# Soil physical property changes at the North American Long-Term Soil Productivity study sites: 1 and 5 years after compaction[1]

**Deborah S. Page-Dumroese, Martin F. Jurgensen, Allan E. Tiarks, Felix Ponder, Jr., Felipe G. Sanchez, Robert L. Fleming, J. Marty Kranabetter, Robert F. Powers, Douglas M. Stone, John D. Elioff, and D. Andrew Scott**

**Abstract:** The impact of forest management operations on soil physical properties is important to understand, since management can significantly change site productivity by altering root growth potential, water infiltration and soil erosion, and water and nutrient availability. We studied soil bulk density and strength changes as indicators of soil compaction before harvesting and 1 and 5 years after harvest and site treatment on 12 of the North American Long-Term Soil Productivity sites. Severe soil compaction treatments approached root-limiting bulk densities for each soil texture, while moderate compaction levels were between severe and preharvest values. Immediately after harvesting, soil bulk density on the severely compacted plots ranged from 1% less than to 58% higher than preharvest levels across all sites. Soil compaction increases were noticeable to a depth of 30 cm. After 5 years, bulk density recovery on coarse-textured soils was evident in the surface (0–10 cm) soil, but recovery was less in the subsoil (10–30 cm depth); fine-textured soils exhibited little recovery. When measured as a percentage, initial bulk density increases were greater on fine-textured soils than on coarser-textured soils and were mainly due to higher initial bulk density values in coarse-textured soils. Development of soil monitoring methods applicable to all soil types may not be appropriate, and more site-specific techniques may be needed for soil monitoring after disturbance.

**Résumé :** Il est important de comprendre l'impact des interventions dictées par l'aménagement forestier sur les propriétés physiques du sol étant donné qu'elles peuvent modifier de façon significative la productivité d'une station en altérant le potentiel de croissance des racines, l'infiltration d'eau, l'érosion du sol et la disponibilité de l'eau et des nutriments. Les auteurs ont étudié les changements dans la résistance et la densité apparente du sol en tant qu'indicateurs de la compaction du sol avant la récolte ainsi qu'un et 5 ans après la récolte et la préparation du terrain dans 12 stations du projet nord-américain de productivité des sols à long terme. Les traitements de compaction sévère du sol s'approchaient de la densité apparente inappropriée pour les racines pour chaque texture de sol alors que les degrés modérés de compaction du sol se situaient entre des valeurs allant de sévères à celles obtenues avant la récolte. Immédiatement après la récolte dans les parcelles où la compaction du sol était sévère, la densité apparente du sol variait de 1 % moins élevée à 58 % plus élevée qu'avant la récolte pour l'ensemble des sites. L'augmentation de la compaction du sol était observable jusqu'à une profondeur de 30 cm. Après 5 ans, le rétablissement de la densité apparente dans les sols à texture grossière était évident en surface (0–10 cm) mais pas aussi évident en profondeur (10–30 cm); presque aucun rétablissement n'était apparent dans les sols à texture fine. Mesurée en pourcentage, l'augmentation de la densité apparente initiale était plus forte dans les sols à texture fine comparativement aux sols à texture grossière

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**D.S. Page-Dumroese.**[2] USDA Forest Service, Rocky Mountain Research Station, 1221 South Main Street, Moscow, ID 83843, USA.
**M.F. Jurgensen.** School of Forest Resources and Environmental Sciences, Michigan Technological University, Houghton, MI 49931, USA.
**A.E. Tiarks**[3] **and D.A. Scott.** USDA Forest Service, Southern Research Station, 2500 Shreveport Highway, Pineville, LA 71360, USA.
**F. Ponder, Jr.** USDA Forest Service, North Central Research Station, 208 Foster Hall, Lincoln University, Jefferson City, MO 65102, USA.
**F.G. Sanchez.** USDA Forest Service, Southern Research Station, P.O. Box 12254, Research Triangle Park, NC 27709, USA.
**R.L. Fleming.** Canadian Forest Service, Great Lakes Forestry Centre, 1219 Queen Street East, Sault Ste. Marie, ON P6A 2E5, Canada.
**J.M. Kranabetter.** British Columbia Ministry of Forests, Bag 6000, Smithers, BC V0J 2N0, Canada.
**R.F. Powers.** USDA Forest Service, Pacific Southwest Research Station, 3644 Avtech Parkway, Redding, CA 96002, USA.
**J.D. Elioff and D.M. Stone.** USDA Forest Service, North Central Research Station, 1831 Highway E. 169 E., Grand Rapids, MN 55744, USA.

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[2]Corresponding author (e-mail: ddumroese@fs.fed.us).
[3]Retired.

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surtout à cause d'une densité apparente initiale plus élevée dans les sols à texture grossière. La mise au point de méthodes de suivi des sols applicables à tous les types de sol pourrait ne pas être appropriée et des techniques mieux adaptées à chaque site pourraient être nécessaires pour le suivi du sol après une perturbation.

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## Introduction

Increased forest management and concern over changes in soil productivity are among the topics debated by forest managers and the public. A key element in this debate is the use of mechanized equipment to extract timber products and the subsequent soil compaction and recovery times (Greacen and Sands 1980; Cullen et al. 1991; Froehlich and McNabb 1984; Jansson and Johansson 1998; Landsberg et al. 2003; Miller et al. 2004). A potential consequence of severe soil compaction is the significant loss of site productivity (Powers 1991; Morris and Miller 1994). Where soil compaction occurs, total porosity decreases and soil strength and volumetric water content increase, resulting in increased water runoff and soil erosion, less rooting volume, and poor aeration (Greacen and Sands 1980; Elliot et al. 1998; Williamson and Neilsen 2000). Ultimately, the degree of compaction caused by harvesting or site preparation is affected by soil properties (e.g., texture, organic matter, and water content) at the time of disturbance (Bock and VanRees 2002).

Changes in soil water content from compaction affect temperature flux; which results in altered microclimatic conditions (Fleming et al. 1998), leading to reduced root growth and stand productivity (Greacen and Sands 1980; Gerard et al. 1982). Direct correlations of compaction impacts on forest plant growth are frequently unclear because compaction is often associated with other detrimental disturbances, such as soil displacement, mixing, and rutting. In addition, plant growth on compacted areas (skid trails, landings etc.) has sometimes been found to be greater than on nonimpacted soil because of reduced weed competition (Miller et al. 1989; Miller and Anderson 2002).

Various studies have shown that once compacted, forest soils often recover slowly (many decades) to undisturbed levels of bulk density or soil strength (Sands et al. 1979; Froehlich et al. 1985; Tiarks and Haywood 1996). Recovery rates are dependent on many factors, but chief among them are number of repeated harvest cycles, soil moisture conditions during harvest, soil texture, and rock-fragment content (Miller et al. 1996; Williamson and Neilsen 2000; Liechty et al. 2002). The extent of compaction, initial bulk density, depth of impact, and subsequent soil recovery are all factors that determine the consequences of timber harvesting or site preparation on productivity. In addition, duration and variability of compaction can be significant from site to site or at depth in the soil profile (Beckett and Webster 1971; Blythe and Macleod 1978; Courtin et al. 1983). For instance, variability within soil textural groups, forest stands, or on skid trails can be as great as or greater than the variability between them (Courtin et al. 1983).

Few studies have assessed the long-term effects of compaction on soil productivity or forest sustainability on large, relatively uniform study plots. However, many studies have assessed the effects of harvesting operations or skid trail construction on changes in soil compaction level (Table 1). Often data are not collected over a long time period, are confounded by other site disturbances, do not directly assess compaction impacts on subsequent vegetation growth, or do not have a base-line comparison. The impetus for initiating the North American Long-Term Soil Productivity (LTSP) study was to test the linkage between soil impacts and tree growth (Powers et al. 1990; Fleming et al. 2006; Powers 2006). In this paper we evaluate (1) the effectiveness and variability of compaction treatments on the LTSP sites across a variety of soil textural classes and (2) the recovery of soil bulk density and soil strength 1 and 5 years after harvesting and site preparation.

## Materials and methods

The North American LTSP study sites were established to conform to the National Study Plan described by Powers (2006). A series of plots (0.4 ha in size) with common treatment protocols were installed in major timber types and on different soil groups throughout the United States and Canada (Table 2). All data used in this paper came from 12 LTSP sites that were at least 5 years old. Additional descriptions of each installation can be found in Powers (2006) and Fleming et al. (2006). Main soil treatments (3 × 3 factorial design) were three levels of organic matter removal (bole-only removal, whole-tree removal, and whole-tree plus forest-floor removal) and three levels of compaction applied to the soil surface (none, moderate, and severe). At most study locations, main treatments were split in half to provide a weed versus no-weed (herbicide) comparison. All study sites had three replications of each treatment.

The aspen stands at the Huron-Manistee, Ottawa, and Chippewa sites were winter logged to protect suckering roots. Other sites were harvested during the summer, but all plots receiving the no-compaction treatment were not driven on during either harvesting or site preparation. The desired compaction level was achieved by driving over plots with heavy equipment (e.g., bulldozer, grappler, asphalt roller) or compressing with high ground pressure equipment. Logging debris and forest-floor material were removed before compaction so that mineral and organic components would not be mixed. At each of the 12 sites, compaction was deliberately scheduled when the soil was near field capacity to ensure maximum macropore reduction. Severe compaction was intended to approach, but not meet, growth-limiting bulk densities or soil strength for each particular soil texture (Daddow and Warrington 1983), and we attempted to reach bulk density levels within 20% of the approximate growth-limiting bulk density in the surface 0–10 cm of soil. Moderate compaction levels were designed to come close to the midpoint between no and severe compaction. After mineral soil compaction was complete, forest floor and slash were

**Table 1.** Average change in surface (0–15 cm) bulk density immediately after harvest operations for various small-scale skid-trail studies.

| Soil texture | Bulk density Initial ($Mg \cdot m^{-3}$) | Final ($Mg \cdot m^{-3}$) | Increase (%) | Reference |
|---|---|---|---|---|
| Sand | 1.35 | 1.60 | 16 | Sands and Bowen 1978 |
| Volcanic ash over limestone till | 0.53 | 0.93 | 41 | Cullen et al. 1991 |
| Volcanic ash over quartzite till | 0.76 | 0.92 | 18 | Cullen et al. 1991 |
| Tertiary volcanic ash | 1.67 | 1.81 | 8 | Cullen et al. 1991 |
| Silt loam over glacial till | 0.95 | 1.4 | 33 | Jansson and Johansson 1998 |
| Sandy loam | 0.92 | 1.15 | 20 | Allbrook 1986 |
| Loam | 0.72 | 0.96 | 25 | Aust et al. 1993 |
| Loamy volcanic ash | 0.93 | 1.07 | 15 | Froehlich et al. 1986 |
| Volcanic ash | 0.84 | 1.08 | 28 | Froehlich et al. 1986 |
| Silty clay | 1.19 | 1.32 | 11 | Corns 1988 |
| Clay over till | 1.05 | 1.29 | 20 | Corns 1988 |
| Loam (eolian) | 0.67 | 0.70 | 12 | Corns 1988 |

**Table 2.** Sample size, site characteristics, and soil properties for 5-year-old Long-Term Soil Productivity installations.

| Textural class | Installation name* | $n^{\dagger}$ | Clay content (%) | Rock-fragment content (%) | Preharvest bulk density ($Mg \cdot m^{-3}$) |
|---|---|---|---|---|---|
| Sand | Huron-Manistee | 8 | 2 | 1 | 0.96 |
| Loamy sand | Nemagos Lake | 10 | 3 | 11 | 1.1 |
| Sandy loam | Goldsboro | 4 | 12 | 0 | 1.33 |
| Sandy loam | Rogers | 5 | 15 | 22 | 0.91 |
| Skeletal-loam | Topley | 9 | 15 | 35 | 1.45 |
| Fine sandy loam | Malbis | 10 | 12 | 0 | 1.36 |
| Very fine sandy loam | Chippewa | 8 | 10 | 1 | 1.02 |
| Silt loam | Freest (1–3) | 10 | 6 | 0 | 1.32 |
| Silt loam (volcanic) | Council | 16 | 17 | 3 | 0.67 |
| Cherty silt loam | Carr Creek | 4 | 26 | 44 | 1.48 |
| Clay loam | Challenge | 5 | 21 | 30 | 0.94 |
| Clay | Ottawa | 8 | 60 | 0 | 1.03 |

**Note:** Texture, clay content, rock-fragment content, and average preharvest bulk density are from the surface (0–10 cm). British Columbia soil depth is 0–20 cm.

*For more information on each installation, see Powers et al. (2006).

†Sample size for each plot and depth interval.

returned, as needed, to achieve each plot treatment combination. Methods of compaction, measurement of compaction, and organic matter removal varied for each LTSP installation; however, main and split-plot treatments were consistently maintained. Each plot was regenerated with tree species indicative of surrounding native forest types.

Pre-and post-harvest (at 1 and 5 years) collection of soil strength and bulk density were conducted in a manner that conformed to established published protocols (i.e., Blake and Hartge 1986; Muller and Hamilton 1992; Lichter and Costello 1994; Page-Dumroese et al. 1999), but were necessarily different at each installation because of differences in rock-fragment amounts and size, sampling equipment, or timing (Table 2). Bulk density samples were collected from the 0–10, 10–20, and 20–30 cm depths on the Malbis, Freest (all three sites from Powers (2006)), Missouri, Goldsboro, Council, Ottawa, Huron-Manistee, and Chippewa sites; at 0–10 and 10–20 cm depths on the Nemagos Lake site; and at 0–20 cm depth on the Topley site. Soil strength was measured at Council and Freest using a recording penetrometer at 1.5 cm increments adjacent to the bulk density sampling sites. Three penetrometer measurements (replicates) at each sampling point were taken to a depth of 60 cm. Soil strength measurements were taken at approximately the same time each year to minimize seasonal soil moisture differences. Rock-fragment content was measured by either field estimates or gravimetric laboratory mass. Total bulk density was corrected for rock-fragment content as necessary (Andraski 1991; Page-Dumroese et al. 1999). Soil texture was determined using established published protocols (i.e., Gee and Bauder 1986). Several study sites had clay content >20%, but none of the sites had an appreciable component of shrink–swell clays. At the Council and Challenge sites, pore volume was estimated using undisturbed cores and a pressure chamber (Lenhard and Bloomsburg 1979). At the Topley, Missouri, and Council sites, average fifth-year soil moisture and temperature were recorded on two subplots (no herbicide applied) at the 10 cm soil depth using moisture and temperature wafers (ELE International/SoilTest, Inc., Loveland, Colorado) and an analog output sensor.

On four sites (Malbis, Freest, Goldsboro, and Council), we estimated the number of samples necessary to be within

**Table 3.** Average bulk density and change from undisturbed values for select Long-Term Soil Productivity installations (installation name followed by textural class in parentheses).

| | | 1 year after site treatment | | 5 years after site treatment | |
|---|---|---|---|---|---|
| Depth (cm) | Compaction level | Avg. bulk density ($Mg \cdot m^{-3}$)* | Change from preharvest (%)† | Avg. bulk density ($Mg \cdot m^{-3}$)* | Change from preharvest (%)† |
| **Huron-Manistee (sand)** | | | | | |
| 0–10 | None | 1.12 (11)a | 14 | 1.03 (22)a | 6 |
| | Moderate | 1.28 (8)b | 24 | 1.16 (18)b | 17 |
| | Severe | 1.34 (8)c | 28 | 1.20 (8)b | 19 |
| | *p* value | <0.001 | | <0.0001 | |
| 10–20 | None | 1.31 (8)a | 10 | 1.28 (7)a | 8 |
| | Moderate | 1.41 (7)b | 16 | 1.38 (6)b | 14 |
| | Severe | 1.45 (8)c | 18 | 1.43 (7)c | 17 |
| | *p* value | <0.0001 | | <0.0001 | |
| 20–30 | None | 1.39 (10)a | 5 | 1.37 (7)a | 3 |
| | Moderate | 1.46 (7)b | 9 | 1.44 (11)b | 8 |
| | Severe | 1.51 (6)c | 12 | 1.49 (9)c | 11 |
| | *p* value | <0.001 | | <0.001 | |
| **Nemagos Lake (loamy sand)** | | | | | |
| 0–10 | None | 1.04 (10)a | –3 | 1.00 (15)a | –9 |
| | Severe | 1.25 (11)b | 15 | 1.06 (15)a | –3 |
| | *p* value | <0.0001 | | 0.7132 | |
| 10–20 | None | 1.14 (13)a | 4 | 1.17 (14) a | 7 |
| | Severe | 1.44 (9)b | 19 | 1.27 (12)b | 2 |
| | *p* value | <0.0001 | | <0.0001 | |
| **Goldsboro (sandy loam)** | | | | | |
| 0–10 | None | 1.22 (16)a | 9 | 1.13 (22)a | 14 |
| | Moderate | 1.46 (13)b | 40 | 1.25 (23)a | 24 |
| | Severe | 1.45 (13)b | 23 | 1.17 (20)a | 13 |
| | *p* value | 0.0462 | | 0.9637 | |
| 10–20 | None | 1.41 (12)a | 23 | 1.44 (21)a | 7 |
| | Moderate | 1.54 (10)b | 28 | 1.48 (18)a | 11 |
| | Severe | 1.52 (10)b | 27 | 1.41 (21)a | 9 |
| | *p* value | 0.0195 | | 0.6799 | |
| 20–30 | None | 1.47 (11)a | 24 | 1.45 (20)a | 8 |
| | Moderate | 1.60 (11)b | 30 | 1.41 (19)a | 11 |
| | Severe | 1.57 (16)b | 29 | 1.31 (25)a | –18 |
| | *p* value | 0.0305 | | 0.7013 | |
| **Topley (skeletal-loam)** | | | | | |
| 0–20 | None | 1.56 (18)a | 8 | 1.66 (15)a | 14 |
| | Moderate | 1.74 (18)b | 14 | 1.79 (16)b | 16 |
| | Severe | 1.75 (18)b | 17 | 1.74 (13)b | 16 |
| | *p* value | <0.0001 | | 0.0016 | |
| **Malbis (fine sandy loam)** | | | | | |
| 0–10 | None | 1.26 (7)a | –6 | 1.22 (10)a | –5 |
| | Moderate | 1.33 (12)b | –1 | 1.27 (11)b | –4 |
| | Severe | 1.35 (15)b | –1 | 1.28 (9)b | –5 |
| | *p* value | <0.0001 | | <0.0001 | |
| 10–20 | None | 1.43 (6)a | 0 | 1.34 (11)a | –7 |
| | Moderate | 1.50 (9)b | 6 | 1.45 (10)b | 3 |
| | Severe | 1.51 (8)b | 5 | 1.45 (11)b | 1 |
| | *p* value | <0.0001 | | <0.0001 | |
| 20–30 | None | 1.49 (6)a | 3 | 1.39 (10)a | –3 |
| | Moderate | 1.51 (7)b | 6 | 1.46 (8)b | –1 |
| | Severe | 1.51 (7)b | 3 | 1.43 (10)c | –3 |
| | *p* value | 0.0584 | | <0.0001 | |
| **Chippewa (very fine sandy loam)** | | | | | |
| 0–10 | None | 1.17 (14)a | 14 | 1.14 (15)a | 12 |
| | Moderate | 1.34 (10)b | 25 | 1.21 (14)b | 17 |
| | Severe | 1.39 (10)c | 28 | 1.24 (12)b | 19 |
| | *p* value | <0.0001 | | 0.001 | |
| 10–20 | None | 1.45 (12)a | 12 | 1.42 (10)a | 10 |

**Table 3** (*concluded*).

| Depth (cm) | Compaction level | 1 year after site treatment: Avg. bulk density ($Mg \cdot m^{-3}$)* | 1 year after site treatment: Change from preharvest (%)† | 5 years after site treatment: Avg. bulk density ($Mg \cdot m^{-3}$)* | 5 years after site treatment: Change from preharvest (%)† |
|---|---|---|---|---|---|
| | Moderate | 1.57 (10)b | 18 | 1.45 (10)ab | 12 |
| | Severe | 1.62 (9)b | 31 | 1.49 (11)b | 14 |
| | *p* value | <0.0001 | | 0.0141 | |
| 20–30 | None | 1.56 (12)a | 10 | 1.39 (11)a | –1 |
| | Moderate | 1.63 (9)b | 14 | 1.39 (35)a | –1 |
| | Severe | 1.65 (7)b | 15 | 1.53 (37)a | 8 |
| | *p* value | 0.0050 | | 0.099 | |
| **Freest (1–3) (silt loam)** | | | | | |
| 0–10 | None | 1.31 (8)a | –3 | 1.31 (9)a | –3 |
| | Moderate | 1.41 (8)b | 7 | 1.36 (8)b | 4 |
| | Severe | 1.42 (8)b | 8 | 1.35 (10)b | 2 |
| | *p* value | <0.0001 | | 0.0050 | |
| 10–20 | None | 1.54 (7)a | 2 | 1.53 (8)a | 2 |
| | Moderate | 1.62 (5)b | 4 | 1.61 (8)b | 3 |
| | Severe | 1.60 (6)b | 3 | 1.60 (7)b | 2 |
| | *p* value | <0.0001 | | <0.0001 | |
| 20–30 | None | 1.54 (4)a | 2 | 1.60 (8)a | –4 |
| | Moderate | 1.59 (5)b | 2 | 1.52 (7)b | 0 |
| | Severe | 1.56 (6)a | 1 | 1.57 (7)a | –1 |
| | *p* value | 0.0021 | | 0.0434 | |
| **Council (silt loam; volcanic)** | | | | | |
| 0–10 | None | 0.60 (4)a | –2 | 0.61 (4)a | 0 |
| | Moderate | 0.72 (2)b | 6 | 0.70 (3)b | 3 |
| | Severe | 0.83 (3)b | 18 | 0.83 (3)b | 18 |
| | *p* value | <0.0001 | | <0.0001 | |
| 10–20 | None | 0.68 (5)a | 6 | 0.65 (5)a | 0 |
| | Moderate | 0.76 (4)ab | 8 | 0.74 (5)a | 5 |
| | Severe | 0.92 (6)b | 22 | 0.91 (6)b | 21 |
| | *p* value | 0.0543 | | <0.0001 | |
| 20–30 | None | 0.71 (4)a | 30 | 0.70 (5)a | 28 |
| | Moderate | 0.81 (5)b | 47 | 0.78 (4)a | 43 |
| | Severe | 0.95 (3)b | 58 | 0.93 (5)b | 50 |
| | *p* value | <0.0001 | | <0.0001 | |
| **Ottawa (clay)** | | | | | |
| 0–10 | None | 1.10 (11)a | 7 | 1.16 (13)a | 12 |
| | Moderate | 1.18 (12)b | 13 | 1.20 (10)a | 15 |
| | Severe | 1.27 (10)c | 19 | 1.29 (12)b | 21 |
| | *p* value | <0.0001 | | 0.0002 | |
| 10–20 | None | 1.21 (8)a | 1 | 1.29 (8)a | 7 |
| | Moderate | 1.25 (8)b | 4 | 1.34 (7)b | 11 |
| | Severe | 1.29 (8)c | 7 | 1.38 (7)b | 14 |
| | *p* value | <0.0001 | | <0.0001 | |
| 20–30 | None | 1.21 (7)a | –1 | 1.29 (18)a | 5 |
| | Moderate | 1.24 (7)b | 1 | 1.28 (10)a | 4 |
| | Severe | 1.28 (7)c | 4 | 1.37 (6)b | 11 |
| | *p* value | <0.0001 | | 0.0042 | |

**Note:** Values in parentheses are the coefficients of variation (%).
*In each column, within each location and depth, values with the same letter are not significantly different.
†Negative values as percent change from preharvest indicate a lower bulk density than was originally sampled before harvest.

15% of the mean both preharvest and 5 years after harvest and site preparation activities based on preharvest sampling. We show 0.4 ha preharvest data and 0.2 ha (split-plot) postharvest samples, since half of each plot was treated with herbicide. For each plot, the number of samples necessary to estimate the mean value and degree of confidence was determined using the following equation:

$$n = \frac{t_{n-1}^2 S_y^2}{E^2}$$

where $n$ is the number of samples necessary, $t^2_{n-1}$ is the value of the Student's $t$ distribution with $n - 1$ degrees of freedom, $S^2_y$ is the variance of the population (assumed to be the same as the sample population), and $E^2$ is the allowable error (Freese 1962).

### Statistical analyses

Data from each site were subjected to an analysis of variance (ANOVA). Mean separation was tested using Dunn's multiple comparison test. Significant differences are noted between each compaction level (none, moderate, and severe), soil depth (0–10, 10–20, and 20–30 cm), location (Malbis, Freest, etc.), and sample period (1 and 5 years after harvest). Because organic matter was removed prior to compaction then returned to each plot, 1- and 5-year bulk density results were unaffected by the organic matter removal treatments. Therefore, results from the different organic matter removal treatment plots were combined for each level of compaction.

## Results and discussion

### Compaction efficiency

Moisture content is one of the most important factors influencing the compactiblity of soils (Soane 1990); hence all study sites were compacted when soil moisture was near field capacity. For all sites after 1 year, moderate compaction in the 10–20 cm depth resulted in an increase in bulk density ranging from 4% to 28%, while severe compaction plots at this same depth resulted in an increase in bulk density ranging from 3% to 31% (Table 3). Our ability to compact soil deeper in the soil profile (20–30 cm) was just as variable as at the 10–20 cm depth. The relatively fine-textured volcanic ash-cap soils in Idaho were extremely susceptible to deep (20–30 cm depth) soil compaction (47% increase in bulk density in moderate compaction plots; 58% increase in bulk density in severe compaction plots), while one of the other fine-textured sites (Ottawa) did not exhibit such increases in bulk density at this depth.

In a field study of this magnitude, it is very difficult to establish and accurately measure soil bulk density values within narrowly defined treatment specifications across different soil types and using different equipment. This is clearly shown in the establishment of compacted plots at the Malbis site, where after 1 year bulk density values were less at the 0–10 cm depth after compaction than prior to treatment. Deeper in the soil profile (10–20 and 20–30 cm), bulk density increases of 3%–6% were measured 1 year after compaction. The measurement techniques used may not have been precise enough to differentiate the changes in bulk densities between years.

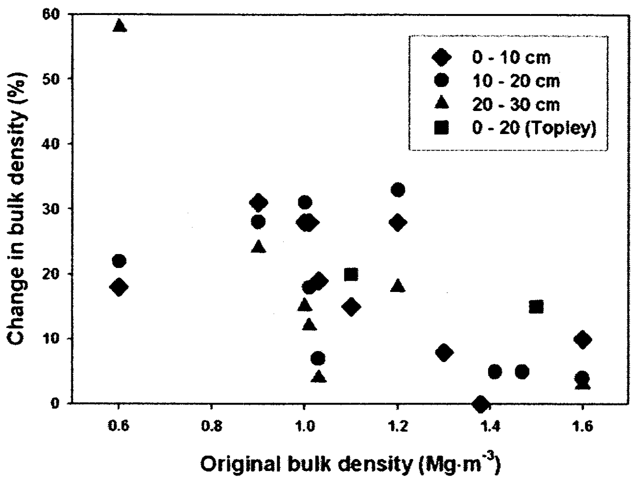
Generally, differences between the moderate and severe compaction levels were small, if detectable at all. Before harvesting, soil bulk density values in the 10–20 and 20–30 cm depths were not significantly different for most sites (Table 3). On cherty silt loam plots (Carr Creek, Missouri), surface bulk densities (0–10 cm depth) in the moderate and severe treatments were 8% (ending bulk density: 1.65 $Mg \cdot m^{-3}$) and 15% (ending bulk density: 1.78 $Mg \cdot m^{-3}$) higher than bulk density in the uncompacted control (F. Ponder, personal communication, 2005). On a clay-loam soil (Challenge), bulk density increased 18% in both the moderate and severe compaction treatments. However, on the sandy-loam Rogers site, moderate compaction plots increased 13% above preharvest conditions and the severe compaction plots increased 19%. Both the Challenge and Rogers sites had increased bulk density with increasing depth (R. Powers, personal communication, 2005). The Nemagos Lake site (with no mid level of compaction) also showed a significant increase in bulk density in the severe compaction treatment as compared to bulk density at preharvest levels. Soil organic matter in the mineral soil is important for reducing the impacts of machine traffic on soil bulk density changes (Soane 1990). Because organic matter on the LTSP sites was removed prior to compaction, we saw no significant impact of organic matter level on bulk density. However, as roots and organic material decay within the soil profile, the importance of organic matter for maintaining soil structure may become more evident.

Levels of soil compaction (as measured by bulk density) achieved with these large-scale field plots were often of a similar magnitude to those reported for a variety of skid-trail studies implemented with ground-based equipment (Table 1). This indicates that, in most cases, we were able to mimic small-scale changes on large-scale plots. As vegetation develops on these treatments, we will be able to determine how applicable skid-trail studies are to larger areas and whether recovery time is affected (see also Fleming et al. 2006).

Daddow and Warrington (1983) summarized numerous studies and delineated 1.75 $Mg \cdot m^{-3}$ as the growth-limiting bulk density for sandy loams and loamy sands. In addition, they defined 1.4 $Mg \cdot m^{-3}$ as being limiting to root growth in fine-textured soils. Lousier (1990) indicated that soil bulk densities near 1.2–1.4 $Mg \cdot m^{-3}$ were sufficient to stop root growth in most forest ecosystems. Our data indicate that bulk densities higher than these root-limiting levels already existed on the Malbis, Freest, Goldsboro, Missouri, and Topley sites. Since these sites all supported highly productive stands, setting broad rules of root-limiting bulk densities may not be feasible. However, the high initial soil densities strongly influenced the degree of compaction attained and may indicate that these sites could be susceptible to productivity losses with small increases in bulk density.

Overall, initial soil bulk density determined the degree of severe compaction (Fig. 1). As initial bulk density increased, the level of change decreased. Fine-textured soils often had the lowest initial bulk density, but the largest increase after treatment, with a majority of compaction occurring after a single equipment pass. This pattern of a larger percent increase in bulk density on fine-textured soils has been measured elsewhere (Williamson and Neilsen 2000). Percent increase in bulk density has been suggested as a method for determining change in soil productivity after trafficking; however, this may limit activities on soils with low initial bulk densities. In addition, sites with a high initial bulk density may exhibit a detrimental change in macroporosity due to subsequent trafficking that may go undetected with a percent increase standard. The percent increase criteria for soil compaction of varying soil types also may not reflect changes to biological properties or plant growth response (Williamson and Nielsen 2000). Landres et al. (1999) pro-

**Fig. 1.** Percent change in soil bulk density after severe compaction relative to initial soil bulk density.




pose a soil evaluation system based on the natural range of variation where soil properties after harvesting are compared to preharvest conditions. In this case, preharvest data would be collected to evaluate the natural range of variation for similar landscapes and then used to determine significant changes due to management (Landsberg et al. 2003). Assessment of preharvest conditions has also been recommended for evaluation of detrimental changes in soil nutrients due to displacement and burning (Page-Dumroese et al. 2000). In the USDA Forest Service, soil quality standards and guidelines set a 15% increase in bulk density for determining a detrimental disturbance (Powers et al. 1998). This guideline requires some survey of undisturbed soil conditions for a postharvest comparison. However, the British Columbia Ministry of Forests uses a postharvest visual assessment of disturbance relative to adjacent undisturbed soil as a proxy for regulating long-term effects (British Columbia Ministry of Forests 1997; Curran 1999), and along with some preharvest work determines the appropriate silvicultural prescription and possible restoration needs.

## Pore-size distribution

Compaction affects pore-size distribution and therefore available water, mainly because soil volume decreases during compression of pore space (Startsev and McNabb 2001). Changes in soil porosity were assessed at three LTSP installations (Council, Challenge, and Rogers). On the Council site after severe compaction of the silt loam volcanic ash surface soil, total porosity declined 25% in the 10–20 cm depth (data not shown). At this same depth, macropore volume declined 34%, while micropore volume remained relatively unchanged (<5%). On the Challenge and Rogers sites, severe compaction of soils with varying textures also resulted in overall decline of total porosity (9%, loam; 20%, clay; and 13%, sandy loam) throughout the soil profile (to a depth of 45 cm) (Gomez et al. 2002). On both sites, 5-year growth responses to compaction treatment were inconclusive (Gomez et al. 2002; D. Page-Dumroese, unpublished data). On the Challenge and Rogers sites, ponderosa pine (*Pinus ponderosa* Dougl. ex P. & C. Laws.) growth differences were related to soil texture, water, and air regimes, not to specific soil physical property changes (Gomez et al. 2002). Compaction-caused reductions in total porosity may result in little change in moisture retention, and therefore plant growth proceeds relatively unaffected until root growth is inhibited (Sands et al. 1979). However, soil texture is important for determining the impact of increased micropores. For example, on a soil with high clay content, 10% air-filled porosity (*v*/*v*) may be adequate for plant growth (Håkansson 1990), while on a sandy soil (with a low content of fine material) air-filled porosity may need to be near 30% for air permeability to be adequate (Håkansson and Lipiec 2000).

Soil temperature and moisture content during the growing season for three sites is shown in Figs. 2*a* and 2*b*. Although generally not statistically significant, severe compaction often resulted in a slight increase in average soil temperature at 20 cm throughout the growing season. On the Topley and Carr Creek sites, severe compaction generally resulted in increased moisture content at 20 cm regardless of organic matter treatment. However, on the Council site, severe compaction did not increase soil moisture during the growing season. Additionally, on the Council site, soil water declined slightly as more organic matter was removed from the soil surface. Compaction has been shown to have a variable effect on soil moisture content of forest soils, and a significant increase in soil bulk density may not affect soil water (Froehlich and McNabb 1984). During compaction, micropores may be unaffected and soil porosity changes could be confined to the mesopore space (Startsev and McNabb 2001), resulting in little change in soil moisture content. Changes in pore-size distribution are highly dependent on soil texture and soil water regime, and the use of soil porosity as a monitoring tool for managers will require site-specific data (Gomez et al. 2002).

## Five-year recovery

After 5 years, every site except Topley exhibited some level of bulk density recovery as compared to the 1-year postharvest measurement (Table 3). In general, for both compaction treatments (moderate and severe), the Malbis site had fully recovered to predisturbance levels (compaction levels less than or not significantly greater than preharvest levels). On the Freest sites after 5 years, plots with the greatest amount of residual compaction were the surface 0–10 cm in the moderate compaction plot (within 4% of the preharvest level). The Chippewa plots (very fine sandy loam) showed full recovery in the 20–30 cm depth 5 years after treatment, while the other two depths had an average recovery of 26% (0–10 cm depth) and 35% (10–20 cm depth). On the Council plots, which showed the greatest initial change in bulk density, there was only a slight amount of recovery in the surface soil after 5 years. Surprisingly, the clay soil (Ottawa) at the 20–30 cm depth showed an increase in bulk density after 5 years in all three compaction treatments. This increase may only be a reflection of site variability, but other factors, such as organic matter loss after the canopy was removed or raindrop impact on the exposed soil, may contribute to this increase. Fine-textured soils appear to be the slowest to recover after site treatment. In fact, the clay-loam soil (Challenge) has not recovered to preharvest

**Fig. 2.** Average fifth growing season (May–September) (*a*) temperature and (*b*) moisture at 20 cm soil depth on three soil textures as affected by compaction and organic matter level. Error bars represent the standard error of the mean.

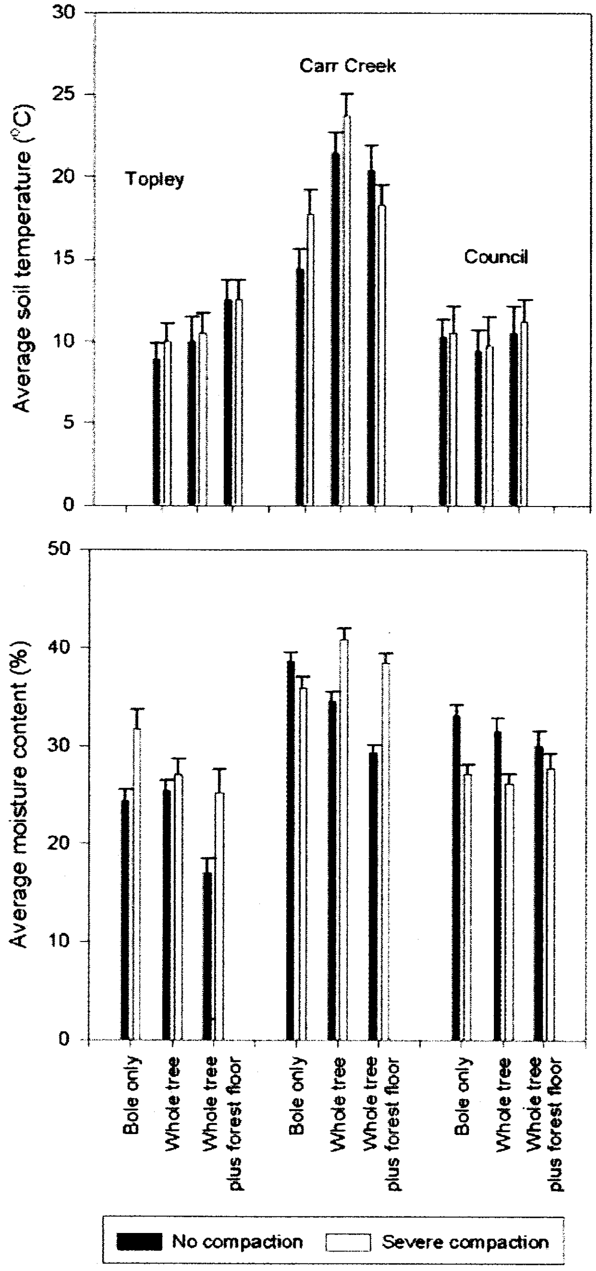
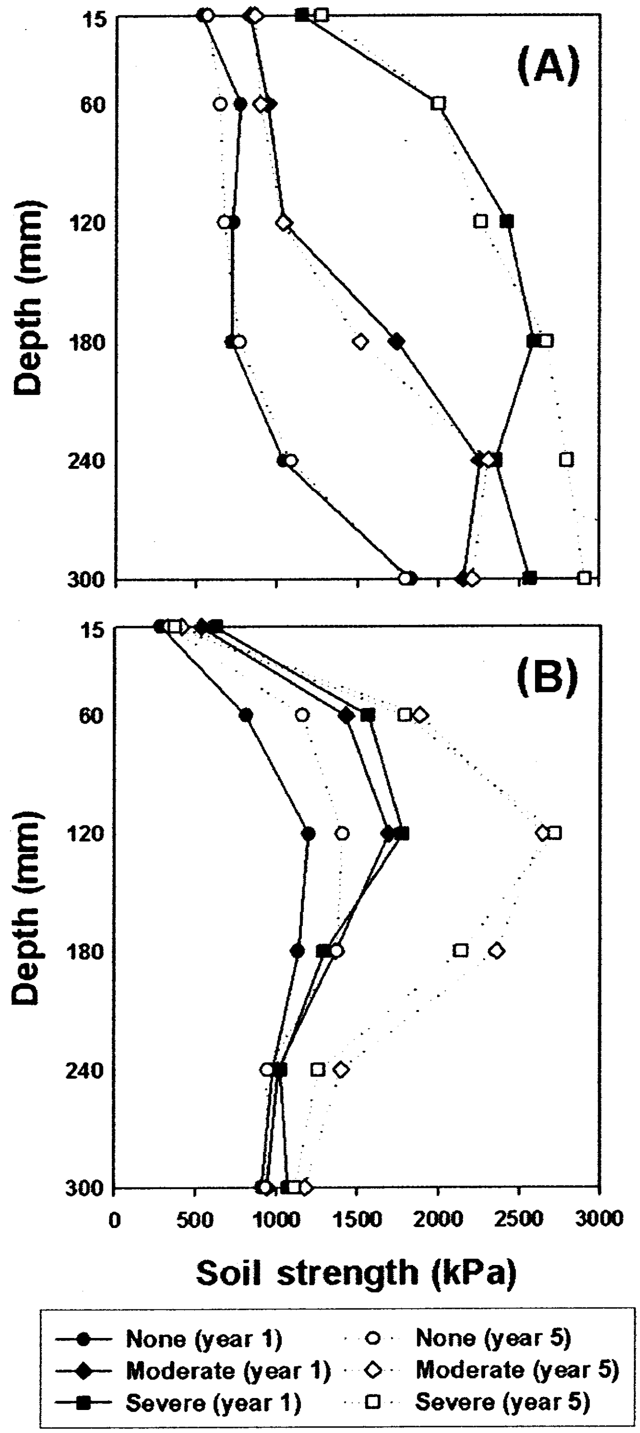



**Fig. 3.** Average soil strength in the soil profile as affected by treatment compaction level for (*a*) Council and (*b*) Freest 1–3.




conditions after 10 years (R. Powers, personal communication, 2005; data not shown).

Examination of herbicide impacts show that only plots on the Malbis and Freest sites had a significant reduction in surface (0–10 cm) bulk density with understory reestablishment (data not shown). Vegetation regrowth on the Malbis sites may have accelerated a bulk density decrease in the 0–10 cm depth of the moderate compaction plots. These plots had returned to the original preharvest bulk density after 5 years ($p = 0.0056$). On the surface (0–10 cm) of the Freest plots soil had recovered to near predisturbance levels in the herbicide-treated, severely compacted plots ($p = 0.0482$; 2% higher than preharvest). Although there was no significant herbicide effect at the other sites, the level of recovery at these study sites after 5 years was unexpected, since many authors report a return to the initial, uncompacted state is

**Table 4.** Average number of soil bulk density samples necessary in each 0.4 ha plot (preharvest) and 0.2 ha plot (postharvest) to be within 15% of the population mean (α = 0.1) for select Long-Term Soil Productivity study sites (installation name followed by textural class in parentheses).

| | | Postharvest (5 years after treatment) | | | | | |
|---|---|---|---|---|---|---|---|
| | | No compaction | | Moderate compaction | | Severe compaction | |
| Depth (cm) | Preharvest (undisturbed) | No herbicide | Herbicide | No herbicide | Herbicide | No herbicide | Herbicide |
| **Goldsboro (sandy loam)** | | | | | | | |
| 0–10 | 15 | 19 | 15 | 8 | 6 | 10 | 12 |
| 10–20 | 9 | 7 | 6 | 8 | 10 | 10 | 9 |
| 20–30 | 12 | 8 | 10 | 5 | 8 | 8 | 7 |
| **Malbis (fine sandy loam)** | | | | | | | |
| 0–10 | 9 | 6 | 3 | 31 | 10 | 7 | 5 |
| 10–20 | 11 | 6 | 6 | 16 | 7 | 13 | 6 |
| 20–30 | 14 | 3 | 4 | 8 | 13 | 11 | 4 |
| **Freest (1–3) (silt loam)** | | | | | | | |
| 0–10 | 15 | 10 | 17 | 12 | 8 | 13 | 14 |
| 10–20 | 25 | 8 | 23 | 5 | 8 | 18 | 11 |
| 20–30 | 10 | 7 | 17 | 8 | 10 | 11 | 9 |
| **Council (silt loam; volcanic)** | | | | | | | |
| 0–10 | 11 | 11 | 8 | 15 | 10 | 14 | 13 |
| 10–20 | 10 | 8 | 5 | 9 | 9 | 10 | 10 |
| 20–30 | 8 | 9 | 4 | 8 | 9 | 9 | 7 |

**Note:** Sample numbers are based on sites with three replicates. Sample sizes (*n*) are shown in Table 2.

often slow or nonexistent (Hatchell et al. 1970; Froehlich and McNabb 1984; Corns and Maynard 1998; Stone and Elioff 1998). Recovery to preharvest levels on these LTSP sites can be attributed to a host of environmental factors such as high rock-fragment content, a fluctuating water table, or freeze–thaw cycles (Fleming et al. 1998; Stone and Kabzems 2002). Slower recovery on the Idaho sites may be due to compression of the glass shards of the volcanic surface soil (Shoji et al. 1993). Although soil bulk density increases are fairly easy to quantify, the direct effects on vegetation regeneration and growth are not always immediately apparent (Miller et al. 1989; Powers and Fiddler 1997; Kozlowski 1999; Gomez et al. 2002; Miller and Anderson 2002; Landsberg et al. 2003). Sites with a high initial bulk density, but with small bulk density increases after treatment, exhibit the fastest recovery, since incremental increases are small.

### Soil strength measurements

Compacted soils resist penetration by plant roots because of either small or rigid pores that prevent roots from growing through the soil. Penetrometer values represent a measure of mechanical resistance of the soil to root penetration (Sands et al. 1979). An example of soil strength change after compaction treatment is shown in Figs. 3*a* and 3*b*. Both the Freest and Council sites show an increase in soil strength with depth and compaction intensity. Although bulk density measurements at the Freest sites indicate recovery after 5 years, soil strength measurements do not reflect this same recovery. Contrary to results on the Freest sites, on the Council plots both soil bulk density and soil strength measurements indicate little recovery after 5 years.

Reduced root penetration at high soil strength has been demonstrated in a variety of field studies, including loblolly pine (*Pinus taeda* L.) (Hatchell et al. 1970), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) (Youngberg 1959), and radiata pine (*Pinus radiata* D. Don) (Sands et al. 1979) stands. When soil strength exceeded 3000 kPa in radiata pine plantations, root growth was restricted (Sands et al. 1979). However, root-limiting soil strength, on a variety of soils (loamy fine sand, fine sandy loam, very fine sandy loam, and loam) in the United States, was found to be closer to 2500 kPa (Taylor et al. 1966). Both the Freest and Council sites approached these two assessments for root-limiting soil strength values. Since soil strength values decrease as soil water content rises, root growth may be proceeding on these sites at high water contents, but may be restricted as soils dry (Gomez et al. 2002). The impacts of increasing soil strength are mixed, and data can be found supporting tree growth reductions, increases, both increases and decreases, or no effect (Sands and Bowen 1978; Greacen and Sands 1980; Miller et al. 2004). On the sandy-loam soil (Rogers), compaction increased the number of days that water was available for plant uptake from 45 days (no compaction) to 131 days (severe compaction). However, on the clay-loam soil (Challenge), days of available water decreased with increasing compaction (Gomez et al. 2002). In the southern United States, soil strength, not bulk density, was found to be the critical impedance factor controlling root penetration into the soil profile (Taylor and Burnett 1964). In addition, clay and volumetric water content have been highly correlated with resistance to root penetration (Gerard et al. 1982). Differences in total organic matter and soil surface traffic load will also affect the degree to which soil strength changes during harvest or site preparation activities (Sands et al. 1979; Williamson and Neilsen 2000; Liechty et al. 2002).

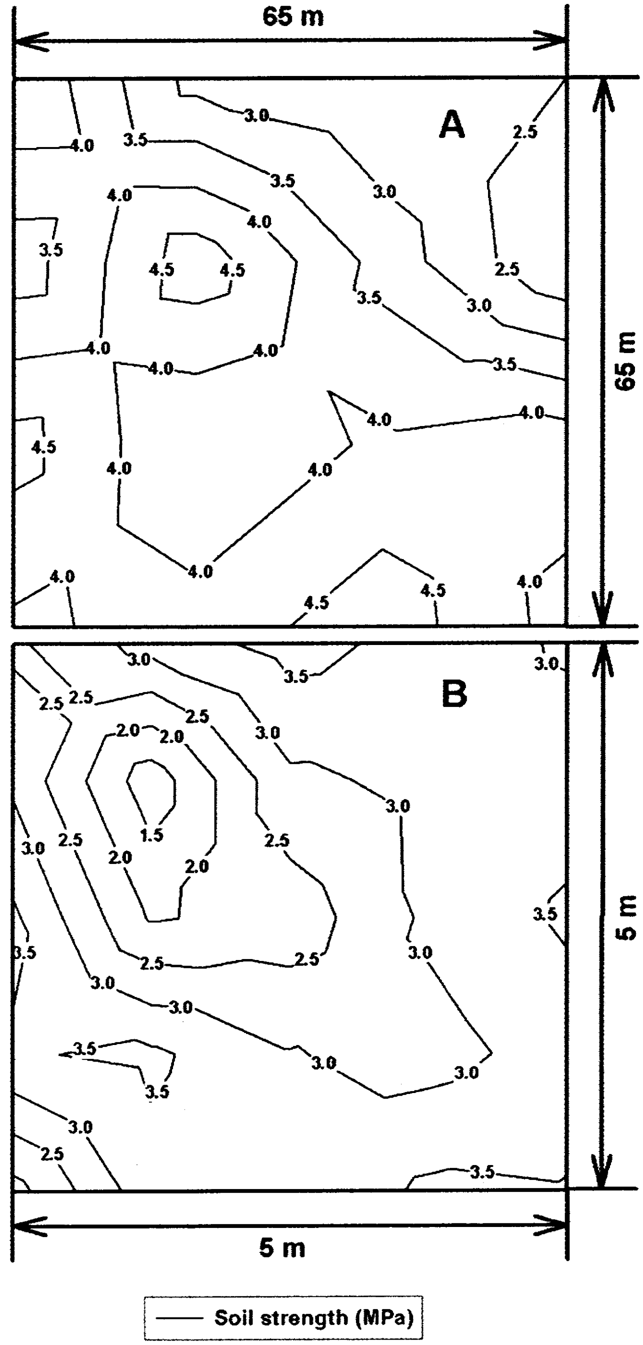
Soil strength measurements are relatively easy to collect on sites once initial instrument setup is complete (Atwell 1993) and could be a method for evaluating a site before actual soil quality monitoring is conducted. Areas can be initially defined as similar or different and a sampling system devised for a given site. This may be more time consuming, but may offer a more productive way to gather soil strength data for interpretation of short- and long-term harvest and site preparation effects. In addition, collecting a gravimetric soil moisture sample concurrently with soil strength is necessary to adjust for the possible influence of soil moisture between sample dates (Landsberg et al. 2003).

## Variability within plots

For several LTSP sites we estimated the sample size that was necessary to be within 15% of the mean 0.4 ha plot bulk density value. Estimates for 0.4 ha ranged from 8 to 25 samples before harvesting and from 3 to 23 samples postharvest (Table 4). The smaller range in sample size is similar to the samples sizes we selected (Table 2). After 5 years, the herbicide-treated plots generally required a smaller sample size than the untreated plots. This is likely due to fewer roots in the surface soil horizons, which can contribute to higher variability. In addition, we calculated the number of sample points necessary to be within 15% of the mean for soil strength on the Freest and Council 0.4 ha plots. Optimum sample size on the Freest plots was calculated to be approximately 38 sample points and for Council it was 20 sample points in each 0.2 ha plot (data not shown). Usually, selection of sample size for each site was dictated by field crew availability, time constraints, and budgets.

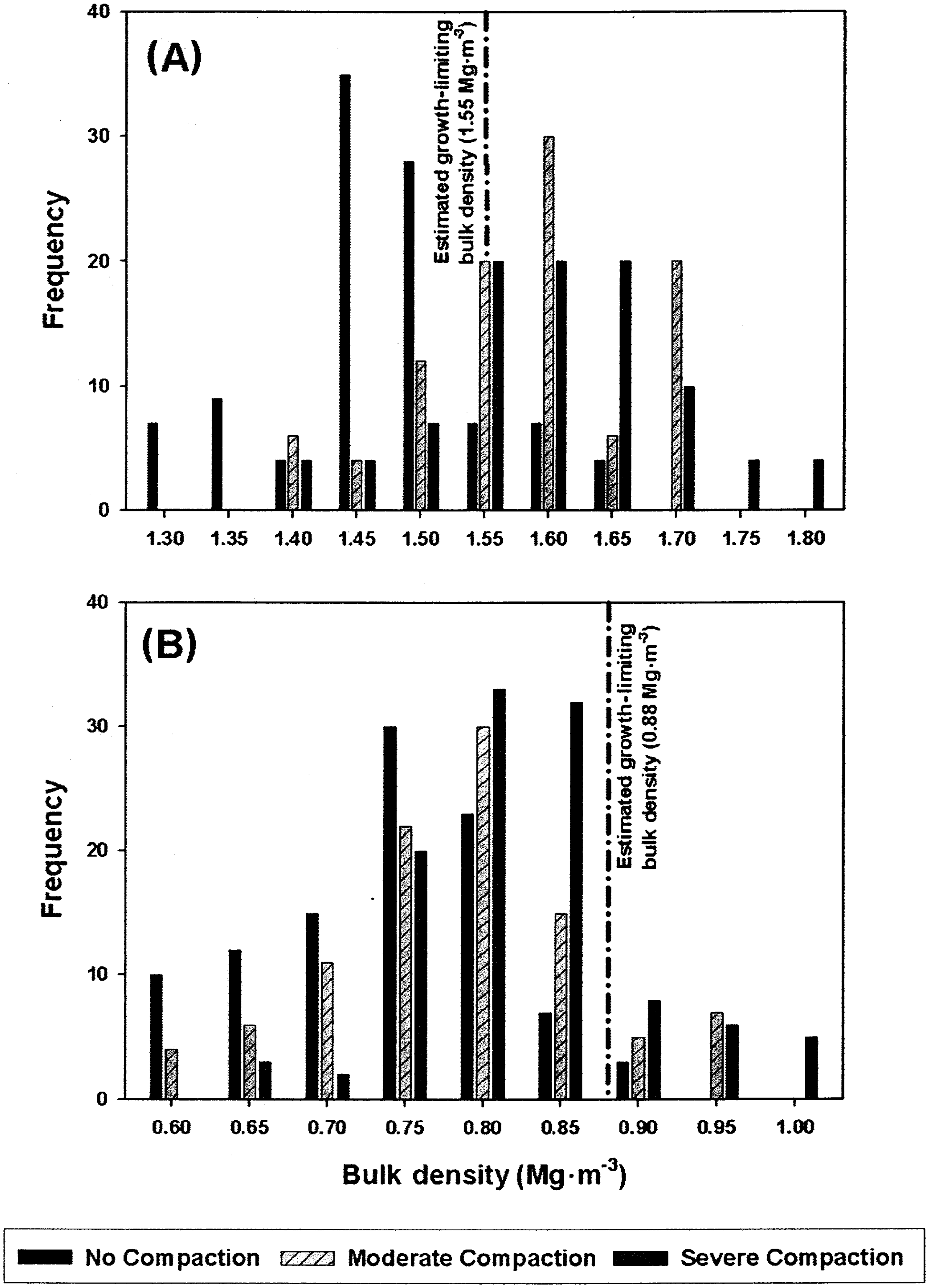
Lateral variability is often a problem in forest ecosystems, even within small areas (Courtin et al. 1983), and most forest studies are limited to the forest floor and surface mineral soil and do not include the deeper mineral soil physical properties (e.g., Grier and McColl 1971). Beckett and Webster (1971) have reported that up to half the plot variability can be present within 1 $m^2$ and within-plot variability changes little with the size of the plot. In British Columbia, on both high- and low-productivity ecosystems, bulk density was one of the least variable measurements, and the estimate of the required sample size (±20% with 90% confidence) was 4–6 samples on 0.8–3.3 ha plots. Sample sizes of 14–28 were needed if a 95% confidence and ±10% error were used (Courtin et al. 1983). These values are similar to our calculations of the number of bulk density samples needed to accurately approximate mean conditions on each 0.4 ha plot. Because of problems associated with large numbers of samples (cost, analysis, transport, etc.), several authors have noted that when studying other highly variable soil properties (i.e., some forest elemental concentrations, rock-fragment content), compositing is often necessary to reduce within-plot variability (Mader 1963; Courtin et al. 1983).

**Fig. 4.** Soil strength contour lines of a severely compacted plot on the Council plots for (*a*) the entire plot (65 m on a side) and for (*b*) a 5 $m^2$ subplot within the larger treated area.




Assessment of the importance of soil physical changes in the broader context of the range of natural variability is important when considering the impacts of timber harvesting or mechanical site preparation and their subsequent consequences on vegetation response (Block et al. 2002; Bock and VanRees 2002).

**Fig. 5.** Frequency distribution of soil bulk density values 1 year after compaction from (*a*) Malbis (fine sandy loam) and (*b*) Council (silt loam, volcanic). Note initial differences in soil bulk density range.



Although one aim of this study was to achieve uniform compaction, we were not always successful. On a fairly large scale (0.4 ha) we evaluated a severe compaction plot (0–15 cm depth) in Idaho for soil strength at 48 sample points (16 points with 3 replicate samples at each point) using the standard sampling protocol (Fig. 4*a*). Soil strength values range from 2500 to 4800 kPa, and although some differences occur, soil strength changes appear fairly uniform, except near large tree stumps. At a smaller scale (5 $m^2$), the same plot was intensively sampled (225 sample points: 75 points with 3 replicate samples at each point) (Fig. 4*b*). This smaller scale and intensive sampling scheme shows some of the soil strength variation that is possible across any given plot. At this scale, soil strength measurements range from 1200 to 4800 kPa. The small-scale plot did not have any tree stumps, but several were present near the edges. Spatial variability associated with these soil strength measurements is not uncommon. Small-scale plot data are highly influenced by traffic variability, while large-scale plot variability can be attributed to larger landscape features such as stumps or microtopography (Carter et al. 2000). Spatial dependence of soil strength measurements often occurs at more than one scale (O'Sullivan et al. 1987; Carter et al. 2000); however, spatial variability of the subsurface horizons is likely to be less pronounced than surface variability (Carter et al. 1999). These variability results are not surprising considering the factors that affect compaction of uneven ground surfaces. Since we had removed logging debris and applied a relatively uniform traffic pattern, the variability of compaction during operational logging is likely much higher.

We also evaluated the uniformity of bulk density values from two locations. The frequency distributions of bulk density values 1 year after harvesting for each compaction treatment on the Malbis (Fig. 5*a*) and Council (Fig. 5*b*) sites show that compaction does not occur uniformly (all one value). Rather, bulk density values shifted from low to high bulk density as traffic intensity increased. For both sites, plots with no postharvest compaction showed a range from many very low bulk densities to a few high values. After compaction, there were few low bulk density values and many higher values. For example, on the Malbis no-compaction treatments, a majority (~75%) of the bulk density values were less than the growth-limiting bulk density (Daddow and Warrington 1983). After treatment (severe compaction), nearly 60% of the samples had values greater than reported growth-limiting bulk densities. On the Council site no-compaction plots, approximately 90% of each 0.4 ha plot was below the estimated growth-limiting bulk density. Severe compaction did not substantially increase the amount of each plot below the estimated root-limiting bulk density, but more values were closer to this value than before compaction. This same bulk density shift was noted on the Challenge and Rogers plots and also occurred on the other LTSP study sites as well (i.e., bulk density was not uniform across the entire plot).

Knowing the spatial distribution of soil compaction in relation to root distribution is critical to understanding the effects of compaction on forest productivity. Roots use soil resources far from the main stem and are able to adjust their distribution to maximize available resources (Sands and Bowen 1978). In the example shown in Fig. 3*b*, after canopy closure, root distribution of each tree will cover a larger area than the spatial pattern of soil strength. Using the growth of young trees to measure impacts of soil compaction must be done with caution under these circumstances. Tree growth in areas of high soil strength may improve as roots expand into areas of lower strength. Compaction effects on productivity will not be clear until all trees in a given stand have had the opportunity to spread out into the entire available soil volume.

Spatial variability also affects the way in which soil quality standards are used to establish limits of allowable impact. For example, the Malbis compaction treatments increased bulk density by only 3%–6%. However, this small change in absolute values increased the frequency of densities above the critical level from 25% to 60% (Fig. 5*a*). Absolute densities at Council increased by 6%–58% relative to the original densities, while the frequency of densities greater than the growth-limiting value changed very little. Soil characteristics, including differences between the initial density and the growth-limiting density, as well as the spatial variability, need to be considered during establishment of standards.

## Conclusion

In all instances we were able to significantly increase soil bulk density above the undisturbed level. Attaining a severe compaction level was difficult and not always a significant increase over the moderate compaction level. One major component in determining our compaction "success" was plot variability. Plot layout, rocks, soil texture, stumps, and initial bulk density all influenced our ability to achieve two levels of compaction on all sites. Plot variability was not always captured with our relatively small sample size, but predicted plot sample numbers were fairly uniform for most study sites (from 9 to 14). Within-plot variability on these fairly large plots may necessitate altering sampling protocols in the future. Soil penetrometers may be practical tools for detecting within-plot differences and could be used as a method for prescreening sites before intensive sampling begins on any management area.

Soil bulk density and soil strength showed a range of recovery; from none to full recovery after 5 years. However, the change in pore-size distribution on two of the study sites may indicate that while bulk density has decreased over time, macroporosity may not have recovered. In addition, on the Freest sites, although bulk density showed recovery, soil strength readings did not. Similar responses on other sites (i.e., bulk density decrease and no change in soil strength) may also be occurring.

The LTSP installations offer an opportunity to assess soil changes over a long time period than is normally evaluated for smaller scale field studies. By the time trees on these sites reach crown closure, compaction effects on growth should be evident. Maintaining soil productivity is critical following any harvesting or site preparation activities. However, the decisions about how many passes logging equipment can take, where logging equipment should be allowed to travel, and how much soil impact is acceptable are all dependent on the soil texture, forest type, available slash to buffer equipment, initial condition of the soil, and preharvest conditions. Loss of macropores on fine-textured soil may prove to be more deleterious to plant growth than a percent change in bulk density. Site-specific sampling schemes will be needed to predict the longevity and extent of compaction, especially on areas where compaction is not uniform. The protocols for soil compaction sampling may require premanagement assessments to establish base-line levels as a comparison. This base-line information will likely provide more meaningful information about the impacts of harvesting or site preparation on long-term productivity and site sustainability. Any consequences of soil compaction must also be measured against tree performance over a long period of time.

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