

Soil Compaction Effects on Growth of Young Ponderosa Pine Following Litter Removal in California's Sierra Nevada

A. Gomez, R. F. Powers, M. J. Singer,* and W. R. Horwath

ABSTRACT

Increased use of heavy equipment and more frequent entry into forest stands has increased the potential for soil compaction and decreased productivity. We examined compaction and tree growth relationships on three California soils of contrasting textures (clayey, loamy, and sandy loam) on plots from which the organic soil horizon had been removed. Compacted and noncompacted treatments were compared. Changes in bulk density (D_b), soil strength, and total porosity, measured during the growing season, were greatest in the 15- to 30-cm depth at all sites. Bulk density increases were greatest in the loamy soil (30%) and least in the sandy loam (23%). Total porosity decrease in the upper 45 cm averaged 20, 9, and 13% for the clay, loam, and sandy loam textures, respectively. In the 30- to 45-cm soil depth, compacted soils reached critical water potentials (<-1.5 MPa) 50 d sooner in the loam and 67 d sooner in the clay. In the sandy loam, compaction extended the period of plant-available water for 86 and 48 d in the 1- to 15- and 15- to 30-cm soil depths. Midday stem water stress was greater for trees in compacted plots of loamy and clayey textures, but less on sandy loam. Soil compaction did not reduce tree growth universally in these 3- to 8-yr-old plantations. Effects were detrimental, insignificant, and beneficial for clayey, loamy, and sandy loam soils, respectively. Results show that compaction effects depend strongly on soil texture and soil water regime. Soil physical values, per se, are not always reliable criteria for evaluation.

MORE FREQUENT USE of heavy equipment in intensive forest practices is leading to soil compaction and reduced productivity (Kozlowski, 1999; Powers 1999b). Soil compaction decreases total porosity and increases D_b , volumetric water content, and soil strength (Greacen and Sands, 1980), and the effects in forests may last for decades (Wert and Thomas, 1981; Froehlich et al., 1985). When soil horizons are compacted, root growth is mechanically impeded, limiting access to water and nutrients, and reducing plant productivity (Wronski and Murphy, 1994; Whalley et al., 1995). Laboratory studies have shown that physical and mechanical soil changes caused by compaction can vary with soil texture (Unger and Kaspar, 1994). Plant responses in the field depend more on the extent to which soil-water relationships are affected by compaction than on soil texture or the absolute physical changes of soil properties (Unger and Kaspar, 1994; Wolkowski, 1990). Therefore, soil compaction effects on tree growth should be interpreted in terms of plant and soil-water relationships. Froehlich and McNabb (1984) described an inverse, linear relationship between D_b and seedling height growth that was apparently independent of soil texture. The USDA

Forest Service evaluation for harmful effects from compaction often is based on the percentage increase in D_b (Powers et al., 1998). If linearity of response is preserved among different soil textures, the task of predicting soil compaction effects on plants would be relatively easy. However, according to Wolkowski, (1990), the simplicity of the Froehlich and McNabb model may obscure the importance of water and air regimes under soil compaction. To obtain integral indices, some researchers (da Silva et al., 1994) have suggested the incorporation of soil aeration, soil strength, and soil water potential measurements in one single index called *least limiting water range* to describe the soil quality in terms of plant growth. Kelting et al., 2000, found the least limiting water range index very useful in evaluating tree growth on disturbed soils in South Carolina and concluded that factors related to an air-water balance and soil physical properties were important for explaining response of tree growth to compaction.

Except for Powers and Fiddler (1997) and Powers (1999b), literature relating soil compaction to ponderosa pine (*Pinus ponderosa* P. Lawson & C. Lawson) growth have been limited to loamy soil textures (Cochran and Brock, 1985; Froehlich et al., 1986; Helms and Hipkin, 1986), from which a reduction in productivity has been demonstrated on compacted soils. Nonetheless, forest soils are varied in texture, and more information about the effects of compaction on ponderosa pine growing on soils of different textures is important for designing better management plans for this species. Because compaction can affect soil water availability and aeration, the topic is particularly relevant in both very wet sites of the Southern Coastal Plain (Kelting et al., 2000) and droughty sites such as those common in California and regions of similar Mediterranean climate (Powers, 1999b).

The objectives of this work were to: (i) assess soil physical changes as a result of soil compaction in three forest soils with a range of soil texture in the Sierra Nevada in California; and, (ii) evaluate the significance of these changes in terms of water regime and relative ponderosa pine growth. We hypothesize that soil compaction effects on ponderosa pine growth in the Sierra forests depend on the changes in soil water regime more than in the absolute soil physical changes.

MATERIALS AND METHODS

Sites

Our study is part of the North American Long-Term Soil Productivity (LTSP) research network. The LTSP was initiated in 1989 to examine how pulse disturbances in site organic

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matter and soil porosity influence soil properties and processes supporting forest productivity (Powers, 1991, 1999b). The LTSP network is linked by a common experimental design involving three levels of organic matter removal during harvesting (bole only, whole tree, and whole tree, understory, and forest floor), crossed factorially with three levels of soil compaction (none, moderate, and severe). Treatment plots (0.4 ha) are regenerated to the regional species of interest. One-half of each treatment plot is kept weed-free with herbicides to avoid confounding by differential effects of weed competition (Powers, 1999b; Powers and Fiddler 1997). To date, 62 LTSP installations are functioning in the USA and Canada, along with >40 affiliated experiments on public and private lands (Powers 1999a). Nine LTSP sites are on the western slope of California's Sierra Nevada mountains, and three were chosen for the research reported here (Fig. 1).

Our sites were selected to provide a broad range in soil texture. They represent some of California's most productive forest soils (Table 1). All support mixed-conifer timber growing under essentially identical climate. These stands originated about a century ago following clearcutting and railroad logging. All sites were inventoried carefully prior to the harvesting and before initiating this experiment, and treatment plots were chosen from prospective plots with similar stand and soil characteristics. The site was then clearcut and treated according to standard LTSP protocols (Powers 1991, Powers and Fiddler 1997). Blodgett Forest plots, with loam surface texture, were established in 1994 in El Dorado County on land managed by the University of California near Georgetown, CA (38°52' N, 120°40' W) at an elevation of 1350 m. The Blodgett soil originated from an andesitic mudflow and is classified as Cohasset series (Fine-loamy, mixed, superactive, mesic, Ultic Haploxeralfs). The remaining sites, Challenge and Rogers, with clay and sandy loam surface texture, respectively, are located on the Plumas National Forest northeast of Oroville, CA (39°29' N, 121°13' W; and 39°46' N, 121°20' W, respectively), and were established in 1991 and 1996. The Challenge elevation is 790 m and the elevation at Rogers is 1200 m. Soil at Challenge originated from metamorphosed volcanic material and is in the Challenge series (Fine, mixed, superactive, mesic, Typic Palexerults). At Rogers, where the soil evolved from granodiorite, the soil is the Chaix series (Coarse-loamy, mixed, superactive, mesic Typic Dystroxerepts). Three soil profiles were described in unharvested areas of the three sites, and their characteristics are shown in Table 2.

Mean annual precipitation for all the sites varies between 1651 and 1727 mm, most of which occurs between October and March. Other than rare thunderstorms, little rain falls between June and October. Climatological data showed that May precipitation averaged 137 mm for the 1996 to 1999 study period, varying between 10 and 238 mm. June through September is droughty, and this 4-mo period received an average annual rainfall of only 40 mm during the study. No precipitation fell in July 1997, 1998, or 1999, nor in August 1996 or



Fig. 1. Location of three long term soil productivity research sites evaluated in this project.

1998. Only once (June 1997) was monthly precipitation as great as 48 mm. The natural vegetation surrounding the experimental sites is even-aged, ~100-yr-old mixed-conifer forest. Trees are sawtimber size and include sugar pine (*P. lambertiana* Douglas), ponderosa pine, white fir [*Abies concolor* (Gordon & Glend.) Lindl. ex F. H. Hildebr.], and Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco].

Treatments and Tree Measurements

We examined effects of soil compaction vs. no soil compaction. Compaction was accomplished with multiple passes of a vibratory soil compactor applying 4.9 Mg m⁻¹ of static linear force on plots with complete organic matter removal. The aim was to achieve the degree of compaction associated with heavily used skid trails and landings. Using a gasoline-powered soil auger to create a small, friable planting hole, conifers had been planted at 2.4-m intervals in a regular grid pattern and

Table 1. General characteristics of the three research sites.

Location (Elevation)	Mean annual precipitation	Soil depth†	Particle size			Soil texture	Organic C
			Sand	Silt	Clay		
	mm	cm	%				%
Challenge (790 m)	1727	0–15	31	28	41	Clay	4.5
		15–30	27	26	47	Clay	2.8
Blodgett (1350)	1651	0–15	49	38	13	Loam	8.1
		15–30	51	34	15	Loam	4.6
Rogers (1200 m)	1727	0–15	66	25	09	Sandy loam	2.8
		15–30	65	26	09	Sandy loam	1.9

† Soil sampling was centered in the soil depth range.

Table 2. Soil profile characteristics of the three study sites before harvest. Each profile is the mean of three pedons. Colors are for moist soil.

Horizon	Blodgett				Challenge				Rogers			
	Depth	pH	Color	Texture†	Roots‡	Horizon	Depth	pH	Color	Texture	Roots	Horizon
	cm						cm					cm
O1	10–4						4–0					O1
O2	4–0						0–12	6.1	5YR 4/4			O2
A1	0–11	5.8	5YR 3/2	l	2vf-f 1m-co	A	0–12	6.1	5YR 4/4		3m-f 2m	A1
A2	11–29	5.8	5YR 3/3	l	2vf-f 1f-co	B1	12–39	6.2	2.5YR 3/4	d		A2
B1	29–55	5.5	5YR 3/4	l	2f-m 2m-co	B2t	39–67	6.2	2.5YR 3/6	c		A3
B2	55–105	5.4	5YR 4/4	cl	1f-co	B3t	67–105	6.2	2.5YR 4/6	c		B1
R	105–150	Weathered andesitic mudflow				B4t B5 C	105–148 148–218 >218	6.0 6.0 Weathered metamorphic andesite	2.5YR 4/6 2.5YR 4/7 c	c c	1vf-m	C R

† Texture: l = loam; cl = clay loam; c = clay; fsl = fine sandy loam; sl = sandy loam.

‡ Roots: Numbers 1, 2, and 3 refer to quantity class; few (<1), common (1 to <5), and many (≥5 per unit area), respectively. Unit area for very fine and fine roots is 1 cm², and 1 dm² for medium and coarse roots. Symbols: vf = very fine (<1 mm); f = fine (1–2 mm); m = medium (2–5 mm); co = coarse (5–10 mm in diameter).

were 1- to 5-yr old at the start of our study. Although several species had been planted, we focused on ponderosa pine, the most common plantation tree in California. To assure that differences resulted from the treatment and not from herbaceous competition (Powers and Fiddler, 1997), weed competition was minimized by periodic application of glyphosate [N-(Phosphonomethyl)glycine] in all the sites. These plots were selected because previous studies (Gomez, 2000) indicated correlation between the compaction treatment and physiological indices like plant water potential and foliar ¹³C carbon signature. Therefore, selecting plots along a gradient of soil texture with similar conditions within sites, except for the compaction treatment, allowed us to relate soil compaction effects to tree growth.

To test the treatment effects across time, tree growth parameters were measured annually (in August) for four consecutive growing seasons from 1996 to 1999. Stem volumes were estimated from ground level diameter and tree height, assuming a conical shape of the stem. Trees were selected systematically along four transects per treatment plot. Sample size varied from 14 to 32 trees and from three to six soil samples per plot. The degree of reproducibility of measurements, suitability of trees, the cost of each method, and the variation of parameters determined the size of the samples. Also, in summer 1999, midday stem water potential was measured by the pressure bomb for 10 to 12 trees per treatment, using the no-transpiring leaf method as published by McCutchan and Shackel (1992). Treatments were not replicated at a given installation, and we recognize that applying inferential statistics to treatment comparisons at a single location represents pseudoreplication. However, unusual effort is made at LTSP installations before harvest to ensure that all plots were as uniform as possible in such measurable physical characteristics as stand density, site index, thickness of the forest floor and A horizon, soil color and depth, gravel content, and such surficial disturbance as skid trails and landings (Powers, 1991; Powers and Fiddler, 1997). Treatments were then assigned randomly, giving us some assurance that emergent differences among plots are likely due to treatment and not to pretreatment conditions.

Soil Measurements

Soil D_b was measured in April 1999 using a hammer-driven device. Soil cores were collected at 5-cm increments. Each 5.8-cm × 5-cm (diameter × length) soil core was centered on 7.5-, 22.5-, and 37.5-cm depths to represent the 0- to 15-, 15- to 30-, and 30- to 45-cm soil depths. Sampling at the first depth included the A horizon, and deeper samples were transitional (Table 2). Collectively, these zones include the major proportion of fine roots (Powers, 1984; Table 2). Four to six samples were collected per treatment in case some were damaged during handling. Samples were oven-dried at 105°C and weighed to calculate D_b. Total soil porosity for the third depth (30–45 cm) was estimated from D_b and an assumed particle density of 2.6 Mg m⁻³. For soil depths 0- to 15- and 15- to 30-cm, particle density was calculated by adjusting for organic carbon content as indicated by Rowell (1994).

Soil water characteristic curves were determined based on water content after applying pressure ranging from 0.03 to 1.5 MPa (Hanks, 1992). Soil sampling was performed in April when soil moisture content was optimum for recovering samples. Soil cores 5.8 × 5 cm in diameter and height were used for loamy and sandy soils, and 5.8 × 2.5 cm for clayey soils. Successive weights of samples at different pressure allowed the calculation of water content at the pressure applied. Three replicates were analyzed for every treatment and soil depth; thus, a total of nine samples were analyzed for each treatment.

Table 3. Stem volume and midday stem water potential (MSWP) of three young ponderosa pine plantations under soil compaction and different soil textures. Coefficients of variation (%) in parentheses.

Site (Age)	Soil texture class	Stem volume in 1999		Difference	MSWP in Summer†		Difference in MSWP
		No compaction	Soil compaction		No compaction	Compaction	
		$\text{dm}^3 \text{ tree}^{-1}$		%	MPa		
Challenge (8 yr)	Clay	32.99 (46)	18.17 (47)	-45**	-1.34 (8.4)	-1.54 (6.6)	-0.20**
Blodgett (5 yr)	Loam	4.94 (57)	4.63 (56)	-6 NS	-1.03 (7.9)	-1.25 (7.9)	-0.23**
Rogers (3 yr)	Sandy loam	0.34 (42)	0.93 (50)	+173**	-1.12 (5.2)	-0.87 (8.4)	+0.25**

** $P = 0.01$ according to t -test.

† Midday Stem water potential measured in August 1999.

Soil strength was measured once in early May 1999 with a Rimik CP-20 (Agridry Rimik PTY Ltd., Toowoomba, QLD, Australia) recording cone penetrometer equipped with a data logger. Cone angle was 30° , tapering to a 1-cm^2 base. This device was hand driven below the projection of the tree crown into the soil up to a 45-cm depth. Soil strength was recorded at 5-mm depth intervals. The same operator made 14 to 32 measurements per plot. May was selected because it corresponds with high rates of root growth (Anderson, 1991; Bloomfield et al., 1996) and a period when soils are similarly near field capacity. Average gravimetric soil water content for the 0- to 45-cm soil depth, at the time of measurement, was 43 ± 3.4 , 25 ± 3.2 , and 20 ± 2.8 % for Blodgett, Challenge, and Rogers sites, respectively. Soil moisture was determined gravimetrically for each depth at five or more dates between 15 May and 23 Sept. 1999. Volumetric fraction was calculated using the measured D_b for every treatment and depth. Samples were collected from the boundaries of the projected crown of the tree.

Statistical Analyses

Recognizing the risks of pseudoreplication, statistical analyses were performed for every location separately using the SAS statistical package (SAS Institute, 1988). A single model linking tree growth with soil parameters was precluded because analysis of variance of tree growth showed significant interaction between site and treatment (Gomez, 2000). Because treatment responses were site dependent, a global model for the three sites was not appropriate. Therefore, the t -test procedure of SAS was used to compare soil compaction and noncompaction treatments within sites. The Wilcoxon test was used in the cases where the size of samples was relatively

small and the normal distribution was difficult to test (Cody and Smith, 1997). Differences were considered statistically significant at $P = 0.10$.

RESULTS

Tree Growth

Soil compaction did not influence stem volume at the Blodgett site with loamy soil texture. However, compaction was associated strongly with reduced growth at Challenge, and increased growth at Rogers ($P = 0.01$, Table 3). Volume differences were apparent by 1997, and separations were increasing with time (Fig. 2).

Bulk Density and Total Porosity

Compaction produced significant changes in D_b and total porosity in the upper 30 cm on all soils and to 45 cm in the sandy loam (Table 4). Absolute values for D_b were highest for the clay and lowest for the loam. Changes were greatest at the 15- to 30-cm depth for all soil types and were similar on a percentage basis. Variation in D_b was higher in the third depth (30–45 cm) in the clayey soil, in the second depth (15–30 cm) in the loamy soil, and in the first depth (0–15 cm) in the sandy loam. Compaction reduced total soil porosity in the upper 45 cm by an average of 9% (loam) to 20% (clay) (Table 4). Although compaction caused the greatest D_b increase in the loam (30%, 15–30 cm), this corresponded to only 14% loss in total porosity. The greatest porosity

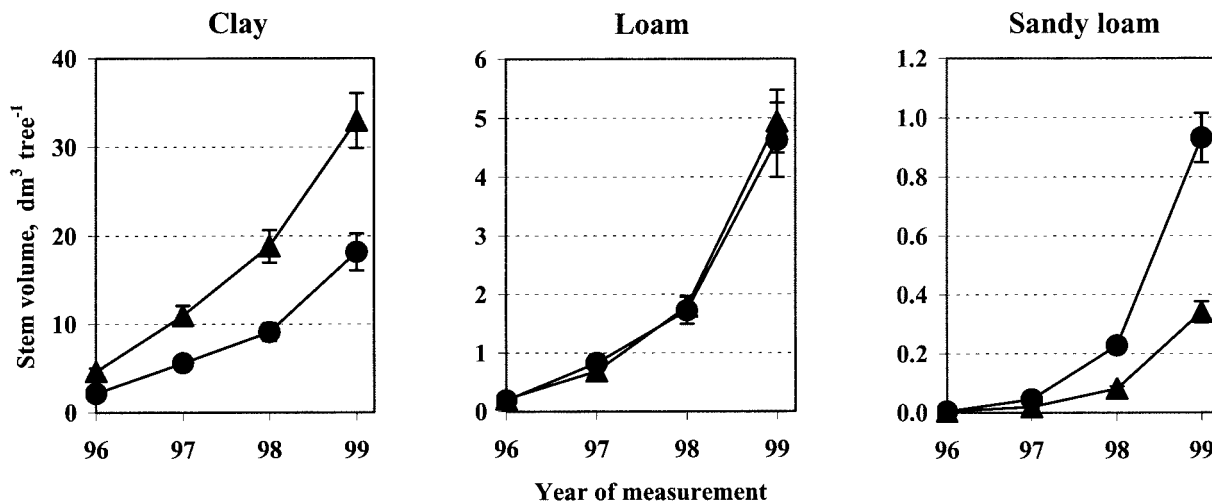


Fig. 2. Cumulative stem volume for ponderosa pine at the three study sites for noncompacted (triangle) and compacted (circle) treatments. All sites are for full forest floor + logging slash removed. Age of plantations in 1999 was 8, 5, and 3 yr, respectively. Vertical bars represent standard errors.

Table 4. Mean physical characteristics of soil by depth for the three study sites. Coefficients of variation (%) in parentheses.

Site (Soil texture)	Soil depth range	Bulk density		D_b increase	Total porosity		Porosity decrease	Statistical significance†
		No compaction	Compaction		No compaction	Compaction		
	cm	Mg m^{-3}		%	$\text{m}^3 \text{m}^{-3}$		%	
Challenge (Clay)	0–15	1.22 (4.9)	1.41 (5.8)	16	0.51 (4.8)	0.43 (7.6)	16	*
	15–30	1.24 (8.1)	1.58 (9.7)	27	0.51 (7.7)	0.37 (16.2)	27	‡
	30–45	1.30 (28.9)	1.49 (13.5)	15	0.50 (28.8)	0.42 (18.4)	16	ns§
Mean				19			20	
Blodgett (Loam)	0–15	0.75 (3.6)	0.89 (7.5)	19	0.68 (1.7)	0.62 (4.6)	9	*
	15–30	0.82 (7.9)	1.07 (8.5)	30	0.66 (3.9)	0.57 (6.5)	14	**
	30–45	0.98 (2.2)	1.05 (5.5)	7	0.62 (1.4)	0.59 (3.7)	5	ns
Mean				19			9	
Rogers (Sandy loam)	0–15	1.13 (10.2)	1.28 (16.3)	13	0.55 (8.1)	0.50 (16.5)	9	‡
	15–30	1.14 (5.5)	1.39 (8.1)	23	0.56 (4.4)	0.46 (9.7)	18	**
	30–45	1.31 (2.3)	1.49 (8.5)	14	0.49 (2.4)	0.43 (11.4)	12	*
Mean				17			13	

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

† Significance applied to both bulk density and total porosity. Analysis according to Wilcoxon test.

‡ Significant at the 0.10 probability level.

§ ns not significant at the 0.10 probability level.

loss was at 15 to 30 cm in the clayey soil (27%). For all soils, porosity losses were greater at 15 to 30 cm than at any other depth.

Soil Water Content

During the period we measured soil water (131 d), volumetric water content decreased in the order of loam > clay > sandy loam (Fig. 3). As expected, the surface (0–15 cm) dried faster than deeper zones, but the effect of compaction on water content was most obvious in the sandy loam soil where compaction increased soil volumetric water content. For the clayey soil, compaction had little effect on total soil water con-

tent. By the last sampling date, there was an increase in volumetric water content of the surface soil (0–15 cm) in some of the plots (particularly the sandy loam). This was caused by a rain event between the last two measurements. Gains in volumetric water were greatest in the sandy loam, where the effect of the rain event was evident at all soil depths. The third soil depth of this soil showed the greatest change.

Water Holding Capacity

Under compaction, the first two soil depths of the clayey soil showed similar water retention up to ≈ 0.7 MPa (Fig. 4). Both depths were classified as clay loams

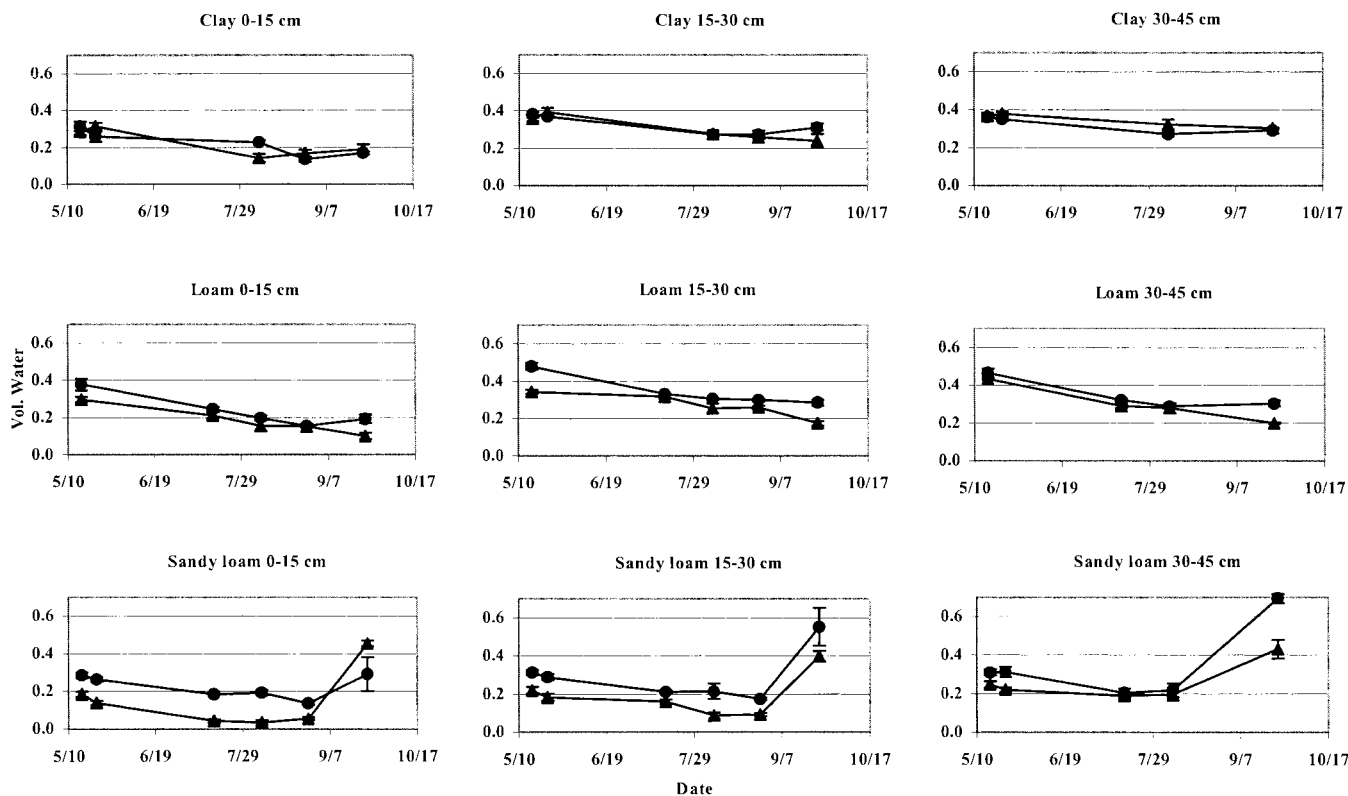


Fig. 3. Volumetric water content from May to September for the study sites at three soil depths. Triangles represent no soil compaction and circles represent soil compaction treatments. Vertical bars represent standard errors.

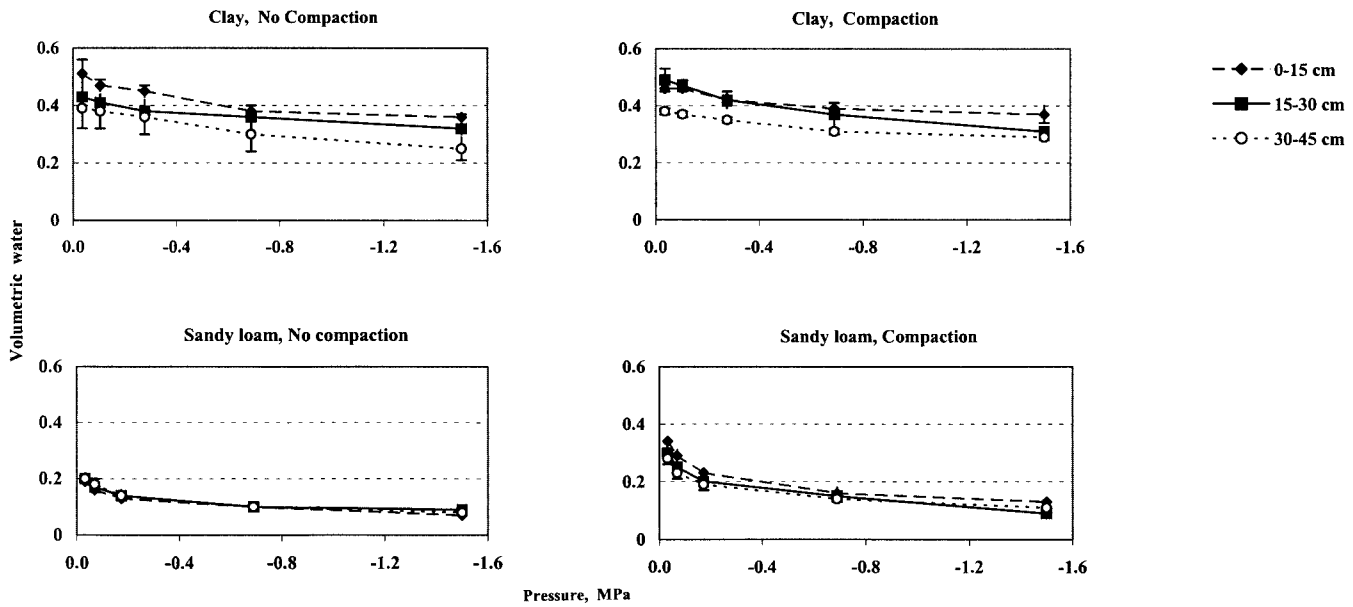


Fig. 4. Water retention curves (-0.03 to -1.5 MPa) for two sites at three soil depths. Triangles represent no soil compaction and circles represent soil compaction treatments. Every point is the average of three samples. Where not obscured by symbols, vertical bars represent standard errors.

(Table 2). The third soil depth, however, showed a different trend in water holding capacity in both compaction treatments denoting a zone with different pore size distribution in relation to the upper zones (a B2t horizon with clay texture began at 39 cm, Table 2). For the sandy loam, water retention capacity was increased by compaction, especially in respect to water held at potentials greater than -0.1 MPa. Differences between soil depths were not evident, suggesting that within compaction treatments there is a high similarity in pore size distribution among soil depths. Only slight textural changes were noted in the upper meter of the profile at Rogers, and little clay was evident throughout the profile (Table 2).

Soil water potential indicated that compaction significantly increased the amount of plant available water (-0.03 to -1.5 MPa) in the second depth of the loamy soil and in all soil depths of the sandy loam (Table 5). The amount of available water was not statistically different between treatments in the clayey soil, probably

due to the higher data variation from this soil compared with the other soils.

Combining the water retention parameters presented in Table 5 and the water contents from Fig. 3, we calculated the number of days elapsed between 15 May and the first day the soil reached a water potential of -1.5 MPa (Table 6). Linear changes in soil water lost were assumed for these calculations because of the Mediterranean climate of the area in which soils are drying from spring through summer. Water potentials suitable for plant growth were maintained longer in the second depth (15–30 cm) of the compacted plot in the loamy soil. Compaction decreased the amount of plant-available water in the first (0–15 cm) and the third (30–45 cm) depth. However, this trend was stronger in the third depth, where noncompacted soil had plant-available water potentials for 50 d longer. For the clayey soil, the number of days with water potentials exceeding -1.5 MPa was similar between compaction treatments in the upper 30 cm of the soil, but compaction reduced avail-

Table 5. Water retention parameters for three different forest soils with and without compaction.

Site (Soil texture class)	Soil depth range	Volumetric water content				Available water		Difference in available water†
		No compaction		Compaction		No compaction	Compaction	
		Field capacity	Wilting point	Field capacity	Wilting point			
Challenge (Clay)	0–15	0.51	0.36	0.46	0.37	0.15	0.09	−0.06 ns‡
	15–30	0.43	0.32	0.49	0.31	0.11	0.18	+0.07 ns
	30–45	0.38	0.25	0.38	0.29	0.13	0.09	+0.04 ns
Blodgett (Loam)	0–10	0.24	0.21	0.39	0.32	0.03	0.07	+0.04§
	15–30	0.37	0.25	0.46	0.30	0.12	0.16	+0.04¶
	30–45	–	–	–	–	–	–	–
Rogers (Sandy loam)	0–15	0.19	0.07	0.34	0.13	0.12	0.21	+0.09¶
	15–30	0.20	0.09	0.30	0.09	0.11	0.21	+0.10¶
	30–45	0.20	0.08	0.28	0.11	0.12	0.17	+0.05¶

† Difference tested according to Wilcoxon test.

‡ ns not significant.

§ Only this data obtained from Paz (2000).

¶ $P = 0.10$.

Table 6. Number of days, after 15 May, the soil water potential was within the range of available water (-0.03 to -1.5 MPa).

Site (Soil texture class)	Soil depth range cm	No compaction	Compaction	Difference [†] d
Challenge (Clay)	0–15	0	0	0
	15–30	55	53	-2
	30–45	131	64	-67
Blodgett (Loam)	0–15	61	28	-33
	15–30	83	104	+21
	30–45 [‡]	126	76	-50
Rogers (Sandy loam)	0–15	45	131	+86
	15–30	83	131	+48
	30–45	131	131	0

[†] The minus symbol denotes cases where the compacted treatment reduced the number of days with soil water potential within the range of available water.

[‡] Estimated with the water potential parameters from the depth 15–30 cm shown in Table 3.

able soil water by 67 d in the heavily textured B2t zone. Compared to the other soils, the clayey soil had the fewest days with plant-available water. Water potential in the upper soil layer (0–15 cm) of the clayey soil was lower than -1.5 MPa from the first day of measurement in both compacted and noncompacted treatments. For the sandy loam, compaction extended plant-available water by 86 and 48 d for the first and second soil depths, respectively. The deepest zone did not show differences in water potential due to compaction, as plant-available

water potentials were maintained throughout the observation period.

Soil Strength

Without compaction, soil strengths were greatest throughout the clayey Ultisol and least in the sandy loam Inceptisol (Fig. 5). Changes in strength with depth mirrored clay contents (Table 1) and the presence of an argillic horizon (Table 2), being lowest at Rogers and highest at Challenge. Compaction increased soil strength at all depths and all sites, with the magnitude of the differences between compacted and noncompacted soil decreasing in the order loam > sandy loam > clay. Maximum absolute values in compacted soils were in the order loam > clay > sandy loam. When compacted, soil strength for all the soils reached values exceeding 3 MPa at 20 cm, and >2.5 MPa between 20 and 45 cm. Except for clayey soil where surfaces had been exposed longer to raindrop impact (and possible pore sealing and slight surface erosion), the first 3 cm had low soil strength for noncompacted and compacted treatments. Lowest soil strength, however, occurred in the sandy loam, and the trend for this soil shows that mechanical impedance to root growth declines below 15 cm. In the clayey soil, the differences in soil strength between compaction treatments decreased with soil depth. In fact, at the 45-cm depth the control treatment had soil strength >2.5 MPa, denoting a natural zone (the B2t) with high mechanical resistance in the soil profile. This Ultisol remains clayey to >2 m.

Soil Compaction and Stem Water Potential

Effects of soil compaction on physical changes in D_b , soil porosity, or soil strength did not uniformly correspond to a reduction in stem volume (Table 3). In the loamy soil where strength from compaction and D_b (15–30 cm) were proportionally increased the most, no significant differences in stem volume were observed. However, effects on plant water stress in August were clearly detected at all the sites. Midday stem water potential in August for soils of loamy and finer textures indicated that trees growing in compacted soil were more water-stressed. At Blodgett, compaction lowered stem water potential by 0.23 MPa, but the 6% reduction in stem volume was not significant. On the clayey soil at Challenge, tree growth and stem water potential were reduced significantly when soil strength or D_b was in-

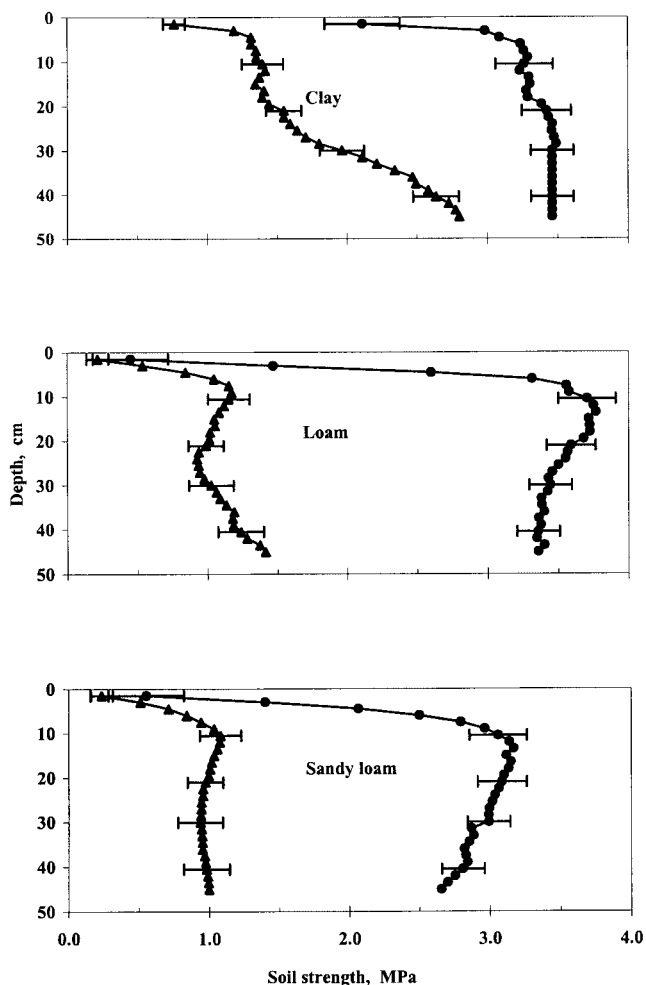


Fig. 5. Soil strength measurements performed in spring for three soils under compaction (circle) and no-compaction treatments (triangle). Horizontal bars indicate standard errors. Values represent the average of 14 to 32 measurements.

creased. On the sandy loam at Rogers, the soil physical effects were reversed. Better tree growth occurred in the compacted treatment.

DISCUSSION

The uncompacted soil densities in Table 4 differ from those found by Rawls et al. (1982), who reported bulk densities of 1.39, 1.42, and 1.45 Mg m⁻³ for clay, loam, and sandy loam soil texture, respectively. Rawls et al. (1982) studied soils from 32 states of the USA and included mostly agricultural soils with an average carbon content of 0.66%. Possibly, our differences resulted from the fact that ours were forest soils with relatively high carbon content. In addition, only 8 of 1323 sites were from California in the study of Rawls and collaborators.

Low organic carbon and the presence of ~5% gravel (2–5 mm) in the clay soil may have contributed to the higher density. Bulk density values between soil compaction and noncompaction treatment found for the loamy Cohasset soil series are in the range reported by Helms and Hipkin (1986) and Howard and Singer (1981) for similar soils on the Tahoe National Forest. Howard et al. (1981) reported that maximum D_b of such soils peaks at ~1.0 Mg m⁻³, which, according to Table 4 values, indicates our plots were severely compacted. In Helms and Hipkin's (1986) retrospective study, ponderosa pine volume was 22% less after 16 years on compacted soil, and effects were evident by the 4th yr. But Helms and Hipkin's study was confounded by the fact that slash residues resulting from salvage logging had been piled by bulldozer. This practice commonly removes a fraction of topsoil and exposes a less-fertile, denser soil horizon. In our 4 yr of observation, differences in stem volume due to soil compaction were not evident. This raises several questions. How important was the absolute change in D_b caused by compaction? Why were trees in the compacted treatment more water stressed in summer, and why did this not translate into reduced tree growth?

The loamy soil at Blodgett was highly compacted. It reached percentage increases in D_b comparable with that of the other sites, and should have shown a tree growth reduction according to Froehlich and McNabb's (1984) linear model. But the average D_b to the 45-cm depth was only 1.0 Mg m⁻³, which is considered a suitable D_b for root growth (Foil and Ralston 1967; Davis et al., 1983; Conlin and Van Den Driessche, 1996). More importantly, the loamy soil had the highest organic carbon content (Table 1) and the greatest total porosity (Table 4). A difference as small as 2% in organic matter significantly affects soil compactibility (Gomez et al., 1995). Therefore, D_b remained numerically low despite extreme efforts at compaction. Despite low D_b , this soil showed the highest soil strength under compaction, and the theoretical threshold for severely reduced root growth (2.5 MPa) was surpassed during the growing season. Regardless, growth was not affected significantly at Blodgett, and it appears that the deleterious effect of increased soil strength was balanced by other factors.

Considering that all the study sites receive similar

precipitation and that they are in a Mediterranean climate in which soils are drying from spring through summer, soil strengths will increase and differences will become even greater as summer proceeds (Powers et al., 1998). Most of the root growth occurs in fall and in spring (Bloomfield et al., 1996), but fine root growth of ponderosa pine in the Sierra Nevada has been reported from June to August (Anderson, 1991). This small proportion of root growth in summer may be useful in maintaining adequate plant water status, but its contribution to net assimilation and growth that late in the year probably is minimal (Powers and Reynolds, 1999). More likely, tree growth was not affected by compaction in the loamy soil at Blodgett because soil porosity remained high and plant-available water was maintained in the 15- to 30-cm feeder root zone during critical periods of growth through the dry season (Table 6). We conclude that trees on this compacted soil were more water stressed in August because high soil strength and soil water content very close to the wilting point (Fig. 3) precluded root expansion and decreased water uptake. Tree growth was not affected because by August, tree growth had essentially been completed on the Cohasset soil irrespective of compaction (Powers 1984; Anderson 1991).

Regardless of the compaction level, available water lasted at least 76 d in the loamy soil for the soil depth of 15- to 45-cm. Therefore, the period of plant-available water extended well into the growing season. Apparently, ponderosa pine can tolerate high soil strength in summer as long as macroporosity is adequate and the prevalent water regime is similar to that of the Blodgett site. Macroporosity in this soil was reduced from 0.25 m³ m⁻³ to 0.14 m³ m⁻³ by severe compaction (Paz, 2000), but the macroporosity remaining probably is adequate for root respiration (Grable and Siemer, 1968). Nonetheless, ponderosa pine does not seem to overcome compaction effects in drier soil regimes with fine-textured soils like the clay at Challenge. There, high soil strength and D_b and low water potential of surface soil combine to impact more days of the potential growing season (Table 6). Gomez (2000) corroborated the effects of soil compaction on water status through the analysis of ¹³C in foliar tissue.

In comparison with the other sites, the loamy soil reached higher soil strength at lower bulk densities and higher soil water content. The fact that there were no effects of compaction on tree growth at Blodgett does not suggest that compaction can be ignored in other soil water regimes. Indeed, the major implication is that compaction effects on tree growth would be worse under drier conditions. Therefore, soil strength and soil and water regimes interact in a way that affects tree growth response.

Results showed that in the xeric conditions of the Sierra Nevada, compaction, tree growth, and soil water effects are strongly linked, a relationship pointed out before by Dexter (1987) and Boone (1988). In the clayey soil, low plant-available water and high soil mechanical resistance under compaction may have impaired fine root growth and the ability of the tree to satisfy water

demand. Furthermore, the clayey soil had the lowest total porosity and average pore size of the three soils. Compaction further reduced total porosity by an average of 20% throughout the top 45 cm (Table 4). Earlier work (Powers and Fiddler, 1997; Powers, 1999b), showed that this represented more than a one-third loss in aeration porosity. This loss of aeration porosity on a fine-textured soil suggests that the soil may have been anaerobic during some of the early growing season and droughty later in the year.

Bulk densities in the clayey soil at Challenge were the highest and total porosities were the lowest of any site. There, compaction reduced stem volume by 45%. If we assume that the average total porosity loss of $0.1 \text{ m}^3 \text{ m}^{-3}$ was entirely at the expense of macropores (Reicosky et al., 1981), the clayey soil is approaching the critical aeration value of $0.1 \text{ m}^3 \text{ m}^{-3}$, which is considered a threshold for root respiration and growth (Grable and Siemer, 1968). Therefore, restricted root growth due to mechanical impedance and lack of soil water and possibly aeration is more evident in the clayey soil than in the loam. In their greenhouse study, Simmons and Pope (1988) showed how root growth is reduced by low aeration porosity when soils are wet and by high strength when soils become drier. This interplay between aeration, moisture availability, and strength is the underpinning of the *least limiting water range* concept of da Silva et al. (1994). The management implications are that given this particular climatic regime, even low levels of soil compaction in sites with clayey soils like Challenge will cause significant reductions in tree growth.

Findings for the sandy loam soil of Rogers are dramatically different. The increased water holding capacity through compaction resulted in a gain of 173% in stem volume when compared with the noncompaction treatment (Table 3). This suggests another type of relationship among compaction, tree growth, and water regime. Soil strength seems not to be a problem in this soil. Presumably, average pore diameters are greater in this sandy loam than in either of the other soils, and root tips may penetrate large soil voids comparatively easily despite high resistance between soil particles. Critical strength values were observed at $\approx 15 \text{ cm}$, but in deeper zones soil strength decreased because there is no argillic horizon in the upper 50 cm (Fig. 5, Table 2). This soil dries quickly and lower soil water potentials also develop sooner (Fig. 4). The important finding is that compaction increased soil water availability in every part of the sandy loam soil profile (Table 5). We attribute this to a reduced volume of very large pores and a concomitant increase in the surface area and available water holding capacity of midsize pores. In short, a more favorable pore-size distribution. The implication is that compaction of sandy loam at the level of this experiment enhances soil moisture availability while maintaining adequate aeration, and does not constitute a physiological problem to trees. On the contrary, if other processes like soil erosion do not seriously impair the functionality of the system (which could be minimized by organic matter retention), moderate compaction seems to be a potential forest practice that improves the soil water availability in droughty sandy loams. Similar findings were reported

by Troncoso (1997), Swearingen (1999), and Stone and Elioff (1998) on sandy LTSP sites elsewhere.

Because many coniferous forests in the Sierra Nevada are governed by a summer-dry Mediterranean climate, soil water has immense control of biological processes. Therefore, predicting short and long-term effects of soil compaction is critically important. Our findings did not support the linear model proposed by Froehlich and McNabb (1984), because the percentage increase in D_b did not correspond to a proportional reduction in stem volume change. Changes in soil water and air balance and resistance to root penetration—not D_b —is critical to plant growth (Reicosky et al., 1981, Simmons and Pope 1988, da Silva et al., 1994). We agree with Dexter (1987), Boone (1988), and Wolkowski (1990) that it is the change in soil water–root and soil air–root processes along with soil strength that defines the direction and magnitude of soil compaction effects.

CONCLUSIONS

Bulk density was significantly increased by the soil compaction treatment at all the sites. Regardless of soil texture, changes were about the same order of magnitude on a percentage basis. However, absolute values were in the order clay > sandy loam > loam. When compacted, all the soils reached soil strength values exceeding 3.0 MPa in the surface horizon (0–15 cm), but a lower mechanical impedance profile was found in the sandy loam. The magnitude of the differences in soil strength between compacted and noncompacted soil decreased in the order loam > sandy loam > clay. Maximum absolute values of soil strength in compacted soils were loam > clay > sandy loam. Effects of soil compaction through physical changes in D_b or soil strength did not uniformly correspond with a reduction in plant growth for all the sites. In the loamy soil where soil strength was the highest, no significant differences in tree growth were observed. The deleterious effects of mechanical impedance on plant growth were evident in the clayey soil. In the sandy loam soil, physical changes were beneficial as water retention was improved by an increase in the amount of fine pores. Trees on loam and clay textured compacted plots were more water stressed in summer than noncompacted controls, suggesting there were differences in the health of the root system in the compacted plots. In sandy loam, soil mechanical impedance effects in compacted soil were mitigated with more plant-available water. We conclude that impacts of soil disturbances on tree growth are highly dependent on soil texture and soil water regime. Therefore, absolute soil physical parameters are not always reliable criteria for evaluation. Future management practices should be site specific and account for interactions between soil pore size and climate. While these soils represent the heart of the highly-productive mixed-conifer forest region of California's Sierra Nevada, further research is needed to see how well our findings apply to other soils and climates. We believe that the interrelationship between soil water potential, soil strength, and D_b relative to forest growth is highly relevant to sustained productivity, and is a most promising field of research.

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