PRODUCTIVITY OF PLANTED SHORTLEAF PINE IN ARTIFICIALLY COMPACTED CLARKSVILLE SOIL

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ABSTRACT.—After 9 years, tree survival was 72, 65, and 70 percent for not compacted, medium compacted, and severely compacted treatments, respectively, for shortleaf pine (*Pinus echinata* Mill.) planted in a forest clearcut on the Carr Creek State Forest in Shannon County, Missouri. The study is in one of the USDA Forest Service's Long-term Soil Productivity Sites to assess the effects of soil disturbance on site productivity across a range of forest sites.

Both total height growth and diameter growth of shortleaf pine at breast height were markedly higher for compacted treatments than for treatments not compacted. Controlling understory vegetation also increased both tree height and diameter at breast height growth. Soil bulk density differences were significant only for the 10-20 cm depth, which were 1.40 and 1.84 g•cm^3 for not compacted and compacted plots at the beginning of the study, were 1.32 and 1.80 g/cm^3 for the same depth and treatments after 8 years. Results suggest that soil compaction associated with tree harvesting on this soil persisted at some depths for more than 5 years. Soil compaction benefited both survival and growth of shortleaf pine. Further discussion is warranted as to how soil physical properties associated with compaction are advantageous to shortleaf pine growth.

INTRODUCTION

Compaction is perceived as one of the leading causes of soil degradation resulting from forest operations (Brais 2001, Froehlich 1988, Powers and others 1990). Soil compaction commonly reduces the growth of young trees that regenerate on sites following harvesting with ground-based machines (Greacen and Sands 1980). Tree susceptibility to compaction, however, has been shown to be species-specific (Wästerlund 1985, Mohering and Rawls 1970, Froehlich and others 1986, Corns 1988) and different soils compacted to the same degree may induce different growth responses (Wästerlund 1985, Powers 1999). For example, shoot and root weight of Douglas-fir (*Pseudotsuga menziesii* var. gluca [Beissn.] Franco) and western white pine (*Pinus monticola* Dougl. Ex D. Don) seedlings were not affected by compaction after one growing season, but root volume was 41 percent less for the Douglas-fir seedlings and seedling height was 6 percent greater for western white pine (Page-Dumerose and others 1998). Corns (1988) reported that lodgepole pine (*P. contorta* Dougl. var.) root weight, shoot weight, stem diameter, and stem height declined due to compaction on all four soils tested, yet white spruce [*Picea glauca* (Moench) Voss] growth on two of the soils did not decline but increased twofold. Wästerlund (1985) also reported species differences with Norway spruce [*Picea abies* (L.) Karst] growth being more impeded by compaction than Scotch pine (*P. sylvestris* L.) growth.

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Once compacted, forest soils can remain compacted for decades (Froehlich and others 1985). Even in cold climates where freezing and thawing are assumed to loosen soil to considerable depths, the bulk density of compacted soil decreases slowly (Voorhees 1983, Corns 1988). The persistence of soil compaction over several decades has been shown to reduce the growth of Douglas-fir for similar periods of time (Wert and Thomas 1981, Heninger and others 2002).

The effects of compaction in forest soils are not always associated with reduce tree growth. On several California sites, Gomez and others (2002) reported that compaction effects on 4-year-old ponderosa pines (*Pinus ponderosa*) varied with soil texture and soil water regime. Stem volume on compacted soils was less, the same, and higher on clayey, loamy, and sandy loam soils, respectively. Powers and others (2005) reported that soil compaction significantly improved tree performance in 10-year-old Long-term Soil Productivity Study (LTSP) installations. Compaction was also found to be beneficial to black spruce (*Picea mariana* Mill.) and jack pine (*Pinus banksiana* Lamb.) growing on coarse-textured soils classified as humo-feric podzols in northwestern Quebec (Brais 2001). Growth increases on these soils were linked to harvest traffic compaction causing a more favorable pore-size distribution, which improved the balance between aeration porosity and available water holding, similar to the findings by Gomez and others (2002). The effect of harvest traffic on soils was described earlier by Hyder and Sneva (1956) and Rashid and Sheikh (1977).

They concluded that compaction generally reduces the available water-holding capacity of fine-textured soils, but in coarse-textured soils, compaction can reduce the size of very large pores and increase water retention.

The LTSP, composed of large-scale field experiments located at sites across the United States, was developed to assess the effects of soil compaction and surface organic matter removal on site productivity across a range of forest sites (Powers and others 1990). Similar projects on industry lands have also been developed. This paper examines (1) the effect of three levels of soil compaction on the 9-year growth of young planted shortleaf pine (*Pinus echinata* Mill.); and (2) soil bulk density 1 and 8 years after harvesting and site preparation in the Missouri LTSP.

MATERIALS AND METHODS

Site Description

The study was implemented in 1994 in the Ozark Region of southeastern Missouri on the Carr Creek State Forest in Shannon County, on northeastern aspects on sideslopes of two ridges. Before harvesting, the study site was occupied by a mature, second-growth oak-hickory forest with a site index ranging from 22.6 to 24.4 m based on black oak (*Quercus velutina* Lam.) at 50 years (Hahn 1991). Slopes of 20-28 percent are characteristic of the site. Soils are silt loams that developed from cherty residuum, primarily of the Clarksville series (loamy skeletal mixed mesic Typic Paleudults) (Gott 1975).

Experimental Design

Main soil treatments (3 x 3 factorial design) were three levels of organic matter removal (boles-only removal, whole tree removal, and whole-tree plus forest floor removal) and three levels of compaction (none, moderate, and severe) applied to the soil surface. Main treatments were split in half to provide a weed versus no weed (herbicide) comparison. All treatments were replicated three times. The desired compaction level was achieved by driving over plots multiple times with a 14-ton vibrating sheep-foot roller. Logging debris and forest-floor material were removed before compaction so that mineral and organic components would not be mixed. Severe compaction was intended to approach 80 percent of the approximate growth-limiting bulk densities in the surface 10 cm of soil (Daddow and Warrington 1983). Moderate compaction levels were designed to come close to the midpoint between no and severe compaction. Soil bulk density measurements were taken after one, three, five, and eight passes (Blake and Hartge 1986). Bulk density samples were collected from the 0-10, 10-20, and 20-30 cm depths. After mineral soil compaction was complete, forest floor and logging debris were returned, as needed, to achieve each plot treatment combination. Following treatment installation, 1-0 seedlings of red oak (*Q. rubra* L.), white oak (*Q. alba* L.), and shortleaf pine were planted in rows at a spacing of 3.66 m apart in and between rows at a ratio of three oaks of each oak species to one shortleaf pine. The oak to shortleaf pine ratio approximated the preharvest oak to shortleaf ratio. Complete description of the site and the LTSP installation are provided elsewhere (Ponder and Mikkelson 1995).

For this report, only shortleaf pine and the three levels of soil compaction with and without weed control were used. For the first 2 years after planting, a 0.5-m-radius area around all seedlings was sprayed annually in the spring with a mixture of glyphosate and simazine to control weeds. Thereafter, weeds were controlled in only half of all plots.

Post-harvest (after 8 years) bulk density measurements were collected from no and severe compaction treatments only, using the method described by Page-Dumroese and others (1999). Generally, Page-Dumroese and others (2006) reported that differences between the moderate and severe compaction levels have been small, if detectable at all, after 5 years for LTSP installations. An irregularly shaped hole was carefully excavated to the desired soil depth. Soil from the hole was placed in zip-locked plastic freezer bags. Once excavated, the hole was filled with expanding polyurethane foam, and a plywood plate weighted with a rock was placed on the surface. The plate ensured that continued expansion of the foam would fill any irregularities in the hole. The foam was left to cure for at least 8 hours. The foam cast was then removed from the hole and returned to the laboratory where excess soil, small rocks, and roots were removed from the outside of the foam. Foam cast volume was determined by water displacement.

Seedling survival, height, and diameter were measured after planting and annually thereafter. Diameter at 2.54 cm above the soil surface, which is not presented here, and diameter at breast height (DBH), when trees reached at least 1.4 m tall, were measured.

Statistical Analyses

The experiment was analyzed as a randomized complete block design. Survival was analyzed using the PROC LIFETEST procedure (Allison 1995). Growth and bulk density data were analyzed using analysis of variance with the PROC GLM procedures in SAS Version 8.2 (SAS Institute 1999). All statistical tests were performed at the $\alpha = 0.05$ level of significance. Because organic matter was removed prior to compaction, then returned to each plot, 1- and 8-year bulk density results were assumed to be unaffected by organic matter removal treatments. Therefore, results from the different organic matter removal treatment plots were combined for each level of compaction.

RESULTS

Bulk Density

Eight years after applying compaction treatments, soil bulk densities for the 0- to 10- and the 20- to 30-cm depths did not differ (p = 0.0991 and p = 0.6202) between no and severe compaction. Compaction was only 5 and 14 percent higher than no compaction for the two depths (Table 1). But at 10 to 20 cm depth, average bulk densities for severe compaction were 24 percent higher (p = 0.0041) than for no compaction. Average bulk densities were not affected by weed control.

Survival and Growth

After the first 9 years following planting, survival of shortleaf pine averaged 70 percent (Table 2) and has not been affected by compaction or weed control treatments (p = 0.2781 and 0.1102). Most of the 30-percent mortality occurred during the first growing season.

Table 1 .—Average bulk density of a Clarksville cherty silt loam soil 9 years after soil compaction and weed control treatments. Standard deviations are in parentheses.

Treatment	Depth	Bulk density[1]
	cm	Mg/m^3
Compaction		
None	0-10	1.37(0.33)a[2]
Severe	0-10	1.60(0.28)a
p value		0.0991
Weed control		
With	0-10	1.47(0.39)a
Without	0-10	1.49(0.25)a
p value		0.9967
Compaction		
None	10-20	1.40(0.24)a
Severe	10-20	1.84(0.41)b
p value		0.0041
Weed control		
With	10-20	1.71(0.48)a
Without	10-20	1.53(0.30)a
p value		0.1931
Compaction		
None	20-30	1.70(0.44)a
Severe	20-30	1.79(0.40)a
p value		0.6202
Weed control		
With	20-30	1.79(0.27)a
Without	20-30	1.70(0.53)a
p value		0.6085

[1]Mean of 12 samples.
[2]Within the column, for each treatment and depth combination, values with the same letter are not significantly different.

Although bulk density for the moderate compaction level was not measured, total height and DBH were. Shortleaf pine in moderate and severe compaction plots averaged 41 cm taller and 12 mm larger in diameter than trees in the no compaction treatment plots (Table 2). Total height growth and DBH differences between moderate and severe compaction were not significant. Vegetation control increased both height and DBH (p = 0.0202 and p = 0.0001) compared to no vegetation control (Table 2). Interactions between vegetation control and compaction for total height growth and DBH were not significant (p = 0.1009 and p = 0.5434).

DISCUSSION

Coarse fragments (rocks, stones, chert, etc.) and large roots make it extremely difficult to accurately determine bulk density on these soils. Bulk density measurements taken immediately after treatment application were accomplished using soil cores (30 cm in length x 9 cm in diameter) extracted from plots using a newly developed soil-coring device (Ponder and Alley 1997). A subset of the bulk density data showed that the compaction increased bulk density for the 0-10 cm depth approximately 8 percent (to 1.65 Mg/m^3) for moderate treatments and approximately 15 percent (to 1.78 Mg/m^3) for severe treatments. However, upon examination of the complete data set, it was discovered that the sampler introduced error during the coring process, causing an overestimation of bulk density (Lichter and Costello 1994). The magnitude of error cannot be determined because the sampler error was not discovered until several years later, by which time plots may have begun to recover from compaction. Although the error is now apparent, there is no reason to believe that levels of

Table 2. --Average survival, total height, and diameter at breast height (DBH) of shortleaf pine as affected by three levels of soil compaction and weed control, 9 years after planting.

Treatment	Survival	Total height	DBH
	Percent	cm	mm
Compaction			
None	72a	586.3a[1]	96.5a
Medium	65a	613.7b	103.3b
Severe	70a	641.0b	112.9b
p value	0.2781	<0.0001	0.0019
Weed control			
With	69a	632.9a	131.3a
Without	70a	603.5b	82.1b
p value	0.1102	<0.0202	0.0001

[1]In each column, within compaction and weed control levels, values followed by the same letters are not significantly different according to Duncan Multiple Range test.

soil compaction based on earlier bulk density measurements were not achieved. Large-scale field plots similar in size to those in the current study have been successfully compacted to different levels using ground-based equipment (Page-Dumroese and others 2006) with several years of vegetation development and measurements (Fleming and others 2006). The polyurethane foam method was used for remeasuring bulk density in year 8.

Once compacted, forest soils usually require several decades to recover to undisturbed levels of bulk density (Sands and others 1979, Tiarks and Haywood 1996). Recovery rates depend on many factors, including the frequency of harvest cycles, soil moisture conditions during harvest, soil texture, and rock-fragment content (Miller and others 1996, Williamson and Neilsen 2000, Liechty and others 2002). Natural soil processes such as swelling and shrinking due to moisture changes, movement of soil particles by freezing and thawing (including frost heave), and biological activity tend to restore soil physical properties to predisturbance conditions (NCASI 2004). Froehlich and McNabb (1984) described three criteria necessary for these processes to be effective: 1) the soil must be sensitive to the process; 2) the climate must produce the temperature and moisture regimes necessary for the process to occur; and 3) the cycles or processes must occur with sufficient frequency and duration. 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 (Page-Dumroese and others 2006). In the case of the present study, although some amelioration of initial treatment bulk density has probably occurred over time, the amount cannot be adequately measured because of errors in the initial measurements. Any future recovery should be detected in the next round of bulk density measurements.

Snow and ice damaged some trees during the winter of 2000-2001. Thirty-four trees (14, 9, and 12 trees respectively, in no, moderate, and severe compaction treatments) with crooked main stems, broken and deformed branches, and broken tops were removed in the summer of 2002. The number of trees damaged did not vary with compaction, but all except one of the trees removed were in the weed control plots. Apparently, the damage occurred when the build-up of snow and ice in tree crowns became greater than what trees could bear without bending. The duration of the snow and ice weight was sufficient to cause breakage and permanent bending. Subsequently, when trees resumed springtime growth, new growth added to the already crooked stems, deforming them more. Trees receiving weed control were 29 cm taller and had more diameter growth (table 2) and their crowns were larger and could collect more snow and ice than smaller crowned trees in no weed control subplots. Hence, trees in no weed control subplots had very little damage.

The better shortleaf pine growth in the compacted treatments as compared to trees in the no compacted treatment is not completely understood. Compaction can alter the water-holding capacity of soils and has different effects depending on the texture of the soil. Compaction generally reduces the available water holding capacity of fine-textured soils; in coarse-textured soils, compaction can reduce the size of very large pores and increase water retention (Hyder and Sneva 1956, Rashid and Sheikh 1977). Shortleaf pine is a species that is found across a broad range of sites due to its tolerance of a wide range in soil conditions; however, it does best on soils with silt loam and fine sandy loam textures (Lawson 1992). The soil in this study was a silt loam (Clarksville cherty silt loam with ~ 40-70 percent angular fragments by volume < 15 cm in diameter). The impact of coarse fragments on properties of the Clarksville due to compaction is questionable. Once compacted, does it behave as a fine-textured or somewhat coarse-textured soil? Rock fragments alter the physical properties of soils in ways that can increase water availability. Surface and subsurface rock fragments can act as mulch, reducing evaporation from soils primarily in the upper 25 cm of the profile (van Wesemael and others 1995). Soils containing significant rock fragments have lower fine-earth water content in their top layer due to the small water retention capacity of stony soils (Childs and Flint 1990, van Wesemael and others 1995). Therefore, evaporation rates are lower in soils containing rock fragments compared with stone-free soils. The soil compaction process for the Missouri study pressed the rock fragments on the soil surface, which ranged from 30 to 50 percent, into the upper soil layer, which already contains 15 to 25 percent by volume chert fragments, greatly increasing rock fragment content in that soil layer. A 15-cm thick layer of rock fragment mulch reduced evaporation compared with a non-stony soil (van Wesemael and others 1995).

In a greenhouse experiment using sieved Clarksville silt loam soil, shortleaf pine root growth was limited by compaction due to reduced aeration (Siegel-Issem and others 2005). Although the study demonstrated how shortleaf root growth is inhibited in the compacted sieved or the fine-earth fraction of the soil, it does not contribute to the understanding of how compaction of unsieved Clarksville soil, as in the present study, affects tree growth. Brais (2001) reported that the 5-year mean height of planted white spruce [*Picea glauca* (Moench) Voss] on fine textured soils free of coarse fragments in response to soil compaction due to skidding during timber harvesting was only 28 percent higher in the between track areas and 25 percemt higher in the track areas than in undisturbed areas. But the relative productive rate of trees growing in between track areas (0.44 per year) was higher than that for trees growing in undisturbed areas (0.26 per year), while no significant differences were found between undisturbed and wheel track areas. Moreover, vegetation competition rather than skid trail traffic explained over 40 percent of the differences in total tree height and root collar diameter (Brais 2001).

Compaction has been shown to reduce vegetative competition and increase moisture availability at several LTSP locations and improve survival or growth (Powers and Fiddler 1997, Gomez and others 2002, Li and others 2003, Page-Dumroese and others 2006). Compaction has also been found to increase growing-season soil temperature at many of the LTSP locations (Fleming and others 1999, Kranabetter and Chapman 1999, Page-Dumroese and others 2006). At the Missouri site, both average fifth-year soil water and temperature were higher (14 and 16 percent, respectively), for the severe compacted treatment than for the no compaction treatment (Ponder 2004). Further differences in soil water and temperature were manifested by controlling weeds, which also affected growth. The greater height of trees in the absence of weeds compared to the presence of weeds can likely be attributed to better soil water because the no weed treatment had higher soil water. Five-year seasonal soil water content was 64 percent higher for no weed subplots than for subplots with weeds (Ponder 2004). The difference in mean 5-year seasonal soil water content for no weed subplots was 6 percent higher for severely compacted plots compared to plots not compacted and 34 percent higher for plots with weeds for plots severely compacted, compared to plots not compacted. Also, during the dry, hot season, soil temperatures at the Missouri site were higher in no weed subplots than in subplots with weeds (20.2 ˚C versus 13.4 ˚C, respectively).

CONCLUSIONS

After 8 years, differences in bulk density were present for no compaction and severe compaction treatments for the 10-20 cm depth only. Weed control did not affect bulk density. After 9 years, neither soil compaction nor weed control affected shortleaf pine survival but both benefited growth. Growth differences attributed to compaction and weed control can generally be explained by the increase in soil water. Factors not measured may also be at work such as rooting depth, rooting pattern, and impact of compaction on the soil matrix to influence soil moisture availability. Nine years is a short time in the development of a Missouri shortleaf pine plantation and current rate of growth can change, especially as canopy expansion continues placing greater demand on soil water and nutrients.

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