated by Fe oxides and heavy minerals can range from 3.0 to 5.0 Mg m^{-3} (Padmanabhan and Mermut, 1995; Ruhlmann et al., 2006), while organic soil may have a particle density as low as 0.84 Mg m^{-3} (Redding and Devito, 2006). Since soil bulk density is influenced by particle density, consideration of particle density should be made when predicting MBD. This is particularly important when the soils examined have a wide variation in particle density, as they may for groups of soils developed on diverse geologic materials in mountainous terrain.

Due to the complex interrelationships among soil properties, attempts have also been made to combine several soil properties when predicting MBD. For example, variation in MBD was predicted well by the liquid limit, organic C, and sand ($R^2 = 0.98$) in a study performed by Howard et al. (1981) on 14 forest and rangeland soils in California. Similarly, Ball et al. (2000) showed that MBD, W_{MBD}, and total porosity at MBD were predicted ($R^2 = 0.49$, 0.55, and 0.43, respectively) by a combination of liquid limit and readily oxidizable organic matter for a range of cultivated soils in Great Britain.

Based on these findings, and as part of a larger study performed throughout British Columbia to determine the effects of compaction on forest soil productivity and tree growth, we evaluated the potential for predicting MBD based on properties that can be determined on samples normally collected during field evaluations of bulk density on forested sites. Our objectives were to: (i) evaluate the relationships between MBD and W_{MBD} as determined by the standard Proctor test and other soil properties for a wide range of British Columbia forest soils; (ii) identify the soil properties most important for predicting MBD; and (iii) describe a proposed method for using MBD as a reference bulk density in forest soil compaction studies.

MATERIALS AND METHODS

Study Sites

A total of 147 soil samples were collected from 33 study sites (Table 1) located in timber-growing areas within the Boreal White and Black Spruce (BWBS), Sub-Boreal Spruce (SBS), Interior Douglas-fir (IDF), Interior Cedar–Hemlock (ICH), Coastal Douglas-fir (CDF), and Coastal Western Hemlock (CWH) biogeoclimatic zones of British Columbia (Meidinger and Pojar, 1991). Ninety-three samples from 16 of the study sites were included in a previous study by Krzic et al. (2004).

The most common soil textural classes were silt loam and loam, with substantial variation often occurring within study sites. Soils were classified as Inceptisols or Brunisols and Gleysols (according to the Soil Classification Working Group, 1998), Alfisols or Luvisols (Soil Classification Working Group, 1998), and Spodosols or Podzols (Soil Classification Working Group, 1998), which covered the range of pedogenetic development in British Columbia. The majority of the soils were developed on glacial till, with the exception of one Inceptisol in the ICH developed on colluvium, two Alfisols in the SBS and ICH zones developed on lacustrine parent material, and seven Inceptisols in the CDF and CWH zones developed on glaciomarine parent material (Table 1).

Table 1. Site description, biogeoclimatic (BEC) zones, and annual precipitation for 33 study sites throughout British Columbia.

Study site	BEC†	Precipitation	Soil suborder	Parent material
		mm		
Black Pines	IDF	279	Cryalf	Eolian veneer over glacial till
Dairy Creek	IDF	279	Cryalf	Eolian veneer over glacial till
Emily Creek	IDF	424	Cryept	Glacial till
Kiskatinaw	BWBS	482	Cryalf	Glaciofluvial veneer over glacial till
Kootenay East	IDF	424	Cryept	Glacial till
Log Lake	SBS	615	Udept	Glacial till
McPhee Creek	ICH	755	Udept	Colluvium
Mud Creek	IDF	424	Cryept	Glacial till
O'Connor Lake	IDF	279	Cryalf	Eolian veneer over glacial till
Rover Creek	ICH	755	Udept	Colluvium
Skulow Lake	SBS	425	Cryalf	Glacial till
Topley	SBS	530	Cryalf	Glacial till
Aleza Lake	SBS	930	Cryalf	Lacustrine
Miriam Creek	ICH	420	Cryalf	Glacial till
Vama Vama	ICH	601	Cryalf	Lacustrine
Gates Creek	ICH	410	Cryalf	Glacial till
Phoenix	ICH	450	Cryoll	Glacial till
Aitken	BWBS	464	Cryalf	Glacial till
Bernadet	BWBS	498	Cryalf	Glacial till
Blackhawk	BWBS	619	Cryalf	Glacial till
Blueberry	BWBS	489	Cryalf	Glacial till
Boot Lake	BWBS	581	Cryalf	Glacial till
Apollo	SBS	497	Cryalf	Glacial till
John Prince	SBS	565	Udept	Glacial till
Weedon	SBS	606	Udept	Glacial till
Younges	SBS	615	Cryalf	Glacial till
Port Alberni	CWH	2116	Udept	Glaciomarine
Duncan Eagle	CDF	1039	Udept	Glaciomarine
Duncan Keating	CDF	1039	Aquept	Glaciomarine
Duncan Somenos	CDF	1039	Ustept	Marine or Lacustrine
Kennedy Lake	CWH	3295	Udept	Glaciomarine
Saanich Cowichan	CDF	906	Aquept	Glaciomarine
Saanich Fairbridge	CDF	906	Udept	Glaciomarine

† Biogeoclimatic zone: IDF, Interior Douglas-fir; BWBS, Boreal White and Black Spruce; ICH, Interior Cedar–Hemlock; SBS, Sub-Boreal Spruce; CWH, Coastal Western Hemlock; CDF, Coastal Douglas-fir.

The sites sampled for this study included 12 long-term soil productivity study (LTSP) installations, three long-term landing rehabilitation trials, seven provincial park sites, five oil-exploration-disturbed sites, four road rehabilitation sites, and two stumping-disturbed sites (Fig. 1). The LTSP sites in British Columbia are part of the North American LTSP network that includes the USDA Forest Service, Canadian Forest Service, British Columbia Ministry of Forests and Range, and various universities and industry groups (Powers, 2006).

Sample locations were selected to be representative of typical site conditions. For the LTSP sites, sample locations had been harvested with minimal soil disturbance. Soils from landing and oilfield rehabilitation trials usually experienced some scalping of surface layers, while soils from the stumping trials were characterized by some mixing of surface soil layers. Samples (∼35 kg each) were collected at 0- to 0.1-, 0.1- to 0.2-, or 0- to 0.2-m depth after removal of the forest floor (if present). The number of samples collected at each site varied between two and 12.

Soil Analysis

Maximum Bulk Density

The MBD and W_{MBD} were determined using the standard engineering Proctor test (Proctor, 1933; ASTM, 2000). Soil samples were air dried until friable and then passed through a 19-mm sieve followed by sieving through a 4.75-mm sieve and further air drying. To carry out the test, an initial estimate was made for each sample of the water content at which MBD would be achieved. Because W_{MBD} is typically slightly less than the plastic limit, the initial estimate involved determining the water content of a sample that had been moistened to the point where, after squeezing in the hand, it would remain in a lump when hand pressure was released, but would break cleanly into two pieces when "bent" (ASTM, 2000). Water was then added to a 2.3-kg subsample until it reached the estimated water content, and then four more subsamples were prepared, two with soil water content (W) below, and two with W above this value. The five subsamples were then left in sealed plastic bags to equilibrate overnight. During the test, soil was compacted in a standard mold (9.43×10^{-4} m^3) using a 2.5-kg rammer falling freely from a height of 0.3 m. The soil was added to the mold in three layers and 25 blows of the rammer were applied to each layer. Total compactive effort applied to the sample was approximately 600 kN m m^{-3} (or 595 kJ m^{-3}). The compacted sample was used to determine bulk density and corresponding water content. Soil water content was determined gravimetrically (w/w) by drying samples at 105°C for 16 h. Dry bulk densities vs. W values were plotted on a graph and the points were fitted with a best-fit curve (third-order polynomial). From the resulting compaction curve, MBD was determined from either (i) the peak of the curve, or (ii) the highest sample value when the peak of the curve lay below that level. Approximately 0.5 kg from each sample was sieved through a 2-mm sieve to determine the percentage of fine fraction, which was used to correct MBD. The volume of mineral coarse fragments was determined from dry mass and assumed to have a particle density of 2.65 Mg m^{-3}. Fine-fraction MBD was calculated as the mass of dry, coarse-fragment-free mineral soil per volume of moist soil, where volume was also calculated on a coarse-fragment-free basis. All MBD values are reported on a fine-fraction basis.

Particle Density

Particle density was determined by the gas displacement method (Flint and Flint, 2002), which was modified so that the expansion chamber (instead of the sample chamber) was pressurized to 239 kPa with room air. The expansion chamber was then opened to the sample chamber. Volumes of the two chambers, hose, and transducer were not measured directly; instead, a model describing the volume–pressure relationship was derived based on the changing volume of the sample chamber with known-volume plastic disks. Soil samples <2 mm, oven dried at 60°C for 48 h, were used for the test. The samples used for determination of particle density were not treated to remove organic matter, so the reported particle density for each sample reflects an average particle density for the entire fine fraction, including organic and mineral components.

Soil Organic Matter

Soil total C was determined by the dry combustion method (Nelson and Sommers, 1996) using a LECO analyzer (LECO Corp., St. Joseph, MI) on a sample that had passed through a 2-mm sieve. The estimate of the "readily oxidizable organic matter" was obtained as the weight difference before and after treatment of the sample with H_2O_2 and expressed as the gravimetric fraction of the original mass of soil. Hydrogen peroxide treatment involved heating a 50-g sample with 75 mL of H_2O_2 (30%) and 300 mL of water to 80°C and adding small increments of H_2O_2 until no further reaction was observed.

Soil Oxides

Soil oxides of Al, Fe, Mn, and Si were extracted by 0.2 mol L^{-1} acid ammonium oxalate solution. This method extracts active Al, Fe, Mn, and Si oxides, including a fraction of oxides bound by organic matter (Loeppert and Inskeep, 1996). The extracted ions were measured by inductively coupled plasma spectrometer.

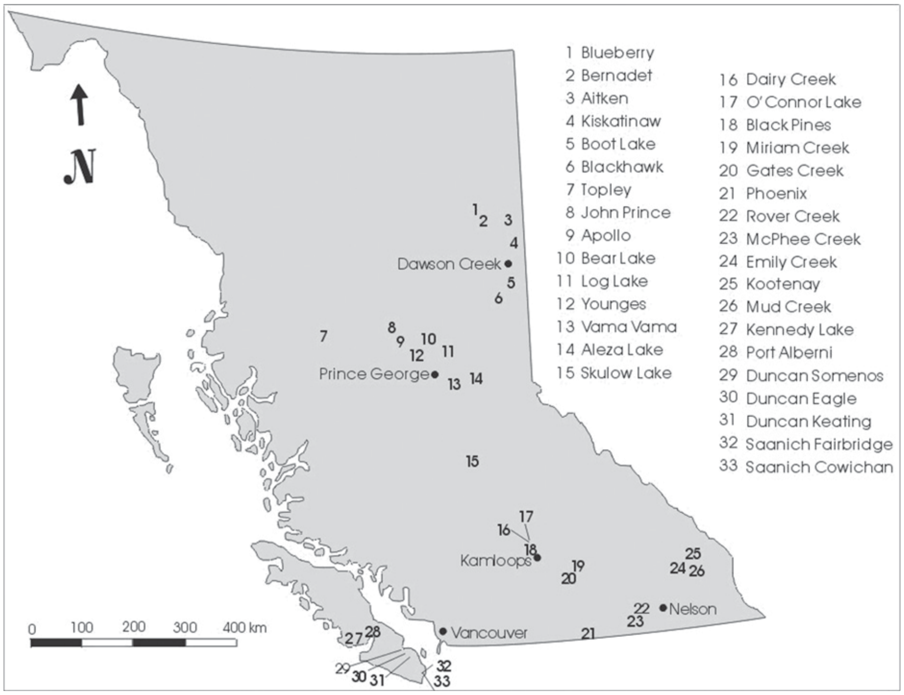

Fig. 1. Location of 33 study sites in British Columbia. Sites 1–3, 5, and 6 are oil-exploration-disturbed sites; Sites 4, 7, 11, 15–18, and 22–26 are long-term soil productivity study installations; Sites 13, 14, and 19 are long-term landing rehabilitation sites; Sites 20 and 21 are stumping-disturbed sites; Sites 8–10 and 12 are road rehabilitation sites; and Sites 27–33 are provincial park sites.

Particle Size Distribution

Soil particle size distribution was determined by the hydrometer method (Gee and Or, 2002). Samples were pretreated with H_2O_2 (30%) and heat, while samples from the IDF zone that may have contained carbonates were also treated with a NaOAc buffer. Particle size distribution was described using the Canadian System of Soil Classification (Sheldrick and Wang, 1993) in terms of the percentage of clay (<0.002 mm), fine silt (0.002–0.005 mm), medium silt (0.005–0.02 mm), coarse silt (0.02–0.05 mm), very fine sand (0.05–0.10 mm), fine sand (0.10–0.25 mm), medium sand (0.25–0.50 mm), coarse sand (0.50–1.00 mm), and very coarse sand (1.00–2.00 mm).

Peakedness (kurtosis) and symmetry (skewness) of the particle size distribution curve were calculated using the equations proposed by Webster and Oliver (1990):

$$\text{skewness: } Y_1 = M_3 / M_2^{3/2} \qquad [1]$$

$$\text{kurtosis: } Y_2 = \left(M_4 / M_2^2\right) - 3 \qquad [2]$$

where $M_2 = (1/n)\Sigma(X_i - \mu)^2$ is the second moment of the distribution about the mean of the observation, $M_3 = (1/n)\Sigma(X_i - \mu)^3$ is the third moment of the distribution about the mean of the observation, $M_4 = (1/n)\Sigma(X_i - \mu)^4$ is the fourth moment of the distribution about the mean of the observation, n is the number of observations, X_i is the ith observation, and μ is the mean of the observations.

Plastic and Liquid Limits

The plastic limit was determined as the gravimetric water content at which a soil sample could be rolled by hand into a thread of 3-mm diameter without breaking (McBride, 2002). The liquid limit was determined using the one-point Casagrande method (McBride, 2002). The soil water content at which 20 to 30 blows are required to close a groove along a distance of 13 mm was determined gravimetrically after drying at 105°C for 16 h. The liquid limit was calculated using the following equation:

$$\mathrm{LL} = W\left(N/25\right)^{0.12} \qquad [3]$$

where LL is the liquid limit, N is the number of blows, and W is the gravimetric water content.

Statistical Analysis

Distribution of the data was summarized by principal component analysis (PCA) using the SAS PRINCOMP procedure (SAS Institute, 1990). Before the PCA, "missing values" in the data matrix (i.e., 34 samples without plastic limit and three without liquid limit) were filled by the SAS PRINQUAL procedure with the minimum generalized variance method (SAS Institute, 1990). Simple regression analyses between dependent (i.e., MBD, W_{MBD}) and independent variables (i.e., soil properties) were run. Samples without plastic or liquid limits were not included in the regression. In addition, multiple regression analysis was used to select soil properties that were highly correlated with dependent variables. A stepwise method was selected in multiple regression analysis because certain soil properties (e.g., plastic and liquid limit, total C, and oxidizable organic matter) may have multiple impacts on soil MBD. Significance levels of the χ^2 score for variable entry and stay were set at 0.25 and 0.10, respectively.

RESULTS AND DISCUSSION

The minimum, maximum, and mean values of the soil properties are presented in Table 2, while a partial correlation matrix for the relationship between dependent variables (MBD, W_{MBD}) and selected soil properties is presented in Table 3.

Table 2. Soil properties for 33 study sites in British Columbia (n = 147).

Soil property	Min.	Max.	Mean	SD
Maximum bulk density, Mg m^{-3}	0.91	1.98	1.51	0.23
W_{MBD}†, kg kg^{-1}	0.09	0.50	0.22	0.08
Particle density, Mg m^{-3}	2.33	2.97	2.66	0.10
Total C, g kg^{-1}	1.8	77.4	23.4	16.5
Oxidizable organic matter, g kg^{-1}	2.2	76.7	28.6	15.3
Clay, g kg^{-1}	19	703	201	136
Silt, g kg^{-1}	94	728	450	114
Sand, g kg^{-1}	29	851	349	172
Fe oxide, %	0.10	1.19	0.51	0.25
Mn oxide, %	0.002	0.31	0.05	0.04
Al oxide, %	0.08	1.56	0.32	0.28
Si oxide, %	0.03	0.66	0.11	0.11
Liquid limit, kg kg^{-1}	0.15	0.61	0.33	0.11
Plastic limit, kg kg^{-1}	0.14	0.57	0.26	0.08

† Water content at which maximum bulk density was achieved.

Relationships between Maximum Bulk Density, Water Content at Maximum Bulk Density, and Other Soil Properties

Particle Density

Particle density for soils from our study sites ranged from 2.33 to 2.97 Mg m^{-3} (Table 2), with relatively large variation observed among the sites (27 out of 33 sites had within-site particle density differences >5%). The MBD was significantly (R^2 = 0.36) positively correlated with particle density (data not shown).

Although compaction effects on forest soil productivity are more directly related to changes in porosity, f (volume of pores/total soil volume), than bulk density, it is bulk density (and MBD) that is most commonly used to describe the forest soil condition (Smith et al., 1997). For groups of soils where particle density varies only slightly, bulk density and MBD can accurately reflect changes in f as they affect plant growth because the change in MBD is inversely related to the volume of pores. For groups of soils with a range of particle densities, however, changes in bulk density and MBD will reflect both differences in the volume of solids and particle densities, and the compaction state as it affects growth might be better described by the change in f rather than by the bulk density. In Fig. 2, we plotted the Proctor test curve of the soil with the highest particle density (2.97 Mg m^{-3}), then replaced its particle density with the lowest one (2.33 Mg m^{-3}) and plotted the five points again. The derived MBD of the hypothetical soil was 28% lower than that of the soil with the highest particle density (Fig. 2a), even though f remained the same (Fig. 2b).

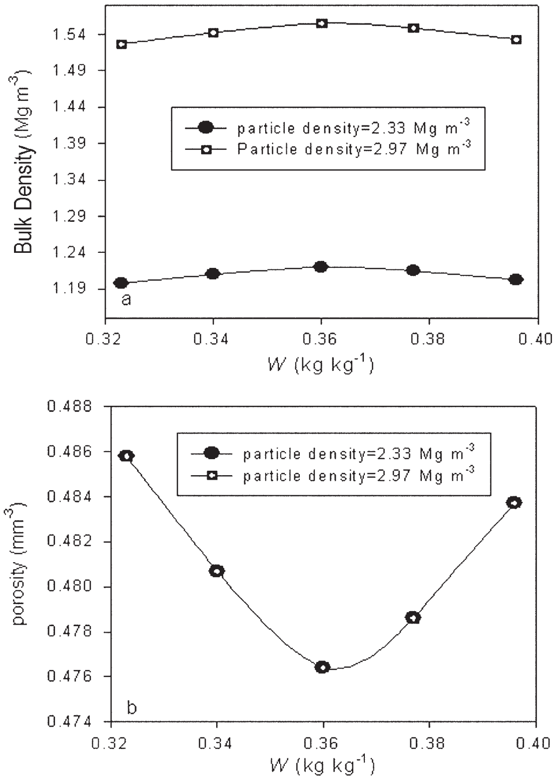

Fig. 2. Change of (a) soil bulk density and (b) porosity with water content (W) in the standard Proctor test. The bottom curve in (a) is hypothetical, derived by replacing the particle density of 2.97 with 2.33 Mg m^{-3}.

In forest compaction experiments where the particle density varies widely, determining the f of field soils and relating it to the f determined at MBD (i.e., f_{MBD}) could serve as an alternative index of the soil compaction state. This is analagous to the approach of Joosse and McBride (2003), who proposed relating the void ratio of structurally intact agricultural soils to that of remolded soils subjected to slurry consolidation and uniaxial compression tests (preconsolidation). The use of f and f_{MBD} could also be advantageous for evaluating compaction effects on soils with different parent materials, as described by Smith et al. (1997).

Soil Organic Matter

The MBD was negatively and W_{MBD} positively related to total C and oxidizable organic matter (Table 3). The MBD is commonly considered to be linearly related to organic matter (Soane, 1990; Zhang et al., 1997; Krzic et al., 2004). In this study, however, for both total C and oxidizable organic matter, exponential models gave a better description of the relationship (R^2 = 0.70 and 0.64, respectively; data not shown) than linear models (R^2 = 0.65 and 0.61, respectively; data not shown). Linear models described well the relationships between W_{MBD} and total C and oxidizable organic matter (R^2 = 0.65 and 0.54, respectively; data not shown).

Greacen and Sands (1980) reported that increased organic matter in sandy soils under radiata pine (*Pinus radiata* D. Don) forests in South Australia was associated with reduced compaction (measured as bulk density) under a given load. In a study performed by Ball et al. (1989) on Gleysol and Cambisol (FAO, 1998) or Inceptisol (Soil Survey Staff, 2006) soils from Scotland, a reduction in MBD of 0.18 g cm^{-3} per increase of 1% organic C was observed. In our study, total C had a similar effect on MBD.

Oxidizable organic matter is used as an indicator of the soil organic matter quality, since H_2O_2 oxidizes the colloidal, humified organic matter but not the fibrous residues (Day, 1965). The relationship between MBD and oxidizable organic matter has been reported in several studies. For example, Soane (1990) indicated that highly humified material increased soil aggregate stability and soils with high oxidizable organic matter tended to be less compacted. Ball et al. (2000) have shown that oxidizable organic matter explained 63% of variation in MBD of British agricultural soils.

In our study, MBD and W_{MBD} were better correlated to total C than oxidizable organic matter (Table 3). It has been reported that oxidation of the soil organic matter by H_2O_2 is restricted in the presence of Fe, which tends to stabilize soil organic matter during oxidative degradation (Oades and Townsend, 1963). The weaker relationship of MBD and W_{MBD} with oxidizable organic matter than with total C could be attributed to the presence of Fe oxides, indicating the importance of including several soil properties in a model to increase compactability prediction. On the other hand, Soane et al. (1972) reported lower correlations between MBD and W_{MBD} and organic C ($R = -0.72$ and -0.61, respectively) compared with oxidizable organic matter ($R = -0.81$ and -0.74, respectively) for 58 British agricultural topsoils. They used sodium dichromate mixtures to test organic C, which did not completely oxidize the organic compounds. In addition, the reaction between soil Fe and Mn oxides with dichromate may have further lowered the organic C (Nelson and Sommers, 1996).

Organic matter affects the compaction process in at least two ways: (i) it increases soil resistance to compaction by enhancing the contact between soil particles (Soane 1990); and (ii) its low particle density (Redding and Devito, 2006) compared with soil mineral particles reduces the overall particle density and therefore bulk density, especially when organic matter content is high. For our soils, total C accounted for 30.2% of the variation in particle density. The coefficient of determination for the relationship between f_{MBD} and total C, where the density effect of total C was removed, was 5% lower than that for MBD with total C (Table 3). Therefore, we conclude that the organic matter had the strongest effect in improving soil resistance to the compactive force for our group of soils.

Soil Oxides

The MBD was negatively and W_{MBD} positively related to Al and Fe oxides (Table 3). Linear relationships for Al oxide with MBD and W_{MBD} were both stronger than those for Fe oxide (Table 3), while adding an exponential component further improved the relationships with Al oxide ($R^2 = 0.53$ and 0.44; data not shown). In these relatively young soils of British Columbia that have developed since the most recent glaciation, oxides of Fe and Al are the main cementing agents that enhance aggregate stability (McKeague and Sprout, 1975).

Addition of Fe oxides along with organic C, liquid limit, and sand into the prediction model used in a study by Howard et al. (1981) improved the predictability of MBD by 1% ($R^2 = 0.99$). Contrary to our findings, Fe oxide was positively related to MBD in that study. Howard et al. (1981) used the citrate–bicarbonate–dithionite extraction method, which removed the total Fe oxide. The positive relationship observed in their study appeared to reflect the effect of Fe on soil mass rather than on soil strength, as soil particle density increases with Fe content. The negative relationship between MBD and active Fe oxide (extracted by ammonium oxalate) in our study reflected the enhanced soil strength due to the presence of soil oxides. Consequently, testing of active oxides along with total oxides could provide important information to determine the mechanisms by which these materials affect compaction.

Table 3. Correlation coefficients for comparisons among 17 selected variables.

Variable†	MBD	f_{MBD}	W_{MBD}	PD	Total C	oxOM	Clay	FSI	MSI	FS	MS	CS	VCS	Al oxide	Fe oxide	LL	PL
MBD	1.00																
f_{MBD}	−0.98 ***	1.00															
W_{MBD}	−0.94 ***	0.93 ***	1.00														
PD	0.60 ***	−0.42 ***	−0.56 ***	1.000													
Total C	−0.81 ***	0.78 ***	0.81 ***	−0.55 ***	1.00												
oxOM	−0.78 ***	0.75 ***	0.74 ***	−0.52 ***	0.73 ***	1.000											
Clay	−0.05	0.11	0.20 *	0.20 *	0.14	0.20 **	1.00										
FSI	−0.12	0.13	0.22 **	−0.01	0.14 *	0.25 **	0.70 ***	1.00									
MSI	−0.30 ***	0.24 **	0.26 **	−0.40 ***	0.16 *	0.23 **	−0.26 *	0.13 *	1.00								
FS	0.20 *	−0.20 *	−0.25 ***	0.10	−0.09	−0.24 **	−0.49 ***	−0.62 ***	−0.49 ***	1.00							
MS	0.21 **	−0.21 *	−0.31 ***	0.13	−0.18 *	−0.21 **	−0.50 ***	−0.53 ***	−0.37 ***	0.77 ***	1.00						
CS	0.08	−0.06	−0.20 *	0.10	−0.13	−0.16 *	−0.57	−0.56 ***	−0.34 ***	0.68 ***	0.77 ***	1.00					
VCS	−0.02	0.01 *	−0.15	−0.04	−0.06	−0.03	−0.58 ***	−0.42 ***	−0.03	0.31 **	0.58 ***	0.70 ***	1.00				
Al oxide	−0.61 ***	0.63 ***	0.59 ***	−0.25 **	0.33 ***	0.26 **	−0.22 **	−0.16 *	0.11	0.13 ***	0.08	0.20 **	0.14	1.00			
Fe oxide	−0.40 ***	0.45 ***	0.48 ***	−0.05	0.37 ***	0.46 ***	0.26 ***	0.24 **	−0.02	−0.29 ***	−0.23 **	−0.19 **	−0.22 *	0.39 ***	1.00		
LL	−0.85 ***	0.86 ***	0.89 ***	−0.42 ***	0.78 ***	0.69 ***	0.42 ***	0.29 ***	0.12	−0.32 ***	−0.34 ***	−0.24 **	−0.12	0.43 ***	0.36 ***	1.00	
PL	−0.93 ***	0.92 ***	0.94 ***	−0.52 ***	0.85 ***	0.73 ***	0.21	0.18 *	0.14	−0.16	−0.16 *	−0.04	−0.08	0.69 ***	0.42 ***	0.90 ***	1.00

* Significant at $P < 0.05$.

** Significant at $P < 0.01$.

*** Significant at $P < 0.001$.

† MBD, maximum bulk density; f_{MBD}, porosity at MBD; W_{MBD}, water content at which MBD was achieved; PD, particle density; oxOM, oxidizable organic matter; FSI, fine silt; MSI, medium silt; FS, fine sand; MS, medium sand; CS, coarse sand; VCS, very coarse sand; LL, liquid limit; PL, plastic limit. Other variables that were not significantly correlated to MBD, f_{MBD}, or W_{MBD} are not shown.

Table 4. Relationships among maximum bulk density (MBD) and particle size properties obtained at 33 study sites in British Columbia (n = 147).

Model	R^2	P
MBD = 1.72 − 0.001(medium silt)	0.09	0.000
MBD = 1.45 + 0.0006(fine sand)	0.04	0.021
MBD = 1.45 + 0.001(medium sand)	0.05	0.009
MBD = 1.54 − 0.03(skewness)	0.01	0.335
MBD = 1.51 − 0.005(kurtosis)	0.00	0.732
MBD = 1.27 + 0.002(fine silt) − 0.001(medium silt) + 0.001(coarse silt) + 0.002(medium sand)	0.18	0.000

Particle Size Distribution

Our results show that particle size distribution was not the major factor related to variations in MBD or W_{MBD} across the entire range of soils we studied, even though correlation coefficients were significant between MBD and medium silt, and between W_{MBD} and clay, fine silt, medium silt, fine sand, medium sand, and coarse sand (Table 3). In previous studies, increasing clay content has either been associated with lower MBD (Smith et al., 1997; Nhantumbo and Cambule, 2006) or had little effect on MBD (Ball et al., 2000; Aragon et al., 2000).

Kurtosis and skewness were previously considered to be useful parameters in predicting soil MBD (Moolman, 1981). A low coefficient of kurtosis indicates a well-graded particle size distribution and is expected to lead to a higher MBD, while a low absolute value of the skewness coefficient indicates high symmetry of the distribution curve and higher MBD. In our study, kurtosis ranged from −1.67 to 3.46 and skewness varied from −0.26 to 2.26, but we found no relationship between MBD or W_{MBD} and kurtosis or skewness (Table 4). Smith et al. (1997) suggested that the relationship between MBD and kurtosis would be confounded by the significant relationship between MBD and organic matter, which may also have occurred in our study.

Table 5. Principal component analysis loadings for the first three components of individual variables (n = 147).

Variable†	Loadings‡		
	Component 1§	Component 2¶	Component 3#
MBD	*−0.33*	−0.15	0.00
f_{MBD}	*0.32*	0.14	0.05
W_{MBD}	*0.34*	0.09	0.01
Particle density	−0.19	−0.14	0.17
Total C	*0.30*	0.11	0.00
Oxidizable organic matter	*0.29*	0.04	0.01
Clay	0.12	*−0.38*	0.16
Fine silt	0.14	*−0.35*	0.06
Medium silt	0.13	−0.04	*−0.28*
Coarse silt	−0.03	−0.01	*−0.48*
Very fine sand	−0.08	0.20	*−0.41*
Fine sand	−0.16	*0.30*	0.19
Medium sand	−0.16	*0.29*	*0.29*
Coarse sand	−0.13	*0.33*	*0.26*
Very coarse sand	−0.05	*0.27*	0.15
Kurtosis	0.07	−0.20	*0.36*
Skewness	0.08	−0.20	*0.32*
Al oxide	0.17	*0.29*	0.05
Fe oxide	0.20	−0.04	0.01
Mn oxide	0.16	0.14	0.13
Si oxide	0.08	0.24	0.01
Plastic limit	*0.33*	0.08	−0.04
Liquid limit	*0.33*	−0.01	0.08

† MBD, maximum bulk density; f_{MBD}, porosity at MBD; W_{MBD}, water content at which MBD was achieved.

‡ Values >0.25 are italicized.

§ Accounted for 34% of variation.

¶ Accounted for 19% of variation.

Accounted for 14% of variation.

Plastic and Liquid Limits

The MBD was negatively and W_{MBD} positively related to liquid and plastic limits (Table 3). Liquid and plastic limits have strong linear relationships with MBD (R^2 = 0.72 and 0.87, respectively; data not shown) and W_{MBD} (R^2 = 0.78 and 0.89, respectively; data not shown). An exponential model provided a better relationship between MBD and plastic limits (R^2 = 0.93; data not shown). Our results also showed that if the plastic limit can be determined on a sample, it is more closely related than the liquid limit to MBD and W_{MBD}.

Plastic and liquid limits integrate several soil properties such as particle size distribution, organic matter content, and clay mineralogy. Our findings are similar to those of Soane et al. (1972), who tested 13 properties of 58 Scottish topsoils and found that MBD and W_{MBD} were highly related to the plastic and liquid limits (R = −0.80 and −0.68 for MBD, 0.74 and 0.69 for W_{MBD}). Howard et al. (1981) found that the MBD of California forest and rangeland soils was significantly correlated to the liquid limit (R = −0.96) but they did not report the plastic limit. Ball et al. (2000) reported that the liquid limit accounted for 43 and 48% of the variation in MBD and W_{MBD}, respectively, of British soils, while the relationship between MBD or W_{MBD} and the plastic limit was lower (R^2 = 0.29 and 0.36, respectively). Relative to our data, the correlation coefficient between MBD and liquid limit was higher in a study by Howard et al. (1981) and lower in Ball et al. (2000). The former study tested 14 Californian soils predominated by loam texture, while the latter evaluated 146 British agricultural soil samples with a wide variation in texture. Differences in the soil textures might have accounted for the difference in correlation coefficients among the above studies. In the study by Ball et al. (2000), lower correlation coefficients may have been observed because some nonplastic soils had missing values filled by a statistical tool before running the correlation analysis.

Predicting Maximum Bulk Density by a Set of Soil Properties

Principal component analysis (a multivariate analysis tool to examine relationships among several quantitative variables in a data set) showed that the first three components accounted for 67% of the variation in the data set (Table 5). The first component mainly explained MBD, f_{MBD}, and W_{MBD} and soil properties like liquid and plastic limit, total C, and oxidizable organic matter. The second and third components mainly explained soil texture and Al oxides. This indicated that soil organic matter and liquid and plastic limits had the greatest impact on MBD, f_{MBD}, and W_{MBD}, while particle density, Al and Fe oxides, and some of the particle size classes were of secondary importance.

Principal component analysis allows a reduction in the number of variables used in regression analysis because it identifies factors whose effects are independent of one another. Multiple regression analysis was performed to find the best combination of soil properties that would explain variation in MBD. Because it was not possible to obtain the plastic limit for >20% of the samples, and considering that the plastic limit was previously shown (Ball et al., 2000) to be an important factor affecting MBD, we performed separate multiple regression analyses on soil groups based on their plasticity as shown in Fig. 3. Soils with high plasticity were characterized by either high clay content (up to 700 g kg^{-1}) or high total C (up to 77 g kg^{-1}). Moderately plastic soils had lower contents of clay (up to 560 g kg^{-1}) and total C (up to 57 g kg^{-1}), and made up the largest group of soils in our study. Nonplastic soils had the lowest clay content (up to 170 g kg^{-1}) and variable total C content (4–63 g kg^{-1}). Generally, it is difficult to determine the plastic limit on the very coarse-textured soils that cover some areas of British Columbia.

We were able to predict the MBD of British Columbia forest soils by combining several soil properties (Table 6). When all samples were included in the regression analysis, the liquid limit was the most highly correlated property in explaining MBD among all soil properties included in this study. The liquid limit, in combination with clay content, explained >80% of the variation in MBD. When oxidizable organic matter and Al oxide were added to the liquid limit and clay content, predictability of MBD improved by 8% (Table 6).

When samples were grouped according to their plasticity, fewer variables were needed in the multiple regressions to explain comparable amounts of variation in MBD, compared with the entire sample set. Multiple regressions for the nonplastic soils explained the most variation, while those for the highly plastic soils explained the least, and soils with low and moderate plasticity were intermediate (Table 6). For the nonplastic soils (i.e., those with low clay content), liquid limit and Al oxide were the two most important properties in predicting MBD (R^2 = 0.96). In the moderately plastic group, the plastic limit and oxidizable organic matter were the first two properties entered into the regression to predict MBD (R^2 = 0.89). For highly plastic soils (i.e., those with high clay and organic matter contents), total C and the plastic limit explained 87% of the variation in MBD.

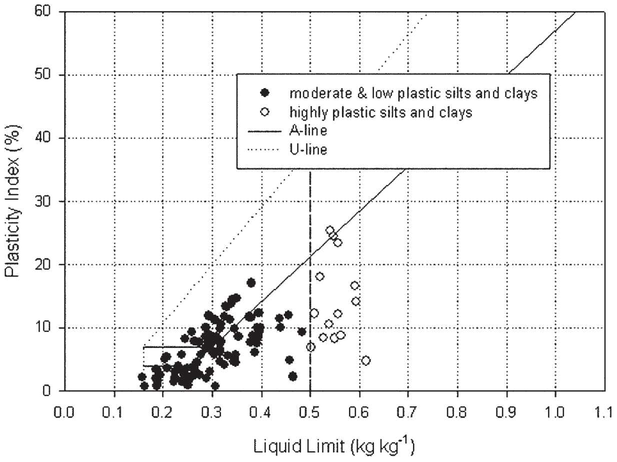

Fig. 3. Plasticity of soils from the study areas, showing highly plastic soils with liquid limit >0.50 and soils with moderate and low plasticity (liquid limit <0.50) as plotted on the Casagrande chart. The A-line represents the division between clays (plot on or above the A-line) and silts (plot below the A-line); the U-line refers to the upper limit.

Table 6. Regression constants and correlation coefficients for relationships between maximum bulk density (MBD) as the dependent variable and selected soil properties as the independent variable.

Dependent variable	Independent variable†							R^2‡
Overall (n = 144)								
	Intercept	Liquid limit	Clay	Oxidizable organic matter	Al oxide	Very coarse sand		
MBD	2.07	−2.11	0.0006					0.83
	2.06	−1.61	0.0006	−0.005				0.88
	2.06	−1.29	0.0004	−0.005	−0.17			0.91
	2.02	−1.35	0.0005	−0.005	−0.16	0.0005		0.92
Nonplastic (n = 29)								
	Intercept	Liquid limit	Al oxide	Very coarse sand	Total C	Clay		
MBD	2.09	−1.79	−0.14					0.96
	2.07	−1.89	−0.12	0.0005				0.97
	1.98	−1.61	−0.11	0.0006	−0.003	0.0006		0.98
Moderately plastic (n = 99)								
	Intercept	Plastic limit	Oxidizable organic matter	Medium silt	Total C	Fine silt	Al oxide	
MBD	2.21	−2.24	−0.004					0.89
	2.26	−2.16	−0.004	−0.0003				0.90
	2.24	−1.83	−0.003	−0.0004	−0.002			0.91
	2.28	−1.79	−0.003	−0.0004	−0.003	−0.0005		0.92
	2.27	−1.62	−0.003	−0.0005	−0.003	−0.0005	−0.18	0.92
Highly plastic (n = 16)								
	Intercept	Total C	Plastic limit					
MBD	1.72	−0.004	−0.82					0.87

†Liquid and plastic limits (kg kg^{-1}); Al and Fe oxide (%); oxidizable organic matter, total C, clay, medium silt, fine silt, fine sand, and very coarse sand (g kg^{-1}).

‡ Significant at $P < 0.001$.

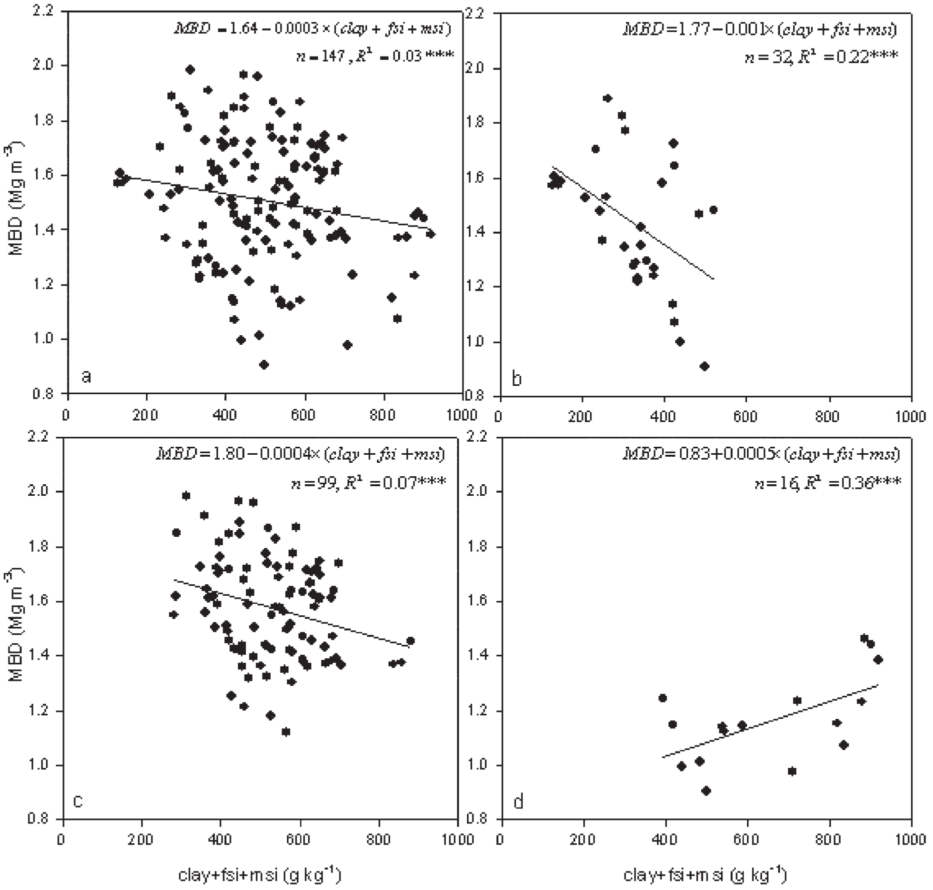

Fig. 4. Relationships among maximum bulk density (MBD) and clay + silt (fsi = fine silt; msi = medium silt) for (a) all samples, (b) nonplastic samples, (c) moderate and low plastic samples, and (d) highly plastic samples. ***Significant at *P* < 0.001.

For the majority of our soils, oxidizable organic matter was preferred to total C when predicting MBD, illustrating the importance of quality-related (i.e., oxidizable organic matter) rather than quantity-related (i.e., total C) soil organic matter in compaction studies. In a study by Howard et al. (1981), organic C was the most important variable in predicting MBD, but they did not determine the active oxides and subgroups of sand and silt size fractions, hence the importance of oxidizable organic matter was not known. Oxidizable organic matter was the second most important variable in predicting MBD in a study by Ball et al. (2000).

In our study, both organic matter (either total C or oxidizable organic matter) and oxides were important for the prediction of MBD (Table 6). In all groups, organic matter (i.e., total C) showed a strong relationship in decreasing MBD (R^2 = 0.59–0.72), which is similar to the results of Smith et al. (1997), who found a strong negative relationship between MBD and total C (R^2 = 0.88), and also to Aragon et al. (2000), who showed a high dependence of MBD on organic C. Including particle size distribution further improved the prediction. Even though clay came second in predicting MBD for the "overall" group, particle size components usually ranked third or lower in the prediction. Unlike Smith et al. (1997), who found a strong relationship between MBD and clay + silt (R^2 = 0.63), there was no relationship between MBD and clay + silt in our nonplastic and moderately plastic groups. Only in the highly plastic group did clay + silt show a high correlation with MBD (Fig. 4), but the positive effect we observed was opposite to that reported by Smith et al. (1997). Smith et al. (1997) found that in the lower range of clay + silt (0–400 g kg^{-1}), the effectiveness of clay + silt and total C appeared to offset each other in the compaction test; only in the higher range of clay + silt (400–1000 g kg^{-1}) did clay + silt enhance the effect of total C in reducing MBD. Hence, the importance of these two properties cannot be compared directly in their study. As total C was positively correlated to clay + silt (R^2 = 0.33) in their study, the strong effect of clay on MBD may be just a covarying result of organic matter on MBD. For the highly plastic group in our study, there was also a close correlation between clay and total C, which was not apparent in the other groupings (Fig. 5), but the relationship we observed showed total C content declining with increasing clay content, opposite to what is commonly expected for a range of soils. Our highly plastic soils group appeared to contain a mix of two subgroups of soils: (i) those with very high clay content but low or intermediate organic matter; and (ii) those with very high organic matter content but low clay content. This may clarify why multiple regressions explained the smallest amount of variation for the highly plastic group.

Because compaction is a dynamic process, the surface area, contacting points, and surface charge tend to be more important than single particles. Soil properties that more directly represent the above mechanisms should give a good description of the compaction process. Plastic and liquid limits have been proven powerful (R^2 > 0.90) in estimating external surface area (Hammel et al., 1983); on the other hand, oxalate-extractable oxides reflect the charge condition of particle surfaces. Organic matter may also be more important than particle size distribution where living and dead roots provide a filamentous network, which resists compactive loads, and highly humified material increases the stability of aggregates (Soane, 1990).

Proposed Method for Using Maximum Bulk Density as a Reference in Forest Soil Compaction Studies

To use MBD as a reference value in soil compaction studies, a method for obtaining the best estimate of MBD across a variable site is required. The standard approach to determining MBD using the Proctor test relies on collecting a 10-L sample from the site and carrying out the laboratory test. On typical forestry sites, such a method may be impractical because site variability makes it difficult to identify the "typical" condition that will best represent conditions throughout the site. A better approach would be to collect samples from each variant of the soil conditions, but this too may become unwieldy because of the large number of samples required. Generally, bulk density sampling requires high numbers of samples to account for the natural variation on forestry field sites (Courtin et al., 1983; Page-Dumroese et al., 1999). The method we propose takes advantage of the strong relationships we have observed between MBD and soil properties that are relatively easy to measure. The method involves four steps.

1. Determine the relationships between MBD and properties for soils typical of the study area. As we, and others have shown, MBD can be predicted with reasonable accuracy from a relatively small number of properties, but the best properties for prediction may be different for different groups of soils. The properties to use in the prediction of MBD can be selected by stratification of samples from a larger data set, as we have described. We stratified our sample set based on plasticity, but other approaches could be applicable in a particular study.
2. Collect bulk density samples from the field sites.
3. Carry out laboratory analyses on the bulk density samples to provide data to be used in multiple regression analysis as we have described here. The analysis will produce a "predicted MBD" for each soil sample that will account for the fine-scale variation in soil properties typical of forestry sites. It may be possible to carry out the analysis for different variables than we have described, depending on the needs of the study and the resources available. For example, in the nonplastic soils of our study, the use of total C and Al oxide explained a large amount of variation in MBD (R^2 = 0.88), although not as much as the liquid limit and Al oxide (R^2 = 0.96).
4. Develop empirical relationships between field bulk density, MBD, and tree growth. We are conducting further investigations to test the applicability of relative measure of bulk density (i.e., field bulk density/MBD) for compaction studies on forest soils in British Columbia that have been described previously (Carter, 1990; da Silva and Kay, 1997).

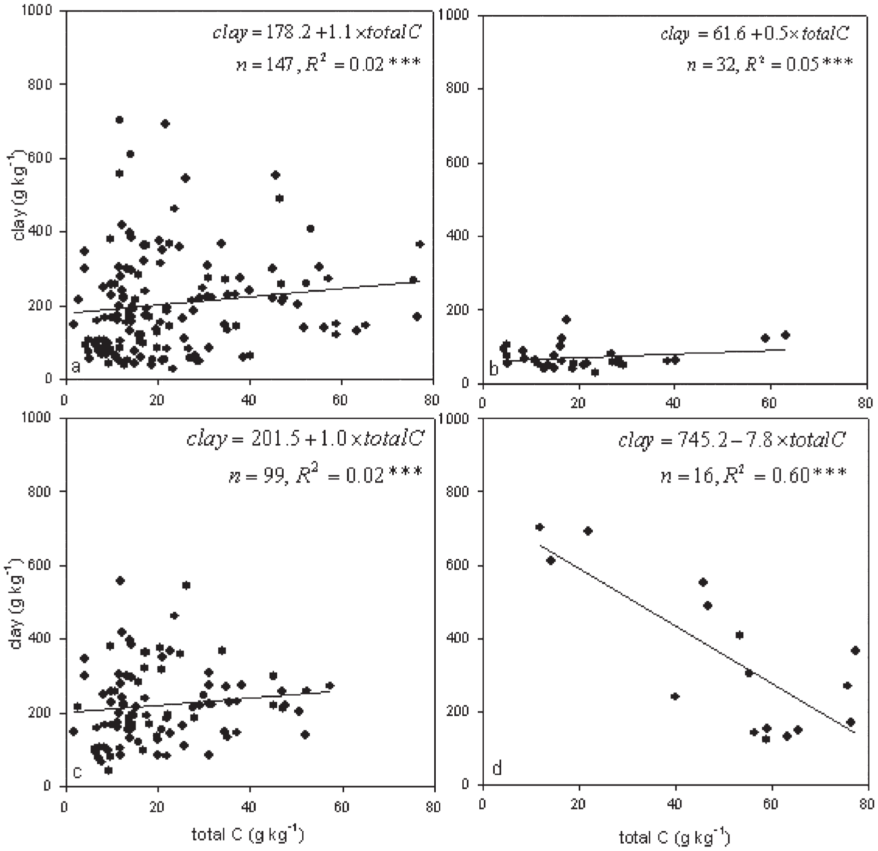

Fig. 5. Relationships between clay and total C for (a) all samples, (b) nonplastic samples, (c) moderate and low plastic samples, and (d) highly plastic samples. ***Significant at $P < 0.001$.

CONCLUSIONS

The significance levels of single soil properties in predicting MBD were in the order of liquid and plastic limits, organic matter, and oxalate-extractable oxides, while particle size distribution alone accounted for very little variation. In the multiple regression analysis for the entire sample set, liquid limit and clay were related to MBD. Inclusion of organic matter, Al oxides, and other components of the particle size distribution (e.g., very coarse sand) further improved the prediction of MBD. Stratification of the sample set by plasticity allowed substantially improved prediction of MBD using multiple regression analysis. The best predictions were obtained for nonplastic soils, while multiple regression explained the least amount of variation for highly plastic samples. Porosity at MBD may be useful for studies relating plant growth to soil physical condition. On the other hand, use of MBD may be preferred over f_{MBD} for evaluating soil conditions where a reference value for soil bulk density is required.

Currently, only bulk density is used widely as a parameter to assess the compaction state of a soil. We have described a method to predict MBD from readily measured soil properties that could enable more effective means of providing reference values for compaction studies. This would be particularly beneficial where these attributes exhibit high point-to-point variation, such as in British Columbia's forest soils. Prediction would involve first determining the plasticity for a soil sample, then using the appropriate equation to determine MBD.

ACKNOWLEDGMENTS

This work was supported by the Natural Sciences and Engineering Research Council (NSERC) of Canada and the Forest Investment Account—Forest Science Program. Technical assistance of Mike Curran, Bob Maxwell, Lesley Dampier, Francois Teste, Shakedur Rahman, Chris Blurton, Korey Green, Sara Harrison, Matthew Plotnikoff, Allison Tremain, Rick Trowbridge, and Will Arnup in the laboratory and with sample collection is greatly appreciated. We also acknowledge the helpful suggestions from Dr. Les Lavkulich during preparation of this manuscript.

REFERENCES

Aragon, A., M.G. Garcia, R.R. Filgueira, and Ya.A. Pachepsky. 2000. Maximum compactibility of Argentina soils from the Proctor test: The relationship with organic matter and water content. Soil Tillage Res. 56:197–204.

ASTM. 2000. Design D698–00a. Standard test methods for laboratory compaction characteristics of soil using standard effort (12,400 ft-lb/ft^3 (600 kN-m/m^3)). ASTM, West Conshohocken, PA.

Ball, B.C., D.J. Campbell, and E.A. Hunter. 2000. Soil compactibility in relation to physical and organic properties at 156 sites in UK. Soil Tillage Res. 57:83–91.

Ball, B.C., R.W. Lang, M.F. O'Sullivan, and M.F. Franklin. 1989. Cultivation and nitrogen requirements for continuous winter barley on a Gleysol and a Cambisol. Soil Tillage Res. 13:333–352.

Carter, M.R. 1990. Relative measures of soil bulk density to characterize compaction in tillage studies on fine sandy loams. Can. J. Soil Sci. 70:425–433.

Courtin, P., M.C. Feller, and K. Klinka. 1983. Lateral variability in some properties of disturbed forest soils in southwestern British Columbia. Can. J. Soil Sci. 63:529–539.

da Silva, A.P., and B.D. Kay. 1997. Estimating the least limiting water range of soils from properties and management. Soil Sci. Soc. Am. J. 61:877–883.

da Silva, A.P., B.D. Kay, and E. Perfect. 1994. Characterization of the least limiting water range of soils. Soil Sci. Soc. Am. J. 58:1775–1781.

Day, P.R. 1965. Particle fractionation and particle size analysis. p. 545–567. *In* C.A. Black (ed.) Methods of soil analysis. Part 1. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Donkin, M.J. 1991. Loss-on-ignition as an estimator of soil organic carbon in A-horizon forestry soils. Commun. Soil Sci. Plant Anal. 22:233–241.

Dorel, M., J. Roger-Estrade, H. Manichon, and B. Delvaux. 2000. Porosity and soil water properties of Caribbean volcanic ash soils. Soil Use Manage. 16:133–140.

FAO. 1998. World reference base for soil resources. World Soil Resour. Rep. 84. FAO, Rome.

Flint, A.L., and L.E. Flint. 2002. Particle density. p. 229–240. *In* J.H. Dane and G.C. Topp (ed.) Methods of soil analysis. Part 4. SSSA Book Ser. 5. SSSA, Madison, WI.

Froehlich, H.A., D.W.R. Miles, and R.W. Robbins. 1985. Soil bulk-density recovery on compacted skid trails in central Idaho. Soil Sci. Soc. Am. J. 49:1015–1017.

Gee, G., and D. Or. 2002. Particle-size analysis. p. 255–293. *In* J.H. Dane and G.C. Topp (ed.) Methods of soil analysis. Part 4. Physical methods. SSSA Book Ser. 5. SSSA, Madison, WI.

Greacen, E.L., and R. Sands. 1980. Compaction of forest soils: A review. Aust. J. Soil Res. 18:163–189.

Hakansson, I., and J. Lipiec. 2000. A review of the usefulness of relative bulk density values in studies of soil structure and compaction. Soil Tillage Res. 53:71–85.

Hammel, J.E., M.E. Sumner, and J. Burema. 1983. Atterberg limits as indices of external surface areas of soil. Soil Sci. Soc. Am. J. 47:1054–1056.

Howard, R.F., M.J. Singer, and G.A. Frantz. 1981. Effects of soil properties, water content, and compactive effort on the compaction of selected California forest and range soils. Soil Sci. Soc. Am. J. 45:231–236.

Joosse, P.J., and R.A. McBride. 2003. Assessing physical quality of plastic soils of differing mineralogy and pre-stress history using mechanical parameters: I. Saturated compression tests. Can. J. Soil Sci. 83:45–63.

Krzic, M., C.E. Bulmer, F. Teste, L. Dampier, and S. Rahman. 2004. Soil properties influencing compactability of forest soils in British Columbia. Can. J. Soil Sci. 84:219–226.

Larson, W.E., S.C. Gupta, and R.A. Useche. 1980. Compression of agricultural soils from eight soil orders. Soil Sci. Soc. Am. J. 44:450–457.

Lipiec, J., I. Hakansson, S. Tarkiewicz, and J. Kossowski. 1991. Soil physical properties and growth of spring barley as related to the degree of compactness of two soils. Soil Tillage Res. 19:307–317.

Lipiec, J., and R. Hatano. 2003. Quantification of compaction effects on soil physical properties and crop growth. Geoderma 116:107–136.

Loeppert, R.L., and W.P. Inskeep. 1996. Iron. p. 639–664. *In* D.L. Sparks et al. (ed.) Methods of soil analysis. Part 3. SSSA Book Ser. 5. SSSA, Madison, WI.

McBride, R.A. 2002. Atterberg limits. p. 519–527. *In* J.H. Dane and G.C. Topp (ed.) Methods of soil analysis. Part 4. SSSA Book Ser. 5. SSSA, Madison, WI.

McKeague, J.A., and P.N. Sprout. 1975. Cemented subsoils (duric horizons) in some soils of British Columbia. Can. J. Soil Sci. 55:189–203.

Meidinger, D.V., and J. Pojar. 1991. Ecosystems of British Columbia. Spec. Rep. Ser. 6. British Columbia Ministry of Forests, Victoria.

Miller, R.E., W. Scott, and J.W. Hazard. 1996. Soil compaction and conifer growth after tractor yarding at three coastal Washington locations. Can. J. For. Res. 26:225–236.

Moolman, J.H. 1981. Soil textural properties influencing compactibility. Agrochemophysica 13:13–19.

Nelson, D.S., and L.E. Sommers. 1996. Total carbon, organic carbon, and organic matter. p. 961–1010. *In* D.L. Sparks et al. (ed.) Methods of soil analysis. Part 3. SSSA Book Ser. 5. SSSA, Madison, WI.

Nhantumbo, A.B.J.C., and A.H. Cambule. 2006. Bulk density test as a function of texture for agricultural soils in Maputo province of Mozambique. Soil Tillage Res. 87:231–239.

Oades, J.M., and W.N. Townsend. 1963. The influence of iron on the stability of soil organic matter during peroxidation. J. Soil Sci. 14:134–143.

Padmanabhan, E., and A.R. Mermut. 1995. The problem of expressing the specific surface areas of clay fractions. Clays Clay Miner. 43:237–245.

Page-Dumroese, D.S., A.E. Harvey, M.F. Jurgensen, and M.P. Amaranthus. 1998. Impacts of soil compaction and tree stump removal on soil properties and outplanted seedlings in northern Idaho, USA. Can. J. Soil Sci. 78:29–34.

Page-Dumroese, D.S., M.F. Jurgensen, R.E. Brown, and G.D. Mrosz. 1999. Comparison of methods for determining bulk densities of rocky forest soils. Soil Sci. Soc. Am. J. 63:379–383.

Powers, R.F. 2006. Long-term soil productivity: Genesis of the concept and principles behind the program. Can. J. For. Res. 36:519–528.

Proctor, R.R. 1933. Fundamental principles of soil compaction. Description of field and laboratory methods. Eng. News Rec. 111:286–289.

Redding, T.E., and K.J. Devito. 2006. Particle densities of wetland soils in northern Alberta, Canada. Can. J. Soil Sci. 86:57–60.

Ruhlmann, J., M. Korschens, and J. Graefe. 2006. A new approach to calculate the particle density of soils considering properties of the soil organic matter and the mineral matrix. Geoderma 130:272–283.

SAS Institute. 1990. SAS/STAT user's guide. Version 6. SAS Inst., Cary, NC.

Sheldrick, B.H., and C. Wang. 1993. Particle size distribution. p. 499–512. *In* M.R. Carter (ed.) Soil sampling and methods of analysis. Lewis Publ., Boca Raton, FL.

Smith, C.W., M.A. Johnston, and S. Lorentz. 1997. Assessing the compaction susceptibility of South African forestry soils: II. Soil properties affecting compactibility and compressibility. Soil Tillage Res. 43:335–354.

Soane, B.D. 1990. The role of organic matter in soil compactibility: A review of some practical aspects. Soil Tillage Res. 16:179–201.

Soane, B.D., D.J. Campbell, and S.M. Herkes. 1972. The characterization of some Scottish arable topsoils by agricultural and engineering methods. J. Soil Sci. 23:93–104.

Soil Classification Working Group. 1998. The Canadian system of soil classification. 3rd ed. Agric. and Agri-Food Can. Publ. 1646. Natl. Res. Counc. of Canada, Ottawa, ON.

Soil Survey Staff. 2006. Keys to Soil Taxonomy. 10th ed. NRCS, Washington, DC.

Topp, G.C., W.D. Reynolds, F.J. Cook, J.M. Cook, and M.R. Carter. 1997. Physical attributes of soil quality. p. 21–58. *In* E.G. Gregorich and M.R. Carter (ed.) Soil quality for crop production and ecosystem health. Elsevier, Amsterdam.

Webster, R., and M.A. Oliver. 1990. Statistical methods in soil and land resources survey. Oxford Univ. Press, Oxford, UK.

Wert, S., and B.R. Thomas. 1981. Effects of skid roads on diameter, height, and volume growth in Douglas-fir. Soil Sci. Soc. Am. J. 45:629–632.

Yee, C.S., and R.D. Harr. 1977. Effect of wetting mode on shear strength of two aggregated soils in the Oregon coast ranges. USDA For. Serv. Res. Note PNW-303. Pac. Northw. For. Range Exp. Stn., Portland, OR.

Zhang, H., K.H. Hartge, and H. Ringe. 1997. Effectiveness of organic matter incorporation in reducing soil compactibility. Soil Sci. Soc. Am. J. 61:239–245.

Zou, C., C. Penfold, R. Sands, R.K. Misra, and I. Hudson. 2001. Effects of air-filled porosity, soil matric potential and soil strength on primary root growth of radiate pine seedlings. Plant Soil 236:105–115.