Minimizing Soil Compaction in Pacific Northwest Forests

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MINIMIZING SOIL COMPACTION IN PACIFIC NORTHWEST FORESTS

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Abstract.--High organic-matter content and other inherent properties make Pacific Northwest forest soils generally low in bulk density, high in porosity, and low in strength. As a consequence, these soils are susceptible to compaction by tractive machines, and stand growth may be decreased from 5 to 15 percent. Natural ameliorative processes do not rapidly loosen compacted soil, and where it remains compacted, stand growth losses are measurable for at least three decades. Prohibiting the use of tractive machines on soils most susceptible to compaction, suspending operations above specified soil moisture contents, or requiring the use of low-ground-pressure machines do not always reduce soil compaction, but tillage of compacted soil can be effective with properly designed and used implements. Reducing the area of compacted soil by designating skidtrails may be the most economical means to maintain site productivity in the Pacific Northwest.

Additional keywords: bulk density, harvesting impacts, root growth, site productivity, soil physical properties, tillage, *Pseudotsuga menziesii*

"Protect the soil while managing the forest" is a frequently cited guideline. Foresters and soils specialists obviously need to work closely, but to be most effective in managing the highly productive forest lands of the Pacific Northwest, we should add the logger or logging supervisor to this team. Soil scientists should understand site factors, foresters or silviculturists should be familiar with the requirements of tree species, and the logging engineer should understand to what extent various machines and practices reduce soil productivity. Operational factors such as machine ground pressure, number of trips, and area covered by skidtrails; site factors such as soil type, permeability, bulk density, or soil strength; and species factors such as type of root system, and response to changes in aeration and mechanical impedance to root penetration need to be considered.

This paper discusses elements from each of the three factors--site, species, operations--that influence potential growth loss (Fig. 1). We will emphasize soil physical properties because they are most susceptible to change, then relate the changes to growth of seedlings and young stands. We will also discuss recent efforts to reduce the initial impact from logging operations and to restore desirable soil properties to compacted soil.

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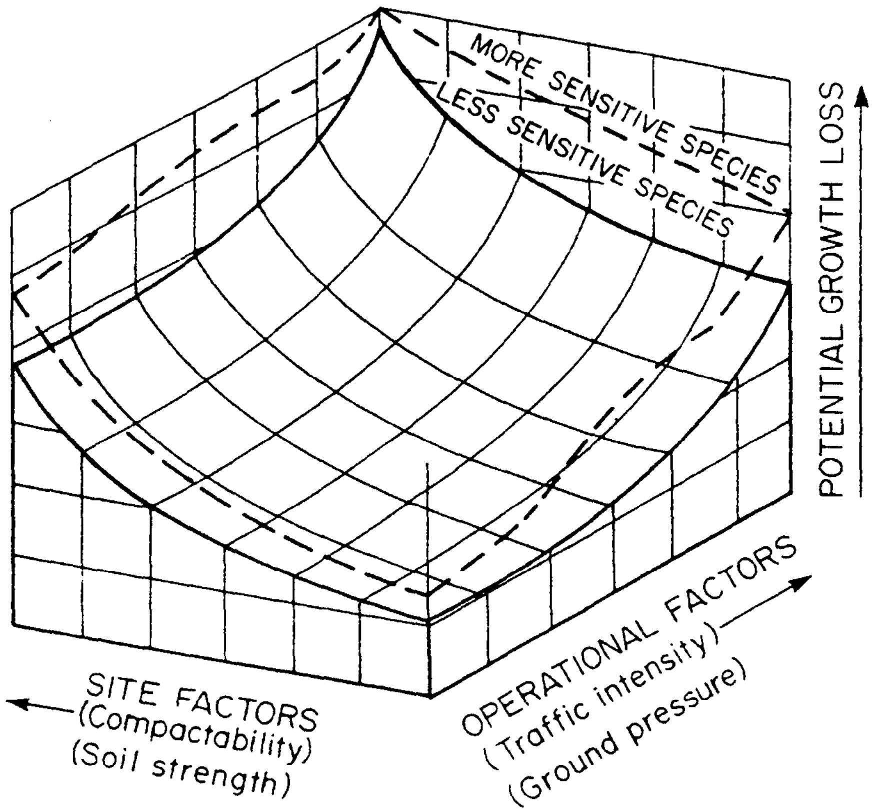

Figure 1.--Interaction of factors that influence seedling growth on compacted sites.

SOIL CHARACTERISTICS

In the Pacific Northwest, vegetation, climate, and geology have interacted through time to produce forest soils that are substantially different from those of other temperate forest regions. A unique aspect of these soils is their low bulk density and high rate of infiltration. Because most of these highly productive soils also have relatively low soil strength, they are easily compacted, displaced, or mixed during timber harvest or site preparation. Therefore, the challenge to manage them without impairing their productivity is particularly important.

Although rocks of volcanic origin, such as basalts, andesites, breccias, and tuffs--sometimes covered with different layers and thicknesses of pumice and ash--occur over large areas of the Pacific Northwest, such diverse lithologies as granitics, arkosic sandstones, pervasively sheared graywacke sandstone, quartz-mica schist and unconsolidated alluvium are also common (Janda 1979). These rocks range in age from Jurassic to early Pleistocene. Despite different lithologies, parent material has not determined the gross characteristics of forest soils in the region as much as regional climate and vegetation.

The climate of the Pacific Northwest results from a complex interaction of the maritime and continental airmasses and the mountain ranges (Franklin and Dyrness 1973). West of the Cascade Mountains of Oregon and Washington, a maritime climate is characterized by a long frost-free season with wet, mild winters and cool, relatively dry summers. East of the Cascade Mountains, the continental airmass has a greater influence, although not as great as in the Great Plains. As a result, the forests of western Washington and northwestern Oregon are classic examples of mesic, temperate coniferous forests. Further south in Oregon, the climate becomes hotter and drier and the forests become a blend of the coniferous forests of the north and the mixed sclerophyll forests of California. East of the Cascade Mountains the forests are mainly Rocky Mountain forest types.

Primarily as a result of the major soil-forming processes of climate and vegetation, forest soils in the region have developed with naturally low bulk densities and concomitant, high macroporosites, regardless of parent material. Bulk densities less than 1.0 Mg/m^3 to depths of 1 m have been reported from many parts of the region (Forristall and Gessel 1955; Steinbrenner 1955; Youngberg 1959; Brown 1975; Bormann and DeBell 1981; Sidle and Drlica 1981). Soils with bulk densities greater than 1.0 Mg/m^3, but seldom exceeding 1.4 Mg/m^3 in the surface 25 cm, generally occur where precipitation and site quality are lower, such as in the interior valleys of southwest Oregon, in recently glaciated areas of Washington, and in some areas east of the Cascade Mountains (Forristall and Gessel 1955; Froehlich 1978; 1979ab; Wicherski 1981).

Several factors contribute to the low bulk density of the soils. Most have sandy loam and finer textures that are not likely to have high natural bulk densities (Peck et al. 1974; Howard et al. 1981). The coarse-silt and sand fractions of some western Cascade Mountain soils may be pseudomorphs of clay which resist dispersion (Paeth et al. 1971). Coarse fragments between 2 and 4.76 mm diameter may also be porous and have particle densities less than 2.65 Mg/m^3 (Flint 1983). Several soils are derived from volcanic ash or pumice, which have bulk densities in the range of 0.38 to 0.85 Mg/m^3 (Cochran 1971; Soil Survey Staff 1975; Geist and Strickler 1978). Others may be high in amorphous clay constituents that contribute to low bulk densities and other properties typical of ash-derived soils (McNabb 1979).

Soil organic matter also contributes directly to the low natural bulk densities and high porosities of many forest soils (Adams 1973; Howard et al. 1981). In the Pacific Northwest, organic matter contents between 8 and 15 percent have been reported for the 0 to 15 cm depth and between 5 and 8 percent for the 15 to 30 cm depth (Youngberg 1959; Sidle and Drlica 1981). Sixteen soil profiles from a range of habitat types in the western Oregon Cascade Mountains had an average 3.9 percent organic matter in horizons 10 to 50 cm below the surface and generally more than 1 percent in all horizons less than 1 m deep (Brown 1975).

The high organic matter content reflects the interaction of evergreen, coniferous forest communities with relatively slow decomposition rates and stable carbon/nitrogen cycles. The original, old-growth forests produced large biomasses, partially because of sustained height growth and longevity (Gholz 1979; Waring and Franklin 1979; Franklin and Waring 1980). As a result, the forest floor contains large accumulations of organic debris (Grier and Logan 1977). These accumulations are sustained by large inputs of biologically fixed nitrogen by actinorhizal species, nonsymbiotic fixation in decaying logs and epiphytic plant communities, and efficient cycling of nutrients

(Cromack et al. 1979; Sollins et al. 1980). As much as one-half of the annual dry-matter transfer to the forest floor is in the form of woody debris that may take hundreds of years to decompose (Sollins 1982). Fine litter decomposes more slowly than coniferous litter from other regions (Fogel and Cromack 1977). More important, net primary production belowground, and decomposition of roots and fungal components may exceed aboveground production and decomposition several fold (Fogel and Hunt 1979; Keyes and Grier 1981, Santantonio 1982).

COMPACTION PROCESSES

"Soil compaction" is the phrase sometimes used to describe the overall condition of a forest site after machine operations, although several other alterations, including puddling, disturbance and displacement of the soil may occur (Dyrness 1965). "Disturbance" implies a mixing of the litter or soil layer(s) with little horizontal movement. "Displacement" may include disturbance but means horizontal displacement of soil as well. It is assumed to be more serious as the volume and distance of soil movement increases. Disturbance and displacement may occur independently of soil compaction.

The effects of soil compaction may be difficult to distinguish from associated effects of disturbance and displacement, and measurement of changes in site productivity resulting from compaction may include such effects as well. This paper emphasizes soil compaction, with the recognition that attempts to distinguish its effects alone are nearly impossible unless studies are designed specifically to do so.

Soil puddles when it is wet. Puddling is most serious when soil moisture potentials are higher than field capacity because moist soil aggregates have low strength (Braunack and Dexter 1978). During puddling, soil aggregates are sheared and the structure that they contribute to the soil is destroyed. Volume change is assumed to be small because the soils are nearly saturated, with no air space to displace. Macropore space, however, is still plentiful in Pacific Northwest forest soils at moisture contents near field capacity. Therefore, soil compaction and soil puddling can occur simultaneously.

Soil compaction reduces porosity, primarily the gaseous phase, and increases bulk density by reducing the interaggregate pore space (Hodek and Lovell 1979). "Bulk density" defines the mass of dry soil per unit bulk volume of the solid, liquid, and gaseous phase. Therefore, bulk density is the unit of measure most often used to describe soil compaction, but it does not describe the potential for compaction. Soil strength ultimately determines whether the particle rearrangement that reduces porosity will occur. Rearrangement can occur only if the stress applied to the soil by machines or other sources overcomes the original frictional and elastic strain-resistance of the soil (Li 1956).

The initial strength of a soil is a function of opposing forces, those that work to naturally consolidate the soil and those that tend to loosen it; thus, initial strength reflects the stress history of the soil. As a result, there is no simple relationship between soil strength and bulk density (Barley and Greacen 1967). Bulk density and porosity of soil are largely determined by its particle size distribution, gradation, particle roughness, organic matter content, mineralogy of the clay fraction (particularly for finer textured soils), and structure (Bodman and Constantin 1965; Lee and Suedkamp 1972; Cruse et al. 1980; Howard et al. 1981; DeKimpe et al. 1981; Aylmore and Sills 1978). The natural forces that tend to loosen soils are activity of soil flora and fauna, freezing and frost heaving of soil, swelling of finer textured soils during rewetting, and windthrow. Natural forces that tend to consolidate soils are thawing, wind motion transferred to roots, radial growth of roots, and shrinkage resulting from water loss. The natural bulk density of a soil is the result of such physical and biological factors and the inherent resistance to consolidation due to particle strength and interparticle bonding.

The application of an external load to a soil by machines, foot traffic, etc. normally increases soil bulk density linearly with the logarithm of the consolidating force applied. This relationship is most often characterized by a uniaxial consolidation test of unsaturated soil (Barley and Greacen 1967; Greacen and Sands 1980). The slope of the line defining the relationship is termed the compression index and is a unique property of a soil (Larson et al. 1980)

Determining the amount of compaction that will occur from loading a soil, however, is more complex than implied from a simple consolidation test. Soil water potential has an important effect (Larson et al. 1980). Duration of loading may also be a factor (Vomocil et al. 1958; Dexter and Tanner 1974). Kneading compaction, in which differential shear stresses may develop in the soil, produces more compaction than an equivalent static load (Soehne 1958). Vibration of machines produces considerably more compaction in coarser-textured soils than an equivalent static load (Terzaghi and Peck 1967; Cruse et al. 1980).

PREDICTING SOIL COMPACTION

Compactibility

A common method used to minimize soil compaction is to restrict machine operations on the basis of texture or moisture conditions, which involves interpreting a soil compaction test borrowed from engineering (Proctor 1933). The test yields a moisture-density curve that is soil specific (Fig. 2); it is, however, a function of the stress applied to the soil (Fig. 3). With decreasing compactive effort, the peak in the moisture-density curve occurs at a lower bulk density and a higher moisture content. Therefore, if this test is to provide information on how soil texture and moisture affect soil compaction, the moisture-density curve must represent specific site conditions.

Texture

Maximum bulk densities obtained from moisture-density curves are sometimes used to rank soil susceptibility to compaction (Diebold 1954; Larson et al. 1980; Howard et al. 1981). Soils with the highest compacted bulk density are judged most susceptible. They generally have a broader distribution of particle sizes, i.e., coarser-textured soils, or medium-textured soils with less than 40 percent silt-sized particles (Diebold 1954). Fine-textured soils cannot be compacted to high densities because they have proportionally more

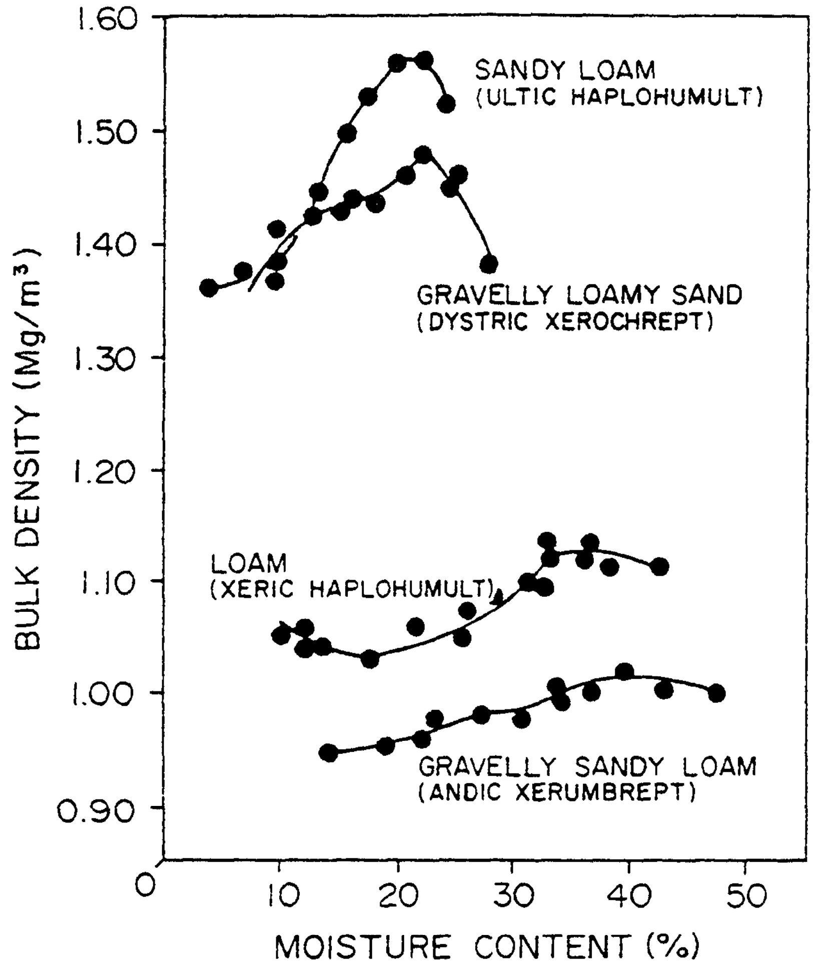

Figure 2.--Effects of moisture and soil type on compacted bulk density (standard test, Proctor 1933) on four soils from the western slopes of the Sierra-Nevada Mountains of northern California (Froehlich et al. 1980).

micropore space that is resistant to densification and they retain more water than coarser-textured soils.

When compacted, or natural bulk densities of soil from different parent material are used to identify soils most susceptible to compaction, changes in soil strength with compaction are often overlooked. In Figure 4, the Tolo, a Typic Vitrandept, is derived from recent volcanic ash and is low in bulk density. Nevertheless, it increases in strength at the same rate as other soils with much higher bulk densities. Therefore, classifying soils with high bulk densities as more susceptible to compaction fails to consider that the strength of all soils will increase when compacted.

The consolidation of agricultural soils has been studied in detail by Larson et al. (1980). The compression index of soil was found to increase approximately linearly as the clay content increased from 2 to about 33 percent. At higher clay contents, the compression index was nearly constant. Compression indices were slightly higher for soils dominated by 2:1 type clay

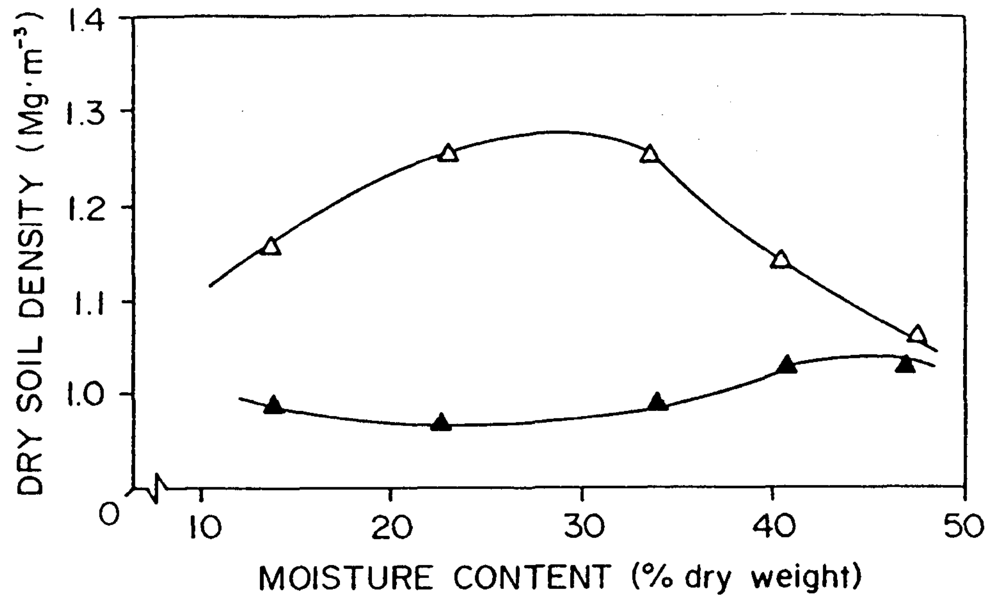

Figure 3.--Moisture-density curves for a sandy loam Andic Xerochrept compacted at standard Proctor level (△) and at 12.5 percent of standard Proctor level (▲). Undisturbed bulk density of the soils is 0.84 Mg/m^3. Bulk density after 20 trips with a crawler tractor is 1.08 Mg/m^3.

minerals than for soils containing kaolinite or iron oxides. All compression indices were determined on soils with water potential between -5 and -100 J/kg.

Moisture

While limiting machine operations to times when soil moisture is below a specified level may reduce compaction on some soils (Chancellor 1971; Miles et al. 1981), others have nearly flat moisture-density curves and compact to similar bulk densities over a wide range of soil moisture (Soehne 1958; Raghavan et al. 1977; Froehlich et al. 1980). How much compaction occurs at different moisture contents appears to be related to the particle size distribution and clay mineralogy of the soil (McNabb, unpublished data). Based on low energy moisture-density curves, the compaction of both well-graded coarse-textured soils and fine-textured soils with expandable clay minerals are somewhat affected by moisture content (moisture sensitive), but poorly graded coarse-textured soils and fine-textured soils with non-expanding clay minerals compact to similar bulk densities regardless of moisture content (moisture insensitive). Only well-graded soils have sufficient fines to fill the pores between the larger soil grains; poorly-graded soils have too many or too few fines. Regardless of whether a soil is classified as moisture sensitive or insensitive, substantial compaction can occur at any moisture content.

Soil moisture affects compaction most at water potentials around field capacity, when changes in soil structure are most likely to occur (Braunack and Dexter 1978). For a given soil, structure changes at the same degree of saturation regardless of the stress applied (Larson and Gupta 1980). The degree of saturation at which change occurs increases from about 35 percent to 60 percent as soil clay content increases from near zero to 33 percent.

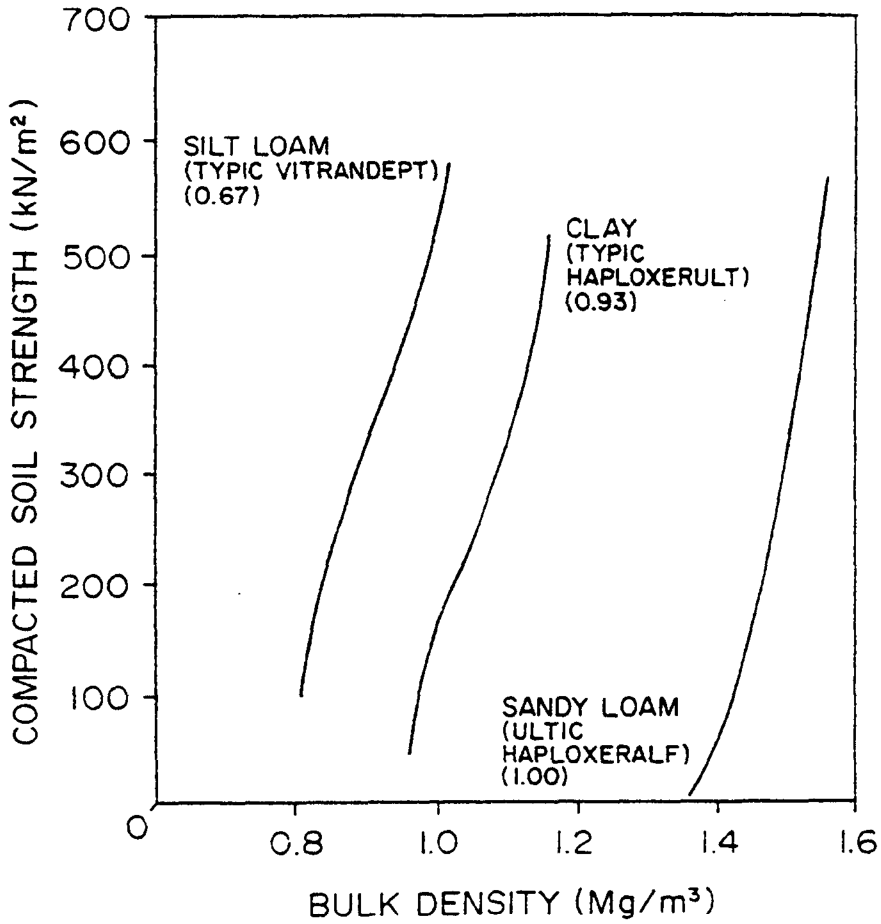

Figure 4.--Change in bulk density and soil strength resulting from increasing compactive effort (from 5 to 35 blows per layer with a standard Proctor hammer). Numbers in parentheses are natural bulk densities, Mg/m^3. (McNabb, unpublished data).

At higher clay contents, the required degree of saturation is nearly constant. Organic matter content of the soil may affect this relationship and contribute to the amount of variability as well (DeKimpe et al. 1981). Therefore, avoiding machine operations on moisture sensitive soils at moisture contents near field capacity may help minimize both compaction and puddling.

Predicting Soil Compaction

An ability to predict how much and under what conditions soil will compact would greatly improve soil management. Unfortunately, efforts to predict soil compaction quantitatively have been few until recently. A moisture-density curve may suggest the amount of compaction and the effect moisture can have on some soils; however, a compactive simulation must be selected that will yield a moisture-density curve with bulk densities equivalent to those caused by harvesting machines. This differs from the traditional use of moisture-density curves to provide a quality control standard for evaluating soil as a construction material.

The moisture-density curves obtained by the Proctor (1933) test overestimate the bulk densities normally produced by harvesting machines (Fig. 3). While a lower energy level yields bulk densities in the general range of those expected from common tractive logging machines, the test is not consistently reliable for predicting soil compaction from machines in the field. A high energy moisture-density curve also underestimates optimum moisture content. In Figure 3, the low energy optimum moisture content is higher than field capacity, a characteristic common to many high-porosity forest soils in the Pacific Northwest.

Most predictions of increases in bulk density use some measure of the soil compressibility and how it is affected by soil moisture (Raghavan et al. 1977; Larson et al. 1980). These equations use an estimate of machine pressure on the soil to determine compaction; however, compaction is also affected by the number of passes the machine makes across the soil (Fig. 5). (Steinbrenner 1955; Amir et al. 1976; Froehlich et al. 1980). Compaction caused by a given machine further depends on whether the machine is traveling uphill or downhill, which shifts the relative loading of the tracks or wheels (Sidle and Drlica 1981). Therefore, predictions of soil compaction under field conditions must integrate several complex relationships.

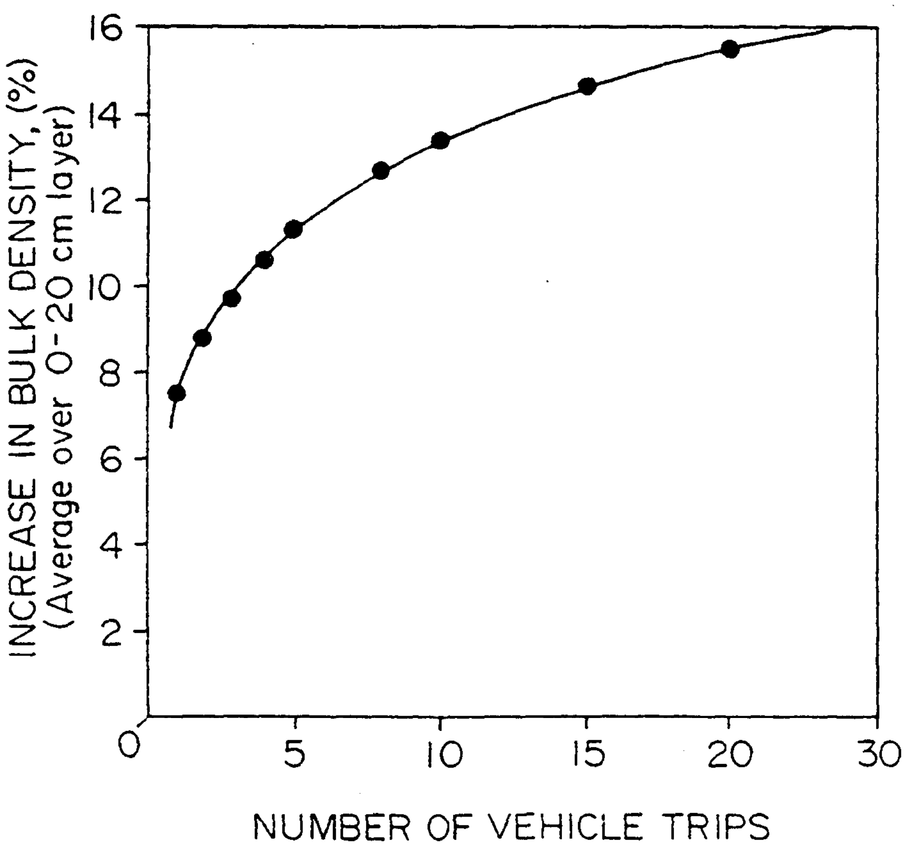

Figure 5.--Relationship between increases in bulk density and the number of machine trips. The density curve was produced by a prediction equation (Froehlich et al. 1980) using average soil strength, moisture, and machine-derived pressure.

The compaction of four Sierra-Nevada forest soils, as either a relative or percentage change in bulk density, has been predicted by multiple linear regression with considerable success (Froehlich et al. 1980). The soils ranged in texture from loam to gravelly loamy sand. An equation using number of passes, cone index measure of soil strength, machine-derived pressure, moisture content, organic matter content, and depth of litter accounted for about 69 percent of the variation in compaction caused by three machines: a rubber-tired skidder, crawler tractor, and torsion-bar suspension machine (n=36). Machine-derived pressure was an approximation of the maximum dynamic loading of the front or rear axle of a skidder or of the leading or trailing portion of tracks, including load weight and effects of slope on weight distribution (Lysne and Burditt 1983). This approximation was a more useful predictor of soil compaction than the static weight of the machine (Table 1). The data illustrate the large differences between static and typical pressures produced by tractive machines.

The number of passes and the cone index measure of soil strength alone accounted for 54 percent of the variation in this study. The first few trips produced the most compaction, about 70 percent occurring by the fifth trip. The cone index measure of soil strength was most closely correlated with compaction as it reflected the initial bearing capacity of the soil and probably integrated several other soil properties, including moisture. At low bulk densities, soil moisture had little effect on cone index values. Soil moisture between 10 and 40 percent, which correspond to water potentials between -80 and to -800 J/kg in wettest conditions and near -1,500 J/kg in driest conditions, was not an important variable in this study.

Table 1.--Ground pressure of logging vehicles on different ground slopes[a] (after Lysne and Burditt, 1983)

	Static	Dynamic pressure with log turn									
	unloaded	Leading track or tire					Trailing track or tire				
Machine	pressure	-20°	-10°	0°	+10°	+20°	-20°	-10°	0°	+10°	+20°
	kPa										
Crawler tractor; 17,687 kg with 6,802 kg load	64	115	80	40	10	*[b]	40	70	110	145	170
Torsion suspension skidder; 13,152 kg with 6,802 kg load	41	110	70	45	20	*	*	25	60	90	120
Rubber-tired skidder; 9,070 kg with 3,628 kg load	66	100	85	70	60	-	50	70	85	110	-

[a] Ground slope in direction of travel while skidding logs.
[b] Pressure is negligible.

Predictions of soil compaction have been restricted to a standard depth; predicting the actual depth of compaction is complicated by layered soils, roots, large rock fragments, and the type of tractive machine (Froehlich et al. 1980). Fewer trips, stronger soils, heavier vegetation cover, and machines with lower dynamic loading would result in different bulk density profiles (Fig. 6).

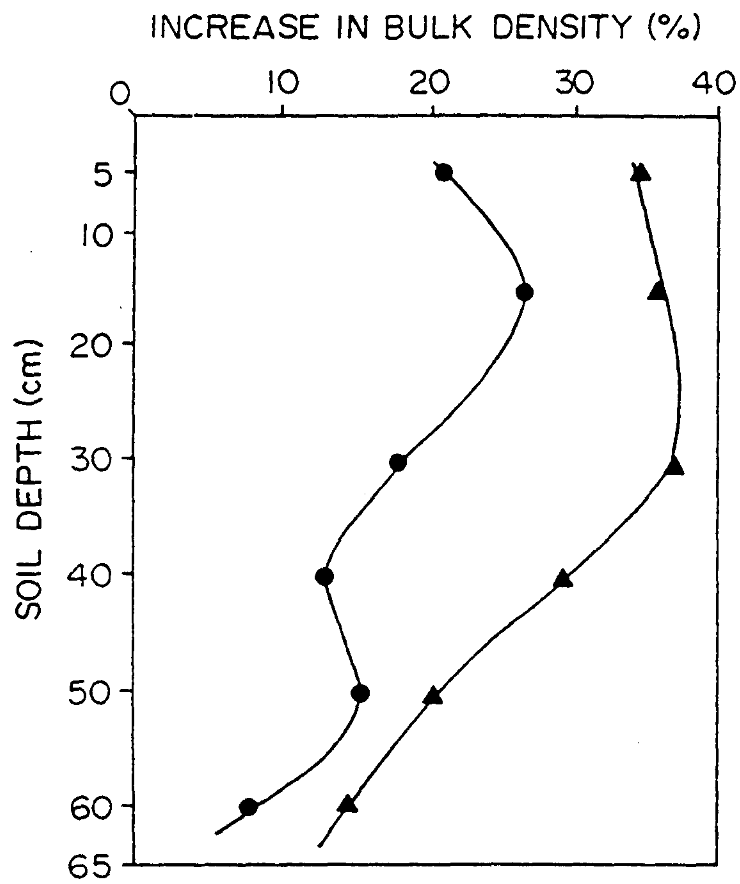

Figure 6.--Average increase in bulk density with depth on heavily used skid-trails (20 trips) on two soils in central Idaho. Soils were formed on granite ( ) Typic Xerosamment and on basalt ( ) with some volcanic ash, Dystric Cryochrept (Froehlich et al. 1983).

EFFECTS OF COMPACTION

Soil Strength

An increase in soil strength is one of the most notable effects of compaction. The relationship between bulk density and soil strength, however, is more complex than apparent in Figure 4. In soils of similar texture, rough particle surfaces increase interparticle friction and, consequently, soil resistance to movement more than smooth particle surfaces (Cruse et al. 1981). Soil moisture may also affect strength. For example, penetrometer resistance (an indirect measure of soil strength) of four medium- to coarse-textured soils in southeastern United States increased as the moisture potential decreased from -20 to -67 J/kg, although bulk density remained constant (Taylor and Bruce

1968). With decreasing soil moisture, penetrometer resistance increased faster at higher bulk densities. In contrast, the penetrometer resistance of a sandy soil in Australia did not differ significantly over a wider range of moisture contents (Sands et al. 1979). Williams and Shaykewick (1970) found that as the water potential decreased from -59 to -1,510 J/kg strength of a clay soil increased but strength of a loam remained relatively constant. These inconsistencies illustrate the complex effects that bulk density, texture, and soil moisture have on soil strength. These effects are only partially accounted for by differences in negative moisture potentials and amount of water-filled porosity (Barley and Greacen 1967).

Aeration

Compaction always reduces air-filled porosity although not always water-filled porosity (Fig. 7) (Froehlich et al. 1980). Lack of decrease in water-filled porosity and differences in the definition of water potential at water-filled porosity may account for some of the scatter in reported relationships of air-filled porosity and bulk density.

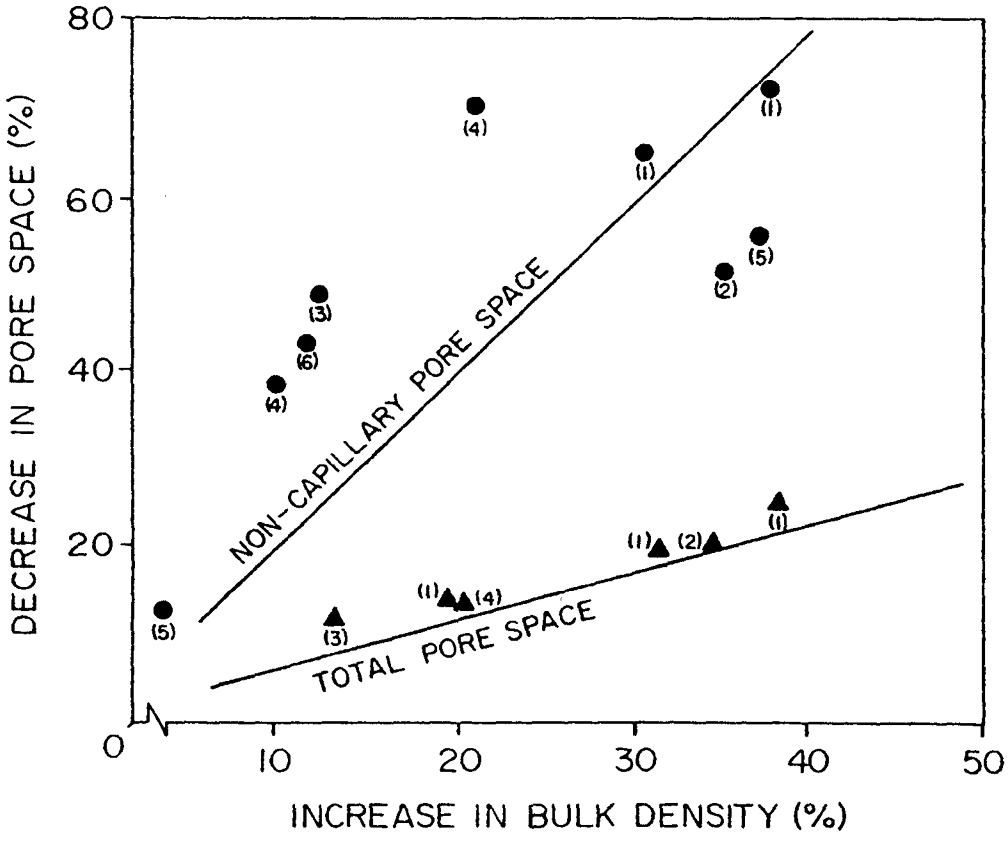

Figure 7.--Relationship between decrease in non-capillary ( ) and total pore space ( ) and the increase in bulk density caused by compaction of several forest soils. From Campbell et al. 1973 (1); Hatchell et al. 1970 (2); Moehring and Rawls 1970 (3); Dickerson 1976 (4); Steinbrenner 1955 (5); and Froehlich et al. 1980 (6).

Reduction of air-filled porosity has an obvious effect on diffusion of gases in soil (Grable 1971). A minimum of 3 to 4 percent of the air-filled pore space in a soil must interconnect for adequate diffusion of oxygen to a depth of 1 m or more. Total air-filled porosity must be higher, at least 10 percent, for low rates of diffusion and more if oxygen demand is higher.

Water Movement and Retention

The saturated flow of water through compacted soil is substantially less because pore space is reduced, principally the large pores (Fig. 8). Because micropore space in soil may not be changed by compaction, unsaturated hydraulic conductivity is less affected and may sometimes increase (Sands et al. 1979; Greacen and Sands 1980).

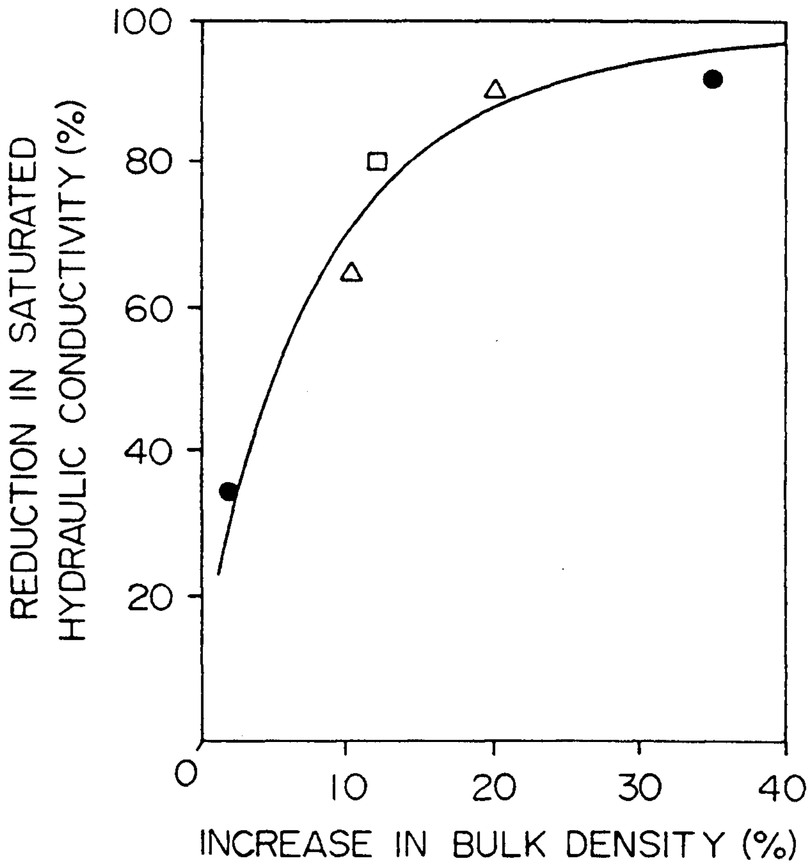

Figure 8.--Reduction in saturated hydraulic conductivity associated with an increase in bulk density. From Dickerson 1976 ( ); Steinbrenner 1955 ( ); and Froehlich 1980 ( ).

Moisture retention is often higher in compacted soils (Warkentin 1971; Greacen and Sands 1980; Froehlich et al. 1980). The moisture-retention properties after compaction, however, are soil specific. Retention of compacted, sandy soils may increase, that of loam soils may decrease, and that of clay soils may either increase or decrease. Although available soil moisture may increase, particularly in sandy soils (Sands et al. 1979), the absolute change is generally small and unimportant compared to other changes in physical properties.

Root Growth

Decreased crop yield after soil compaction reflects effects on the plant root system that may include complex interactions between soil strength, water and nutrient availability, aeration, and mycorrhizal populations (Greacen and Sands 1980). Factors that are often ignored are the amount and frequency of precipitation and the drainage characteristics of the soil (Smith 1977).

The effect of soil compaction on mycorrhizae is largely unknown, but Skinner and Bowen (1974) reported that compacting a sandy soil reduced mycelial strand penetration by *Rhizopogon luteolus* 80 percent in a laboratory experiment. Reduced mycorrhizae formation could be a more serious consequence of soil compaction on tree growth than reduced root growth *per se*.

Poor aeration is the most often cited cause of poor growth of tree roots in compacted soil (Minore 1968; Pereira and Kozlowski 1977; Ruark et al. 1982; Zaerr 1983). Flooding experiments have clearly established that species differ in tolerance to poor aeration and that tolerance may vary with season (Minore 1968). For example, survival of *Pseudotsuga menziesii* (Mirb.) Franco seedlings was reduced after only 1 week of flooding in winter; other conifer species were not affected after 4 weeks. Poor aeration may be more serious in summer than winter.

The effect on trees of poor aeration when the soil is less than saturated is not well known, although considerable information is available for agronomic crops. An air-filled porosity of 10 percent is often cited as the minimum requirement for maintaining aboveground growth or crop yield (Vomocil and Flocker 1961; Grable 1971). However, laboratory experiments with agronomic crops show that root growth may sometimes be impaired if air-filled porosities are below 35 percent (Eavis 1972; Warnaars and Eavis 1972; Bar-Yosef and Lambert 1981; Voorhees et al. 1975).

The adverse effects of the high strength of compacted soil on tree root growth have often been ignored, although naturally high strength has commonly been identified as a major cause of reduced root growth in fragipan horizons (Grossman and Carlisle 1969). Root densities (cm/cm^3 of soil) were also lower in higher strength, B horizons of Typic Fragiudalfs beneath mature stands of *Quercus coccinea* Muenchh (McNabb 1972). Cochran (1971) found rooting depth of *Pinus ponderosa* Laws. and *P. contorta* Dougl. ex Loud. was less in pumice soils compacted to 0.60 Mg/m^3 with air-filled porosities greater than 20 percent than in soil with a bulk density of 0.38 Mg/m^3. He concluded that mechanical impedance resulting from pumice particle bridging reduced root growth. Fewer *Pinus radiata* D. Don roots penetrated soils derived from podzolized dune sands where penetrometer resistance was greater than 3,000 kPa (Sands et al. 1979). Although some species are equally affected by soil strength (Fig. 9), western conifer species grow differently in the same compacted soil (Minore et al. 1969). This suggests that species diversity may exist, although the differences may be morphological. Seedlings that produce a distinct taproot may be affected more by high soil strength (Cochran 1971).

The complexity of the interaction between soil aeration and strength in compacted soil is conceptualized in Figure 10. The relationship is largely independent of texture, although the midpoint may move slightly to the left

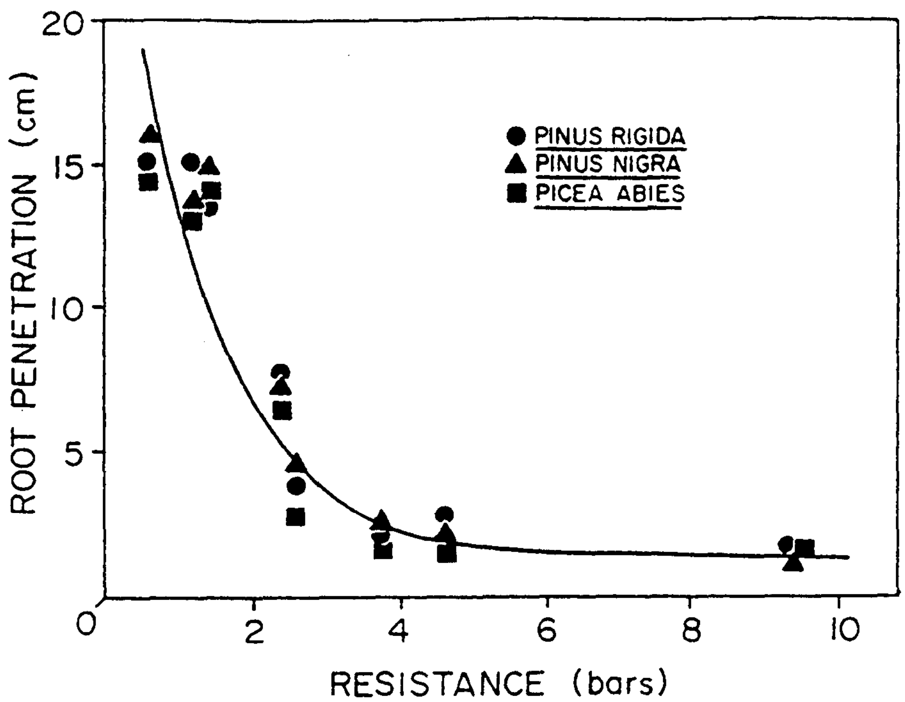

Figure 9.--Reduction of root-penetration depth of three tree species with increasing soil resistance (Zisa et al. 1980).

for finer-textured soils with naturally smaller pores. More important is how climatic and site drainage characteristics affect the degree of saturation, and whether there are temporal differences in root response to poor aeration. This conceptual approach applies particularly well to perennials, for which the effects of compaction on root growth must be integrated over an entire year. Extremes in the degree of saturation in a single year may adversely affect root growth for several years.

Changes in soil strength and aeration appear to be the two main results of compaction that affect root growth. Their relative importance is determined by precipitation frequency, plant demand for water, and drainage characteristics of the site. Aeration is generally not a problem in coarse-textured, well-drained soils, where root growth may be directly related to soil strength (Taylor et al. 1966; Sands and Bowen 1978). It is a more serious problem in finer-textured soils where air-filled porosity is low and drainage is slow. If nutrients and water are readily available, crop yields may not be reduced by high soil strength, although the volume of the root system may be reduced (Taylor and Bruce 1968). Therefore, water or nutrients become limiting only when plant demands exceed the ability of the root system to penetrate high strength soil.

Reduced root growth of several forest species has been associated with increases in bulk density (Minore et al. 1969; Zisa et al. 1980; Heilman 1981). These associations and others obtained for agronomic crops has sometimes been used to define a "critical" or growth-limiting bulk density above which roots will not penetrate a soil (Daddow and Warrington 1983); however, the bulk density of a specific soil varies with texture as well as with many other factors.

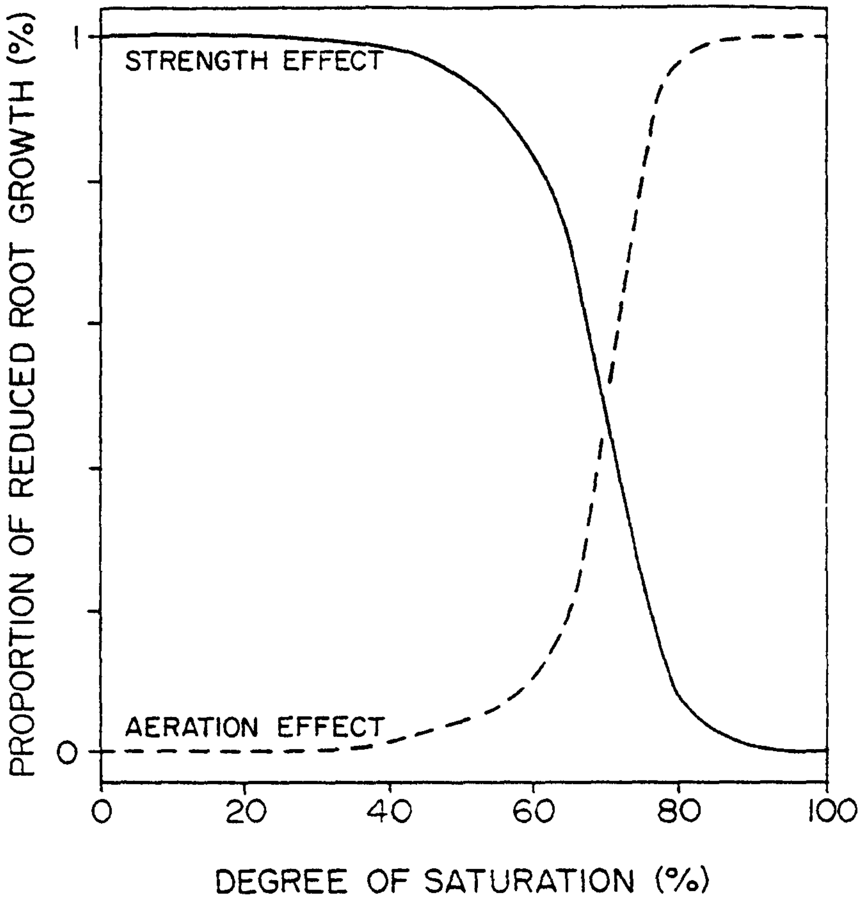

Figure 10.--Conceptualized relationship of the relative importance of soil strength and aeration in reducing root growth in compacted soil at different degrees of saturation (volume water/volume of pore space).

Root growth is often reduced in proportion to the change in bulk density up to a maximum bulk density (Heilman 1981). This maximum density cannot be used as a "critical" value for a given texture class because the bulk density at which root elongation slows or ceases is also dependent on the moisture availability, strength, and aeration characteristics of a particular soil and site (Taylor and Gardner 1963; Taylor et al. 1966). The concept of a "critical" bulk density is only valid if it is soil specific and defines the soil moisture and climatic conditions of the site to which it is being applied.

Although bulk density values are not directly related to the effect of compaction on root growth, changes in bulk density serve as indexes of changes in physical properties that do regulate root growth. The relationship between bulk density and plant growth is an association rather than a cause and effect, and extrapolation of an association to unlike soils or sites is not appropriate. When quantifying plant response to compaction, relative changes in bulk density may be more useful than absolute bulk density, providing differences in initial bulk densities are not excessive.

Growth of Seedlings and Young Stands

Soil compaction is nearly always associated with a reduction of shoot growth (Youngberg 1959; Minore et al. 1969; Hatchell et al. 1970; Sands and Bowen 1978). A relationship between increased bulk density and decreased seedling height growth is proportional, at least for existing data (Fig. 11). This is surprising because the data are for three species and six soils, ranging from sandy loam to clay, which makes the relationship independent of species and soil. When expressed as percentage of change from control bulk density and height, the relationship is strong, but when expressed as change in height growth related to absolute bulk densities, it is weak.

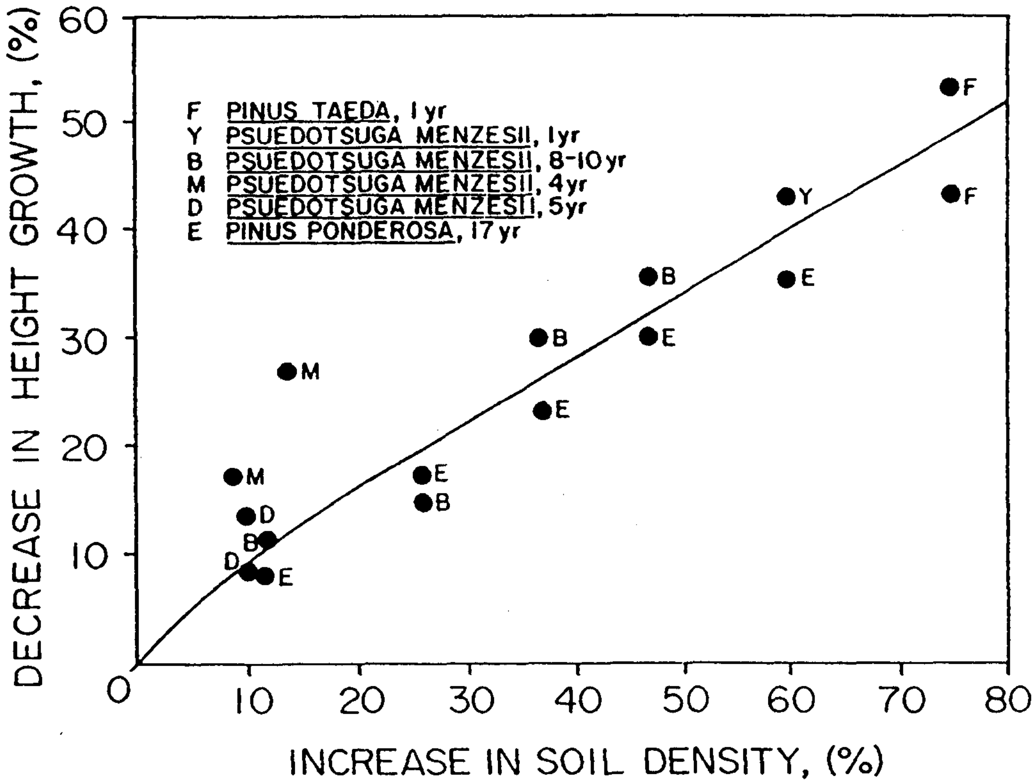

Figure 11.--Relationship between the increase in bulk density and the decrease in seedling height growth. From F-Foil and Ralston (1967); Y-Youngberg (1959); B-Bureau of Land Management; and D,M,E-Froehlich 1979b. Line is fitted visually.

The reduced height growth of seedlings in compacted soils obviously lowers productivity. Extrapolation from the average growth of 7-year-old P. menziesii (McArdle et al. 1949), indicates that a 35 percent increase in bulk density may reduce Site II quality land to Site III (Fig. 12). Further increases may decrease site quality even more.

Long-term studies of the effects of soil compaction on planted seedlings are continuing. Reduced height growth of P. ponderosa in southwest Oregon was still apparent after 17 years (Froehlich 1979b); the relationship between change in bulk density and height is similar to that of much younger seedlings (Fig. 11). In south central Washington, growth of P. ponderosa averaging 14

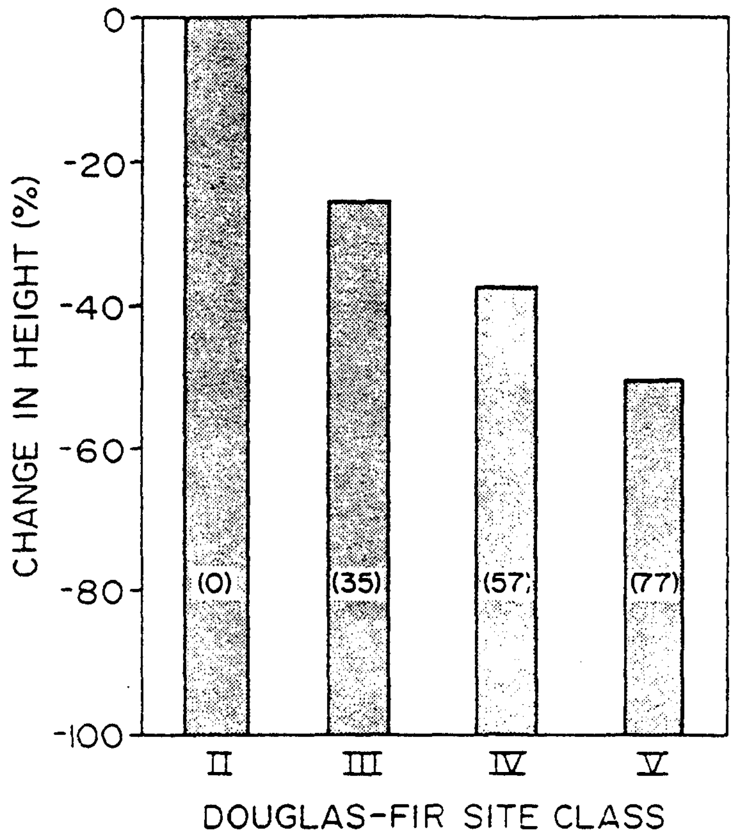

Figure 12.--Relationship between average height of 7-year old *Pseudotsuga menziesii* seedlings with site class (McArdle et al. 1949). Change in site class is associated with compaction increasing bulk density (percentage increase in bulk density in parentheses).

years-of-age was not reduced until the increase in bulk density exceeded 10 percent (Froehlich and Robbins 1983). With increasing age, growth of seedlings on moderately to heavily compacted soil appeared to lag progressively below those on less compacted soil.

Soil compaction affects volume growth more than it does height growth. In the southwest Oregon study of *P. ponderosa*, a 26 percent increase in bulk density was associated with a 17 percent reduction in height growth but a 48 percent reduction in stem volume. When potential stand growth was adjusted by the percentage of trees growing in soils of different intensities of compaction, average stand growth was estimated to be reduced 14 percent. In the south central Washington study, a 26 percent increase in bulk density was associated with a 13 percent loss of height growth and a 33 percent reduction in stem volume.

Natural stands older than 20 years show losses in height and diameter growth similar to those in young planted stands. On compacted soil, 26-year-old *Pinus taeda* L. had 13 percent less height growth and 53 percent less volume growth than on adjacent undisturbed areas (Perry 1964). Similar results have been reported for an even older *P. menziesii* stand in the Pacific

Northwest (Wert and Thomas 1981). On compacted skidtrails, 32-year-old trees had 30 percent less height growth and 55 percent less volume growth than trees growing 3 m or more from the skidtrails. Estimated overall volume growth for the area was reduced 11.8 percent because of less growth in the skidtrails. Growth reductions should persist for several more years; bulk densities were significantly higher at the 20 and 30 cm depths, and the soils were still considered to be heavily compacted, although bulk density was decreasing at the surface.

Following commercial thinning, the reduction of growth of individual trees appears to be a function of the percentage of root zone compacted, intensity of compaction, and root damage. Logging traffic causing rutting on three sides of a tree reduced basal area growth of P. taeda by 36 percent and traffic ruts on four sides of a tree reduced growth by 43 percent (Moehring and Rawls 1970). Volume growth of thinned trees is not reduced as much when rutting does not occur; growth of individual P. ponderosa trees in moderately to heavily compacted soil in eastern Oregon lost only 6 to 12 percent growth (Froehlich 1979a). In western Oregon, P. menziesii growing in moderately compacted soil (10 to 40 percent of the rooting area compacted) were reduced an average 17 percent, whereas trees growing in heavily compacted soil (more than 40 percent of rooting area compacted) lost 27 percent (Froehlich 1979b). Basal area growth for the entire stand was estimated to be reduced 5 to 13 percent, depending on the proportion of area compacted.

AMELIORATION OF COMPACTION

Natural Recovery

Frost heave, freezing-thawing, wetting-drying, and biological activity are the major processes acting to loosen compacted soil. For any of these processes to be effective, several criteria must be met: the soil must be sensitive to the process, the climate must produce the necessary temperature and moisture regimes, and the cycles must occur frequently.

Wetting and drying may shrink and swell some soils, and the volume changes may cause them to break into structural units contributing to soil aggregation. Properties that affect volume change are the amount and type of clay minerals, particle arrangement, exchangeable cations, composition of the soil solution, and organic and chemical bonding agents (Larson and Allmaras 1971). Large volume changes are most likely to occur in soils dominated by smectite clays; volume changes in sandy soils are generally negligible. Extremes in the wetting and drying cycle are most effective in causing susceptible soils to shrink and swell.

Simple freezing and thawing of a soil cannot result in large changes in soil volume because water expands only about 9 percent during freezing. For example, soils with volumetric water content of 0.3 cm/cm^3 could theorotically increase in volume by about 3 percent but would be less if the soil is partially saturated. The freezing of water within soil pores, however, decreases the water potential of soil aggregates, causing soil drying. Therefore, it is difficult to separate the fracturing caused by water freezing from that associated with drying, particularly for soils prone to shrink and swell (Larson and Allmaras 1971).

Frost heave produces larger volume change in soil than simple freezing and thawing of initial water content, but the conditions necessary for frost heave are more exacting. Two important factors are heat flux of the soil and movement of water from unfrozen soil to the point of freezing (Chalmers and Jackson 1970; Heidmann 1976). Maximum frost heave occurs when the rate of soil cooling is nearly offset by the heat released in the phase change of water from liquid to a solid. Depth of frost penetration is affected by the thermal conductivity of the soil, air temperature, and litter and/or snow cover of the soil. Frost heave requires that about 90 percent of the pore space be filled with water (Dirksen and Miller 1966). Because unsaturated hydraulic conductivity of the soil controls water movement to the point of freezing, frost heave is most likely in medium-textured soils or compacted, coarse-textured soils, i.e., in soils having the highest unsaturated hydraulic conductivities. Compaction may make fine-textured soils less susceptible (Larson and Allmaras 1971).

Both soil flora and fauna can loosen and mix soil. Borrowing and mound building insects, worms, and animals may annually move many tons of soil per hectare (Hole 1981; Levan and Stone 1983; Kalisz and Stone 1984). Their potential for loosening compacted soil, however, is probably considerably less. Root growth is commonly reduced in compacted soil and the growth of fungi may be reduced even more (Skinner and Bowen 1974). The roots of young plants often utilize channels remaining in the soil from the decay of the previous root system (McMinn 1963); a factor decreasing their ability to loosen dense soil. Reports of faunal activity in compacted soil are few (Larson and Allmaras 1971), although Dexter (1978) observed that one species of earthworm tunnelled through soil, regardless of its strength, by ingesting the material. The mobility of some forms of soil fauna also allow them to avoid compacted soil. The importance of biological processes in loosening compacted soil should increase substantially when it is covered with litter that protects roots and soil fauna living in the top few centimeters partially loosened by mechanical processes.

Rates of natural amelioration of compacted soils are variable. Surface layers of some soils have recovered in as little as 2 years where frost heaving processes are active (Mace 1971), but in milder climates, compaction of skid-trails has persisted for more than 3 decades (Vanderheyden 1981; Wert and Thomas 1981; Froehlich et al. 1983).

Most reports of rapid recovery are for shallow depths. Thorud and Frissel (1976) estimated the recovery time of a coarse-textured soil at 0 to 7.6 cm to be between 4.5 and 9 years, while bulk densities at greater depths did not decrease over the same period. Mace (1971) also observed rapid rates of recovery in surface layers of specific soils. Recovery of Coastal Plain soils in northern Mississippi was projected to take 8 to 12 years, but samples were taken only from the 0 to 5 cm depth (Dickerson 1976).

The return of the subsurface soil layer to near preharvest bulk densities takes much longer (Thorud and Frissel 1976). Soils along the Atlantic Coastal Plain require about 18 years to recover but this estimate is complicated by use of different skidding machines on the older sites (Hatchell and Ralston 1971). Although bulk densities of surface soils returned to normal on one western Oregon site after 32 years, soil at the 20 to 30 cm depth remained heavily compacted (Wert and Thomas 1981). Power (1974) reported that bulk density at the 25 cm depth had not changed appreciably after 40 years at another site. In a chronosequence of 81 plots in the western Cascade Mountains of Oregon, Vanderheyden (1981) was unable to detect a reduction in bulk density of compacted soils at 5.1, 15.1, or 30.5 cm over a period of 38 years.

The failure of natural processes to rapidly reduce bulk densities of compacted soil is evident from these studies. The several from the Pacific Northwest, where bulk densities remain nearly unchanged for decades, emphasize the importance of climatic extremes for accelerating natural recovery. The maritime climate, particularly west of the Cascade Mountains, generally keeps the soils from freezing to an appreciable depth and produces only one distinct wetting-drying cycle annually. Where colder temperatures are more common, winter snowpacks generally insulate the soil from cold. Forest soils in the Pacific Northwest are generally low in smectite clay minerals and high in amorphous clay constituents or volcanic ash which do not swell when wetted (Birrell and Fieldes 1952; Schalscha et al. 1965).

Even in cold climates, reduction of bulk density by frost penetration may not be as great as previously believed. In southwestern Minnesota, bulk density of compacted subsoil was not changed in corn or alfalfa fields after 9 years (Blake et al. 1976). In another study, natural processes did little to reduce compacted bulk densities of soils that had overwintered, although they were assumed to freeze to 1 m (Voorhees et al. 1983). Freezing did reduce penetrometer resistance of the soil in the spring after compaction, which indicates some natural recovery may have occurred.

Until natural recovery of compacted soil is documented on a site specific basis, the effects of soil compaction should be assumed to persist for several decades on forest sites.

Mechanical Tillage

In the Pacific Northwest, several tools are commonly used to loosen compacted soil, although few were designed for tillage (Andrus and Froehlich 1983). Brush blades do not loosen the deeper layers of compacted soil and often added to the soil displacement at the trail edges. Measurements on three sites showed that from 28 to 49 percent of the volume of compacted soils was shattered. Rock rippers tended to fracture soil to greater depths and worked reasonably well in rocky, coarse-textured soils. On finer-textured soils and moist, coarse-textured soils, the soil shattering tended to be limited to less than 50 percent of compacted soil volume.

In tests of two small (6 blades, 0.8 m diameter) and two large disk harrows (16 and 24 blades, 0.9 m diameter), the small disks tilled only 10 to 17 percent of the compacted soil, the larger disks 40 and 55 percent, respectively. Depth of penetration limited the effectiveness of disks; multiple passes would be required to till to a lower depth. The disk harrows were efficient at controlling competing vegetation but appeared to be of limited value in loosening a layer of compacted soil 0.4 m deep.

An effort has been made to develop a winged-subsoiler attachment for common logging tractors. The goal was a tool that could till at least 80 percent of the compacted soil in a skidtrail in a single pass. Preliminary trials with a prototype showed that the addition of wings to a curved, subsoiler shank increased soil shattering 30 percent in a rocky loam and 64 percent in a silty clay soil. Three winged shanks mounted on a tool bar were tested on several compacted soils. Consistently, over 80 percent of the 0.4 m-deep layer was fractured by the tool in a single pass.

Direct costs for deep tillage of skidtrails are similar to other forms of mechanical site preparation, approximately $110.00/ha of skidtrail (1982 costs), to which move-in, supervision, and delay costs must be added. The investment should be borne by gains in productivity. Neither the long-term effect of tillage nor its economic ramifications have been studied.

Improved seedling survival and growth after tilling of compacted soil have not been as thoroughly documented as losses resulting from compaction. Tillage has generally been successful with changes in seedling survival between -9 and 39 percent, when compared to seedlings planted in compacted soil (Table 2). The gains in height growth were generally greater than gains in survival, ranging between 8 and 73 percent. But both quality of the tillage operation and soil conditions were variable and difficult to determine. For example, soil moistures ranged from wet to dry and tillage depth from 0.18 m to more than 1 m.

Whitaker (1983) compared growth of germinating seedlings of two conifers in soil cores (0.15 x 0.32 m long) taken from tilled and nontilled compacted subsoils. Shoot height and weight, root weight, and leaf areas were all increased by tilling the compacted soil (Fig. 13). Tillage had reduced the cone-index measure of soil strength in the 0 to 0.1 m depth from 23.3 kg/cm^2 in the compacted soil to 12.6 kg/cm^2 in the tilled soil. These results may be a conservative indication of gains from tillage because the cores were kept moist throughout the experiment; thus, the plants were not subjected to moisture stress in which a seedling with limited root mass would be at a greater disadvantage.

Tillage has generally not been used in established stands to improve stand growth on compacted soil because it might damage roots and, at least temporarily, reduce growth. Any growth increase gained by tilling stands must overcome the initial loss due to root damage.

Current Methods

Attempts to minimize soil compaction in the Pacific Northwest include prohibiting tractor and skidder logging on soils susceptible to compaction, allowing logging only when soil moisture is below some maximum level, specifying low-ground-pressure machines, using cable systems for logging sites formerly skidder-logged, and restricting logging traffic to a limited amount of skidtrail. Our findings indicate that these methods are not equally effective.

All soils, regardless of bulk density, increase in soil strength when compacted. Although compression indices vary with clay content, they are similar for most fine-textured soils (Larson et al. 1980). Thus, ranking soils according to some arbitrary compactibility scale is ineffective and, more importantly, fails to protect soils rated as least susceptible.

Table 2.--Seedling response to tillage (Andrus 1982)

Site and Species	Stand Age	Tillage treatment	Increase in growth	Difference in survival
	-yr-		--------%-------	
New Zealand. Deep clay loam. Radiata pine. (Berg 1975).	3	Skidtrails, landings; ripped to 18-24 inch depth.[a]	36(1)[b]	+30
	1.2	Compacted ridge tops; ripped to 18-24 inch depth.[a]	73(1)	+10
N.E. Bavaria. Heavy clay. Logged area. Scotch pine. (Burschel et al. 1977).	8	Rotary tilled to 8 inch depth.[a]	33(2)	-
		Ploughed to 16 inch depth.[a]	56(2)	-
New Zealand. Gravelly loam. Radiata pine. (Craig et al. 1977).	2	Ploughed and disked.[a]	17(1)	-9
		Ripped to 39 inch depth.[a]	17(1)	+20
New Zealand. Shallow stony soil. Radiata pine. (Guild 1971).	3	Ripped to 18-24 inch depth.	8(1)	+37
Australia. Irrigated nursery. Silty clay. Plow pan at 8 inch depth. (Minko 1975).	1	Deep ripped.[a]	60(1)	-
Western Oregon. Skidtrails. Douglas-fir. (Powers[c]).	5	Disturbed with brush blade.	50(1)	-
New Zealand. Glacial tillite with high clay content. Eroded area. Radiata pine. (Ritchie 1965).	2.5	Ripped on contour to 18 inch depth.[a]	70(1)	+38
Scotland. Peaty gley podzol with hardpan on boulder till. Japanese larch, lodgepole pine, and Scots pine. (Thomson and Neustein 1973).	15	Ripped to 17 inch depth and ploughed to 7 inches.[a]	13(3)	-
		Ploughed to 13 inch depth.[a]	23(3)	-

[a] Fertilizer applied to tilled and control plots.
[b] (1) Height growth, (2) Dry phytomass production, (3) Study compared 6 tillage treatments but no control plots were established; for growth comparison purposes, the tillage treatment resulting in the least height growth was used as the control.
[c] Personal communication, 1981.

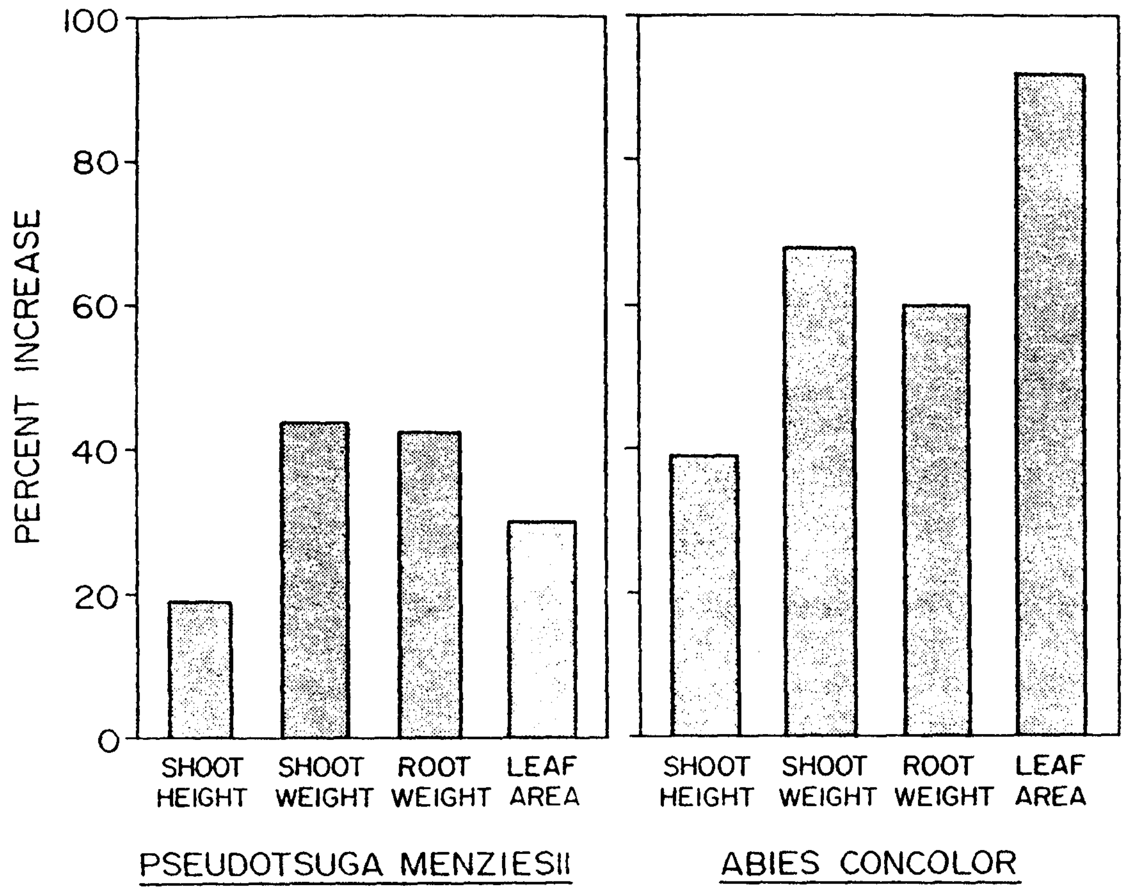

Figure 13.--Growth of Pseudotsuga menziesii and Abies concolor seedlings in soil cores extracted from tilled skidtrails compared to growth in nontilled soil cores. Tilled cores were extracted from the ripline after ripping with a small crawler tractor. Seedlings were grown from germinated seeds for 228 days (Whitaker 1983).

Soil moisture at the time of logging may have little effect on the amount of compaction. The moisture-density relationship of some soils changes slowly as moisture increases; therefore, compaction is independent of moisture (Fig. 2). In other soils, the relationship is somewhat affected and a specific moisture content, most often near field capacity, can indicate when the soil is most susceptible to compaction. Identifying this moisture content in the field, however, is extremely difficult because of variability within even a small harvest unit. Soil moisture also depends on yearly variation in precipitation that can vary the time that soils may be dry enough for machine operation. Limiting machine operations on the basis of soil moisture is only partially effective at reducing compaction, is difficult to administer, and disrupts harvest scheduling.

Specifying the static ground pressure of tractive equipment is less effective in reducing soil compaction than commonly assumed (Table 1). Number of passes and initial soil strength are more important in determining increases in bulk density.

Restricting machine movement to a limited number of skidtrails may reduce the portion of a stand that growth is impaired by compaction. During conventional, ground-based harvesting operations, machine operators are commonly allowed to select travel routes as needed. As a result, the area covered by skidtrails may vary from 18 to 40 percent for a single entry (Froehlich 1974). Repeated entries for thinnings or partial cuts increase the area in skidtrails. Eliminating skidtrails, regardless of usage, effectively reduces compaction; compaction of lightly used skidtrails is similar to heavily used skidtrails because most compaction occurs with only a few passes of a machine (Fig. 5). Conversely, increasing the number of passes over a limited number of skidtrails only slightly increases bulk density of those trails.

Restricting the number of trails is best accomplished by designating their location before harvest. Two studies have measured the cost and effectiveness of harvesting with skidders or tractors. The machines used chokers from preplanned skidtrail systems. Bradshaw (1979) observed that production was reduced 10.8 percent and skidding costs were increased 29 percent with designated trails in a partial cut. Froehlich et al. (1981) determined the cost of logging by winching logs to designated skidtrails spaced 30, 46, and 76 m apart in the thinning of a 35-year-old stand of P. menziesii. Overall productivity was relatively unaffected by even the longest winching distance. The increase in time for winching and resetting chokers when needed was offset by a decrease in skidding time on the designated trails. Tesch and Lysne (1983) also reported time per turn did not differ when a skidder left designated skidtrails to choke logs versus when the winch line was pulled to logs from the skidtrail during the commercial thinning of a mixed-conifer stand averaging 41 cm in diameter.

Harvesting from preplanned, designated skidtrails is the best option for preventing productivity losses from soil compaction during harvesting (McNabb and Froehlich 1984). Preplanned skidtrails can economically be held to about 10 percent of the harvest area and should serve as routes of entry for all succeeding harvests. Tillage of the skidtrails, if desirable, will also be more economical because of the smaller areas that must be treated. Designated skidtrails, however, are not fully compactible with the more mechanized harvest systems, including the use of grapple-equipped machines, nor possible on low-strength soils that cannot support machines after the first few passes.

CONCLUSIONS

The vegetation, climate, and geology of the Pacific Northwest have generally produced well-aggregated, porous forest soils with high organic matter contents. Physical characteristics of these soils are a low bulk density and strength and a high macroporosity and hydraulic conductivity. Compaction of these soils by ground-based harvesting machines can change these properties, generally to the detriment of growth of commercial conifer species.

Reduced growth from soil compaction in forest stands of the Pacific Northwest is a serious problem because of the apparent longevity of compaction. Natural processes that loosen compacted soils are basically ineffective. As a consequence, compaction during the final harvest or harvest of old-growth forests may persist for a substantial portion of the future rotation. Commercial thinnings or other harvest entries can cause additional soil compaction and growth reduction. The amount of growth reduction caused by multiple harvest entries is additive, based on the portion of a site in compacted skidtrails.

Preventing compaction reduces the impact of ground-based harvesting machines on forest soils, although the several techniques used are not equally effective. All soils studied have been susceptible to compaction, and differences due to texture, moisture condition, or response to different machines have not been sufficiently large or consistent to conclusively recommend them for preventing compaction. Restricting machine operation to a limited number of preplanned, designated skidtrails is currently the most efficient method, although its applicability may be limited on some soils and may preclude the use of some machines. Tillage techniques that more effectively loosen compacted forest soils are becoming available; however, tillage may be less effective than planning future harvesting operations to minimize compaction.

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