SOIL COMPACTION AFFECTS GROWTH OF YOUNG SHORTLEAF PINE FOLLOWING LITTER REMOVAL AND WEED CONTROL IN THE MISSOURI OZARKS

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ABSTRACT.—More frequent use of heavy equipment in intensive forest practices can lead to soil compaction and reduced productivity. The growth of 8-year-old planted shortleaf pine (*Pinus echinata* Mill.) and seasonal soil moisture stress and soil temperature were measured on cherty silt loam soil from which surface organic materials (whole tree plus leaf litter) had been removed before applying compaction treatments. Three levels of compaction and two levels of understory control were compared. Trees were significantly taller and had more height and diameter at breast height (d.b.h.) growth in compacted treatments than in the no compacted treatment and when the understory was absent than when present. Mean seasonal soil moisture stress was much higher for compacted treatments than for the no compaction treatment during the measurement period, except for September. But differences were significant only for May (severe compaction>no compaction) and September (severe compaction<no compaction). Soil temperature, although higher for compacted treatments than for the no compaction treatment, was not significantly different between treatments. Both soil moisture stress and soil temperature were higher when the understory was present than when absent.

Compaction affects nearly all properties and functions of the soil, physical as well as chemical and biological. Compaction causes a rearrangement of the soil particles resulting in the alteration of pore size distribution, decreased porosity, and changes in the movement and content of heat, air, water, and nutrients in the soil (Grable and Siemer 1968). These changes in bulk density affect infiltration, drainage, water availability, aeration, root exploration, and nutrient uptake, all of which can directly influence soil productivity.

The compaction of soils during forestry operations reduces the rate of establishment of natural regeneration, has been shown to reduce tree growth for periods spanning at least a decade, and can have deleterious effects on tree form (Wronski and Murphy 1994). Forest harvesting, especially whole tree harvesting and litter raking, can remove considerable biomass, leaving the residual forest floor significantly disturbed. Severe compaction and organic matter removal can affect both the quality and productivity of the soil. Studies conducted in North America have shown that tree growth and forest productivity decrease due to compaction. For example, the reduction in ponderosa pine (*Pinus ponderosa* Dougl. ex Laws) height and volume growth attributed to soil compaction in southwest Oregon was still evident 17 years later (Froehlich 1979). On the Coastal Plains of South Carolina, one-year-old loblolly pine height growth on compacted skid trails was 40 to 50 percent less than height growth on non-compacted soil (Hatchell and others 1970).

While there is ample evidence supporting the reduction in growth caused by soil compaction, it has not always produced negative growth effects (Miller and others 1996, Cochran and Brock 1985). For example, on several California sites, the effect of compaction on 4-year-old ponderosa pine varied with soil texture and soil water (Gomez and others 2002a). These authors reported that compaction reduced the growth young ponderosa pine in California on fine textured soils due to increased soil strength, but soil compaction increased growth on a sandy textured soil due to increased water holding capacity.

Coile (1948) reported that the growth of shortleaf pine increased as soil available water increased in the subsoil in the North Carolina Piedmont. Mohr (1896) concluded that sands were a poor growth medium for shortleaf and on the better sites subsoil textures were heavier than topsoil textures. Each soil has unique properties that interact to respond to compaction in different ways to affect tree growth.

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Understanding the effects of compaction on site productivity is among many factors affecting the development of young trees.

The specific objectives of this work were to: (i) assess the height and diameter response of shortleaf pine to soil compaction after 8 years and (ii) assess the effect of understory treatments with and without compaction on height and diameter of shortleaf pine.

Materials and Methods

Site Description

The study is in one of the USDA Forest Service's Long-Term Soil Productivity (LTSP) sites and located in the Carr Creek State Forest in Shannon County, Missouri. The LTSP study, 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). The silt loam soils on the Missouri site are primarily of the Clarksville series (Loamy-skeletal, mixed mesic Typic Paledults). Soils are derived from Ordovician and Cambrian dolomite with some areas of Precambrian igneous rock (Missouri Geological Survey 1979). Weathered material has formed a deep mantle of cherty residuum (Gott 1975). Initial soil chemical properties of the 0-20 cm depth were: pH (1:1 water) 5.7; total C, 3.3 %; total N, 0.11%; P, 16.9 mg/kg; Ca, 789 mg/kg; and Mg, 61 mg/kg (Ponder and others 2000). Prior to harvest, the site had a well-stocked, mature, second-growth oak (*Quercus* spp.)-hickory (Caraya spp.) forest. The site index indicated that the height of 50-year-old black oak (*Q. velutina* Lam.) should range from 74 to 80 feet on this site (Hahn 1991). Mean annual precipitation and temperature is 112 cm and 13.3° C, respectively (Barnton 1993). Moisture drains easily through the soil to subsurface channels.

Experimental Design

The LTSP study includes nine treatments derived from combinations of three levels each of organic matter removal and soil compaction. The three levels of organic matter removal included: (1) merchantable boles removed (boles only), (2) all living vegetation removed (whole tree), and (3) all living vegetation plus forest floor removed, exposing mineral soil (whole tree + forest floor). Merchantable boles included trees with diameters at breast height (d.b.h.) of 25 cm or larger. The three levels of compaction included: (1) no compaction (C_0), (2) moderate compaction (C_1), and (3) severe compaction (C_2). The targeted bulk density of severe compaction treatment was an increase of 30% more than the bulk density of the no compaction treatment. The moderate soil compaction treatment was intermediate between the severe compaction and no compaction treatments. The latter was accomplished by using heavy road construction equipment. Mean bulk density increased to up to 1.8 g cm^3 compared to 1.3 g cm^3 for the no compacted treatment. A complete description of the site and the LTSP installation are provided elsewhere (Ponder and Mikkelson 1995).

For this report, three levels of compaction and two levels of vegetation management were used. For the first 2 years after planting, a 3-foot radius area around each shortleaf pine seedling was sprayed annually in the spring with a mixture of glyphosate and simazine mixture to control weeds. Beginning in the 3rd growing season, half of each plot was kept weed-free (understory absent) to permit planted trees to grow freely without weeds. Weeds were not controlled (understory present) in the other half of the plot.

Seedling heights were measured after planting and annually thereafter. Diameter at breast height was measured when trees reached 1.4 m tall or taller. Soil moisture stress (soil moisture resistance) and temperature to a depth of 30 cm were measured monthly during the growing season using Soiltestä moisture cells in the no compaction and severe compaction treatments at 10 cm increments from 0 to 30 cm deep for some years. Current-year shortleaf pine leaves were collected in August of years 4 and 8 for macronutrient analyses. For this report, 5- and 6-year data for soil moisture stress and temperature and 4- and 8-year data for leaf nutrient concentrations were used. Data were not available for all years for leaf nutrients nor soil moisture stress and temperature. All measurements and analyses were done according to standard procedures. Rainfall measurements were also recorded at the weather station on the study site.

Table 1.—The effect of soil compaction and understory on mean annual survival of 8-year-old shortleaf pine in Missouri.

	Year							
Treatment	1	2	3	4	5	6	7	8
Soil compaction				Survival (Percent)				
No	81	81	78	75	74	72	72	72
Moderate	67	66	66	66	66	66	66	65
Severe	75	74	74	74	72	72	70	70
Understory								
Absent	73	73	72	72	70	69	69	69
Present	74	74	73	72	72	72	72	70

Table 2.—The effect of soil compaction and understory control on 8-year height and d.b.h. (diameter 4.5 ft above the ground) growth of shortleaf pine planted after forest floor removal.[1]

Treatment	Total height growth	Total d.b.h. growth
Soil compaction	cm	cm
None	273±171a[2]	32±13a
Moderate	304±136a	34±12a
Severe	373±132b	39±13b
Understory		
Absent	310±151a	40±13a
Present	324±142a	31±12b

[1]Values after the ± symbol are mean standard deviations.
[2] For soil compaction or understory treatment, columnar means followed by the same letter are not significantly different at $\alpha = 0.05$ Tukey's Studentized Range test.

Statistical Analyses

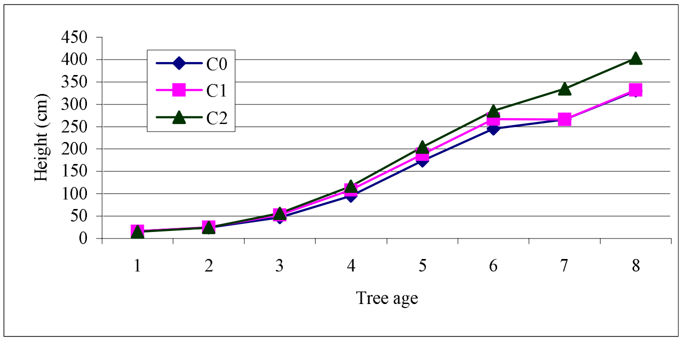
The experiment was analyzed as a split-plot design with three levels of soil compaction two levels of understory as the subplots. Survival was analyzed using the PROC LIFETEST procedure described in "Survival Analysis Using the SAS System" (Allison 1995). Annual tree survival data were coded according to tree status, 1 for live trees and 0 for dead trees and subjected to an ANOVA. Survival differences among treatment variables were tested using the Tukey's Studentized Range test at the a = 0.05 level of significance. Total height and d.b.h. growth through year 8, leaf nutrients for years 4 and 8, and soil moisture stress and soil temperature were analyzed using analysis of variance with the PROC GLM procedures in SAS Version 8.2 (SAS Institute, Cary, NC). Prior to analysis, soil moisture stress and soil temperature data were averaged for the fifth and sixth growing seasons. Data for all depths were combined. All statistical tests were performed at the a = 0.05 level of significance.

Results

Survival and Growth

Eight years after planting, survival was not significantly affected by soil compaction or understory treatments (Table 1). Most of the mortality occurred during the first year. This mortality may have been due to the less than ideal soil moisture during the planting period (May through June). Survival after year 1 through year 8 declined only by 10, 2 and 5 percent for no, moderate, and severe compaction treatments, respectively. For understory treatments, survival at the end of the second year was 73 and 74 percent for understory absent and understory present, respectively and declined by 4 percent between year 1 and year 8 for both understory treatments. The interaction between compaction and understory was not significant.

Total height and diameter growth were significantly better for compaction treatments than for the no compaction treatment (Table 2). Differences between moderate and no compaction treatments were not significant for either measurement at the end of 8 years. Differences in tree height between



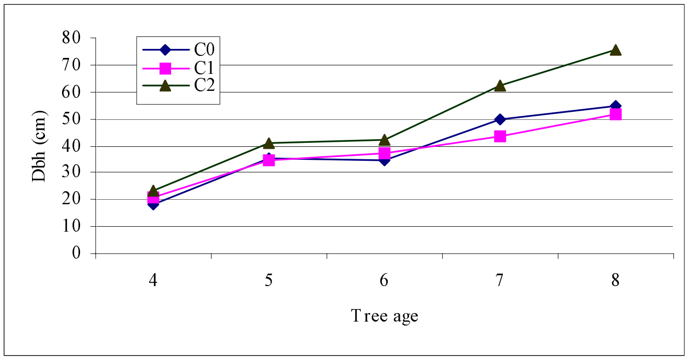


Figure 1.—Annual height and diameter at breast height (d.b.h.) for shortleaf pine growing in compacted soil (no compaction=C0, moderate compaction=C1, severe compaction=C2) in the Missouri Long-Term Soil Productivity (LTSP) study.

treatments began to appear between years 4 and 5, when most trees were tall enough to measure d.b.h. (Fig. 1). The presence or absence of an understory was significant only for d.b.h. growth. Shortleaf pine with the understory absent had more d.b.h. growth than when the understory was present (Table 2). Interaction between soil compaction and understory treatments was not significant.

Leaf Nutrient Concentration

Leaf macronutrient content is presented for the fourth and eight growing seasons (Table 3). Soil compaction had no significant affect on leaf nutrient concentrations in the fourth or sixth growing season, but understory did (Table 3). Leaf N was higher when the understory was absent than when the understory was for both growing seasons. Calcium and Mg were significantly higher for shortleaf pine leaves in the understory present treatment than in the understory absent treatment for fourth growing season but not after six growing seasons. Both P and K were higher for leaves from trees in the understory absent treatment than in the understory present treatment for year 8, but not for year 4. There was a significant interaction for Ca in year 6 (Fig. 2A). Leaf Ca was lower when understory was absent compared to when present for severe compaction. The reverse was true for the no compaction treatment.

Soil Moisture Stress

Soil moisture stress and soil temperature data are presented only for two treatments; no compaction and severe compaction (Table 4). Soil moisture stress readings were higher for severe compaction than for no compaction, except for September. However, readings differed significantly between treatments only for the months of May and September. Differences between understory treatments were significant for all months. But, there were significant interactions for both May and September between understory and soil moisture stress (Figs. 2B and 2C). The interactions showed that regardless of compaction treatment, moisture stress was highest when understory was present. For May, the mean soil moisture stress measurement for severe compaction with understory present was 84.7 ohms 10^{-1} and 29.5 ohms 10^{-1} when understory was absent compared to an average of 17.0 ohms 10^{-1} for these understory treatments and no compaction. For September, mean soil moisture stress was considerably

Table 3.—The effect of soil compaction and understory on leaf macro nutrient concentration of shortleaf pine during the fourth and eighth growing season.

	Nutrient				
Treatment	Nitrogen	Phosphorus	Potassium	Calcium	Magnesium
Fourth growing season			Concentration (g/kg)		
Soil compaction					
No	14.45a[1]	0.88a	6.39a	2.60a	0.71a
Moderate	14.38a	0.96a	6.12a	2.06a	0.67a
Severe	14.91a	1.02a	6.52a	2.02a	0.66a
Understory					
Absent	15.34a	0.96a	6.53a	1.90a	0.63a
Present	13.91b	0.95a	6.18a	2.50b	0.72b
Interaction	0.3703[2]	0.343	0.862	0.568	0.607
Eighth growing season					
Soil compaction					
No	14.97a	1.07a	5.60a	1.76a	0.84a
Severe	14.90a	1.08a	5.59a	2.20a	0.93a
Understory					
Absent	16.57a	1.12a	5.99a	1.90a	0.86a
Present	13.29b	1.03b	5.20b	2.05a	0.91a
Interaction	0.2186	0.634	0.194	0.007	0.067

[1]For soil compaction or understory treatment, columnar means followed by the same letter are not significantly different at $\alpha = 0.05$ Tukey's Studentized Range test.
[2]*p-value.*

higher for no compaction with understory present (158.2 ohms 10^{-1}) than for severe compaction with understory present (80.7 ohms 10^{-1}).

Soil temperature was generally a little higher in the severe compaction treatment than in the no compaction treatment but differences were not significant except for August (Table 4). Differences in soil temperature between understory treatments were significant for all months; soil temperature was higher when the understory was present than when absent. Interactions were not significant.

Discussion

Bulk density data were not presented here but were presented earlier (Ponder and others 1999). The data showed that severe soil compaction effectively increased soil bulk density over no soil compaction. The percent change in bulk density between the no compaction treatment and the severe compaction treatment was 22, 29, and 26 percent for the 10-, 20-, and 30-cm depth increments, respectively. While the bulk density of the moderate compaction treatment was increased above that for the no compaction level, it was less than that for severe compaction. At a given bulk density, soil water content determines root growth potential by influencing soil strength, aeration, and plant available water. Neither soil strength nor plant available water content was measured for this report. However, in a laboratory study, Siegel-Issem (2002) found that compaction moderately increased available water and decreased aeration porosity in the Clarksville soil from this site.

Soil compaction was beneficial to the growth of shortleaf pine growing in the Clarksville silt loam on this Ozark site. However, neither soil moisture stress nor soil temperature data during the months of May thru September explain why. These data showed compacted plots usually had both higher soil moisture stress and temperatures most of the measurement period (Table 4), indicating that compacted plots were drier and hotter than plots with no soil compaction. As soils became drier, soil temperatures increased, heating the air above the soil surface and increasing evaporation. Sauer and others (2002), in a water balance examination, reported that evaporation accounted for 91 percent of the rainfall that fell on a Clarksville soil in Arkansas dominated by tall fescue (*Festuca arundinacea* Schreb.) cover. Excavations at their site showed that the greatest plant root density was near the surface and that the soil layers above 0.5 m appear to be primarily responsible for supplying water for evaporation.

Soil moisture stress variation from year to year depends a lot on rainfall during the measurement period. For example, during this study period, plots received approximately 65.3 cm of rain during May through August and a total of 137.1 cm during one year compared to 20.3 cm during May through August and a total of 79 cm for another year.

Several authors have reported that the performance of young conifers was either better or not significantly different between compacted and not compacted soil treatments (Conlin and van den Driessche 1996, Page-Dumroese and others 1998, Heninger and others 2002, Gomez and others 2002a). For example, soil compaction had little effect on height growth of 13-week-old laboratory-grown lodgepole pine (*P. contorta* Dougl. ex Loud.), with the tallest seedlings occurring at the greatest compaction rate (Conlin and van den Driessche 1996). In another study, Miller and others (1996) reported that average height for 8-year-old Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*), Sitka spruce (*Picea sitchensis* (Bong.) Carr.), and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), did not differ among soil compaction treatments. Western white pine (*P. monticola* Dougl. ex D. Don) seedlings were tallest after soil compaction (Page-Dumroese and others 1998).

Foil and Ralston (1967) reported that loosening the soil from its normal structure reduced the height of loblolly pine (*P. taeda* L.) on light textured soils, but stimulated it on clay soils. They concluded that loosening the light textured soil affected its aeration porosity reducing the amount of available water and nutrients to suboptimal levels. Archer and Smith (1972), Stone and Elioff (1998), and more recently Gomez and others (2002a) demonstrated this concept. The implication is that some level of compaction of sandy loam (medium textured) soils can increase soil moisture availability while maintaining adequate

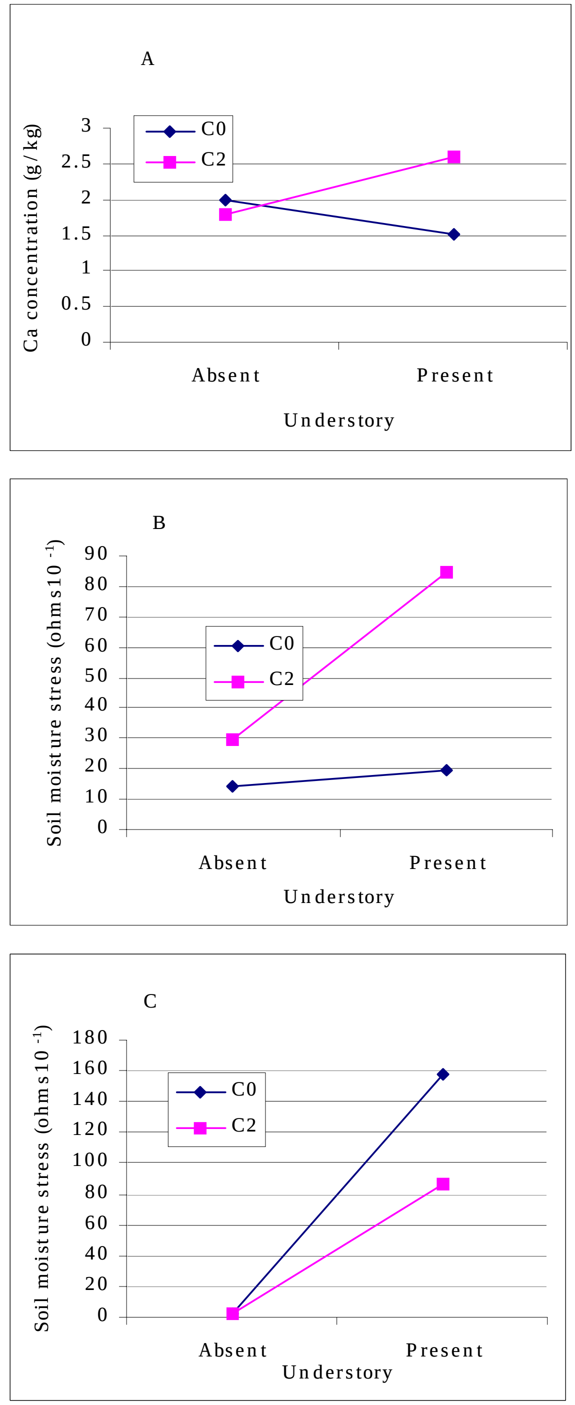


Figure 2.—Interactions between soil compaction (no compaction=C0 and severe compaction=C2)and understory treatments for (A) leaf Ca, (B) soil moisture stress in May, and (C) soil moisture stress in September.

Table 4.—The effect of soil compaction and understory control treatments effect on monthly soil moisture stress and temperature.

		Month				
Treatment	Level	May	June	July	August	September
Soil moisture stress (ohms 10^{-1})						
Soil compaction	No	16.9	26.2	24.2	3.6	54.0
	Severe	52.6	30.4	25.1	6.1	37.7
	p-value	0.001	0.595	0.933	0.126	0.007
Understory	Absent	22.0	1.8	2.8	0.4	2.1
	Present	47.7	56.4	46.2	9.4	109.4
	p-value	0.001	0.001	0.001	0.001	0.001
Interaction	*p-value*	0.006	0.538	0.894	0.106	0.006
Soil temperature (^{0}C)						
Soil compaction	No	15.1	12.1	14.1	14.3	3.5
	Severe	17.0	14.3	13.4	15.5	6.9
	p-value	0.105	0.191	0.781	0.047	0.344
Understory	Absent	13.1	9.8	10.8	11.6	3.3
	Present	18.5	16.3	16.1	17.8	8.5
	p-value	0.001	0.001	0.002	0.001	0.042
Interaction	*p-value*	0.873	0.287	0.187	0.350	0.262

aeration, and does not constitute a physiological problem to trees (Gomez and others 2002b). However, in the present study, soils are cherty silt loams and not sandy loams. But it seems probable that the cherty silt loam is behaving similar to compacted sandy loam. Voids between the fine-earth fraction (<0.002-m diam.) and abundant rock fragment surfaces are the dominant macropores in the chert silt loam soils (Sauer and Logsdon 2002). Upon compaction, soil micropores increase and soil macropores decrease, creating soil moisture characteristic of a finer textured soil. Nash (1963) maintained that soil moisture is the principal factor limiting growth of shortleaf pine, especially in Missouri. It grows best on soils with silt loam and fine sandy loam textures (Lawson 1992).

Additionally, shortleaf pine is apparently more adaptable to the physical changes in the soil environment on this site than the hardwoods that are also being studied (Ponder 2003). The hardwoods grew less in the compacted treatments (data not shown). It has been shown that top growth is less sensitive than root growth to soil disturbance in the early years (Singer 1981, Heilman 1981). Observations of root systems developed in heavy compacted soils show that lateral roots comprised a larger percentage of total root weight than was generally the case in less compact soils (Rodney and Ralston 1967). Work is being initiated in the Missouri LTSP study to compare tree root development between compaction treatments.

While soil moisture stress is an indicator of the soil moisture level, it may not be sensitive enough to effectively relate directly to plant physiological conditions. Soil moisture stress levels created by the two understory conditions were much farther apart but growth differences were significant only for d.b.h. growth (Table 1). This suggest that some of the growth advantage of shortleaf pine in compacted soil may be at a period of the growing season when soil moisture stress is more favorable in compacted soil and not limited to the time of the growing season when there are large differences in soil moisture stress attributed to understory treatments or compaction. Also, the more rapid growth on the compacted plots may have created the greater moisture stress found in May. Moisture stress was less on the compacted plots than on non-compacted plots in September after tree growth had nearly ceased because the compacted plots inherently held more moisture.

Leaf macronutrients were not significantly affected by soil compaction. Earlier, Gomez and others (2002b), using N^{15} and ponderosa pine, reported that they did not observe any significant effects of compaction on leaf N with total removal of the forest floor at two LTSP installations on loam and clay textured soils. These authors suggest that while leaf N differences attributed to soil compaction treatments were small, compaction is a significant factor associated with increased N recovery. Compaction may have prevented losses from the soil by reducing mineralization and increasing the probability of overall nutrient uptake in years to come.

The importance of understory on foliar N concentration was evident for both measurement periods. Weeds are hardy competitors for soil nutrients. Data collected over a number of years from loblolly pine for the LTSP in North Carolina show that foliar N was consistently higher for the understory absent treatment than for the understory present treatment (data not shown). Weeds reduce the amount of water and nutrients available to nearby trees, which are needed for growth. Less water implies reduced mineralization, which in turn influence the acquisition and the availability of other nutrients (Wilson 1994, Zabowski and others 1994).

Summary

The mechanism by which compacted soil in the present study supported better shortleaf pine growth than soil not compacted is not completely understood. Much of the better growth is likely due to better soil physical changes that caused better soil moisture conditions for growth during some part of the growing season. The better growth for trees in the compacted treatment is consistent with a LTSP study in California that has medium textured soils also. Controlling the understory increased leaf N and d.b.h. growth, but not height growth. Forest soils are complex with many components whose interactions can produce varied results. However, for this 8-year period, compaction has had a positive effect on shortleaf pine growth.

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