Conifer Root Proliferation after 20 Years of Soil Compaction

Matt D. Busse, Gary O. Fiddler, and Carol J. Shestak

Soil compaction is known to limit plant growth by reducing soil macroporosity and restricting gas, water, and root movement. Recent evidence from study sites across the United States and Canada, however, suggests that tree growth is not universally affected by soil compaction from forest harvesting practices. Our observational study examined rooting patterns in mixed conifer plantations in the central Sierra Nevada of California to determine whether tree roots use continuous pathways or channels to overcome the physical restrictions of compacted soil. Replicate plots were established 20–25 years earlier to compare compacted and uncompacted treatments after clearcut harvesting. Fine and lateral root counts were taken at multiple depths in soil trenches. Rooting was extensive in compacted plots despite consistently high soil strength values (~3 MPa). No differences in rooting patterns or in fine or lateral root numbers were detected between compaction treatments. The results indicated long-term tolerance by conifer roots to soil compaction without clear use of preferential channels or uncompacted zones.

Keywords: soil compaction, root elongation, soil strength, soil porosity, soil bulk density

Few topics in forest soil science have received more attention than the effects of harvesting on soil compaction. The list of critical functions at risk in compacted soil is considerable (e.g., aeration, water infiltration, erosion, nutrient and water availability, root growth, and site productivity) and underscores the prolonged attention given to the topic (Steinbrenner and Gessel 1955, Ponder et al. 2012). Most soils are easily compacted by machinery (Kozlowski 1999). However, predicting the effect of compaction on site productivity is difficult because of the diversity of potential responses by soils, vegetation types, and climatic regimes (Greacen and Sands 1980).

The Long-term Soil Productivity Study (LTSP) was implemented in 1990 in response to concerns that compaction during harvest operations may lead to detrimental changes in soil and site quality (Powers 2006). The study addressed this premise by establishing a gradient of compaction treatments, from untouched to severely compacted, at 64 forested sites across the United States and Canada. Interestingly, meta-analysis results after 10 years of plantation growth indicated no decline in conifer growth due to compaction at any temperate-zone site (Ponder et al. 2012).

Nambiar and Sands (1992) proposed a hypothesis that might explain the LTSP results. They found that artificially perforating less than 1% of the volume of compacted subsoil into vertical channels, mimicking a legacy of root channels, was sufficient to allow root exploration and normal seedling growth. Whether naturally created soil channels are also sufficiently numerous to support plantation growth in compacted soil is unclear.

We compared compacted and noncompacted LTSP soils for differences in root production two decades after plantation establishment. Three LTSP sites in the central Sierra Nevada, where aboveground conifer biomass was unaffected by compaction (Ponder et al. 2012), were selected for study. Our objective was to determine whether root production was also unchanged in compacted soil. Root systems in the upper meter of soil were exposed by trenching to allow visual and quantitative assessments. Supporting measurements of soil strength and bulk density were taken to verify the long-term presence of compaction.

Methods

Study Sites

The LTSP installations selected are located along the western slope of the central Sierra Nevada mountain range within the Mediterranean climate zone of California (cool, wet winters; warm, dry summers). The installations included “Challenge” on the Challenge Experimental Forest, Plumas National Forest (39°29′46″N, 121°13′21″W; elevation 838 m), “Blodgett” on the University of California Blodgett Forest Research Station (38°54′45″N, 120°39′27″W; elevation 1,310 m), and “Lowell Hill” on the Tahoe National Forest (39°15′51″N, 120°46′59″W; elevation 1,250 m). The sites (replicates) are located within a 40-km radius of each other. Annual precipitation across study sites ranges from 165 to 173 cm and mean annual temperature ranges from 11 to 13°C.

The soil at Challenge is a Xeric Haplohumult (silty clay loam, 34% clay, 8% organic matter; pH 5.8 in the surface 30 cm), whereas...
both Blodgett (loam, 15% clay, 11% organic matter; pH 5.8) and Lowell Hill (loam, 20% clay, 8% organic matter, pH 6.0) soils are Ulici Haploxeralfs. All soils are well drained and deep (>1 m) above volcanic parent material. Rock content was 5% at Blodgett and Lowell Hill and 26% at Challenge. Slopes across the study sites are gentle, averaging less than 15%.


**Experimental Design and Treatment Implementation**

The LTSP study is based on a split-plot factorial treatment design (Powers 2006) that includes three compaction levels (none, moderate, and severe). Treatments (0.4-ha plots) were installed after clearcut harvesting of mature forests in 1990 (Challenge), 1994 (Blodgett), and 1995 (Lowell Hill). We selected two treatments from the larger study to examine root proliferation: severe compaction and no compaction. Both treatments received a similar harvest operation (whole tree plus forest floor removal) and repeated herbicide control of understory vegetation.

Soil compaction treatments were implemented within 6 months of harvesting. Severe compaction was achieved using 21 passes of a 16,000-kg vibrating drum roller applied uniformly across moist soil (near field capacity) without forest floor cover. No machinery entered uncompacted plots either during or after harvesting.

All plots were planted with an equal distribution of ponderosa pine, sugar pine, white fir, Douglas-fir, and giant Sequoia (*Sequoia-dendron giganteum*) barefoot seedlings at a 2.4 × 2.4 m spacing, with the exception that giant Sequoia was absent at Challenge. By 2016, tree dbh ranged from 15 to 25 cm.

**Trenching and Root Profile Distributions**

Two trenches (6 m long, 1 m deep, and 1 m wide) were dug per plot with a backhoe excavator in May 2016 (2 trenches × 2 treatments × 3 replicate sites). The trenches were dug between adjacent rows of trees, a minimum of 0.4–0.8 m away from the stems of 5–6 trees per trench. Soils were moist (> 30% by volume), and root growth was active at the time of trenching.

Root counts were determined immediately after trenching along four horizontal transect lines (5 m in length) per trench, at 5-, 15-, 25-, and 35-cm soil depths. All roots intersecting the transect lines were counted by size category: fine roots (<1.5 mm), small lateral roots (1.5–6.4 mm), and larger lateral roots (>6.4 mm). Visual inspections were made against the exposed trench face for qualitative evidence of root clumping in uncompacted zones or root movement within soil fractures.

**Soil Bulk Density (BD), Relative BD, and Soil Strength**

Soil BD was measured (1) immediately before compaction, (2) during the first growing season after compaction at Challenge only, (3) at year 10, and (4) at year 20. Soil was collected by depth (0–10, 10–20, and 20–30 cm) at 9 random locations per plot using a 5-cm-diameter hammer core (volume, 49.1 cm³). Both total and fine fraction (<2 mm) BDs were determined after oven drying (120° C for 24 h). Relative bulk density (RBD) (field bulk density divided by maximum bulk density for a given site) was determined by the method of Krzic et al. (2004). Soil strength readings were taken in May 2016 every 1.2 m along the length of each trench, a minimum of 0.8 m away from the trench face, using a recording cone penetrometer.

**Statistical Analyses**

The effect of compaction on fine root and lateral root numbers was analyzed using a general linear mixed model in the R statistical package, “lmerTest.” This was a split-plot analysis with compaction as the whole plot and soil depth as the subplot. Compaction, soil depth, and their interaction term were fixed effects and plots (blocked by site) were random effects. Effects were considered significant at *P* ≤ 0.10.

**Results**

**Compaction Legacy**

Little recovery of soil physical properties was detected in the initial 20 years after compaction. Bulk densities were 20–30% higher in the upper 30-cm horizon at year 10 and 20 compared with pretreatment values (*P* = 0.016) (Table 1). Relative bulk density averaged 0.76 (± 0.02) in the surface 30 cm for compacted soil compared with 0.53 (± 0.04) for pretreatment soil. Total porosity (assuming a particle density of 2.65 g cm⁻³) decreased for compacted plots from 68% at pretreatment to 59% by year 20.

Large differences in soil strength were found between compacted and noncompacted plots (*P* < 0.001). The median value at each soil depth was more than 3 MPa for compacted plots, or nearly 3 times as great as uncompacted plots (Figure 1).

**Rooting Distribution**

No effect of compaction on fine root (*P* = 0.85) or lateral root (*P* = 0.97) counts was detected (Figure 2). Instead, a strong linear

---

**Table 1. Soil bulk density at pretreatment and 10 and 20 years after compaction.**

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Depth (cm)</th>
<th>Pretreatment</th>
<th>Year 10</th>
<th>Year 20</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compacted</td>
<td>0–10</td>
<td>0.84 (0.11)</td>
<td>1.09 (0.16)</td>
<td>1.09 (0.16)</td>
</tr>
<tr>
<td></td>
<td>10–20</td>
<td>0.85 (0.10)</td>
<td>1.09 (0.17)</td>
<td>1.06 (0.12)</td>
</tr>
<tr>
<td></td>
<td>20–30</td>
<td>0.86 (0.08)</td>
<td>1.07 (0.16)</td>
<td>1.03 (0.13)</td>
</tr>
<tr>
<td>Not compacted</td>
<td>0–10</td>
<td>0.76 (0.05)</td>
<td>0.82 (0.07)</td>
<td>0.89 (0.06)</td>
</tr>
<tr>
<td></td>
<td>10–20</td>
<td>0.82 (0.07)</td>
<td>0.83 (0.07)</td>
<td>0.90 (0.10)</td>
</tr>
<tr>
<td></td>
<td>20–30</td>
<td>0.87 (0.07)</td>
<td>0.87 (0.06)</td>
<td>0.95 (0.10)</td>
</tr>
</tbody>
</table>

Values are means and SE in parentheses (*n* = 3).

**Figure 1. Soil strength comparison between compacted and uncompacted LTSP treatments.** Penetrometer readings were taken every 1.2 m along the length of each trench. Lines within each box are the median, the box edges are the 25th to 75th percentiles, and whiskers are the 10th and 90th percentiles. Outliers are shown as circles.
Figure 2. Effect of soil compaction on fine roots (<1.5 mm diameter) and lateral roots at multiple depths in the soil profile. Root counts were made along horizontal transect lines (5 m) within each trench. Bars represent means ± SE (n = 3).

Figure 3. Dispersed rooting pattern in compacted (right) and uncompacted (left) plots at the Blodgett LTSP site. The trench depth is 1 m.

decline in fine roots was detected with increasing soil depth ($P < 0.001$) regardless of soil compaction (depth × compaction interaction, $P = 0.22$). Lateral roots showed a moderate, nonsignificant increase in numbers at the intermediate depths of 15 and 25 cm ($P > 0.16$). Visual inspection identified fairly extensive rooting throughout the 1-m soil profile at Blodgett and Lowell Hill and to a depth of 50 cm at Challenge. Roots were evenly distributed in both treatments, and no visual evidence of clumping or growth along preferential pathways was noted (Figure 3).

Discussion

Root production was relatively un restricted by the severe LTSP compaction treatment, as both fine root and lateral root numbers were similar between treatments, and no visual signs of preferential rooting patterns were noted. A plausible explanation for this finding is that the LTSP compaction treatment was too mild to limit root elongation. Evidence from most, but not all, of our physical measurements supports this explanation. For example, BD was 20–30% higher after compaction compared with pretreatment levels. Although substantial, the corresponding total porosity of the compacted soil remained above 50% by volume. Previous studies at our sites have shown that compaction produces a substantial decline in macroporosity, yet partially offsetting increases in meso- and microporosity (Paz 2001, Shestak and Busse 2005). We surmise that root elongation was uninhibited by the redistribution of pores as suggested by Bengough et al. 2011.

Compaction also increased the soil RBD by 40%. However, the mean RBD value of 0.76 at our sites was well below the upper limit of 0.86 suggested for conifer growth in a recent study from Canadian LTSP study sites (Kranabetter et al. 2017).

Unlike the moderate changes in BD and RBD, soil strength values for the compacted plots met or exceeded reported root-limiting thresholds of 2–3 MPa (Sands et al. 1979, Greacen and Sands 1980). We are at a loss to explain this discrepancy between soil measures for predicting limitations to root growth. Clearly the accuracy of a soil strength threshold needs further refinement at our sites, which supports the conclusion of Greacen and Sands (1980) that thresholds are not universally applicable across soil types, sites, or tree species. Alternatively, the least-limited water range (da Silva et al. 1994), which predicts root growth as a function of multiple soil physical parameters (soil strength, air-filled porosity, volumetric water content at field capacity, and permanent wilting point), may offer greater accuracy in predicting root growth than soil strength measurements alone (Siegel-Isse et al. 2005).

This is the first report we know of that examined rooting characteristics after 20–25 years of soil compaction. Interestingly, LTSP studies of shorter duration have also identified indifferences by roots to compaction. Siegel-Iss et al. (2005) found root length densities of pot-grown seedlings were unaffected at compaction levels comparable to our field treatments. Ludovici (2008) found a moderate, yet statistically insignificant, difference in loblolly pine root biomass between severely compacted and uncompacted plots after 10 years. Although our studies offer only a glimpse into the potential responses of tree roots to soil physical changes, they support LTSP findings that soil compaction has had neutral, and in some cases positive, effects on conifer growth in temperate-zone plantations (Ponder et al. 2012, Scott et al. 2014).

The LTSP compaction treatment (21 passes by heavy machinery applied uniformly across moist, bare soil) is severe by today’s harvest standards (Han et al. 2009, Ampoorter et al. 2012), and the increases in BD and soil strength clearly support observations that forest soil is easily compacted (Kozlowski 1999, Page-Dumroese et al. 2006). However, they also illustrate how difficult it is to compact productive soils that are moderately high in porosity and organic matter content to levels detrimental to root growth. Other factors affected by compaction, such as reduced aeration and water infiltration, are probably of more concern than root growth in these Sierra Nevada soils. Whether this finding holds for soils differing in parent material, texture, or total porosity requires further investigation.

Conclusion

Conifer root production was similar in compacted and uncompacted plots 20 years after plantation establishment. Lateral and fine root numbers were comparable throughout the rooting profile, providing evidence of root tolerance to moderately severe soil compaction in productive forests in the Sierra Nevada. We also found that rooting was unhindered at high soil strength values, questioning the universal use of a soil strength threshold to predict rooting restrictions.

Supplemental Podcast

This article includes a podcast interview. Visit the online version of this article to listen to the podcast.
Literature Cited


