EFFECTS OF SOIL COMPACTION ON ROOT GROWTH CHARACTERISTICS OF YELLOW-POPLAR AND SWEETGUM SEEDLINGS[1]

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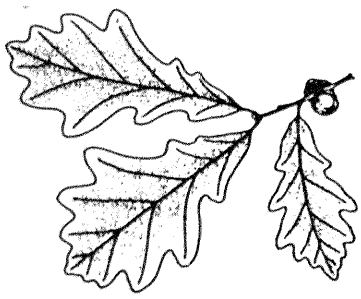

ABSTRACT.--Newly germinated sweetgum (Liquidambar styraciflua L.) and yellow-poplar (Liriodendron tulipifera L.) seedlings were grown under greenhouse conditions for three months in silt loam soils compacted to bulk densities of 1.25, 1.40, and 1.55 g/cm^3. To minimize differences in water and nutrient availability, soil moisture content was maintained near field capacity and the soils were fertilized to specific levels of N, P, and K. Due to differences in root characteristics, lateral root growth of yellow-poplar was more adversely affected by increasing compaction than sweetgum. Percent survival was also lower for yellow-poplar, ranging from 89 percent on the least compacted soil to 33 percent on the highest compaction treatment. Sweetgum exhibited 100 percent survival on all treatments. Significant decreases in total number of roots, depth of primary and lateral root penetration, and horizontal penetration of lateral roots were observed for both species as bulk density increased from 1.25 to 1.55 g/cm^3, with the greatest decreases in each parameter occurring when bulk density increased from 1.25 to 1.40 g/cm^3. Using regression equations, the bulk densities estimated to prevent vertical penetration of lateral roots were 2.20 g/cm^3 and 1.65 g/cm^3 for sweetgum and yellow-poplar, respectively.

INTRODUCTION

Forestry operations such as harvesting and thinning, or topsoiling associated with surface-mine reclamation operations may cause an increase in soil compaction. The establishment and growth of planted tree seedlings following these activities may be adversely affected if compaction of the topsoil and subsurface materials is excessive. Soil compaction increases bulk density and strength, decreases total and macroporosity, alters pore size distribution, and increases the resistance of soil to penetration by plant roots. In compacted soils, infiltration and percolation rates are reduced and water retention characteristics are altered. Soil compaction often results in a reduction of oxygen and carbon dioxide diffusion to and from the plant root (Byrnes et al. 1982, Mitchell et al. 1982).

In field studies, increases in soil compaction associated with vehicular activity resulted in reduced growth rates of loblolly pine (Pinus taeda L.) (Simmons and Ezell 1982, Hatchell et al. 1970), ponderosa pine (Pinus ponderosa L.) (Froelich 1979), radiata pine (Pinus radiata D. Don) (Sands et al. 1979), and Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) (Youngberg 1959). Similarly, pot studies with loblolly pine (Mitchell et al. 1982, Hatchell 1970, Foil and Ralston 1967), and Douglas-fir (Heilman 1981) indicated that root growth, and consequently root penetration, were reduced with increases in soil compaction.

Heilman (1981) estimated that root penetration by Douglas-fir seedlings would be prevented in sandy loam and loam soils compacted to bulk densities of 1.74 to 1.83 g/cm^3. Based on root

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distribution patterns in soils derived from glacial till, Forristall and Gessel (1955) suggested that root penetration by Douglas-fir and western redcedar (Thuja plicata Donn) ceased at bulk densities of 1.25 and 1.80 g/cm^3, respectively. A higher upper limit (1.45 g/cm^3) for Douglas-fir root penetration was found in pot culture studies for seedlings grown in a sandy loam soil (Minore et al. 1969).

Variability observed among studies is due primarily to complex soil-moisture interactions associated with soil texture. Consequently, specific relationships between root growth and soil bulk density are lacking, and the level at which bulk density prevents root elongation of forest tree species is not well defined. Additional research is needed to determine the influence of soil compaction in modifying the physical properties of various soil types and to identify more specifically the levels of compaction at which seedling growth is adversely affected.

Sweetgum and yellow-poplar were selected for investigation primarily because of morphological differences in the root characteristics of the two species. Sweetgum has a very fibrous, highly branched root system while that of yellow-poplar is comparatively coarse and less branched. The objectives of this study were to determine the influence of soil compaction on the root growth of sweetgum and yellow-poplar seedlings, and to identify levels of soil compaction which adversely affect seedling root growth.

MATERIALS AND METHODS

Topsoil materials were collected from the upper 20 cm of three soils. Soil I, collected from a site in Tippecanoe county, Indiana, was classified as a somewhat poorly drained Fincastle silt loam (Aeric Ochraqualf - fine silty, mixed mesic) with 1-3 percent slope and site index (base age 50 years) of 27 to 32 m for yellow-poplar. Soil II was collected from a well drained, eroded phase of Zanesville silt loam (Typic Fragiudalf - fine silty, mixed mesic) with 3-5 percent slope, located in Dubois county, Indiana. The site index (base age 50) for yellow-poplar on this site was 18 to 20 m. Soil III was obtained from a surface mine site located in Clay county, Indiana, which had been reclaimed three months prior to soil collection. The soil media was comprised of a mixture of the A and B horizons of Ava soil (Typic Fragiudalf - fine silty, mixed mesic). This silt loam media was deposited over a cast overburden consisting of soil and Illinoian glacial till. The soil has not yet been reclassified according to SCS guidelines for minesoils and no site index information is available for this site.

Soil from each location was passed through a 2 mm sieve, wetted to attain 15 to 20 percent water content by weight, and resieved. Preliminary studies with these soils indicated that maximum compactibility with minimum required force was obtained within this range of water content (Simmons, unpublished). Based on chemical analyses, soils were fertilized to adjust the available nutrient content to approximately 140 kg/ha nitrogen, 84 kg/ha phosphorus, and 336 kg/ha potassium.

A Riehle Testing Machine fitted with a 15 cm diameter wooden mold was used to compact the prepared soil into 15 x 15 cm PVC pipe containers. A fiberglass screen and a 1.25 cm layer of gravel were used to prevent soil smearing along the bottom interface and to aid in watering from below. Bulk densities of 1.25, 1.40, and 1.55 g/cm^3, representing low, medium, and highly compacted conditions respectively, were established by compacting varying masses of prepared soil to the same volumes in the pots. Soil was added to the containers in 1.25 cm increments, compacted, and the topmost portion loosened to prevent the formation of an interface when the next increment was placed in the container (Bohm 1979).

Each soil and compaction treatment was equilibrated at a moisture content near field capacity (.02-.04 MPa) and a newly germinated sweetgum or yellow-poplar seedling (two leaf stage) was transplanted into each pot. Seedlings were planted in slits 2.5 cm deep and roots were covered with the appropriate silt loam media. Plexiglass covers were fitted to the top of each pot to reduce evaporative losses from the soil surface and seedlings were grown under greenhouse conditions for three months with photoperiods maintained at 16 hours. Pots were watered from below, as needed, to maintain the soil moisture content near field capacity for the duration of the study.

Seedlings were harvested after three months and measured to determine stem height and diameter, caliper of the primary root(s), root volume (Bohm 1979), and length (Rowse and Phillips 1974), and dry weight of the roots, stem, and foliage. Depth of lateral and primary root penetration was determined by sectioning the soil column into 2.5 cm layers and counting the number of roots occurring in each layer. The number of lateral roots penetrating horizontally out of the original planting slit was also determined.

Because of the poor survival of yellow-poplar at the higher compaction treatments, the original randomized complete block design was modified by pooling data from the three soil materials and subsequent analyses were conducted for a completely random design. An analysis of variance (ANOVA) was conducted to determine significant differences in each of the seedling growth parameters associated with soil compaction treatments and differences among means were tested using Duncan's multiple range test. Regression analysis was used to determine correlation between bulk density and selected seedling characteristics.

RESULTS AND DISCUSSION

Yellow-poplar seedling survival was significantly affected by bulk density. Percent survival ranged from 89 percent on the least compacted soils to 33 percent on the highly

compacted soils (fig. 1). No mortality occurred for sweetgum seedlings at any of the soil bulk density treatments. The differences observed in percent survival between the species may be attributed, in part, to differences in root characteristics, which were especially evident at the highest compaction treatment. Because compaction increases soil strength and decreases the number of macropores in the soil system, the coarse roots characteristic of yellow-poplar, were not able to penetrate as extensively into the compacted soil profile as the more fibrous sweetgum roots. The lack of root extension may have caused the increase in mortality of yellow-poplar seedlings at the higher compaction treatments. Using regression analysis, a bulk density of 1.71 g/cm^3 would result in zero percent survival for yellow-poplar seedlings grown in these soils. Since sweetgum exhibited no mortality on any compaction treatment, regression analysis could not be used as a means of predicting seedling mortality from soil bulk density values.

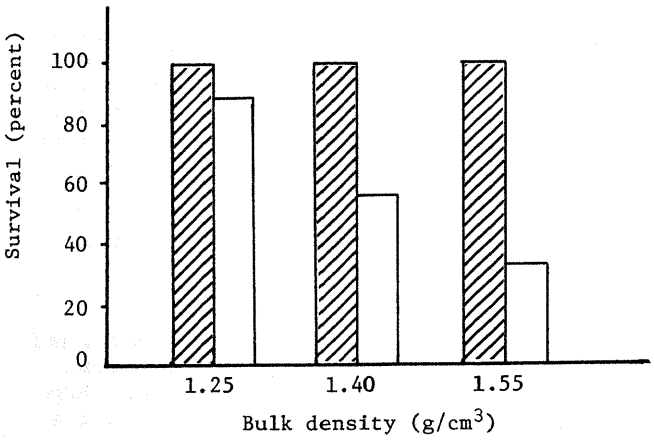

FIGURE 1.-- Effects of bulk density on survival of 3-month-old sweetgum ▨ and yellow-poplar □ seedlings.

Regardless of the compaction treatment, the number of lateral roots of sweetgum was greater than the number for yellow-poplar. This difference is a function of the difference in the root characteristics of the two species (Table 1). For both species, the extent of root penetration was significantly influenced by bulk density. The maximum number of roots at any given depth was greatest on the least compacted soils and declined as bulk density increased. Roots must overcome the strength of the soil to penetrate pores of smaller diameters than themselves. Because of the increased proportion of micropores associated with increases in bulk density, the rate of root elongation and therefore the extent of the root system is reduced with increases in compaction (Greacen and Sands 1980).

Significant differences in depth of lateral root penetration were observed between bulk densities of 1.25 and 1.40 g/cm^3. In the least compacted soils, lateral roots of both species occurred throughout the profile. However, lateral root penetration of sweetgum seedlings grown in medium and highly compacted soils was not observed at depths exceeding 11 cm and 7.6 cm respectively. Lateral roots of yellow-poplar penetrated to a depth not exceeding 5.1 cm in medium compacted soil and 7.6 cm for highly compacted soils. Consequently, the effective rooting volume of seedlings grown in highly compacted soils was significantly less than for those seedlings grown at lower bulk densities.

TABLE 1.--Influence of bulk density on number of lateral roots of 3-month-old sweetgum and yellow-poplar seedlings penetrating to given depths. Values are pooled means for all soil media.

	Lateral Root Penetration					
	Sweetgum			Yellow-poplar		
	Bulk density (g/cm^3)					
Depth (cm)	1.25	1.40	1.55	1.25	1.40	1.55
	number/plant					
0-2.5	96.2a[1]	86.0a	64.3a	31.8a	12.4b	11.3b
>2.5	62.3a	39.3b	19.2b	17.9a	2.6b	4.0b
>5.1	45.6a	20.2b	2.0b	9.5a	0b	2.0ab
>7.6	29.4a	11.3b	0b	4.0a	0b	0b
>10.2	10.0a	0.3b	0b	0.5a	0a	0a
>12.7	3.6a	0a	0a	0.1a	0a	0a

[1]For each species, different letters within a row indicate significance at the p = .05 level using Duncan's multiple range test.

For sweetgum, sixty-five percent of the lateral roots penetrated to a depth exceeding 2.5 cm in the least compacted soils, 46 percent penetrated deeper than 2.5 cm when bulk density increased to 1.40 g/cm^3, and only 30 percent exceeded this depth at bulk densities of 1.55 g/cm^3 (Table 2). Yellow-poplar showed similar trends, with 56 and 21 percent of the lateral roots observed at depths greater than 2.5 cm in soils compacted to 1.25 and 1.40 g/cm^3 respectively. On the highly compacted soils 35 percent of the lateral roots exceeded this depth. Comparatively, the increase above the values reported for the medium compaction treatment was due primarily to a large variability encountered at the highest compaction treatment. Using regression equations, the bulk density at which lateral root penetration would cease was predicted to be 2.20 g/cm^3 for sweetgum and 1.65 g/cm^3 for yellow-poplar. Similarly, predictive equations estimated that lateral root penetration of sweetgum and yellow-poplar would not exceed a depth of 5.1 cm at bulk densities of 1.68 and 1.56 g/cm^3, respectively.

Soil compaction may reduce macroporosity to the extent that growth or survival of roots is determined by oxygen availability when soil moisture content is high. Webster (1978) suggested that poor aeration is likely to limit root growth in compacted soils of finer texture whereas mechanical impedance is more likely to limit root growth in coarse-textured soils. In this study, air-filled porosity (calculated as total porosity

minus volumetric water content) decreased from 24 to 16 percent as bulk density increased from 1.25 to 1.40 g/cm^3; at a bulk density of 1.55 g/cm^3, air-filled porosity was reduced to 10 percent (Simmons, unpublished). These data indicate that a relatively small increase in soil bulk density can cause significant decreases in seedling root growth, due, in part, to poor aeration in the more compact soils. Since changes in soil strength were not determined, no conclusions concerning the interactive effects of increased mechanical impedance and reduced aeration on root growth can be made.

TABLE 2.--Influence of bulk density on average percent of lateral roots of 3-month-old sweetgum and yellow-poplar seedlings penetrating to given depth. Values are pooled means for all soil media.

	Lateral Root Penetration					
	Sweetgum			Yellow-poplar		
	Bulk density (g/cm^3)					
Depth (cm)	1.25	1.40	1.55	1.25	1.40	1.55
	percent					
0-2.5	100	100	100	100	100	100
>2.5	64.8a[1]	45.7ab	29.9b	56.3a	21.0b	35.3b
>5.1	47.3a	23.5b	3.1c	29.9a	0b	17.7ab
>7.6	30.6a	13.2b	0b	12.6a	0b	0b
>10.2	10.4a	0b	0b	1.6a	0a	0a
>12.7	3.7a	0b	0b	0.4a	0a	0a

[1]For each species, different letters within a row indicate significance at the p = .05 level using Duncan's multiple range test.

The number of lateral roots penetrating horizontally out of the original planting slit was also significantly influenced by compaction treatments for both species. The greatest reduction in number of penetrating roots occurred when bulk density was increased from 1.25 to 1.40 g/cm^3 (Table 3). Horizontal penetration of lateral roots of yellow-poplar was negligible on the medium compaction treatment and both species showed no horizontal penetration of lateral roots in the highly compacted soils.

Primary root length and depth of primary root penetration were significantly greater for both species on the least compacted soils (Table 4). Although yellow-poplar had fewer lateral roots than sweetgum, its primary roots were longer and were able to penetrate to greater depths on all compaction treatments than those of sweetgum. Significant differences were also observed in the total root volume of sweetgum, with volumes ranging from 15.1 cm^3 on the least compacted soils, to 13.8 cm^3 on the medium compaction treatment and 8.2 cm^3 on the highly compacted soils. Although differences in this variable were not significant for yellow-poplar, total root volume averaged 1.9 cm^3 and decreased from 2.9 cm^3 on the least compacted soils to 1.2 cm^3 in highly compacted soils.

TABLE 3.--Effects of bulk density on number of lateral roots of sweetgum and yellow-poplar seedlings penetrating horizontally out of original planting slit. Values are pooled means for all soil media.

	Bulk Density (g/cm^3)		
Species	1.25	1.40	1.55
Sweetgum	75.8a[1]	29.4ab	0.8b
Yellow-poplar	20.6a	0.8b	0b

[1]Different letters within a row indicate significance at the p = .05 level using Duncan's multiple range test.

TABLE 4.--Effects of bulk density on primary root length (cm) and depth of primary root penetration (cm) of sweetgum and yellow-poplar seedlings. Values are pooled means for all soil media.

	Bulk Density (g/cm^3)		
Species	1.25	1.40	1.55
Sweetgum			
Length	15.0a[1]	11.1ab	8.1b
Depth of Penetration	9.3a	5.3ab	3.1b
Yellow-poplar			
Length	16.3a	10.2b	6.3b
Depth of Penetration	12.2a	6.6b	4.3b

[1]Different letters within a row indicate significance at the p = .05 level using Duncan's multiple range test.

Soil compaction did not significantly affect stem growth, although weak trends were evident. These results support the work of Heilman (1981) for pot-grown Douglas-fir seedlings, but contradict results reported by Hatchell and others (1970) for older, field-grown loblolly pine seedlings. In this study, water and nutrients were probably not limiting. However, if water and/or nutrients within the soil volume occupied by the restricted root system become limiting, then shoot growth will probably be inhibited unless a greater soil volume can be explored by roots. Under these circumstances a reduction in effective rooting volume imposed by interactions between increased soil strength and decreased aeration will inhibit shoot growth (Greacen and Sands 1980).

SUMMARY AND CONCLUSIONS

Root growth of sweetgum and yellow-poplar seedlings grown in three silt loam soils were significantly influenced by changes in the physical properties of the soils associated with compaction. The total number of lateral roots, depth of penetration of primary and lateral roots, and horizontal penetration of lateral roots decreased significantly with increases in bulk density. Root volume and length, stem height and weight, and root collar diameter followed the same trend, but were not significantly influenced by soil compaction. The lateral root growth of yellow-poplar, a coarse-rooted species, was suppressed to a greater degree than the more fibrous-rooted sweetgum, with increases in soil compaction. This may have, in part, caused the higher mortality rates for yellow-poplar at the higher compaction treatments.

Compaction affects root growth by altering soil physical properties, which in turn influence the complex interactions among soil strength, water and nutrient availability, and aeration. Relatively high water contents and fertility levels used in this study minimized differences in water and nutrient availability associated with different levels of soil compaction. Maintenance of high soil water contents permits an evaluation of the effect of bulk density on root growth when soil strength is lowest. Therefore, the observed growth responses are due primarily to reduced aeration and increased mechanical impedance associated with increases in compaction. The upper limit of soil compaction is critical to the survival of the planted tree, but perhaps of more importance to the land manager is that level of compaction which significantly reduces tree seedling root growth. For yellow-poplar and sweetgum, significant declines in most root growth variables occurred when bulk density increased from 1.25 to 1.40 g/cm^3. Based on the results of this study, any increase in bulk density within this range will likely result in reduced root growth. Before stronger conclusions can be made, further research is needed to determine the effects of soil compaction on specific physical properties and their effects on root growth.

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