Soil Compaction: Effects on Seedling Growth[1]

Steven K. Omi[2]

Abstract-The degree to which a compacted soil affects seedling survival or growth varies according to soil texture, organic matter, moisture content, tree species, and degree of compaction. Soil compaction generally restricts root growth and can inhibit shoot growth. In nurseries, compaction may be rare above the 15-cm depth because nursery soils are cultivated each year; however, below 15 cm compaction is relatively common, and is especially noticeable when drainage is impeded for long periods. The machinery used to manage the crop, the ability to control irrigation and fertilization, and the alternatives for tillage are all important aspects of nursery soil management affecting soil compaction.

INTRODUCTION

This report is the result of a need, expressed by Nursery Technology Cooperative (Oregon State University) members, in particular seedling users, for a literature search on the effects of soil compaction on seedling growth. However, compaction is also of concern to nursery personnel: in an OSU Nursery Survey, compaction was considered a problem by 62 percent of the nurseries surveyed and, relative to all other soil-related problems, was ranked first or second in importance by 24 percent of respondents (Warkentin 1984). Although soil compaction in agricultural crops has been extensively studied (Rosenberg 1964; Greacen and Sands 1980), little information has been published regarding the problem of compaction of forest nursery soils. It is the purpose of this report to review the effects of compaction on soil and seedling growth.

COMPACTION DESCRIBED

Simply stated, soil compaction is a decrease in volume for a given mass of soil (McKibben 1971) as a result of an applied load, pressure, or vibration. It produces rearrangement of soil aggregates and particles, and changes in soil properties (typically, increased bulk density or soil strength, or decreased porosity). Because compaction status of a soil influences air, water, and temperature relationships, it can affect all stages of crop production (McKibben 1971). The energy required to compact soil comes from a variety of sources including rainfall, irrigation spray, foot traffic by animals and people, plant roots, and weight of the vegetation and soil; a significant compacting force is produced by the machinery used to manage and harvest the crop (Greacen and Sands 1980). Whatever the cause, soil compaction may be characterized via several means, including bulk density, soil strength, permeability, and visual observations.

Bulk Density

Bulk density (usually expressed in grams per cubic centimeter) is found by determining the dry weight of soil occupying a known volume (solids plus pore spaces).[3] Bulk-density measurements are commonly used because of their relative ease of sampling, insensitivity to moisture, and known relationships with tree growth (McNabb 1981). The bulk density of most nursery soils is approximately 1.3 g/cm^3, ranging from 0.9 g/cm^3 in sands to 1.6 g/cm^3 in clay loams (Day 1984).

Generally, four methods are used to measure bulk density: core, excavation, clod, and radiation. In the core method, soil cores are collected in a sampler of known volume. This relatively simple procedure does not require complex equipment and leaves the natural soil structure of the extracted core intact so it can be used for other measurements (Adams 1983; Flint and Childs 1984). However, the procedure is time consuming, results can be difficult to obtain in the field, and the presence of large rocks and root fragments can bias the sample (Flint and Childs 1984). In the excavation method, the mass of soil excavated from a hole

1 Paper presented at the 1985 Intermountain Nurseryman's Association Meeting. [Fort Collins, Colorado, August 13-15, 1985].

2 Research Assistant, Nursery Technology Cooperative, Department of Forest Science, Oregon State University, Corvallis, Oregon. Paper 2050, Forest Research Laboratory, Oregon State University.

3 Particle density, another expression for describing soil weight, is the dry weight of soil per solid (excluding pore space) volume.

is divided by the volume of the hole (measured by filling the hole with material of known density or volume, such as water or sand). Like the core method, the excavation method is relatively simple and is suitable for soils having larger coarse fragments. Its disadvantages include the time lag between field sampling and results, accuracy in determining the volume of the excavated hole, and disturbance of the soil sample such that it cannot be used to assess other soil properties (Blake 1965; Adams 1983). In the clod method, clods are removed, weighed, coated with a water-repellent material (such as paraffin), and then immersed in water to determine clod volume. This simple procedure is useful for hard soils; additionally, the clods can be preserved for other measurements as long as the test is done carefully, to maintain clod structure. However, this method is time consuming; and potential bias exists because of the tendency to select samples which are firm enough and of adequate size (Freitag 1971) and because the measurement can exclude the pore spaces between clods (Adams 1983; Flint and Childs 1984).

Whereas the core, excavation, and clod methods disturb the soil, nuclear density probes can nondestructively sample for bulk density. The ability of radioactivity to penetrate the soil reflects the density of soil particles; as soil density increases, the ability to penetrate decreases (Freitag 1971; Adams and Froehlich 1981). The advantages of this method are that many measurements can be taken rapidly in the field, soil disturbance is kept to a minimum, and the same sampling site can be measured more than once. Additionally, since changes in water content cause changes in density, nuclear probes can be used to assess seasonal changes in water content. The disadvantages include the need for expensive equipment, calibration curves to convert counts of radiation to bulk density, and minimizing human exposure to radiation. However, recent improvements in radiation technology make this a worthwhile method for land managers to consider as an alternative to or in combination with conventional techniques.

Although soil bulk density is the most frequently used measurement to assess compaction, it is only an indirect measure of how change in soil physical property affects root growth (McNabb 1981) and gives little information on pore-size distribution or particle arrangement (Freitag 1971). Soil strength (mechanical resistance) and aeration, two significant factors limiting growth in compacted soils and whose effects are often difficult to separate (Warkentin 1984), are the main physical properties affected by increases in bulk density.

Soil Strength

Soil strength refers to the mechanical resistance of soil to an applied force. Shear tests (measuring the torque required to shear the soil along the surface) and penetration tests (measuring the weight required to push a tip, plate, or footing of some type into the soil to a certain depth) can assess soil strength with simple procedures; large areas can be measured quickly, and because soil is only minimally disturbed, several measurements can be taken near the same sampling point (Freitag 1971; Adams 1983). Although both shear and penetration tests seem equally suitable for assessing soil compaction (Freitag 1971), it is important in both cases to standardize procedures and equipment so that results can be reproduced. Soil properties such as moisture or texture (Adams 1983; Warkentin 1984), shape of the penetrating or shearing element, and rate at which elements are advanced into the soil all can affect results (Freitag 1971).

Soil strength typically increases when a soil is compacted, and strength tests have been significantly related with bulk density measurements. Gifford et al. (1977) found soil-core bulk density to be significantly correlated with pocket penetrometer resistance and proving ring penetrometer resistance. Penetrometer resistance may be a better indicator than soil bulk density of seedling performance in compacted soils (Zisa et al. 1980). Several studies have shown that resistance to a metal probe correlates well with soil resistance to root penetration (Gooderham and Fisher 1975; Sands et al. 1979; Zisa et al. 1980).

Permeability

Because compaction alters soil porosity, it can be assessed by the ability of a liquid or air to pass through the pore spaces. An increase in bulk density generally lowers macroporosity (the number of macropores, or noncapillary pores through which water and gas usually flows rapidly) and reduces permeability (Howard and Singer 1981).

In liquid permeability tests, a known amount of fluid (e.g., water) is applied to a soil core or surface and its infiltration rate assessed. However, liquid permeability measurements are not easily made and can be time consuming. Although a strong laboratory relationship has been shown between fluid conductivity and compaction variables, insufficient field testing increases the difficulty in assessing the operational usefulness and accuracy of such a test (Freitag 1971).

In air permeability tests, a known pressure of gas is applied to the soil surface and the backpressure measured (in pounds per square inch, or kilopascals). Air permeability tests are relatively quick and easy and only minimally disturb the soil. However, because the test apparatus must be sealed against air losses, the contact zone between soil and test instrument must be sufficiently leakproof. Moreover, the optimum condition for such tests is a perfectly dry soil (e.g., dry sand) because the presence of water in pore spaces complicates the evaluation of test results: a soil with different water-retention abilities can be expected to produce different air permeameter measurements (Freitag 1971; Gifford et al. 1977). Unfortunately, the optimum dry condition is not usually attained in practice, so the resulting values must be appropriately calibrated (Freitag 1971; Adams 1983).

Visual Observations

Of all techniques for assessing soil compaction, visual observations may be the most rapid and least expensive. Visual evidence includes reduced drainage because of reduced soil permeability, difficulty in penetrating the soil surface (e.g., with a shovel) especially when dry, soil structure changes (e.g., a compacted soil when dry will be brittle and often layered, a noncompacted soil crumbly and granular), and good initial germination followed by stunted plant development later on (Freitag 1971; Adams and Froehlich 1981). However, visual observation is difficult to use in monitoring less than severe compaction levels and, of all techniques, is the most subjective and least quantitative (Adams 1983).

RELATIONSHIPS BETWEEN SOIL FACTORS AND COMPACTION

A compacted soil reflects conditions of increasing bulk density and soil strength, and decreasing porosity and infiltration. Most of the loss in porosity is in the macropores, where air and water movement is normally the least restricted (Greacen and Sands 1980; Adams and Froehlich 1981; Warkentin 1984). However, the degree to which compaction affects soil properties will be influenced by texture, organic matter, and soil moisture.

Texture

Texture refers to the relative proportions of sand, silt, and clay in a particular soil. Grainsize distribution and composition affect the resistance of soil to compaction. Soils with a narrow range of grain sizes resist compaction reasonably well, but soils with a wide range of grain sizes are more susceptible because the smaller grains move into the pore spaces between the larger grains, thereby increasing the packing of soil particles (Lull 1959; Bodman and Constantin 1965; Warkentin 1971; Froehlich 1974).

Organic Matter

Soil resistance to compaction is significantly influenced by organic matter content (Greacen and Sands 1980). Organic matter stabilizes aggregates and alters aggregate strength (Warkentin 1984).

Benefits of organic matter have been observed in both laboratory and field tests. Estimates of bulk density (0.54 to 0.63 g/cm^3) in the surface 20 cm of soil of an old plank road were found to be low because of high organic matter content (Power 1974). Sands et al. (1979) reported that the degree of soil compaction changed with differences in organic matter content under a given constant applied load, bulk density generally decreasing with increasing organic matter content under unsaturated conditions. Yet extremely high levels of organic matter may render soils susceptible to disturbance because of their low soil strength (Froehlich and McNabb 1983).

Soil Moisture

The most significant factor influencing soil compaction is moisture level during the compaction process (Warkentin 1984). In general, resistance to compaction is large when soils are dry because little lubrication (for particle rearrangement) is provided by thin water films (Lull 1959). As moisture content increases, lubrication increases and soil becomes easier to compact. For example, Eavis (1972) found that penetrometer resistance decreased as moisture content (at the time of compaction) of a sandy loam increased. In an unsaturated sandy soil, bulk density increased as applied load (range 60 to 360 kPa) increased (Sands et al. 1979); at the lightest load, it was - 1.3 g/cm^3, at the heaviest 1.4 g/cm^3. But in a saturated soil, even slight applied loads (60 kPa) resulted in bulk densities > 1.5 g/cm^3.

However, bulk density due to compaction does not continue to increase as water content increases. Instead, a water content is reached at which the maximum number of smaller particles are forced between the coarser grains and the remaining spaces filled with water (Lull 1959; Hatchell et al. 1970). Beyond the water content at which maximum bulk density is attained, compaction decreases and the potential for soil puddling (destruction of soil structure) increases (Lull 1959; Sidle and Drlica 1981; Warkentin 1984); upon drying, such soils can be left highly compacted.

The influence of water content on compaction is also affected by soil texture. For example, in laboratory tests, sandy clays may be compacted to 1.7 to 2.1 g/cm^3 at only 8- to 15-percent moisture, clays to 1.5 to 1.7 g/cm^3 at 20- to 30percent moisture (Froehlich 1973). Similarly, Bodman and Constantin (1965) showed that as clay content increased, the percent water content at which maximum bulk density was attained also increased. Warnaars and Eavis (1972) found that penetrometer resistance in fine sands decreased as moisture content increased, but that in coarse sands was relatively unaffected by moisture content. No significant difference in penetrometer resistance at a constant bulk density (1.45 g/cm^3) was found for a sandy soil over moisture contents ranging from 2 to 12 percent (Sands et al. 1979). It is important to emphasize that the previously mentioned results all were from laboratory tests and that, irrespective of the degree of sensitivity to moisture and/or texture, a soil may be susceptible to significant compaction over a wide range of moisture contents in the field (Froehlich and McNabb 1983).

EFFECTS OF COMPACTION ON POROSITY AND DRAINAGE

Porosity

Regardless of the mechanism, the net effect of soil compaction will be reduced air porosity (Grable 1971). Total porosity is defined as the ratio of pore-space volume to total volume (Harris 1971). Of perhaps greater significance than the decrease in total porosity is the change in poresize distribution. Most of the loss in porosity will be in the macropores, and the proportion of micropores will increase (Harris 1971; Greacen and Sands 1980; Adams 1983; Warkentin 1984). Foil and Ralston (1967) showed that increasing bulk density from laboratory compaction on a loam sand (1.07 to 1.33 g/cm^3), loam (1.06 to 1.38 g/cmK), and clay (1.31 to 1.49 g/cm^3) corresponded to approximately 64- to 69-percent reductions in macroporosity. Under field conditions, vehicular-induced compaction which increased bulk density from 0.90 to 1.20 g/cm^3 reduced macropore volume by 50 percent for a range of forest soils (Hatchell et al. 1970). Campbell et al. (1973) found a 28- to 72-percent decrease in macroporosity in logged areas compared to undisturbed plots, depending on the degree of disturbance.

Drainage

The degree to which compaction affects drainage or infiltration of water is related to the changes in soil structure brought about by the compactive effort. Because compaction generally reduces the proportion of macropores and increases the proportion of micropores, water movement becomes restricted and drainage can be impeded.

Significant relationships have been found among increasing bulk density, decreasing infiltration, and decreasing porosity (Lull 1959). Decreased infiltration rates in compacted soils have been reported after logging (Steinbrenner 1955; Steinbrenner and Gessel 1955b; Perry 1964; Hatchell et al. 1970) and as effects of human and animal traffic (Lull 1959). Reduced infiltration and impeded drainage can lead to surface runoff--excess rain may cause waterlogging and associated aeration problems in the rooting zone (Gifford et al. 1977; Greacen and Sands 1980; Sidle 1980). In addition, compacted soils have low temperatures in spring (Gill 1971) and, because of reduced drainage, remain wet and do not warm as fast as noncompacted (i.e., well-drained) soils.

EFFECTS OF COMPACTION ON SEEDLINGS

The abundance of literature addressing plant responses to changing soil conditions resulting from compaction has not always led to the same conclusions (Lull 1959; Rosenberg 1964; Trouse 1971; Greacen and Sands 1980). The contradictory effects reported are probably due to the complexity of interactions among soil strength, aeration, moisture, nutrient supply, and species. In their review of soil compaction, Greacen and Sands (1980) indicated that of 142 studies they surveyed between 1970 and 1977, 82 percent showed reduced crop yield due to compaction, approximately 8 percent increased yield, 6 percent both reduction and increase, and 4 percent no effect. Of these studies, only 18 percent dealt with tree species, but reduced growth due to compaction has been reported for several economically important tree species including *Pinus radiata*, *Pinus elliottii*, *Pinus taeda*, *Pinus ponderosa*, *Pinus nigra*, *Picea abies*, and *Pseudotsuga menziesii*.

Seedling Survival

Effects of compaction on seed germination or seedling survival have varied. For *Pinus taeda* seed sown on a loamy sand, loam, and clay, compaction treatments did not significantly affect germination (Foil and Ralston 1967); however, survival percentages were uniformly reduced on compacted soils, the lowest generally on clay. Likewise, Hatchell (1970) found that over a variety of soil types, a 16 percent average increase in bulk density (1.26 to 1.46 g/cm^3) due to compaction treatments corresponded to a 24-percent decrease in P. *taeda* seedling establishment; on a clay loam, though, compaction had little effect. For *Pinus rigida*, *Pinus nigra*, and *Picea abies*, Zisa et al. (1980) reported that seedling establishment was generally > 75 percent on a sandy loam, regardless of compaction intensity (1.2, 1.4, 1.6, and 1.8 g/cm^3); on a silt loam, only soil compacted to 1.8 g/cm^3 significantly reduced seedling establishment.

The previously cited results were from greenhouse or shade house experiments. Yet several reports of seedling establishment in areas disturbed or compacted due to logging present similar findings. Steinbrenner and Gessel (1955a) report reduced coniferous seedling establishment for naturally regenerated skid roads compared to cutover tractor-logged areas. Duffy and McClurkin (1974) analyzed several soil characteristics on both failed and successful P. *taeda* plantations to determine characteristics useful for site classification. Bulk density was the most important: plantation failure was predicted on sites where bulk density exceeded 1.45 g/cm^3. There are, however, several instances in which soil compaction due to skidding or logging has had no effect on conifer survival from the first or second (Youngberg 1959; Campbell et al. 1973) through the fourth (Hatchell 1981) growing season after planting.

Root Growth

Root growth is generally restricted as soils become more compact. For example, Heilman (1981) found that length of primary root penetration of *Pseudotsuga menziesii* seedlings decreased 71 to 87 percent as bulk density increased from 1.38 to 1.76 g/cm^3 (fig. 1) and that 27- to 30-percent pore space[4] prevented rooting of seedlings 35 to 45 days from germination in loam and sandy loam. Hatchell (1970) showed that for *Pinus taeda* seedlings growing in a range of soil types, shoot to root ratio (dry weights) after the first growing season was negatively related to macroporosity, suggesting that the proportion of roots increased as air space increased.

The degree to which compaction affects root growth depends on species (Minore et al. 1969; Singer 1981; Halverson and Zisa 1982), soil type (Hatchell 1970; Singer 1981), and magnitude of compactive effort, as well as on environmental factors (table 1). Halverson and Zisa (1982), among others, found that of several growth variables measured, root penetration depth (of three conifer species) was the most responsive to compactive effort. Further, whereas effects of compaction on root dry weights have varied (Foil and Ralston 1967; Hatchell 1970; Singer 1981; Tworkoski et al. 1983), reductions in root penetration > 50 percent are repeatedly noted (table 1). Compaction is also likely to alter root distribution in soil. Decreases

4 Percent pore space = 100 - (bulk density/particle density) x 100.

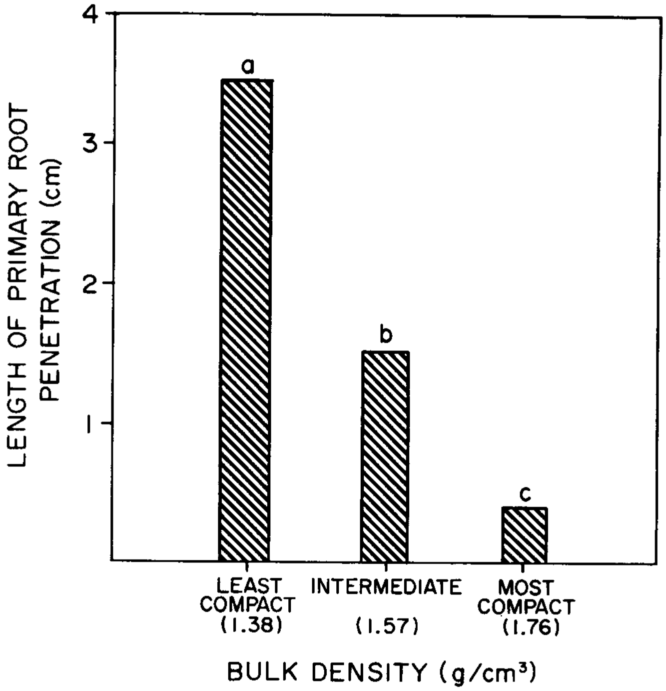

Figure 1.--Length (averaged over three soil types) of primary root penetration of Pseudotsuga menziesii in soils compacted to three bulk densities (adapted from Heilman 1981). Means not followed by the same letter are significantly different at $p < 0.05$.

in. branching (Pseudotsuga menziesii, Tsuga heterophylla--Pearse 1958), and total root number and fine roots (Pinus ponderosa. Pseudotsuga menziesii--Singer 1981) have been observed for species in compacted soil, although lateral roots (Pinus taeda-Foil and Ralston 1967) and fine roots (Fagus spp.-Hildebrand 1983) have, in some cases, proliferated for trees growing in compacted soils.

In a fine-textured, poorly drained, compacted soil, oxygen deficit can limit root growth; but-in a coarse-textured, well-drained compacted soil, or when seedling growth is not limited by lack of water or reduced aeration (Sands and Bowen 1978), reduced root growth or penetration can be related to differences in soil strength (Heilman 1981). Often, however, the factors responsible for poor root growth in compacted soils interact and are difficult to separate. Hatchell (1970) concluded that reduced root growth of Pinus taeda in compacted soils could result from low oxygen supply to roots and high resistance to penetration. Eavis (1972) studied the interaction of mechanical impedance, aeration, and moisture availability for pea growth in a sandy loam soil. Under drier conditions, reduced root growth was due primarily to mechanical resistance if bulk density was high but to moisture stress if bulk density was low. Under wetter conditions, reduced root growth could be due to poor aeration and resistance to penetration in compacted soil but primarily to poor aeration in loose, wet soil.

Shoot Growth

As with root growth, the effect of compaction on shoot growth cannot always be predicted due to the complex interactions among soil physical characteristics and species. If air, water, and nutrients are in sufficient supply and if root length is adequate to meet shoot requirements, poor root development in compacted soils can still support good shoot growth (Hatchell 1970; Greacen and Sands 1980). In some cases, compaction can increase the diffusion of ions (e.g., phosphorus) and improve nutrient uptake; however, under other circumstances, compaction can be detrimental to nutrient status and reduce the mineralization of nutrients from soil organic matter (Kemper et al. 1971; Greacen and Sands 1980). Both large (Forristall and Gessel 1955; Minore et al. 1969) and small (Zisa et al. 1980) effects of compaction on shoot growth have been observed in conifers.

Young (< 2 years) seedling shoot growth varies in response to compaction in laboratory experiments (table 2). Bulk-density increases of 7 to 20 percent have corresponded to reductions of 16 to 56 percent and 11 to 38 percent in shoot dry weight and total height, respectively (Minore et al. 1969; Hatchell 1970; Sands and Bowen 1978). But there are also instances in which increasing compaction has not affected shoot dry weight, shoot growth, or total height (Minore et al. 1969; Heilman 1981; Singer 1981; Tworkoski et al. 1983) or even led to increased shoot growth or shoot dry weight (Trujillo 1976; Singer 1981). These inconsistencies show that compaction effects on young seedlings depend on the interaction of species, age, soil texture, compaction severity, and other soil physical characteristics.

Nearly all field studies relating tree response to compaction have pertained to growth after logging (table 3). In general, tree growth in compacted zones has declined relative to control or undisturbed areas. Estimated reductions in height growth or total height have ranged from 6 to over 50 percent (table 3). Over a variety of tree species, soil types, and field locations, Froehlich and McNabb (1983) found a generally linear relationship between increased soil density and reduced seedling height growth.

THE COMPACTION PROBLEM IN TREE NURSERIES

Despite the concern for soil-related problems, very little research has been done on compaction problems in forest-tree nurseries. Lowerts and Stone (1982) studied the effect of an existing compacted soil layer on nursery growth of Liquidambar styraciflua. After one growing season, seedlings were tallest in nursery plots where bulk densities were < 1.7 g/cm^3 in the surface 39 cm of soil. Furthermore, a significant negative correlation was found between seedling height and bulk density at the 26- ($r = -0.66$), 39- ($r = -0.86$), and 52- ($r = -0.65$) cm depths. Minko (1975) reported of a compacted nursery subsoil (bulk density - 1.5 g/cm^3 at the 20- to 40-cm depth) which impeded Pinus radiata tap root penetration. Yet the density (1.2 to 1.4 g/cm^3 in the top 18 cm of soil) of the

Table 1.--Effect on roots as bulk density increased, over a variety of species and soil types, from selected laboratory studies.

Reference	Species [approximate age]	Soil type	Bulk density values	Effect on roots as bulk density increased
			--- (g/cm^3) ---	
Heilman (1981)	Pseudotsuga menziesii [35 to 45 days]	Loam, sandy loam	1.38-1.57	54% reduction, length of primary root penetration
			1.38-1.76	87% reduction, length of primary root penetration
Tworkoski et al. (1983)	Quercus alba [40 days]	Silt loam	1.0-1.2-1.5	55% reduction, tap root length 59% reduction, primary root number No effect, root dry weight
Pearse (1958)	Pseudotsuga menziesii, Tsuga heterophylla [56-90 days]	Sandy loam	0.59-0.84-1.02	Shorter, stockier, thicker, not as profusely branched
Zisa et al. (1980)	Pinus rigida, Pinus nigra, Picea abies [120 days]	Silt loam	1.2-1.4	~ 75% reduction, depth of root penetration
			1.2-1.8	~ 80% reduction, depth of root penetration
		Sandy loam	1.2-1.4	No effect, depth of root penetration
			1.2-1.6	~ 50% reduction, depth of root penetration
			1.2-1.8	~ 80% reduction, depth of root penetration
Sands and Bowen (1978)	Pinus radiata [150 days]	Sand	1.35-1.48	No effect, main root length or root dry weight
			1.35-1.60	73% and 46% reductions, main root length and root dry weight, respectively
Hatchell (1970)	Pinus taeda [150 days]	Loamy sand	1.26-1.46	55% reduction, root dry weight
		Loam	1.30-1.47	40% reduction, root dry weight
		Silt loam	1.34-1.62	50% reduction, root dry weight
		Sandy clay loam	1.14-1.28	29% reduction, root dry weight
		Clay loam	1.04-1.12	17% reduction, root dry weight
Foil and Ralston (1967)	Pinus taeda [1 year]	Loamy sand, loam, clay	0.8-1.4	~ 64% reduction, root length[1] ~ 80% reduction, root dry weight[1]
Trujillo (1976)	Pinus ponderosa [1 year, 7 months]	Silty clay loam	1.02-1.28	19% increase, root dry weight
Singer (1981)	Pinus ponderosa, Pseudotsuga menziesii [< 2 years]	Clay loam Sandy loam	0.88-1.10 1.06-1.35	Uneven root distribution Decrease in total root numbers Fine roots decrease No effect, root dry weight for Pinus ponderosa 66% reduction, dry root weight for Pseudotsuga menziesii on clay loam (no effect on sandy loam)
Minore et al. 1969)	Abies amabilis, Alnus rubra, Pinus contorta, Pseudotsuga menziesii, Thuja plicata, Picea sitchensis, Tsuga heterophylla [2 years]	Sandy loam	1.32-1.45-1.59	44% reduction, root dry weight for Thuja plicata; no significant effect on other species

[1] Estimates based on regression equation.

cultivated layer was sufficient for root growth; moreover, for two of three nursery blocks, nearly all fine roots were found in the upper soil layer. In addition, some evidence suggested that favorable moisture conditions after early sowing enabled seedling roots to penetrate the compacted subsoil. Recently, an unpublished report[5] showed conditions surprisingly similar to those observed by Minko. In a Northwest conifer nursery, a dense hard layer (bulk density - 1.6 g/cm^3) approximately 15 to 30 cm below the surface restricted root penetration of a grass cover crop; the condition was slightly more severe in dry than in moist soil.

Despite the lack of research "us far, the effects of increasing soil density are of special concern to the nursery manager. Compaction may be rare above the 15-cm depth because nursery soils are cultivated each year; however, below 15 cm compaction is relatively common, and is especially

[5] David K. Maurer, 1983.

noticeable when drainage is impeded for long periods. The machinery used to manage the crop, the ability to control irrigation and fertilization, and the alternatives for tillage are all important aspects of nursery soil management effecting soil compaction.

PREVENTING AND AMELIORATING COMPACTED SOILS

Maintaining soil in good physical condition, loosening or tilling soil where compacted zones already exist, and controlling vehicular traffic to help avoi compaction must be part of an overall plan to maintain a good physical environment for tree growth in the nursery. s

Maintaining Soil Physical Condition

Organic matter can aid soil resistance to cc paction; it improves water retention and increases porosity cation exchange capacity (see Blumenthal and Boyer 1982; rev by Davey 1984). Verti-

Table 2.--Effect on shoots of young seedlings (< 2 years) as bulk density increased, over a variety of species and soil types, from selected laboratory studies.

Reference	Species [approximate age]	Soil type	Bulk density values	Effect on shoots as bulk density increased
			--- (g/cm^3) ---	
Heilman (1981)	_Pseudotsuga menziesii_ [35 to 45 days]	Sandy loam, loam	1.38-1.57-1.76	No effect, total height
Tworkoski et al. (1983)	_Quercus alba_ [40 days]	Silt loam	1.0-1.2-1.5	No effect, shoot height or dry weight
Sands and Bowen (1978)	_Pinus radiata_ [150 days]	Sand	1.35-1.48	16% and 11% reduction, shoot dry weight and total height, respectively
			1.35-1.60	49% and 38% reduction, shoot dry weight and total height, respectively
Hatchell (1970)	_Pinus taeda_ [150 days]	Loamy sand	1.26-1.46	42% reduction, shoot dry weight
		Loam	1.30-1.47	33% reduction, shoot dry weight
		Silt loam	1.34-1.62	56% reduction, shoot dry weight
		Sandy clay loam	1.14-1.28	56% reduction, shoot dry weight
		Clay loam	1.04-1.12	31% reduction, shoot dry weight
Trujillo (1976)	_Pinus ponderosa_ [1 year, 7 months]	Silty clay loam	1.02-1.28	15% increase, shoot dry weight
Singer (1981)	_Pinus ponderosa_, _Pseudotsuga menziesii_ [1 year, 10 months]	Clay loam	0.88-0.99-1.10	32% increase, shoot growth for _Pinus ponderosa_; no effect, _Pseudotsuga menziesii_
		Sandy loam	1.06-1.16-1.35	No effect, shoot growth
Minore et al. (1969)	_Abies amabilis_, _Alnus rubra_, _Picea sitchensis_, _Pinus contorta_, _Pseudotsuga menziesii_, _Thuja plicata_, _Tsuga heterophylla_ [2 years]	Sandy loam	1.32-1.45-1.59	37% reduction, shoot dry weight for _Thuja plicata_; no effect, shoot dry weight for other species

cal mulching can improve root access to additional moisture and increase drainage through subsoiled slots (Gill 1971). Improving drainage to decrease water content can minimize soil compaction (Warken-tin 1984). Steinhardt and Trafford (1974) showed that subsurface drainage of a wet clay reduced wheel sinkage and lateral compaction from tractor traffic. Rotating crops also is instrumental in maintaing good soil condition and has long been used to prevent and ameliorate soil compaction (Larson and Allmaras 1971).

Tilling Soil

The unfavorable soil conditions created by compaction can often be improved if the soil is loosened. Tillage can improve soil aeration, infiltration, and pore-space distribution and lower strength and bulk density. Generally, the beneficial effects of tillage are in the layer of soil disturbance. Voorhees et al. (1978) and Voorhees (1983), for example, showed that fall plowing was effective in ameliorating compaction from wheel traffic but that bulk density was reduced primarily in the plow layer. Compacted layers in the subsoil (plow pans) can be created by plowing to the same depth crop after crop; and the compaction zone below plow depth has been shown to persist for up to 9 years (Blake et al. 1976). However, not all compacted soils respond favorably to tillage. For example, nutrients may become deficient after deep plowing because topsoils generally contain more

Table 3.--Effect on tree height as bulk density increased in disturbed areas (skid trails, roads, logged), over a variety of species and soil types, from selected field studies.

Reference	Species [Age, years]	Soil type	Bulk density values [measurement depth]	Effect on tree height as bulk density increased	Disturbance type
			----- (g/cm^3) -----		
Campbell et al. (1973)	*Pinus taeda* [1]	Clay loam	1.34-1.51 [surface 10 cm]	No effect, height growth	Skid trail
Hatchell et al. (1970)	*Pinus taeda* [1]	Sandy loam	0.75-0.92 [surface] 0.75-1.08 [surface]	21% reduction, total height 53% reduction, total height	Skid trail
Youngberg (1959)	*Pseudotsuga menziesii* [2]	Clay	0.88-0.95[1] [surface 15 cm] 0.88-1.55[1] [surface 15 cm]	22% reduction, height growth 42% reduction, height growth	Skid road, berm
Froehlich (1979b)	*Pseudotsuga menziesii* [4]	Sandy loam	0.87-0.95 [surface 15-23 cm] 0.87-0.99 [surface 15-23 cm]	11% reduction, height growth 21% reduction, height growth	Skid trail
	Pseudotsuga menziesii [5]	Clay loam	0.92-1.01 [surface 15-23 cm]	11% reduction, height growth	
Hatchell (1981)	*Pinus taeda* [5]	Silt loam	--	18% reduction, total height on compacted areas	Skid trail
Lockaby and Vidrine (1984)	*Pinus taeda* [5]	Loam	1.03-1.13 [surface 5 cm] 1.03-1.17 [surface 5 cm]	59% reduction, total height 39% reduction, total height	Primary skid road, deck
Wert and Thomas (1981)	*Pseudotsuga menziesii* [~ 14-18]	Loam	0.91-0.99 [5 cm] (1.09-1.26, 30 cm) 0.91-0.93 [5 cm] (1.09-1.13, 30 cm)	30% reduction, total height No difference, total height	Skid road
Froehlich (1979b)	*Pinus ponderosa* [17]	Sand	0.84-1.15 [surface 30 cm] 0.84-1.24 [surface 30 cm]	23% reduction, total height[2] 29% reduction, total height[2]	Skid trail
Froehlich (1979a)	*Pinus ponderosa* [~ 64]	Sandy clay loam	0.97-1.14 [7 cm] (1.03-1.12, 30 cm)	~ 6 to 12% reduction, growth rate	Usual logging, cattle use

[1] Bulk density values averaged over two plantations.
[2] Estimated effects based on regression equation.

available plant nutrients than subsoils (Burnett and Hauser 1967). In these cases, incorporating fertilizers with tillage (or soon thereafter) could help. Excessive traffic after tillage also should be avoided. Often, soil that is compacted, loosened, then compacted again will be denser after tillage (Cooper 1971). A tradeoff exists between compaction and tillage---although severe compaction can reduce growth, excessive loosening can be costly and can produce a poor environment for root growth (Gill 1971).

Several types of tools are used for tillage in agriculture (see Cooper 1971) and forestry (see Andrus and Froehlich 1983; Froehlich and McNabb 1983; Froehlich 1984). Investigating compacted conditions in skid trails, Andrus and Froehlich (1983) estimated that the portion of compacted soil effectively tilled by three conventional agricultural tools (brush blade, rock ripper, disk harrow) ranged from 20 to 45 percent; yet adding wings to the sides of ripping tines (via a prototype one-winged subsoiler) consistently tilled at least 80 percent of the compacted soil to a depth of - 45 cm. Regardless of the specific tool used, however, it is important to understand the soil conditions at the time of tillage and those created after loosening (Gill 1971). Subsoiling,[6] for example, must be performed under relatively dry conditions so that the implement fractures the compacted zone. When soil is too moist, the implement can pass through the dense soil layer with little amelioration. Furthermore, the restorative action must be dictated by soil conditions, not by a standard operation (e.g., using a tool at a fixed setting).

Tillage experiments have shown a wide range of results. Gill (1971) and Burnett and Hauser (1967) cite numerous studies where tillage has improved either root development or crop yield. Yet in some cases, tillage may bring about the desired soil physical changes without altering yield. Water seems critical in determining crop response. When water is not limiting, yields after tillage may not be increased; but where water movement and root development are restricted by compaction, deep plowing has increased crop yields most (Burnett and Hauser 1967). Burnett and Hauser (1967) concluded the primary benefits of deep tillage to be increases in stored water (due to either improved infiltration or change in particle arrangement) or in root proliferation (enabling roots to obtain water). Additionally, they find that the soil physical changes created by tillage are long term if soils are fine textured, the tillage operation is drastic (e.g., large plows), and compacted zones are essentially genetic, but are more short term if soils are medium to coarse textured, the tillage implement is a subsoiler or chisel, and compacted layers are induced by machinery.

The literature on tillage effects on forest species or soils is not as voluminous as that for crop species. Tilling previously compacted forest soils has generally been beneficial (Andrus and

[6] "Subsoiling" and "ripping" often refer to the same type of tillage treatment, but subsoiling usually is deeper.

Froehlich 1983); over a range of soil and tillage types, increases of 11 to 83 percent in seedling survival and 13 to 73 percent in seedling height growth have been reported. Nursery seedling height of *Pinus radiata* seedlings grown in ripped areas was 60 percent greater than that in unripped areas (Minko 1975). Yet Hatchell (1970) found that loosening treatments of compacted soil cores from a range of soil types did not significantly increase either root or shoot dry weight of *Pinus taeda* seedlings after one growing season, and Warkentin (1984) warned that despite the benefits claimed by nursery managers, the effects of ripping may be only temporary.

Managing Traffic

Intensive management requires the judicious use of machinery to minimize compaction. The following recommendations are from Lull (1959), Gill (1971), Greacen and Sands (1980), Adams and Froehlich (1981), and Warkentin (1984):

Timing operations: If possible, conduct operations on drier soils. Using moisture-based restrictions (especially those based on laboratory tests with unrealistically large forces applied), although sound in theory, is often not practical nor accurate in the field. In addition, delays in field operations due to wet soils increase production costs. Texturally well-graded soils which are low in organic matter may be more susceptible to compaction, so particular care must be taken when traffic is necessary on these sites. Most soils, however, are susceptible to compaction unless already compacted.

Choosing machinery: Modified equipment design (e.g., long-boom sprayers) or use of low-groundpressure equipment may help minimize the forces applied to soil during operations. Gill (1971) stated that the rear wheel of the agricultural tractor was the worst soil-compacting device used in a crop production system. However, the versatility of the rubber tire probably justifies its use, especially on firm ground. When soils are wet, traction devices such as low-pressure tires may provide an alternative. If load and weight are equal, crawler tractors compact the soil less than wheeled tractors, and surface pressures are reduced further if wider tracks are used. However, a larger area is subject to mechanical vibration with crawler tractors; therefore, estimates comparing ground pressure between crawler and tire tractors may not indicate the entire compactive effect. The use of fixed paths in the nursery also helps prevent compaction in the crop area.

CONCLUSION

Compaction can detrimentally affect soil physical characteristics, resulting in poor tree growth. Yet no one knows whether compaction in forest nurseries is severely inhibiting growth of tree seedlings. However, because of the intensive use of the land required by cultural manipulation of soil and crop, the potential for compaction is a concern shared by most nursery managers. Maintenance of good soil physical conditions, proper tillage, and sound management of vehicle traffic are all important parts of a system to prevent and help ameliorate compacted soils.

ACKNOWLEDGMENTS

The author thanks: John Gleason for help during the literature search; Izella Stuivenga and David Merrill for typing; Rob Pabst for useful comments; Carol Perry for editing; and Gretchen Bloom for drafting. Sincere appreciation is extended to reviewers of an earlier version of this report: Paul Adams, Mary Duryea, Alan Flint, Ken Munson, Randy Selig, and David Steinfeld.

LITERATURE CITED

Adams, P.W. 1983. Recognizing and measuring soil compaction. In Workshop: Forest soil compaction: problems and alternatives. [LaGrande, Oreg., March 22-23, 1983] Department of Forest Engineering, Oregon State University, Corvallis.

Adams, P.W., and H.A. Froehlich. 1981. Compaction of forest soils. Oregon State University Extension Service PNW 217, 13 p. Oregon State University, Corvallis.

Andrus, C.W., and H.A. Froehlich. 1983. An evaluation of four implements used to till compacted forest soils in the Pacific Northwest. Forest Research Laboratory Research Bulletin 45, 12 p. Oregon State University, Corvallis.

Blake, G.R. 1965. Bulk density. p. 374-390. In Methods of soil analysis [C.A. Black, ed.]. American Society of Agronomy, Madison, Wis.

Blake, G.R., W.W. Nelson, and R.R. Allmaras. 1976. Persistence of subsoil compaction in a mollisol. Soil Science Society of America Journal 40:943-948.

Blumenthal, S.G., and D.E. Boyer. 1982. Organic amendments in forest nursery management in the Pacific Northwest. USDA Forest Service Administrative Report, 73 p. Pacific Northwest Forest and Range Experiment Station, Portland, Oreg.

Bodman, G.B., and G.K. Constantin. 1965. Influence of particle size distribution in soil compaction. Hilgardia 36:567-591.

Burnett, E., and V.L. Hauser. 1967. Deep tillage and soil-plant-water relationships. p. 49-52. In Proceedings: Tillage for greater crop production. American Society of Agricultural Engineers, St. Joseph, Mich.

Campbell, R.G., J.R. Willis, and J.T. May. 1973. Soil disturbance by logging with rubber-tired skidders. Journal of Soil and Water Conservation 28(5):218-220.

Cooper, A.W. 1971. Effects of tillage on soil compaction. p. 317-364. In Compaction of agricultural soils [K.K. Barnes, W.M. Carleton, H.M. Taylor, R.I. Throckmorton, and G.E. Vanden Berg, eds.]. American Society of Agricultural Engineers, St. Joseph, Mich.

Davey, C.B. 1984. Nursery soil organic matter: management and importance. p. 81-86. In Forest nursery manual: production of bareroot seedlings [M.L. Duryea and T.D. Landis, eds.]. Martinus Nijhoff/Dr W. Junk Publishers, The Hague/Boston/Lancaster for Forest Research Laboratory, Oregon State University, Corvallis.

Day, R.J. 1984. Water management. p. 93-105. In Forest nursery manual: production of bareroot seedlings [M.L. Duryea and T.D. Landis, eds.]. Martinus Nijhoff/Dr W. Junk Publishers, The Hague/Boston/Lancaster for Forest Research Laboratory, Oregon State University, Corvallis.

Duffy, P.D., and D.C. McClurkin. 1974. Difficult eroded planting sites in north Mississippi evaluated by discriminant analysis. Soil Science Society of America Proceedings 38:676--678.

Eavis, B.W. 1972. Soil physical conditions affecting seedling root growth I. Mechanical impedance, aeration and moisture availability as influenced by bulk density and moisture levels in a sandy loam soil. Plant and Soil 36:613-622.

Flint, A., and S. Childs. 1984. Development and calibration of an irregular hole bulk density sampler. Soil Science Society of America Journal 48:374-378.

Foil, R.R., and C.W. Ralston. 1967. The establishment and growth of loblolly pine seedlings on compacted soils. Soil Science Society of America Proceedings 31:565-568.

Forristall, F.F., and S.P. Gessel. 1955. Soil properties related to forest cover type and productivity on the Lee Forest, Snohomish County, Washington. Soil Science Society of America Proceedings 19:384-389.

Freitag, D.R. 1971. Methods of measuring soil compaction. p. 47-103. In Compaction of agricultural soils [K.K. Barnes, W.M. Carleton, H.M. Taylor, R.I. Throckmorton, and G.E. Vanden Berg, eds.]. American Society of Agricultural Engineers, St. Joseph, Mich.

Froehlich, H.A. 1973. The impact of even-age forest management on physical properties of soils. p. 190-220. In Proceedings: Even-age management symposium [R.K. Hermann and D.P. Lavender, eds.]. [Corvallis, Oreg., August 1, 19721 Oregon State University, Corvallis.

Froehlich, H.A. 1974. Soil compaction: implication for young-growth management. p. 49-64. In Proceedings: Managing young forests in the Douglasfir region [A. Berg, ed.]. [Corvallis, Oreg., June 14-16, 1972] Oregon State University, Corvallis.

Froehlich, H.A. 1979a. Soil compaction from logging equipment: effects on growth of young ponderosa pine. Journal of Soil and Water Conservation 34(6):276-278.

Froehlich, H.A. 1979b. The effect of soil compaction by logging on forest productivity. Final report to the U.S. Bureau of Land Management for contract 53500-CT4-5(N), 19 p. School of Forestry, Oregon State University, Corvallis.

Froehlich, H.A. 1984. Mechanical amelioration of adverse physical soil conditions in forestry. p. 507-521. In Proceedings: Symposium on site and productivity of fast growing plantations [D.C. Grey, A.P.G. Schonau, and C.J. Schultz, eds.]. [April 30 to May 11, 1984] IUFRO, Pretoria and Pietermaritzburg, South Africa.

Froehlich, H.A., and D.H. McNabb. 1983. Minimizing soil compaction in Pacific Northwest forests. p. 159-192. In Forest soils and treatment impacts. Proceedings: Sixth North American Forest Soils Conference. [Knoxville, Tenn., June 1983] University of Tennessee, Knoxville.

Gifford, G.F., R.H. Faust, and G.B. Coltharp. 1977. Measuring soil compaction on rangeland. Journal of Range Management 30:457-460.
Gill, W.R. 1971. Economic assessment of soil compaction. p. 431-458. In Compaction of agricultural soils [K.K. Barnes, W.M. Carleton, H.M. Taylor, R.I. Throckmorton, and G.E. Vanden Berg, eds.]. American Society of Agricultural Engineers, St. Joseph, Mich.
Gooderham, P.T., and N.M. Fisher. 1975. Experiments to determine the effect of induced soil compaction on soil physical conditions, seedling root growth, and crop yield. Ministry of Agriculture, Fisheries and Food, Technical Bulletin 29:469480. Wye College, University of London.
Grable, A.R. 1971. Effects of compaction on contact and transmission of air in soils. p. 154-164. In Compaction of agricultural soils [K.K. Barnes, W.M. Carleton, H.M. Taylor, R.I. Throckmorton, and G.E. Vanden Berg, eds.]. American Society of Agricultural Engineers, St. Joseph, Mich.
Greacen, E.L., and R. Sands. 1980. Compaction of forest soils, a review. Australian Journal of Soil Research 18:163-189.
Halverson, H.G., and R.P. Zisa. 1982. Measuring the response of conifer seedlings to soil compaction stress. USDA Forest Service Research Paper NE-509, 6 p. Northeastern Forest Experiment Station, Broomall, Pa.
Harris, W.L. 1971. The soil compaction process. p. 10-44. In Compaction of agricultural soils [K.K. Barnes, W.M. Carleton, H.M. Taylor, R.I. Throckmorton, and G.E. Vanden Berg, eds.]. American Society of Agricultural Engineers, St. Joseph, Mich.
Hatchell, G.E. 1970. Soil compaction and loosening treatments affect loblolly pine growth in pots. USDA Forest Service Research Paper SE-72, 9 p. Southeastern Forest Experiment Station, Asheville, N.C.
Hatchell, G.E. 1981. Site preparation and fertilizer increase pine growth on soils compacted in logging. Southern Journal of Applied Forestry 5(2):79-83.
Hatchell, G.E., C.W. Ralston, and R.R. Foil. 1970. Soil disturbances in logging. Journal of Forestry 68:772-775.
Heilman, P. 1981. Root penetration of Douglas-fir seedlings into compacted soil. Forest Science 27(4):660-666.
Hildebrand, E.E. 1983. Influence of soil compaction on soil functions on forest sites (Inhibitory effect on beech regeneration). Der einfluss der bodenverdichtung auf die bodenfunktionen im forstlichen standort. Forstwissenschaftliches Centralblatt 102(2):111-125.
Howard, R.F., and M.J. Singer. 1981. Measuring forest soil bulk density using irregular hole, paraffin clod, and air permeability. Forest Science 27(2):316-322.
Kemper, W.D., B.A. Stewart, and L.K. Porter. 1971. Effects of compaction on soil nutrient status. p. 178-189. In Compaction of agricultural soils [K.K. Barnes, W.M. Carleton, H.M. Taylor, R.I. Throckmorton, and G.E. Vanden Berg, eds.). American Society of Agricultural Engineers, St. Joseph, Mich.
Larson, W.E., and R.R. Allmaras. 1971. Management factors and natural forces as related to compaction. p. 367-427. In Compaction of agricultural soils [K.K. Barnes, W.M. Carleton, H.M. Taylor, R.I. Throckmorton, and G.E. Vanden Berg, eds.]. American Society of Agricultural Engineers, St. Joseph, Mich.
Lockaby, B.G., and C.G. Vidrine. 1984. Effect of logging equipment traffic on soil density and growth and survival of young loblolly pine. Southern Journal of Applied Forestry 8(2):109-112.
Lowerts, G.A., and J.M. Stone. 1982. The effect of soil bulk density on nursery sweetgum seedling growth. Tree Planters' Notes 33(3):3-5.
Lull, H.W. 1959. Soil compaction on forest and range lands. USDA Forest Service Miscellaneous Publication 768, 33 p. Washington, DC.
McKibben, E.G. 1971. Introduction. P.3-6. In Compaction of agricultural soils [K.K. Barnes, W.M. Carleton, H.M. Taylor, R.I. Throckmorton, and G.E. Vanden Berg, eds.]. American Society of Agricultural Engineers, St. Joseph, Mich.
McNabb, D. 1981. Compaction of southwest Oregon soils--shear strength. Oregon State University Extension Service Forestry Intensified Research Report 3(1):3-4. Oregon State University, Corva l l. is .
Minko, G. 1915. Effects of soil physical properties, irrigation, and fertilization on Pinus radiata seedling development in the Benalla nursery. Forests Commission Victoria Forest Technical Papers 22:19-24.
Minore, D., C.E. Smith, and R.F. Woollard. 1969. Effects of high soil density on seedling root growth of seven northwestern tree species. USDA Forest Service Research Note PNW-112, 6 p. Pacific Northwest Forest and Range Experiment Station, Portland, Oreg.
Pearse, P.H. 1958. A study of the effects of soil compaction on the early development of seedlings of Douglas-fir and western hemlock. University of British Columbia Forest Club Research Note 16, 7 p. Vancouver.
Perry, T.O. 1964. Soil compaction and loblolly pine growth. Tree Planters' Notes 67:9.
Power, W.E. 1974. Effects and observations of soil compaction in the Salem District. USDI-BLM Technical Note 256, 12 p. Salem, Oreg.
Rosenberg, N.J. 1964. Responses of plants to the physical effects of soil compaction. Advances in Agronomy 16:181-196.
Sands, R., and G.D. Bowen. 1978. Compaction of sandy soils in radiata pine forests. II. Effects of compaction on root configuration and growth of radiata pine seedlings. Australian Forest Research 8:163-170.
Sands, R., E.L. Greacen, and C.J. Gerard. 1979. Compaction of sandy soils in radiata pine forests. I. A penetrometer study. Australian Journal of Soil Research 17:101-113.
Sidle, R.C. 1980. Impacts of forest practices on surface erosion. Oregon State University Extension Service PNW 195, 15 p. Oregon State University, Corvallis.
Sidle, R.C., and D.M. Drlica. 1981. Soil compaction from logging with a low-ground pressure skidder in the Oregon Coast ranges. Soil Science Society of America Journal 45:1219-1224.
Singer, M.J. 1981. Soil compaction-seedling growth study. Final technical report to the United

States Forest Service Region 5 for cooperative agreement USDA-7USC-2201 supplement 43, 51 p.
Steinbrenner, E.C. 1955. The effect of repeated tractor trips on the physical properties of forest soils. Northwest Science 29:155-159.
Steinbrenner, E.C., and S.P. Gessel. 1955a. Effect of tractor logging on soils and regeneration in the Douglas-fir region of southwestern Washington. Society of American Foresters Proceedings 19:77-80.
Steinbrenner, E.C., and S.P. Gessel. 1955b. The effect of tractor logging on the physical properties of some forest soils in southwestern Washington. Soil Science Society of America Proceedings 19:372-376.
Steinhardt, R., and B.D. Trafford. 1974. Some effects of sub-surface drainage and ploughing on the structure and compactability of a clay soil. Journal of Soil Science 25:138-152.
Trouse, A.C. 1971. Soil conditions as they affect plant establishment, root development, and yield. Present knowledge and need for research. p. 225-240. In Compaction of agricultural soils [K.K. Barnes, W.M. Carleton, H.M. Taylor, R.I. Throckmorton, and G.E. Vanden Berg, eds.]. American Society of Agricultural Engineers, St. Joseph, Mich.
Trujillo, D.P. 1976. Container-grown ponderosa pine seedlings respond to fertilization. USDA Forest Service Research Note RM-319, 3 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.
Tworkoski, T.J., J.A. Burger, and D.W. Smith. 1983. Soil texture and bulk density affect early growth of white oak seedlings. Tree Planters' Notes 34(2):22-25.
Voorhees, W.B. 1983. Relative effectiveness of tillage and natural forces in alleviating wheel induced soil compaction. Soil Science Society of America Journal 47:129-133.
Voorhees, W.B., C.G. Senst, and W.W. Nelson. 1978. Compaction and soil structure modification by wheel traffic in the northern Corn Belt. Soil Science Society of America Journal 42:341-349.
Warkentin, B.P. 1971. Effects of compaction on content and transmission of water in soils. p. 126-153. In Compaction of agricultural soils [K.K. Barnes, W.M. Carleton, H.K. Taylor, R.I. Throckmorton, and G.E. Vanden Berg, eds.]. American Society of Agricultural Engineers, St. Joseph, Mich.
Warkentin, B.P. 1984. Physical properties of forestnursery soils: relation to seedling growth. p. 53-61. In Forest nursery manual: production of bareroot seedlings [M.L. Duryea and T.D. Landis, eds.]. Martinus Nijhoff/Dr W. Junk Publishers, The Hague/Boston/Lancaster, for Forest Research Laboratory, Oregon State University, Corvallis.
Warnaars, B.C., and B.W. Eavis. 1972. Soil physical conditions affecting seedling root growth. II. Mechanical impedance, aeration and moisture availability as influenced by grain-size distribution and moisture content in silica sands. Plant and Soil 36:623-634.
Wert, S., and B.R. Thomas. 1981. Effects of skid roads on diameter, height, and volume growth in Douglas--fir. Soil Science Society of America Journal 45:629--632.
Youngberg, C.T. 1959. The influence of soil conditions, following tractor logging, on the growth of planted Douglas-fir seedlings. Soil Science Society of America Proceedings 23:76-78.
Zisa, R.P., H.G. Halverson, and B.B. Stout. 1980. Establishment and early growth of conifers on compact soils in urban areas. USDA Forest Service Research Paper NE-451, 8 p. Northeastern Forest Experiment Station, Broomall, Pa.