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Title: The Influence of Soil Compaction on Early Conifer Growth in the Southern Washington Cascades

Abstract approved:

Henry A. Froehlich

This study evaluated the effect of soil compaction on the growth of natural regeneration on volcanic ash-influenced soils in the southern Washington Cascades. Growth of 9 to 18 year-old sapling-sized Ponderosa pine (*Pinus ponderosa* Laws.) was studied on sites ranging from 915 to 1006 m elevation in an area selectively logged in 1959, and for 10 to 13 year-old lodgepole pine (*Pinus contorta* Dougl.) established following a group selection harvest on a 1342 m elevation site logged in 1967. Soils ranged from loam to sandy loam texture. Height, diameter, and volume growth were measured for trees growing under an array of disturbance conditions to determine the influence of soil compaction on their size and growth rates.

A number of soil, vegetation, and site variables were studied to determine possible cause and effect relationships with growth parameters. Bulk density of the surface 30.5 cm was measured within the lateral rooting zone to provide an index of compaction. Trees were destructively sampled to obtain a detailed record of their

development, and to adjust for differences in age as a result of variable establishment delays.

Average bulk density increases of 15.4 and 27.5 percent relative to adjacent undisturbed soil were found for skid trails in the ponderosa pine and lodgepole pine study areas, respectively. The effect of soil displacement overshadowed any possible relationship between bulk density and growth for lodgepole pine. The strong correlation of growth with organic matter content indicates that removal of nutrient-rich surface soil during logging and slash disposal operations may significantly affect site productivity, particularly for poorly developed skeletal soils.

Regression analysis showed that several growth parameters for ponderosa pine were strongly associated with the increase in bulk density despite additional significant relationships with tree age, site index, and overstory cover. Reductions in total growth of 4.8, 7.7 and 20.4 percent were predicted for height, diameter, and stem volume of 14 year-old skid trail regeneration based on the mean bulk density increase. Evaluation of current growth increment was effective in adjusting for differences in tree age. Predicted average reductions in height, diameter, and volume growth of 7.1, 11.8, and 18.9 percent were estimated for young ponderosa pine based on the last five year period. Projected impacts from regression analysis represent conservative estimates, since the mean density increase used is the prediction model included measurements for sample trees growing in soil with bulk densities comparable to undisturbed levels.

When the ponderosa pine sample was stratified into low and high impact groups based on bulk density increases, differences in the shape of height-age and diameter-age curves were apparent. A significant decrease in the rate of growth was noted for trees growing under highly disturbed conditions. Projected effects of compaction on site productivity throughout the rotation are difficult to assess, but measurable reductions in young tree growth coupled with frequent stand entries and the slow rate of natural soil recovery provide a basis for concern for long-term impacts.

Key words: soil compaction, skid trails, southern Washington Cascades, site productivity, natural regeneration.

THE INFLUENCE OF SOIL COMPACTION ON EARLY CONIFER GROWTH IN THE SOUTHERN WASHINGTON CASCADES

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Richard William Robbins

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George W. Brown

Head of Department of Forest Engineering

Dean of Graduate School

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INTRODUCTION

Problem Statement

The use of ground-based yarding systems continues to play an important role in the management of western commercial forests for timber production. On the favorable terrain found throughout much of eastern Oregon and Washington, these vehicles are the dominant form of equipment used during harvesting operations. However, their use can lead to measurable reductions in site productivity through their effect on important soil properties. The potential for soil disturbance is particularly critical where intensive management requires frequent stand entries, as in commercial thinnings or in areas prescribed for uneven aged management.

Soil compaction is an unavoidable result of the use of heavy equipment, but forest soils are particularly susceptible to compaction by virtue of their loose, friable structure and high porosity. With the application of dynamic ground pressure and vibrational forces from mechanized equipment, the soil undergoes particle rearrangement and a substantial reduction in macropore volume. Loss of pore space diminishes the infiltration capacity, and slows the movement of water and air through the soil. Bulk density, which is inversely related to porosity, increases as a result of compaction. The combined effect of these changes together with an increase in soil strength, creates a less favorable environment for plant roots which occupy this medium. If these effects are severe enough, measurable reductions in tree growth are likely to occur in response to altered soil physical properties. On a broader scale, the loss in site productivity at the stand level obviously depends on the proportion of the area disturbed. The skid trail network for most single-entry harvests generally occupies from 15 to 40 percent of the unit, and the soil within these trails is compacted and displaced along a continuum of disturbance levels.

Several decades of research by engineers, agronomists and biologists have contributed a wealth of information to our knowledge of compaction mechanics and the related impacts on soil properties and plant growth. However, many of the reported effects of compaction on forest productivity are the results of 1 to 3 year growth trials conducted under artificially controlled conditions. This often limits their applicability to natural heterogeneous systems characterized by highly variable and complex soil, biological, and microclimatic influences. Although a comprehensive model predicting the effect of compaction on the soil-plant system is a desirable goal specific information on tree growth impacts for a variety of environments, species, and time intervals is necessary for land managers to quantify the economic impact associated with growth losses.

Study Objective

The objective of this study was to determine the effect of soil compaction on the growth of seedling and sapling-sized natural reproduction in selectively cut stands in the eastside Cascade mountains of southern Washington. A secondary objective was to determine if any species or site differences in the sensitivity to compaction could be detected by comparing the growth of low elevation ponderosa pine with high elevation lodgepole pine.

LITERATURE REVIEW

Compaction Process

Soil compaction is defined as the compression of an unsaturated soil mass resulting in reduction of the fractional air volume (Hillel, 1980). Compression from dynamic pressure and vibration causes particles and aggregates to become rearranged and to assume a closer packing, thereby reducing total porosity and increasing bulk density. The increase in bulk density corresponds to a change in pore size distribution towards a smaller proportion of large voids or macropores (Vomocil and Flocker, 1961). Although bulk density is often used as a relative index of compaction, soil strength is the property which governs its resistance to compaction (Greacen and Sands, 1980). If applied stresses are greater than the strength or resistance of the soil, failure occurs and the soil deforms. Additional loading will increase soil density until the strength is sufficient to resist further deformation (Li, 1956).

The increase in soil density and strength during compaction is determined by several properties of the soil and the nature of the forces applied to it. Soil texture and structure, density, moisture content, and organic matter influence the degree of soil compaction (Lull, 1959). Structurally unstable soils with a wide range of particle sizes are readily compacted, while poorly graded soils with relatively stable aggregates offer greater resistance to deformation (Chancellor, 1976). Soils high in organic matter are generally more difficult to compact by promoting favorable soil structure (Greacen and Sands, 1980).

Soil engineering studies have shown that a critical moisture content exists at which a maximum bulk density is achieved for a given soil under a specific compactive effort. At values below this level, high frictional resistance and surface tension limit compaction. At values above the optimum moisture content, water occupies an increasing percentage of the pores and cannot be driven out by the compacting force (Lull, 1959). However, Froehlich et al. (1980) concluded that standard laboratory moisture-density relationships (Proctor tests) generally overestimated the actual densities produced by logging vehicles. Attempts to minimize compaction by imposing seasonal restrictions may be ineffective since many soils tested for moisture-density relationships tend to remain at near optimum water contents for extended periods under normal field conditions (Howard et al., 1981).

Machine-related factors which determine the degree of compaction include total weight, ground pressure, vibration, slippage, and log-turn size. Track or tire pressures exerted on the soil can often exceed the static pressure since uneven pressure distributions frequently occur during skidding operations (Greacen and Sands, 1980). Increasing the total load for a given pressure will increase the depth of compaction (Chancellor and Schmidt, 1962). Heavier drawbar loads will produce slippage which may add to compactive effort. However, Vomocil et al. (1959) found that on agricultural soils, moisture content was responsible for greater compaction than either vehicle speed or drawbar pull.

The number of passes made by a vehicle over a given area is also an important factor in the compaction process. Several studies have shown that most of the compaction occurs during the first several trips over the soil. Froehlich _et al_. (1980) studied the changes in soil properties produced by three vehicles - a JD640 rubber-tired skidder, a D6H crawler tractor, and an FMC torsion suspension skidder. The predicted rate of increase in bulk density within the surface 20 cm is shown in Figure 1 and is based on an average MDP (machine-derived pressure) for the three vehicles tested on four soil types. The study found that over 50% of the maximum predicted increase in bulk density occurred after only two vehicle trips. Hatchell _et al_. (1970) monitored compaction by a crawler tractor on moist soil and found that an average of 2.5 trips resulted in densities within 10 percent of the maximum densities attained. Lenhard (1978) tested vehicular compaction with a rubber-tired skidder on a volcanic ash-influenced soil in northern Idaho and found the greatest increase in bulk density occurred within four passes. The change in density between 4 and 32 trips was minimal, but was associated with an 87% reduction in macropore volume. The author concluded that large changes in pore size distribution may occur with additional compactive despite only small increases in density.

Soil Recovery

Once a soil is compacted, natural forces act to slowly restore

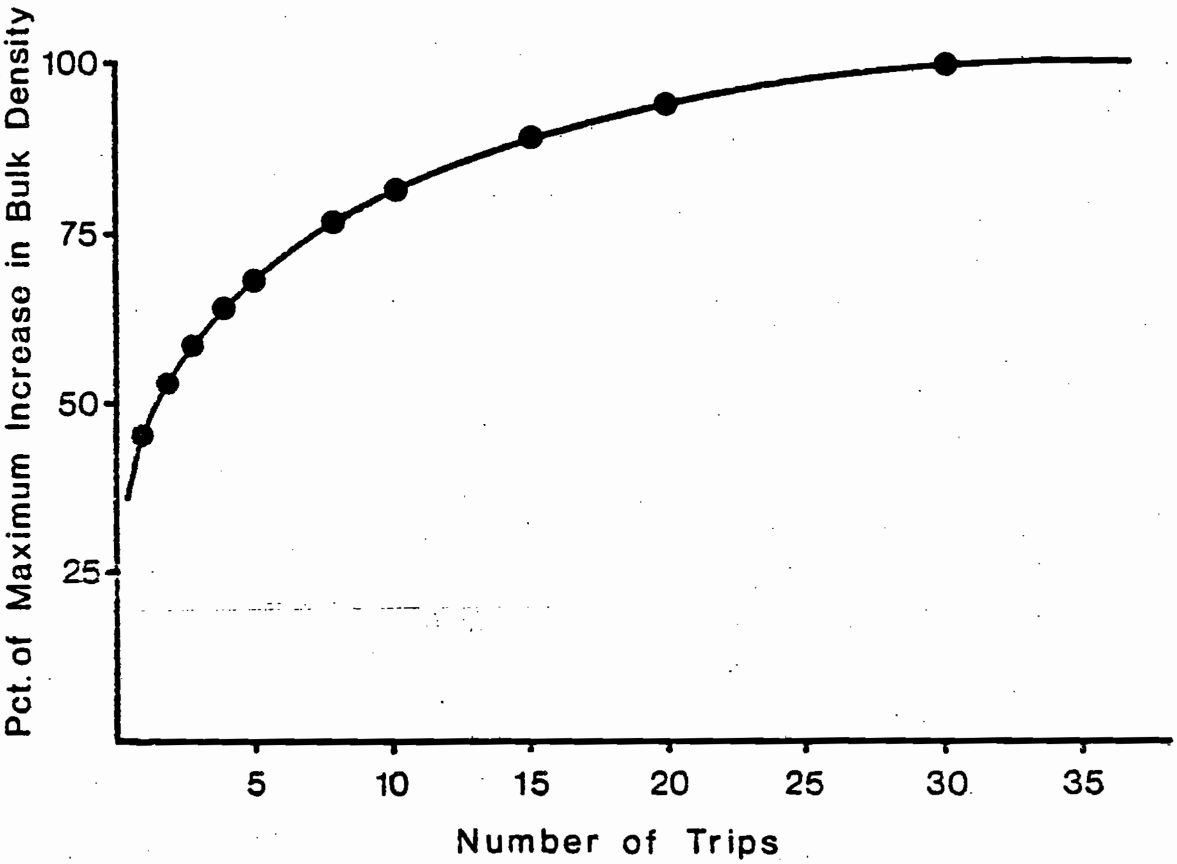

Figure 1. Effect of number of passes by logging equipment on bulk density increase (After Froehlich et al., 1980).

the soil to a condition of lower bulk density and higher porosity. The main processes responsible for natural recovery include: (1) frost heaving, (2) shrinking and swelling, (3) insect and animal activity, and (4) expansion by plant roots. Frost heaving is most effective in soils with a high fraction of silt and fine sand-sized particles (Sowers and Sowers, 1970). However, extensive soil freezing does not occur in the Pacific Northwest as a result of the moderating influences of a maritime climate and protective forest cover (Bullard, 1954; Hale, 1950). Significant shrinking and swelling is limited to soils with smectite clays, which have a 2:1 structure. Burrowing by soil fauna promote soil recovery by mixing surficial organic matter and creating additional macropore space, while plant roots act to restore structure by creating fracture zones in compacted soil (Larson and Allmaras, 1971).

Recovery estimates of compacted forest soil vary widely, due to differences in climate, soil type, sampling depth, initial degree of disturbance, and age of sites studied. Mace (1971) studied recovery of an area logged by tree-length yarding in Minnesota and found that moderate-use level skid trails recovered after one year. However, initial increases in bulk density were slight, and heavily-used trails did not show similar recovery. Perry (1964) estimated a period of 40 years was required for recovery of infiltration capacity on a severely compacted site in North Carolina. Hatchell and Rallston (1971), also working in the southeast, predicted recovery to normal bulk densities after 18 years for log decks based on linear regression. Vanderheyden (1980) monitored bulk density on a chronosequence of clearcut units in the western Oregon Cascades and found no trend of recovery among sites which spanned a 38 year period. However, the high variability in soil type, initial disturbance level, and elevation may have obscured any relationship between recovery and recovery processes. The interaction between site characteristics and recovery processes is complex, but as Froehlich (1973) suggests, some threshold or limit may exist below which a given soil may recover more rapidly than one compacted above such a level. Continued skid trail monitoring for a range of physiographic regions and soil types will be necessary to accurately predict changes in soil properties and provide a basis for inference about the activity of recovery processes for a given area.

Effect on Tree Growth

Soil compaction affects plant growth by altering the basic physical properties of the soil which control root penetration, moisture and nutrient uptake, and aeration. Compaction can significantly affect root growth by offering fewer large pores for entry and exerting greater resistance to root elongation. Reduction in root growth as a result of soil compaction would therefore restrict the amount of water and nutrients reaching the photosynthetic tissue by limiting the rooting area and available soil volume (Sands and Bowen, 1978). However, spatial variability in strength in a soil profile may be large enough to allow roots to enter regions of low strength and partially compensate for an otherwise unfavorable environment (Sands, 1982).

Since compaction reduces the total porosity of the soil at the expense of the macropores, aeration may be restricted at high bulk densities. The critical level of 10 percent air-filled pore space is the most frequently cited value necessary to maintain adequate aeration for plant growth (Grable, 1971). The conversion of macropores to micropores increases the amount of water held at higher tensions (Hillel, 1980). However, the potential benefits from increased water holding capacity is normally outweighed by detrimental changes in soil structure, strength, and gaseous exchange produced during compaction (Warkentin, 1971).

Several studies have shown that seedling establishment and root growth are affected by compaction. Steinbrenner and Gessel (1955) found that skid trails had stocking levels about one-half that of uncompacted cutover land in southwest Washington. Pomeroy (1949) found the greatest losses in seedling establishment occurred on soils where the surface structure was destroyed by soil puddling. Foil and Ralston (1967) reported up to 34% reduction in seedling establishment on heavily compacted soil cores. Compaction had only a limited effect on seed germination, but survival was significantly affected because emerging radicles could not penetrate the dense soil.

Pearse (1958) measured root and height growth of seedlings grown at several densities and found roots grown in compacted soil were markedly shorter and displayed a lesser degree of secondary root branching. Some effect on top growth was evident but the effect was less pronounced than on root development. Heilman (1981) examined the effect of compaction on Douglas-fir seedling growth and found that root penetration declined linearly with increasing bulk density. However, no effect on height growth could be detected. Minore (1969) measured root development on a variety of species in compacted cores. Red alder, lodgepole pine, and Douglas-fir root penetration were least affected by high soil densities, while Sitka spruce, western red cedar and western hemlock could not penetrate the same 1.45 g/cm^3-density cores. No roots from any of the species tested could penetrate a soil density of 1.59 g/cm^3.

If compaction alters the rooting environment of trees to the point where root penetration, aeration, or the uptake of moisture and nutrients become limiting, reductions in stem growth will occur. Table 1 summarizes the results of several studies on conifer height growth for which compacted and control bulk densities were reported and includes an array of age classes, species, and soil types. The studies range from first year greenhouse trials for loblolly pine (Mitchell _et_ _al_., 1982) to measurements of pole-sized 33 year-old Douglas-fir (Wert and Thomas, 1981). Results are graphically presented in Figure 2 in terms of the percent reduction in height growth as a function of the percent increase in soil density. Despite differences in the nature of the studies, a general trend toward greater height growth reduction at elevated bulk densities is apparent.

Field and greenhouse studies designed to evaluate the effect of soil compaction on tree growth require the use of widely different methodologies that limit any direct comparison of reported impacts.

Table 1. Summary of selected greenhouse trials and field studies evaluating height growth response to soil compaction.

Study Design	Species	Growth Period	Soil Texture	% Change From Control D_b	% Change From Control Height	Ref. No.	Reference
Shadehouse study, artific. compacted cores	loblolly pine	6 mo.	loamy sand	+32.7	-27.4	(1)	Foil and Ralston, 1967
	loblolly pine	6 mo.	loam	+30.1	-42.9	(2)	
	loblolly pine	6 mo.	clay	+13.9	-34.0	(3)	
Field study, 1-0 container stock	Douglas-fir	4 yrs.	clay loam	+ 9.8	- 8.5	(4)	Froehlich, 1976
	Douglas-fir	4 yrs.	clay loam	+ 9.8	-13.9	(5)	
	Douglas-fir	4 yrs.	clay loam	+ 9.2	-11.2	(6)	
	Douglas-fir	4 yrs.	clay loam	+13.8	-21.4	(7)	
Field study, 2-0 bare root	Ponderosa pine	17 yrs.	loamy sand	+19.8	-14.5	(8)	Froehlich, 1979
	Ponderosa pine	17 yrs.	loamy sand	+36.3	-28.7	(9)	
Greenhouse study artific. compacted cores	loblolly pine	19 wks.	sandy loam	+16.7	-12.3	(10)	Mitchell et al., 1982
	loblolly pine	19 wks.	sandy loam	+33.3	-25.5	(11)	
	loblolly pine	19 wks.	sandy loam	+50.0	-39.4	(12)	
	loblolly pine	19 wks.	sandy loam	+66.7	-50.0	(13)	
Greenhouse study, artific. compacted cores	radiata pine	5 mo.	sand	+ 9.6	-11.0	(14)	Sands and Bowen, 1978
	radiata pine	5 mo.	sand	+18.5	-37.5	(15)	
Greenhouse study, artific. compacted cores, 1-0 seedlings	Douglas-fir	10 mo.	sandy loam	+ 9.4	+ 3.9	(16)	Singer, 1981
	Douglas-fir	10 mo.	sandy loam	+27.4	-28.8	(17)	
	Douglas-fir	10 mo.	sandy loam	+ 9.4	- 9.2	(18)	
	Douglas-fir	10 mo.	sandy loam	+27.4	-12.7	(19)	
Field study nat. regeneration	Douglas-fir	4 yrs.	silt loam + clay loam	+34.9	-22.2	(20)	Steinbrenner and Gessel, 1955
Field study, nat. regeneration	Douglas-fir	33 yrs.	loam	+ 9.0	-29.9	(21)	Wert and Thomas, 1981
Field study 2-0 bare root	Douglas-fir	2 yrs.	clay	+77.2	-42.1	(22)	Youngberg, 1959

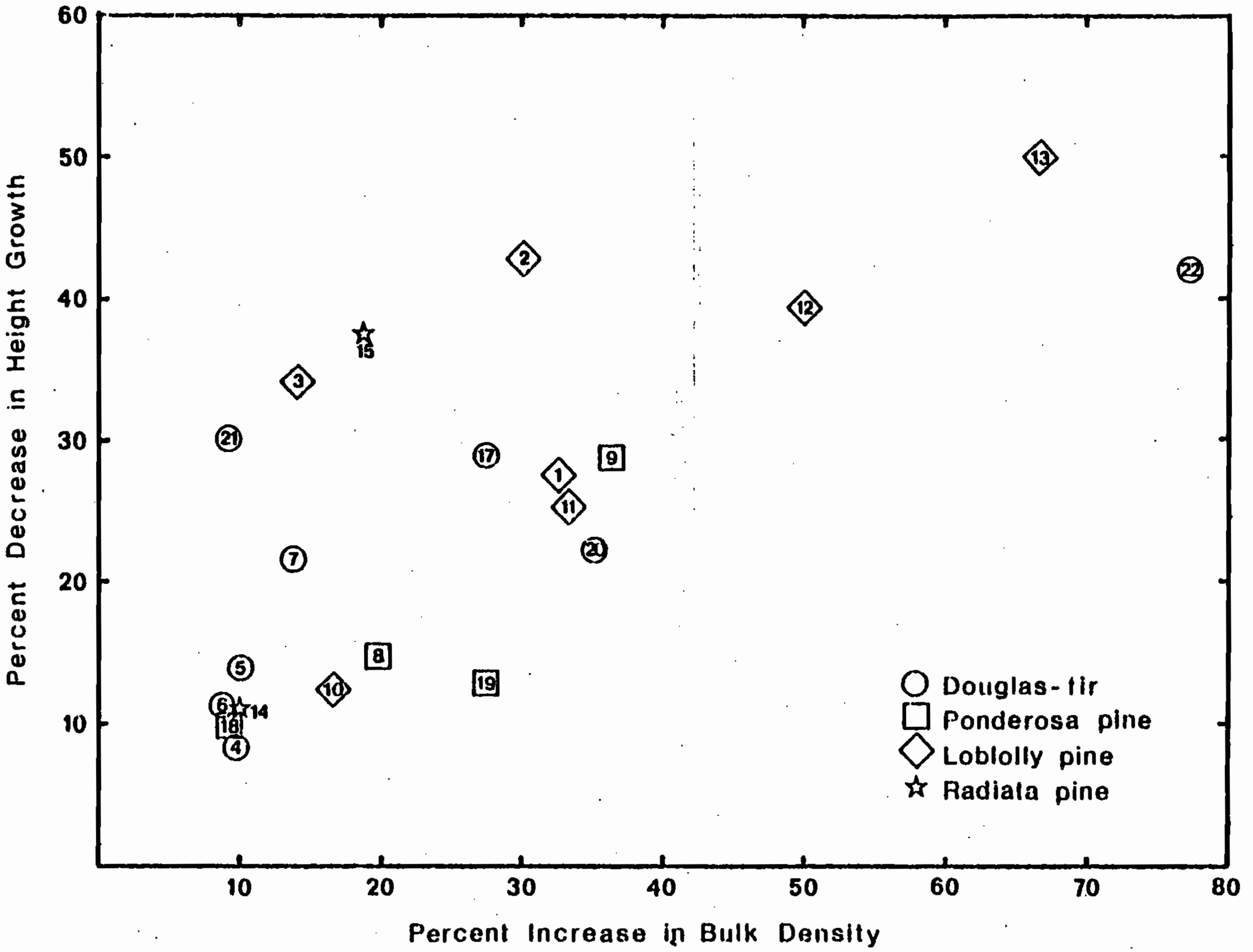

Figure 2. Reported changes in height growth with bulk density increases. Numbers indicate Table 1 references.

Laboratory studies generally provide a greater degree of control over treatments and experimental design. Environmental factors such as light, temperature, competition, soil texture, moisture stress, and nutrient availability can be regulated under controlled conditions to potentially isolate the influence of compaction-induced changes in soil properties on plant growth. Conversely, greenhouse studies can potentially understimate growth impacts by maintaining moisture content and nutrients at levels where height growth is not significantly impaired in compacted cores. Other operational limitations include the relatively short duration of the available study period and the tendency for lateral roots to concentrate along the edge of the containers - a result of the finite rooting volume.

Field studies offer the obvious advantage of greater application to natural stand conditions, where differences in growth processes may become more apparent with seasonal variability in soil water potential. However, the interaction of climatic and edaphic factors which govern plant growth often precludes single-factor analyses and such studies are more likely to show high variability within treatments. Where studies evaluate growth impacts several years after logging, initial disturbance levels are unknown and simplified assumptions concerning dynamic soil properties and stand development during the interim period are required. The high variability common in field studies can also influence the results of greenhouse trials. For example, Whitaker (1983) found no significant difference at the .05 risk level in height growth of Douglas-fir seedlings grown in tilled and compacted soil cores extracted from the field, despite a

44 percent difference in the mean heights of the treatments.

Growth impacts in disturbed areas is often the combined effect of soil displacement as well as compaction. For example, Youngberg (1959) attributed part of the reduction in Douglas-fir seedling growth in skid trails to a combination of nitrogen deficiency and poor aeration. Smith and Wass (1979) studied height growth on 9 to 22 year-old contour skid roads and found marked differences between the inner deeply gouged portion and the outer berm. The latter zone was often associated with growth rates which exceeded that of adjacent undisturbed soil due to a net accumulation of soil rooting volume and nutrients. Average estimated reductions in site productivity were 15 percent for Engelmann spruce and 12 percent for subalpine fir. In a later study (Smith and Wass, 1980), effects ranged from no impact on some sites to a 15 percent reduction for the entire unit, assuming 32 percent coverage by skid trails. One area sampled was a 13 to 16 year old pure lodgepole stand, where no significant difference in growth between disturbed and undisturbed soil could be detected. However, another site showed a 22 percent reduction in height growth for lodgepole pine.

The effect of compaction on productivity in partial cut stands has also been investigated, although comparatively fewer studies have been conducted for intermediate to mature-aged trees than for seedlings. Froehlich (1976) measured soil compaction and tree growth in a 64 year old ponderosa pine stand 16 years after commercial thinning and determined that moderate and heavy compaction was associated with 6 and 12 percent reductions in radial growth rates. The author also found that basal area growth of 34 to 77 year-old Douglas-fir was reduced an average of 14 percent on moderate disturbance class sites and 30 percent on heavily compacted areas. Moehring and Rawls (1970) studied the effect of compaction levels on 40 year-old loblolly pine growing on poorly-drained soils in the southeast. Growth was affected only slightly when compaction was limited to only one side of the tree. Compaction on two, three, and four sides resulted in 13.7, 36.3, and 43.4 percent less basal area added during the next five year period.

The relationship between growth and bulk density has prompted some researchers to establish threshold values or "growth-limiting bulk densities" for various species (Forrestall and Gessel, 1955; Minore, 1969) and soil textures (Daddow and Warrington, 1983). Although bulk density provides a useful index of soil compaction, Zisa _et. al_ (1980) concluded that describing a compacted soil in terms of resistance to penetration, or some alternate measure of soil strength, may lead to a better understanding of the interaction of a growing root with its physical soil environment. However, strength measurements are affected by the interaction of soil moisture and bulk density (Taylor, 1965), and accuracy of field measurements may be influenced by the presence of large roots and coarse fragments. Debate over the most appropriate measure of compaction for correlations to plant growth will no doubt continue, since as Rosenburg (1964) points out, compaction-induced growth responses are often the product of several interrelated changes in soil physical properties.

THE STUDY AREA

The study area is located on the eastern slope of the Southern Washington Cascades on the Yakima Indian Reservation (Figure 1). Elevations in the forested area of the reservation range from about 550 m near the lower limits of commercial stands to 1980 m on the east slope of Mt. Adams. The climatic regime is controlled by large frontal systems which develop over the Pacific Ocean and interact with continental airmasses and the Cascade Range. Precipitation changes markedly with elevation, ranging from about 45 cm near the noncommercial forest fringe to nearly 250 cm at the crest, a high proportion of which occurs in the form of snow. Although the precipitation is not as seasonal as on the western slopes, up to 75% occurs between October 1 and March 31, and the early summer months (June through August) are very dry (Franklin and Dyrness, 1973).

The study focused on the effect of soil compaction on young tree growth in two different vegetation zones. The areas of main interest are the Ponderosa pine (Pinus ponderosa) and grand fir (Abies grandis) zones, where the majority of the commercial timber stands are located. Three representative sample sites were located in the Cedar Valley area on gently sloping uplands and broad valley sideslopes with a southern exposure. A summary of the study site characteristics is shown in Table 2. Elevation ranges from 915 to 1006 m and falls within the 76 to 89 cm precipitation zone. The principal plant community is the Pinus ponderosa/ Calmagrostis rubescens-Carex geyeri association (Franklin and Dyrness, 1973). Other overstory

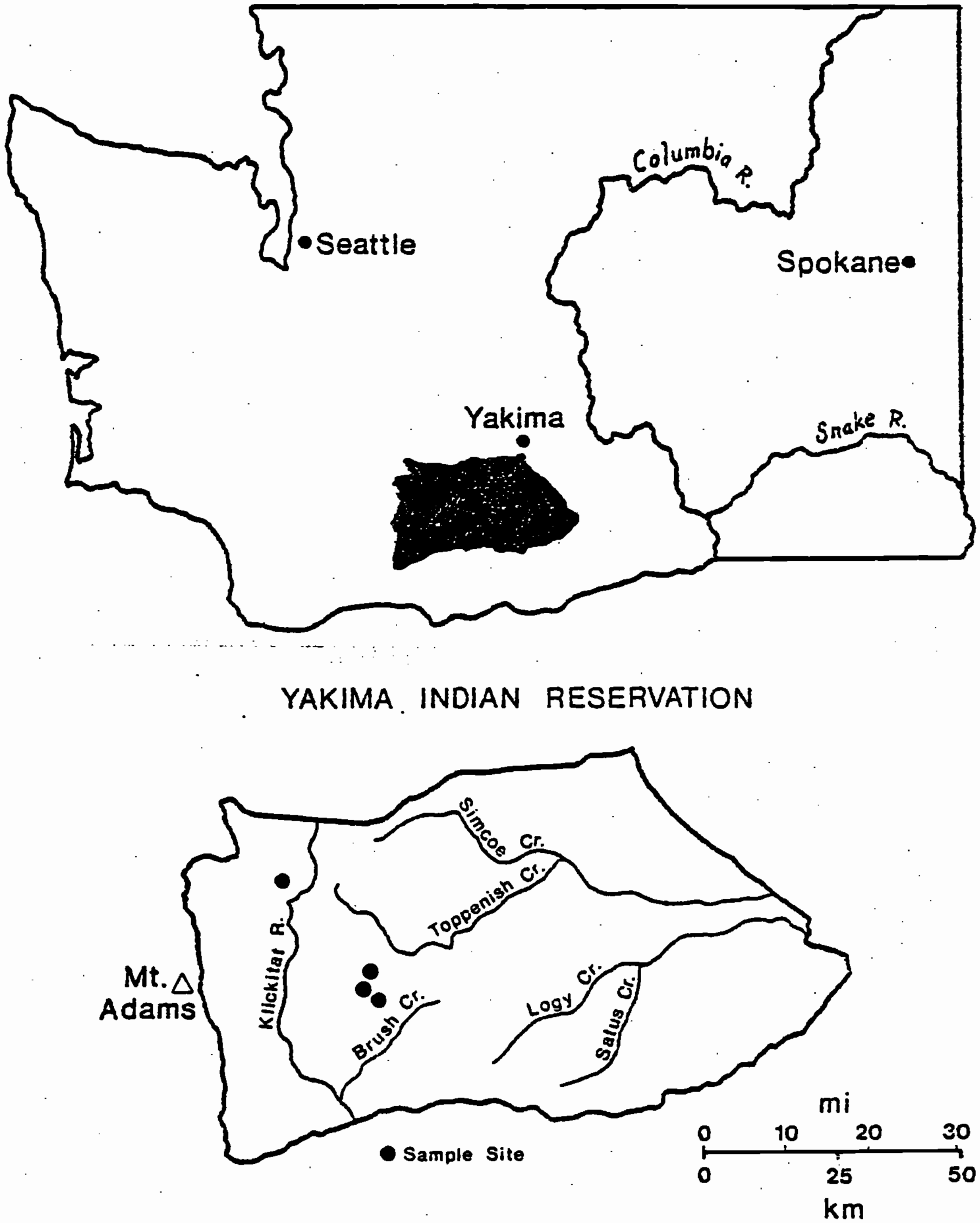

Figure 3. General vicinity of the study area.

species include Douglas-fir (Pseudotsuga menziesii) and grand fir, the latter which may be the climax species in the absence of natural or management-related disturbance. The overstory is an 85 year-old ponderosa pine-grand fir-Douglas-fir stand which was selectively cut in 1959 to remove scattered old growth trees heavily damaged from pine butterfly epidemics. Reproduction is unevenly distributed and height growth of seedlings and saplings is exceedingly slow in the heavily shaded openings. Skid trails cover approximately 20 percent of the harvested land area on the ponderosa pine study sites, based on a qualitative field surveys and aerial photo interpretation.

The second area selected for study is located in the subalpine fir (Abies lasiocarpa) zone at an elevation of 1342 m. Sampling was conducted in the McCreedy Creek area on a gently sloping bench west of the Klickitat River. The area is characterized by longer, cooler winters than the ponderosa pine zone, and receives approximately 114 cm of annual precipitation. Abies lasiocarpa/Pachistima myrsinites is the dominant plant association (Franklin and Dyrness, 1973) and includes a mixture of Pacific silver fir (Abies amabilis), Engelmann spruce (Picea engelmanii), mountain hemlock (Tsuga mertensiana), and lodgepole pine (Pinus contorta). A group selection cut in 1967 allowed rapid establishment of lodgepole pine on disturbed sites, particularly where slash had been burned and the soil was well scarified. The abundant crop of lodgepole pine saplings found on skid trails therefore provided a suitable test species to investigate any compaction-related growth impacts on this subalpine site. The skid trail network occupies approximately 25 percent of the land area

Table 2. Location and description of the study sites.

Site Characteristic	Ponderosa pine			Lodgepole pine
	Site 1	Site 2	Site 3	Site 4
Legal description	Sec. 9, T8N, R14E	Sec. 16, T8N, R14E	Sec. 15, T8N, R14E	Sec. 13 TION, R12E
General location	Cedar Valley	Cedar Valley	Cedar Valley	McCreedy Creek
Slope (%)	0-5	0-5	5-10	0-5
Aspect	S	SW	S	E
Elevation (m)	1006	963	915	1342
Mean annual precipitation (cm)	12-14	12-14	12-14	16-18
Forest cover type	Ponderosa pine - grand fir	Ponderosa pine - grand fir	Ponderosa pine - grand fir	Pac. silver fir - mtn hemlock
Site Index[1]	113	110	100	---
Year logged	1959	1959	1959	1967

[1] Site quality as defined by the average total height (in feet) of dominant trees at 100 year base age (Meyer, 1938).

in these tractor-logged units.

Soils of the reservation are strongly influenced by the geology of Mt. Adams and other volcanoes of the Southern Washington Cascade province. The parent materials are primarily aeolian deposits high in volcanic ash overlying colluvium and residuum from olivine basalt flows and tuffs. The aeolian material is a mixture of silt loam-textured loess and Pleistocene to recent volcanic ash with a loam to sandy loam texture. Volcanic ash-influenced soils in this region are characterized by the presence of amorphous clays, high cation exchange capacity, high porosity, and low bulk density. The depth of this surface layer is quite variable, but generally decreases eastward from the Cascade crest.

At the time of this study, a detailed soil survey of the reservation has not been conducted. In the 1960's, the Bureau of Indian Affairs completed a limited survey in portions of the area, but the mapping is considered inadequate according to current soil inventory standards. However, tentative soil classifications compatible with National Cooperative Soil Survey standards were established in conjunction with this study by soil scientists conducting soil mapping under contract with the BIA (Appendix A). A representative soil pit was examined in the Cedar Valley area where the ponderosa pine growth study was conducted and was classified as a medial over loamy-skeletal, mixed frigid Andic Xerochrept. The lodgepole pine study area in the vicinity of McCreedy Creek was classified as a medial-skeletal, Andic Cryochrept. Both soils are volcanic ash-influenced (Andic subgroup), with the major distinction made between the two classifications on the basis of the moisture and temperature regimes. The lower elevation ponderosa pine zone has a xeric moisture regime and is characterized by a mean annual soil temperature less than 8°C and a difference between summer and winter soil temperature greater than 6°C. In contrast, the lodgepole site receives higher precipitation and is located within the cryic temperature regime, where the mean soil temperature is also less than 8°C but has seasonal extremes less than 6°C.

STUDY METHODS

Field Methods

Site Selection

The study was conducted in partial cut harvest units logged with ground-based yarding equipment on the Yakima Reservation (Figure 3). The initial study design provided for a total of 90 sample trees collected on three sites in mid elevation ponderosa pine stands. Within each site, a sample of 10 trees were to be selected from each of three qualitatively-determined disturbance classes representing zones of low, moderate, and high soil compaction. Unfortunately, low stocking levels of natural regeneration on skid trails precluded the use of a balanced sampling scheme. Seedlings growing in undisturbed or lightly disturbed zones were particularly difficult to locate, since the dense canopy cover of the residual stand and thick litter layer provided unfavorable conditions for seedling establishment. Ultimately, a sample of 86 trees growing under an array of soil, competition, and microclimatic conditions was selected. The sample included 61 ponderosa pine seedlings collected on three sites ranging from 915 to 1006 m and 25 lodgepole pine seedlings from a site located at 1342 m.

Tree Selection and Measurements

The tree selection procedure developed for the study utilized a systematic sample with a random starting point. A schematic representation of the skid trail plot layout is shown in Figure 4. Once a well-stocked portion of the skid trail network was located, a random number between zero and ten was generated to locate the initial sample point. Additional points were established at 3.0 m intervals down the center of the skid trail and marked with wooden survey lath. The nearest dominant or co-dominant tree within a five foot radius of the reference point was selected for measurement, provided certain additional criteria were met. Trees with stem or foliar damage, and those growing on seriously eroded or excavated sites were not selected. In order to minimize variability in growth due to differences in establishment time, only trees greater than one half the age of the oldest trees in the trail were considered for selection.

Once the sample tree was identified, measurements of stand density and vegetative competition were made. The number of established trees within a .00135 hectare plot were tallied to derive stand density estimates. For the purpose of this study, established trees were defined as seedlings of satisfactory vigor greater than 0.3 m total height. Within the same fixed radius plot boundary, the average height and cover of vegetation was recorded on the basis of nonfloristic life form (Brown, 1954), noting the dominant species representing the tree, shrub, and herb classifications. Plant distribution was quantified by recording the minimum and maximum

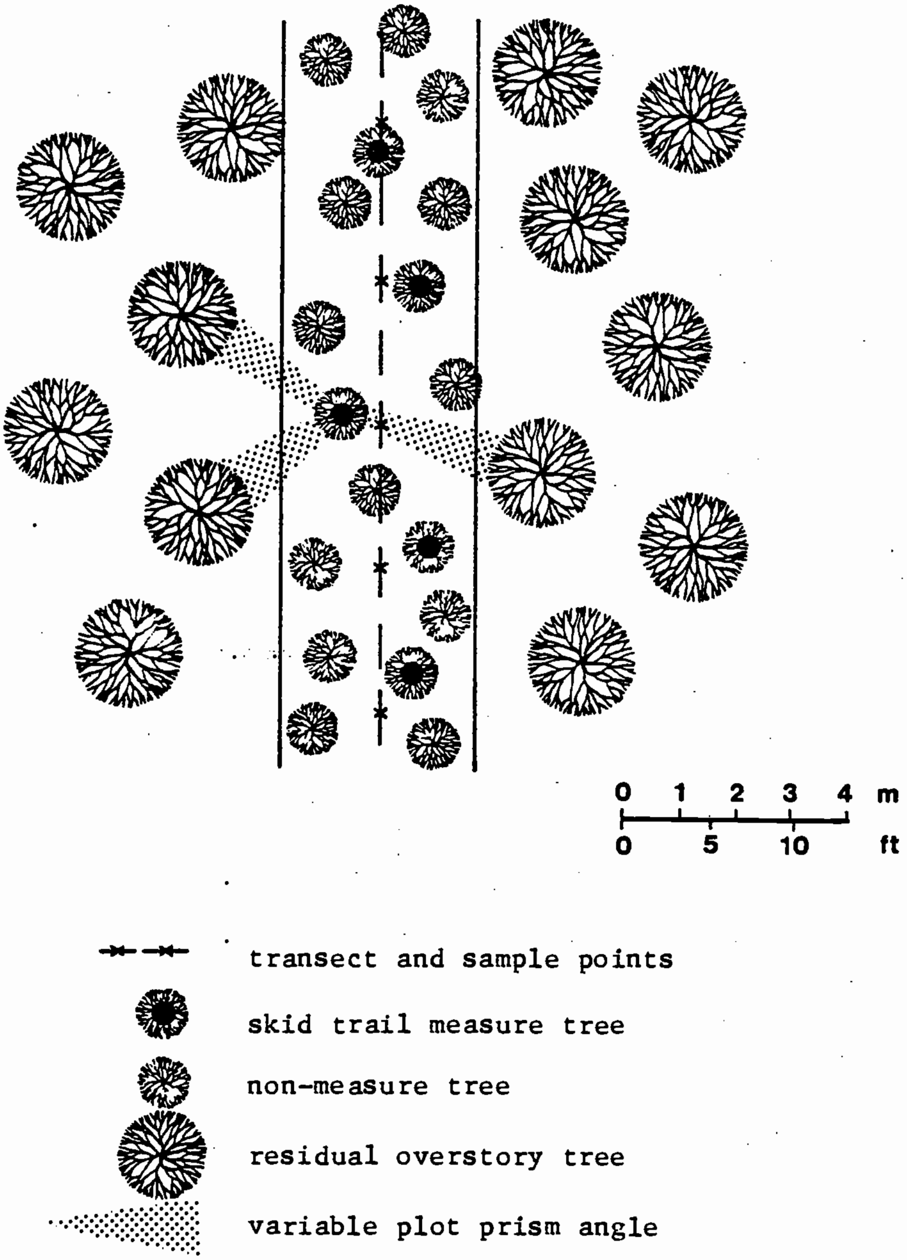

Figure 4. Schematic diagram of plot layout and sampling procedure.

distance of the vegetation from the stem of the sample tree. This information was used to generate a competition index (CI) as defined by Wagner (1982):

$$CI = 0.30 \left[\frac{(\text{height}) \times (\%\ \text{cover})}{100} \right] \times \left[\frac{1}{r_1} - \frac{1}{r_2} \right]$$

where r_1 and r_2 refer to the nearest and furthest distance from the sample tree to the competing vegetation. As the value of r_1 approaches zero, the CI becomes quite large. Therefore, a value of $r_1 = 0.30$ was applied for cases where the vegetative canopy is within 0.30 m horizontal distance of the sample tree. Conversely, where the competing plant canopy extends beyond the limits of the plot radius, a ~~maximum~~ value of $r_2 = 2.07$ m was substituted for the actual distance. The total competition index is then computed as the sum of the individual plant classification indeces:

$$CI_{total} = \sum_{i=1}^{n} CI_i = CI_{tree} + CI_{shrub} + CI_{herb}$$

An important assumption in the use of such an index is that lateral root development coincides with the aerial extent of the canopy cover. Smith (1964) found a nearly 1:1 relationship between crown spread and root extent for several Northwest coniferous species, but limited information is available on the prediction of root extent from crown cover for shrubby and herbaceous vegetation. An additive property of the index is also implied. The use of a weighted scale for various plant strata and species is of course preferable, but would be difficult to apply objectively without the benefit of studies based on site and species-specific data.

The degree of competition for light and soil moisture from the mature overstory stand was indexed by measurements of basal area. A 10-factor prism was used to establish a variable radius plot around each sample tree. Previous research has shown a strong correlation between basal area and aerial canopy density estimates (Minor, 1960; Wilson, 1957). Recent studies have found that canopy leaf area can be accurately estimated by measurements of sapwood cross-sectional area (Waring _et_ _al_., 1982) and total basal area (Snell and Brown, 1978) for many western coniferous species. Measurements of sapwood area at the base of the live crown bears the most direct relationship to canopy leaf area, but for the purpose of this study, measurements of basal area at breast height can be expected to provide a reasonable index of canopy leaf area and crown cover.

Once the vegetative competition information was gathered, the measure trees were destructively sampled to obtain detailed information on their growth rates. Trees were cut near ground level, and stem diameter measurements were taken at the base and at breast height (1.37 m). Additional outside-bark diameters were recorded at 61 cm intervals from the base for taper measurements used to compute total stem volume. A record of annual height growth was established by measuring the cumulative distance from the base to each branch whorl. The total age was verified by examining growth rings on the cut base with an 8 power hand lense. This procedure was also helpful in detecting any false whorls, which were common for lodgepole pine. A 1.4 cm-thick cross section was cut from the base of each tree, labeled, and transported in plastic bags to the laboratory for accurate measurements of radial growth.

Soil Compaction Measurements

Bulk density was selected as the measurement of soil compaction for the study. Although several other soil physical properties can be indexed to compaction (e.g., porosity, strength, infiltration, permeability), bulk density can be measured rapidly and accurately and provides a basis for comparison with previous studies of compaction-productivity relationships. A Campbell Pacific Nuclear densiometer was used to measure bulk density for the study. The device contains a cesium 137 source of gamma radiation in the source probe, a Geiger-Mueller detector housed in the meter, and functions on the principle that the amount of gamma radiation transmitted through the soil and received by the detector is inversely proportional to the density. A calibration curve developed from laboratory tests with soils of known density permits use of the device to accurately estimate soil density in the field. A series of 10 half-minute standard counts were taken at the beginning and end of each day to develop a ratio of field count to standard count used in the bulk density calibration equation.

Bulk density of the surface 30.5 cm was measured on two sides of each sample tree within an area corresponding to the vertical projection of the maximum crown diameter. Single probe half-minute readings were taken until two consecutive values agreed within one percent. Radiation counts recorded at each position were averaged to compute the field:standard count ratios. Soil samples were taken in conjunction with these measurements for soil moisture determination required for calculation of dry bulk density. Similar measurements were taken in the undisturbed soil adjacent to the skid trails to express the degree of compaction on a relative basis. A series of double probe readings were taken at 10.2 cm intervals down to a 50.8 cm depth to develop density profiles for a representative point in the skid trail and undisturbed soil at each sample site.

A bulk soil sample was collected at each of the four sample site locations and returned to the lab to determine textural classification, particle size distribution, moisture-density relationships, and organic matter content. Samples were collected and analyzed separately for the 0 to 15.2 cm and 15.2 to 30.5 cm depths. Additional information documented to characterize the sites included site index, slope, aspect, and elevation.

Lab Analysis

Moisture and Organic Matter Content

Gravimetric moisture content was determined by drying a sample of approximately 25 grams for 12 hours in a 105°C conventional oven. The difference in weight at the beginning and end of the drying period was computed to express the moisture content as a fraction of the dry soil weight. Five gram subsamples from each of the oven-dried soils were placed in small porcelain crucibles and ashed in a 550°C furnace for 9 hours. At the end of the combustion period, the samples were allowed to cool in a dessicator and weighed to the nearest .01 gram to determine the percent total organic matter expressed as a unit weight of dry mineral soil. The eight bulk samples were also analyzed for total organic matter content by the Walkley-Black method[1] (Mortensen, 1965) for comparison with the loss on ignition.

Particle Size Distribution

The standard USDA textural classes for the bulk samples were determined by the hydrometer method (Day, 1965). Prior to the test, soil was air dried and sieved through a number 10 (2 mm) sieve. Samples of approximately 50 grams were pretreated with concentrated hydrogen peroxide to reduce aggregation and remove the organic matter. After oven drying to find the dry weight, a five percent solution of sodium pyrophosphate was added and allowed to disperse the aggregates for 24 hours. The solutions were then mechanically

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[1] Testing performed by the Soil Testing Laboratory, Oregon State University.

agitated in a mixer, placed in a standard cylinder and diluted with distilled water to obtain a 1.0 liter solution. Hydrometer readings were recorded at 1, 4, 15, 30, 60, 120, 240, 480, and 1440 minutes.

A series of nested sieves were used to analyze the material between 0.05 mm and 2.0 mm, or the sand-sized particles according to the USDA classification. In decreasing order of opening size, the sieves used were 0.841, 0.420, 0.250, 0.105, and 0.074 mm. Approximately 200 grams were dispersed with a five percent sodium phyrophosphate solution for 24 hours and wet-sieved with the 0.05 mm screen to remove the silts and clays. The material retained was oven-dried at 105°C for 24 hours, weighed, and sorted with the sieve nest for five minutes to derive the percent passing each of the openings.

Soil Moisture-Density Relationships

The effect of soil moisture on the compactive behavior of the soils was examined by conducting Proctor tests. These laboratory tests were designed to determine the "optimum moisture content" at which the maximum density is attained for a specified compactive effort. Soil from the 0 to 15.2 cm and 15.2 to 30.5 cm depths from each site was sieved through a number 4 screen (5 mm) and divided into 2.0 kg subsamples with a sample splitter. The samples were moistened to achieve a range of moisture contents and placed in plastic bags to equilibrate for 48 hours. The standard test (ASTM D-698, 1980) was carried out by mechanically compacting the samples with an automated Proctor machine (Soil Test, Inc.) in 3 separate layers, each receiving 25 blows with a 2.5 kg hammer dropped from a 30.5 cm height. A modified (low energy) compaction test was also conducted by applying 8 percent of the energy in the standard test, or 10 blows to each layer with a 0.5 kg hammer (Froehlich, et al. 1980).

Radial Growth

Cross-sections cut from the base of each tree were analyzed in the laboratory to accurately measure radial growth. The sections were stored in a refrigerated locker throughout most of the post-field sampling period to minimize shrinkage. To enhance the springwood-summerwood contrast, the disks were smoothed on a belt sander and sanding wheel. Four radii were drawn at 90° angles eminating from the pith to minimize problems associated with radial asymmetry. Annual growth rings were measured along the four axes with an optical micrometer mounted in a 10 power microscope. Estimates of inside-bark diameter were made for each year since tree origin by doubling the average of the four radial distance measurements.

Stem Volume Calculations

Measurements of basal diameter, total height, and stem taper for each tree provided a means to compute gross stem volume. The volume of the stem can be calculated with good accuracy using Smalians formula if several incremental stem diameter measurements are made

(Husch, 1972). Smalians formula provides optimum volume estimates for geometric solids approximating a paraboloid frustrum, and can be expressed as:

$$V = \frac{\pi}{4} \quad \frac{(d_0{}^2 + d_1{}^2)\Delta h_1}{2} + \frac{(d_1{}^2 + d_2{}^2)\Delta h_2}{2} \quad . \; . \; . + \frac{(d_{n-1}{}^2 + d_n{}^2)\Delta h_n}{2}$$

$$= .3927 \sum_{i=1}^{n} (d_{i-1}{}^2 + d_i{}^2)\Delta h_i$$

where V = gross stem volume

d = stem diameter

Δh = vertical length of the segment

n = number of segments

For all but the top segment, the value of Δh used in the equation was 61 cm. Volumes were readily computed using a FORTRAN program (Appendix B).

A mathematical model relating stem volume as a function of basal diameter and total height was necessary to derive estimates of previous volume at a given reference age and periodic volume growth for possible correlation with a measure of soil compaction. The nonlinear equation proposed by Schumacher and Hall (1933) was utilized:

$$V = aD^bH^c$$

where a, b, and c are constants determined from the log-log regression of volume (V) as a function of diameter (D) and height (H):

$$\ln(V) = \ln(a) + b[\ln(D)] + c[\ln(H)]$$

The logarithmic equation is more compatible with the homogeneity of variance assumption for linear regression.

Separate equations were developed for ponderosa pine and lodgepole pine to allow for possible differences in form factor (Appendix C). A strong relationship of volume to height and diameter is evident in both cases from the high coefficient of determination values ($r^2 > .99$). The equations were then used in conjunction with their respective mean bark factor (DOB/DIB ratio) and stem analysis data to derive estimates of previous stem volume. For simplicity, the DOB/DIB ratio and form class for these young trees are assumed to be constant over time -- assumptions which are reasonably safe given the brief period of projection. Since volume growth is directly related to biomass production, the procedure added an important dimension to the analysis of compaction-related growth impacts.

RESULTS AND DISCUSSION

Soil Analysis

The analysis of the particle size distribution for soils from the two study areas classified the texture as loam to sandy loam. Table 3 summarizes the principal features of the soils from the sample plot locations. With the exception of site 1 in the ponderosa pine zone, the percentage of sand, silt, and clay within the surface 30.5 cm was very consistent. A higher fraction of sand was expected for the high elevation lodgepole pine site, since a field profile analysis detected a loamy sand textured volcanic ash cap within the surface 5.1 cm (Appendix A). However, this shallow layer was combined with finer-textured material below it for the laboratory analysis, which classified the soil as sandy loam.

Organic matter contents in the undisturbed soil were very low, in contrast to more fertile soils on the west side of the Cascade Range. The percent total organic matter on a dry soil weight basis ranged from only 3.7 to 6.5 percent in the surface 15.2 cm, and decreased to 1.8 to 3.5 percent in the 15.2 to 30.5 cm layer. The reduction in organic matter content with depth was more evident for the lodgepole pine (McCreedy Creek) site. Soils at this elevation are typically more skeletal, and most of the nutrient capital is located within a shallow surface layer. Additional nutrient analysis for determination of total nitrogen or mineralizable-nitrogen was not conducted. However, if a nearly constant ratio between total organic

Table 3. Description summary of the fine soil fraction (<2mm) for the study sites.

Soil Property		Ponderosa pine			Lodgepole pine
		Site 1	Site 2	Site 3	Site 4
% sand	(0-15.2 cm)	45	59	55	61
	(15.2-30.5 cm)	48	58	54	57
% silt	(0-15.2 cm)	45	33	36	31
	(15.2-30.5 cm)	42	35	38	36
% clay	(0-15.2 cm)	10	8	9	8
	(15.2-30.5 cm)	10	7	8	7
USDA textural classification	(0-15.2 cm)	loam	sandy loam	sandy loam	sandy loam
	(15.2-30.5 cm)	loam	sandy loam	sandy loam	sandy loam
% total organic matter[1]	(0-15.2 cm)	6.5	3.7	4.3	4.1
	(15.2-30.5 cm)	3.5	3.1	2.6	1.8
Undisturbed D_b[2]	(0-30.5 cm)	.913ab	.972a	.918ab	.844b
Soil taxonomic classification		medial over loamy-skeletal, mixed frigid Andic Xerochrept			medial-skeletal Andic Cryochrept

[1] Determined by Walkley-Black method.

[2] Mean bulk density values (D_b) followed by the same letter are not significantly different based on the Students-t range of the LSD test ($\alpha = .05$).

matter content and total N can be assumed, the organic matter analysis provides at least a gross index of total N levels. Data from Geist (1977) on the nutrient status of several volcanic soils in eastern Oregon supports this assumption.

The total organic matter for the eight undisturbed bulk samples determined from the Walkley-Black method were compared with the values obtained from ashing paired samples in a muffle furnace. The two methods showed a fairly high correlation ($R^2 = .86$), but ashing consistently overestimated the weight of the organic fraction of the samples (Figure 5). The overestimates are probably due to the effect of residual moisture contained in the samples after drying in the conventional oven, since volcanic ash soils are characterized by particles with high internal porosity.

Bulk densities in the 0 to 30.5 cm depth of the undisturbed soil average less than 1.0 g/cm^3 at all locations (Table 3). No significant difference ($\alpha = .05$) in the undisturbed bulk density was found among the ponderosa pine sample sites. The mean soil density at the lodgepole site differed from only one of the sample locations in the ponderosa pine zone. Non-significant differences in the other cases may be a result of the limited sample size available from the undisturbed soil at each location.

Proctor Tests

Results of the laboratory soil moisture-density tests are shown in Figures 6 and 7. The Standard Proctor test produced curves with

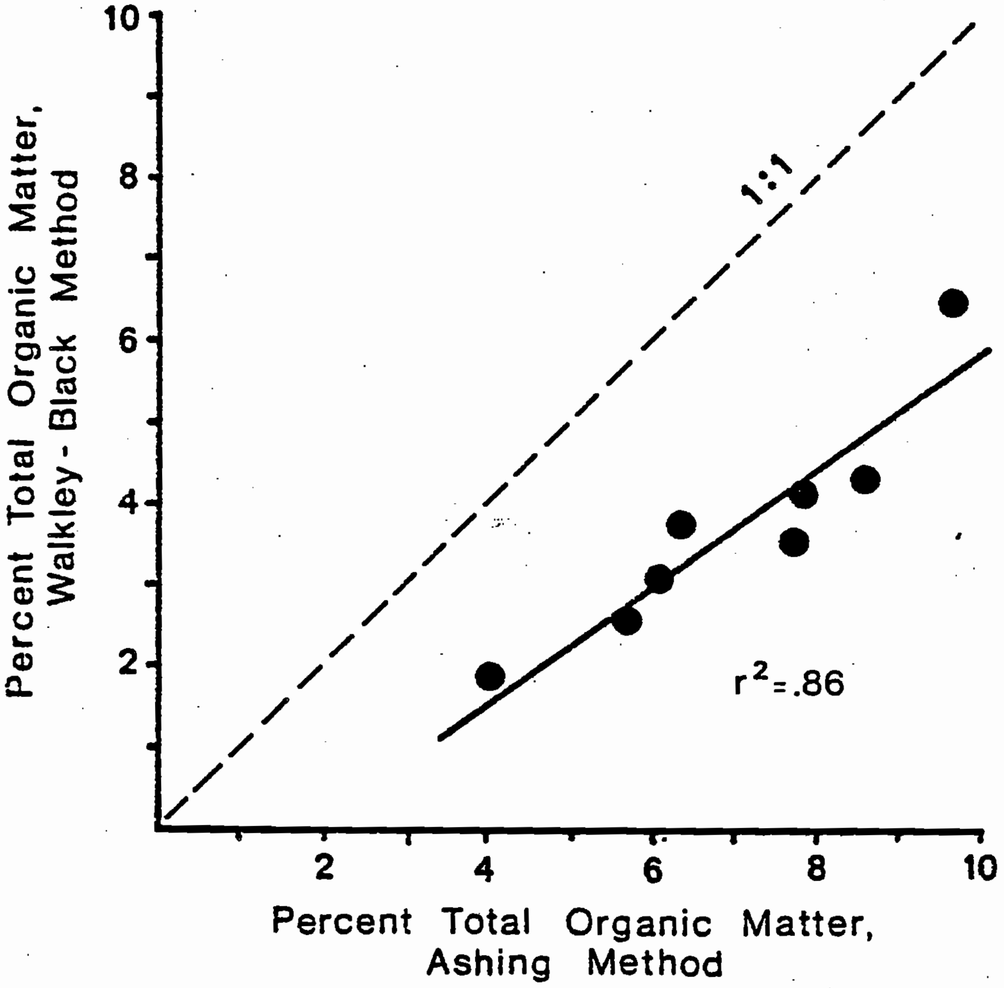

Figure 5. Comparison of ashing and Walkley-Black method of total organic matter determination.

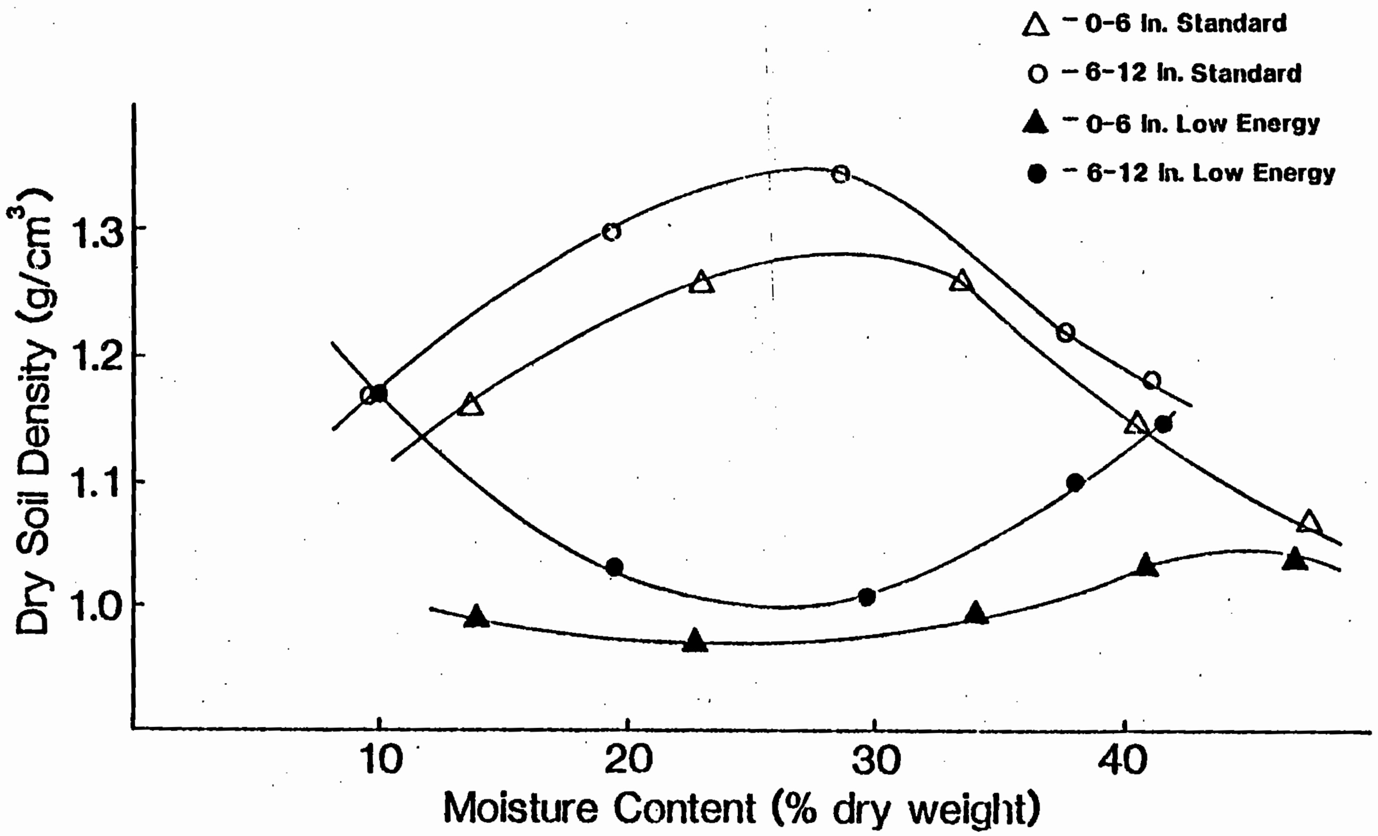

Figure 6. Proctor curves for Ponderosa pine sample area soil.

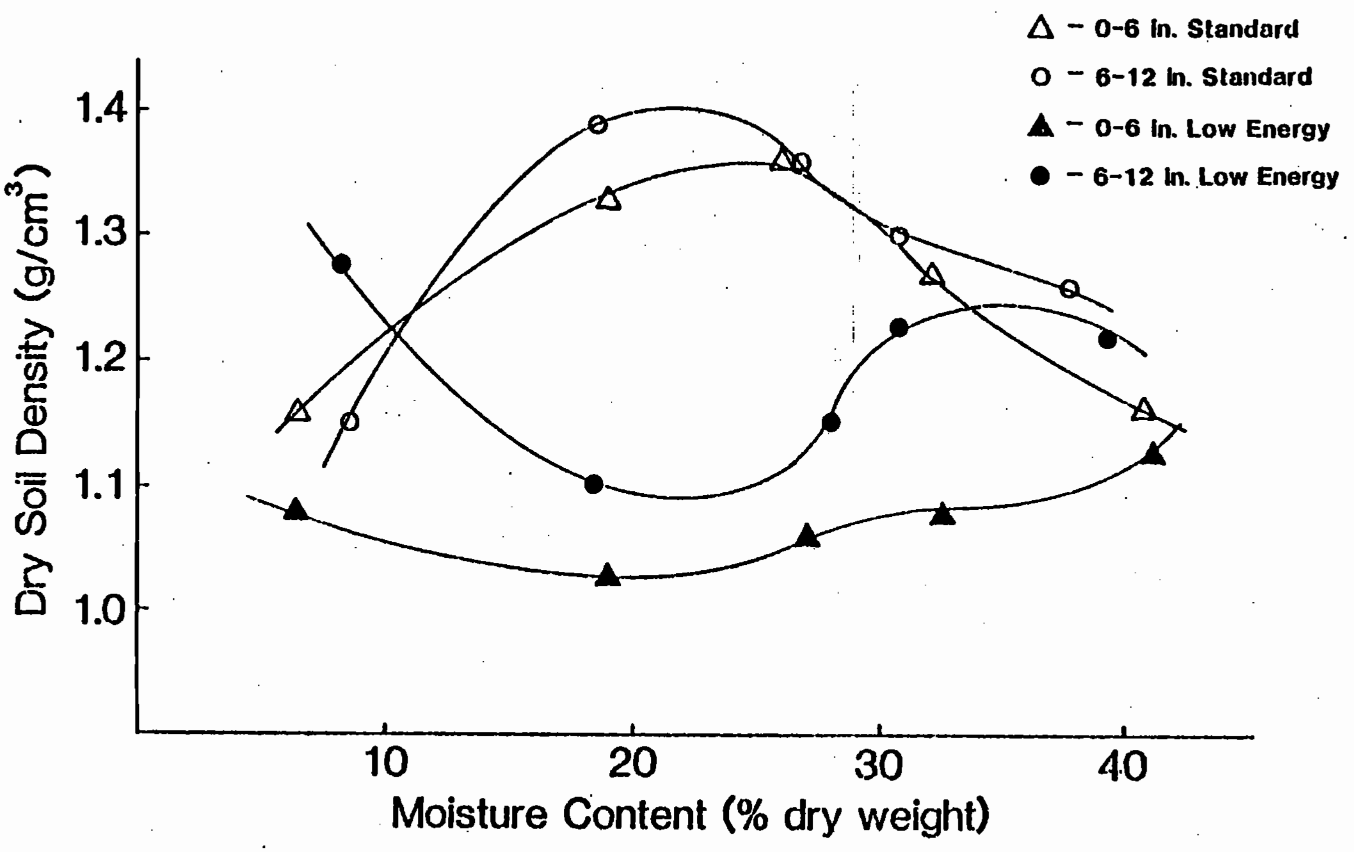

Figure 7. Proctor curves for lodgepole pine sample area soil.

well-defined maximum dry bulk densities at moisture contents between 20 and 30 percent for both soil types. At low moisture contents, negative pore-water pressures develop which bond particles together and provides shear strength to resist compaction under high energy loads. As the moisture content increases, water acts as a lubricant and allows particles to reorient their relative positions to achieve a maximum density. At moisture contents above this critical level, water occupies most of the large pores and cannot be compressed by the compactive energy applied during the test. The flatness and lower relative densities for the 0 to 15.2 cm soil depth for both sample areas may be influenced by the higher level of organic matter found in the surface horizon.

Comparison of Standard Proctor test results with actual field densities found on recently constructed skid trails have shown that the test over-estimates densities by 24 to 29 percent (Froehlich *et al.*, 1980). The modified Proctor test, which uses only 8 percent of the standard test energy, generally produced flatter curves with poorly defined maximum dry bulk densities typically achieved with low energy compaction tests. The surprisingly low densities achieved between 20 and 30 percent moisture content are due to the high threshold energy required to overcome the particle bridging effects from capillary pressure. Comparison of the laboratory values with bulk densities measured on a recently constructed skid trail in the ponderosa pine study area (1.25 g/cm^3) indicates that some mid-range of compactive energy may produce bulk densities closer to measured values. In general, compactive forces generated by ground-based logging vehicles are more complex than those associated with laboratory kneading-compaction tests. If researchers are correct in their assumption that a lower compactive energy test approximates skid trail densities more closely, the most important point is that forest soils are readily compactible over a wide range of moisture contents found throughout much of the operating season.

Skid Trail Bulk Densities

Measurements of skid trail bulk density were made in conjunction with tree growth measurements at each sample area location. Mean bulk density values for the two areas are shown in Table 4 together with other descriptive data. Bulk density within the surface 30.5 cm at the ponderosa pine site was 1.07 g/cm^3, representing a 15.4 percent difference from the undisturbed condition after 23 years. The average density of the 0 to 30.5 cm depth for the lodgepole pine zone was surprisingly similar, 1.08 g/cm^3, but when referenced to measurements in the undisturbed stand represents a 27.5 percent increase in bulk density.

The larger relative increase for the lodgepole pine site is probably due to a combination of differences in available recovery period and initial disturbance levels. The site was logged 15 years earlier under a group selection cut, while trails in the ponderosa pine stands were established 23 years ago in a light selective harvest, factors which limit direct comparisons of relative soil recovery rates for the two areas. In addition, sampling on all sites was

Table 4. Data summary for tree growth and site variables.

		Ponderosa pine		Lodgepole pine	
Variable	Symbol	$\bar{X}$	s	$\bar{X}$	s
Height (cm)	HT	199.4	79.0	257.6	120.6
Basal diameter (cm)	DIA	4.45	2.08	5.21	2.84
Stem volume (cm^3)	VOL	1973.0	2912.0	4565.5	5273.4
Age (yrs)	AGE	13.7	1.7	11.4	1.0
Bulk density (g/cm^3)	D_b	1.072	.120	1.076	.082
Percent difference in bulk density (%)	$\%\Delta D_b$	15.4	14.4	27.5	9.8
Soil organic matter content (%)	%OM	7.8	1.6	5.9	1.0
Residual overstory basal area (m^3/hectare)	BA	17.8	7.7	5.4	2.9
Skid trail stand density (#/hectare)	TPH	10208	8250	3618	1703
Competition index[1]	CI	.78	.88	.65	1.05
Site index[2]	SI	107	6.0	--	--

[1] Non-dimensional index of competition from the reproductive stand (after Wagner, 1982).

[2] Site quality as defined by the average total height (in feet) of dominant trees at 100 year base age (Meyer, 1938).

restricted to well-stocked trails with older regeneration in order to focus on site productivity impacts related to soil compaction. The bulk density differences are therefore conservative estimates, but compare closely with those reported by Froehlich (1979), who found 18 percent higher densities at the 0 to 15.2 cm depth on skid trails 16 years after commercial thinning in an eastern Oregon ponderosa pine stand.

Changes in bulk density with depth for the ponderosa pine study area are shown in Figures 8 and 9. A general trend of increasing bulk density with depth is apparent for both the undisturbed soil and in skid trails. The tendency for the bulk density of undisturbed soil to rise with profile depth is a common soil characteristic. This apparently results from a lower content of organic matter, less aggregation and root penetration, and consolidation from the weight of the overlying layers. The reason for the decrease in bulk density at the 30.5 cm depth in the undisturbed soil is unknown, but may be a result of measurement by the nuclear densiometer of tree roots or buried organic material. Recovery of skid trail bulk densities by natural processes is probably most active in the surface 6 inches, and may also have contributed to the stepped profile shown for the difference in density (Figure 9).

Reliable estimates of soil density recovery rates cannot be projected from the data since the study design and sample size were directed toward an assessment of growth impacts. However the high density levels found in the surface 30.5 cm of the skid trails, along with the low relative activity of natural restoring forces, suggest

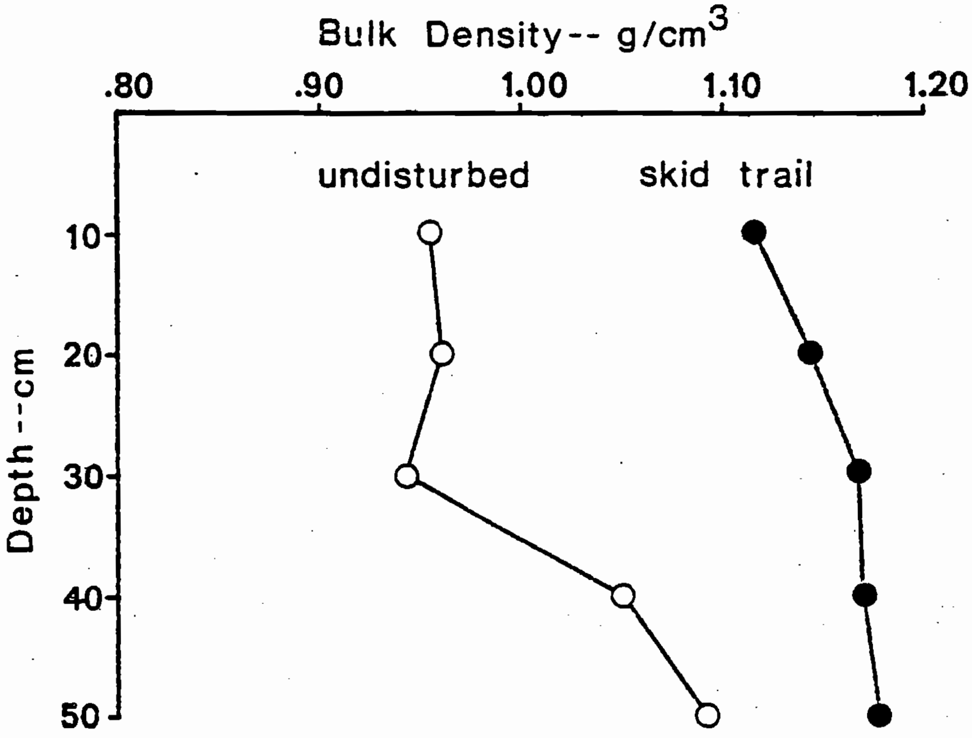

Figure 8. Bulk density profiles for the ponderosa pine sample area.

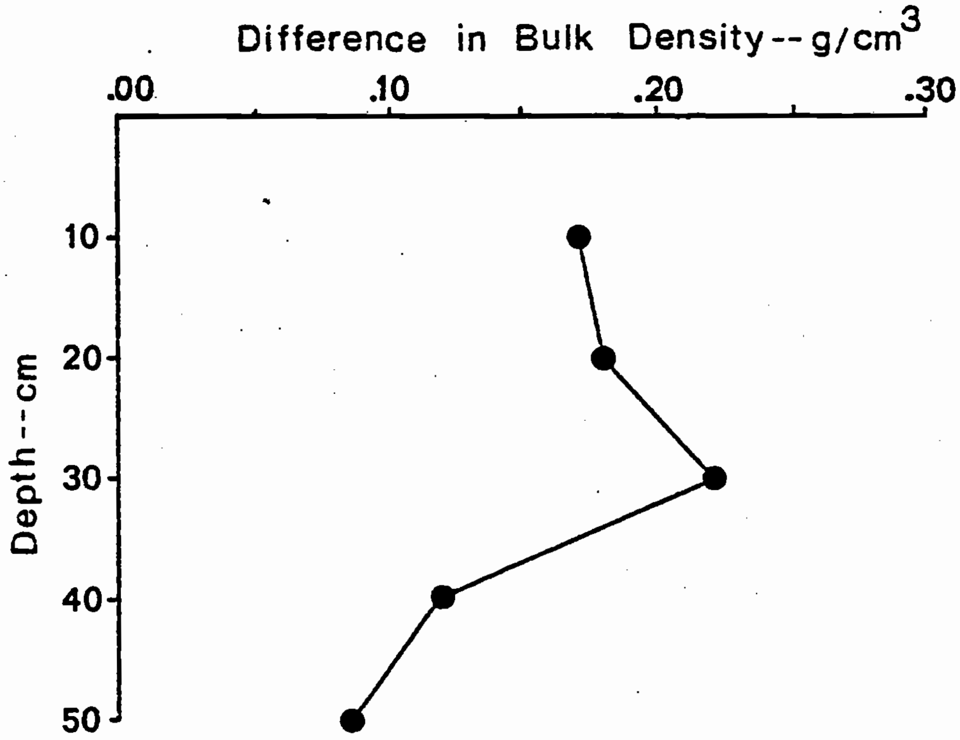

Figure 9. Changes in bulk density with depth for the ponderosa pine sample area.

that rapid recovery from compaction is unlikely. Recovery of soil structure, porosity, and bulk density in skid trails is governed to a large degree by the clay mineralogy and climate of the study area. Volcanic ash-influenced soils are characterized by amorphous clays, with an overall trend from allophane, a 1:1 phyllosilicate, weathering to metahalloysite, a less disordered 1:1 phyllosilicate (Patton, 1978). The absence of 2:1 lattice clays in these soils would therefore limit their capacity for shrinking and swelling. Although soil disturbance and removal of the plant and litter cover provides a greater opportunity for soil frost formation, the protective snow cover and moderate temperature extremes limit the role of freezing and thawing as a restorative process. Similar inference about the relative activity of biological influences are difficult to construct, but their dependence on physical recovery processes suggests that soil organisms cannot readily loosen compacted forest soil in this environment.

Growth Parameters and Site Factors

The variable nature of the natural stands presented a substantial challenge for the task of selecting meaningful growth indexes and probable site factors to be included in the analysis. Most previous studies of compaction-related growth impacts in sapling-sized stands have examined only total height. The principal advantages of analyzing this feature are its lower sensitivity to stand density and competition (Spurr and Barnes, 1973), and its ease of measurement.

However, other morphological characteristics may reflect the impact of plant stress induced by compaction. An analysis of diameter and volume growth was therefore included in the study. Data collected on stand density (TPH) and measurements of understory and overstory conifer competition (CI,BA) were tested as predictor variables to help explain part of the variation in the sample. Soil factors included in the analysis were the percent difference in bulk density from the undisturbed soil ($\%\Delta D_b$) and the percent total organic matter (%OM) measured in the vicinity of each sample tree. Site index (SI) was used as an integrating variable to account for possible differences in site productivity for the ponderosa pine sample locations. Values obtained for the site variables and total growth are summarized in Table 4.

An analysis of the total age of the sample trees shows considerable variation in the age class distribution (Figure 10). Ponderosa pine saplings are approximately normally distributed between ages 9 and 18, with a mean age of nearly 14 years (Table 4). Since the stand was logged in 1959, establishment delays for the skid trails ranged from 4 to 13 years. Lodgepole pine saplings averaged 11.4 years, and ranged from 10 to 13 years old- or an establishment delay of only 1 to 4 years. Age values reported here slightly underestimate actual total age, because ring counts were made at the base of stems cut at a 2.5 cm height. Differences in tree age was an obvious source of potential variation in total growth, and was therefore included as an independent variable in the regression analysis.

To help normalize the effect of variable age classes within each

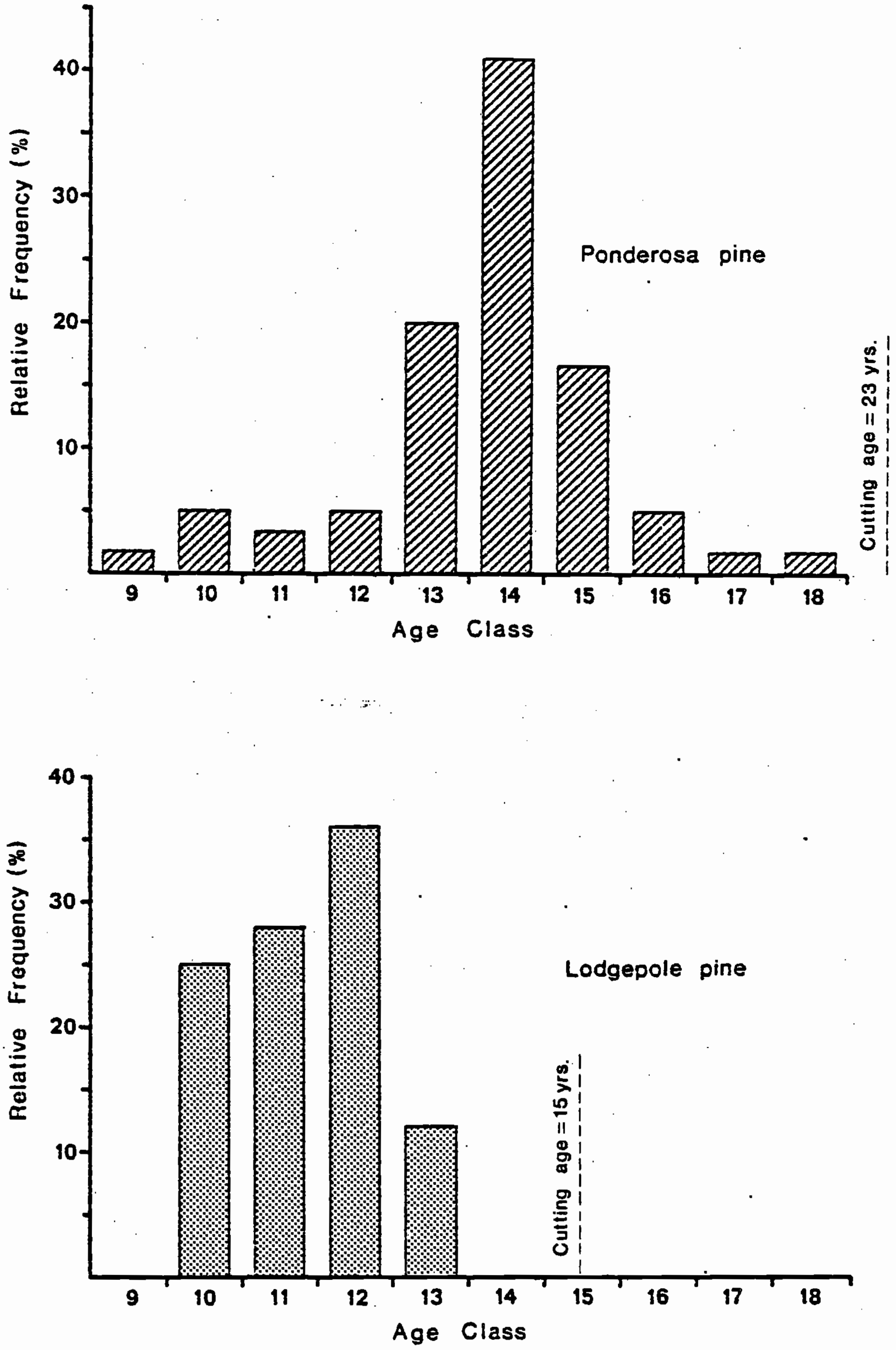

Figure 10. Age class distribution for the sample areas.

stand, a measure of current incremental growth was evaluated. Stem analysis data from most of the trees showed that height and diameter-inside bark growth rates were nearly constant over the last three to five years. The incremental height, diameter, and volume growth for the last five year period were therefore selected as additional parameters for correlation with soil and competition factors.

The relationship between the difference in bulk density and the total height and basal diameter growth for ponderosa pine and lodgepole pine is shown in Figures 11 and 13. The larger sample size for ponderosa pine afforded a more continuous range in soil density than for the lodgepole site, where sampling was curtailed by snow. Considerable variation in total growth is apparent for both species, but growth-density relationships appear to be stronger in the former case. Similar trends are also apparent for the current annual height and diameter growth computed on the basis of the last five year period (Figures 12 and 14). The current annual diameter growth rate for ponderosa pine shown in Figure 12 appears to be correlated with bulk density increases to a greater degree than height growth rate. The strength of these correlations were formally tested using multiple regression, the results of which are discussed in the following section.

Regression Analysis

Multiple regression equations were developed to determine the relationship between tree growth and the set of independent

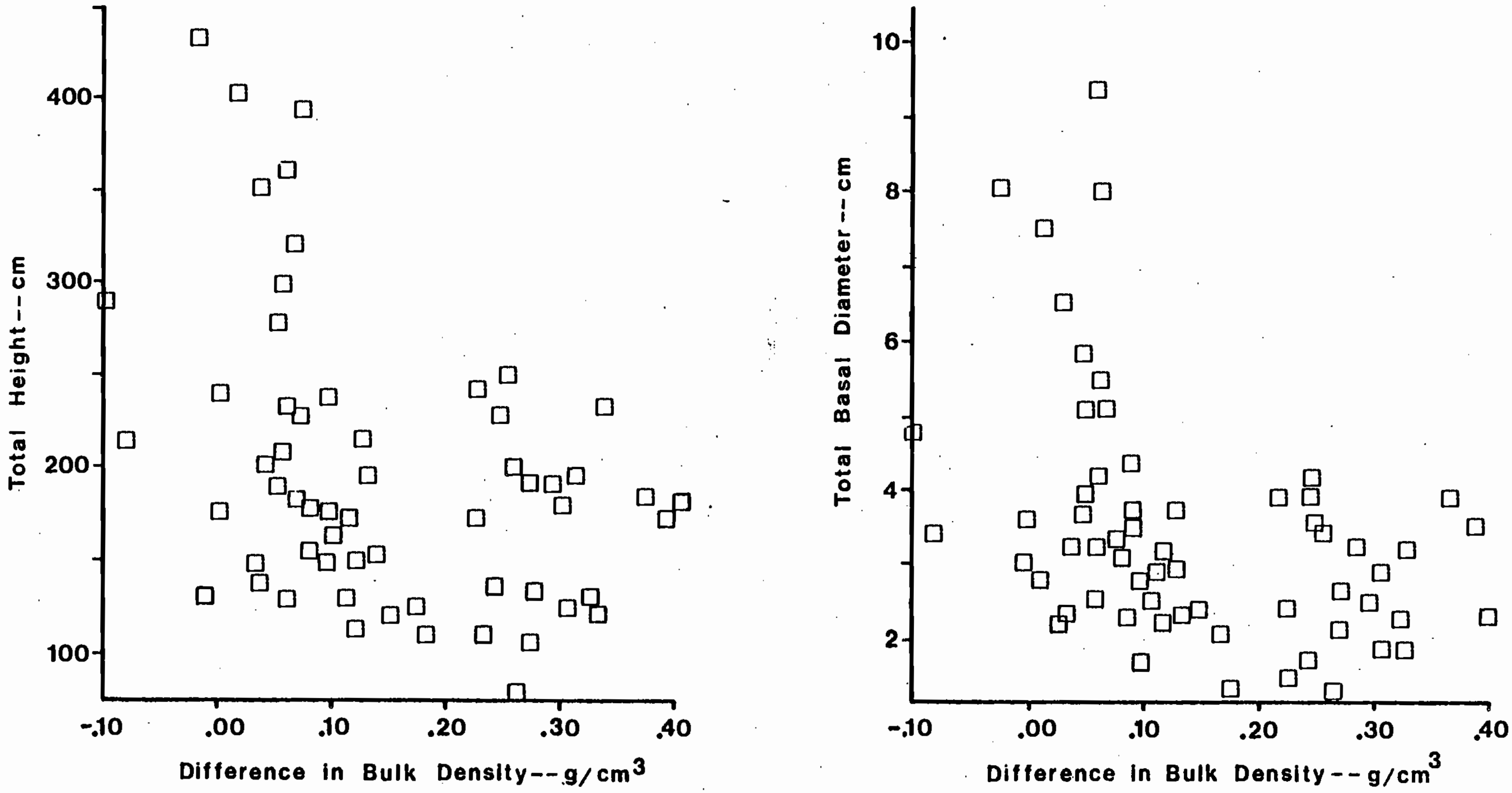

Figure 11. Total growth-bulk density relationships for ponderosa pine.

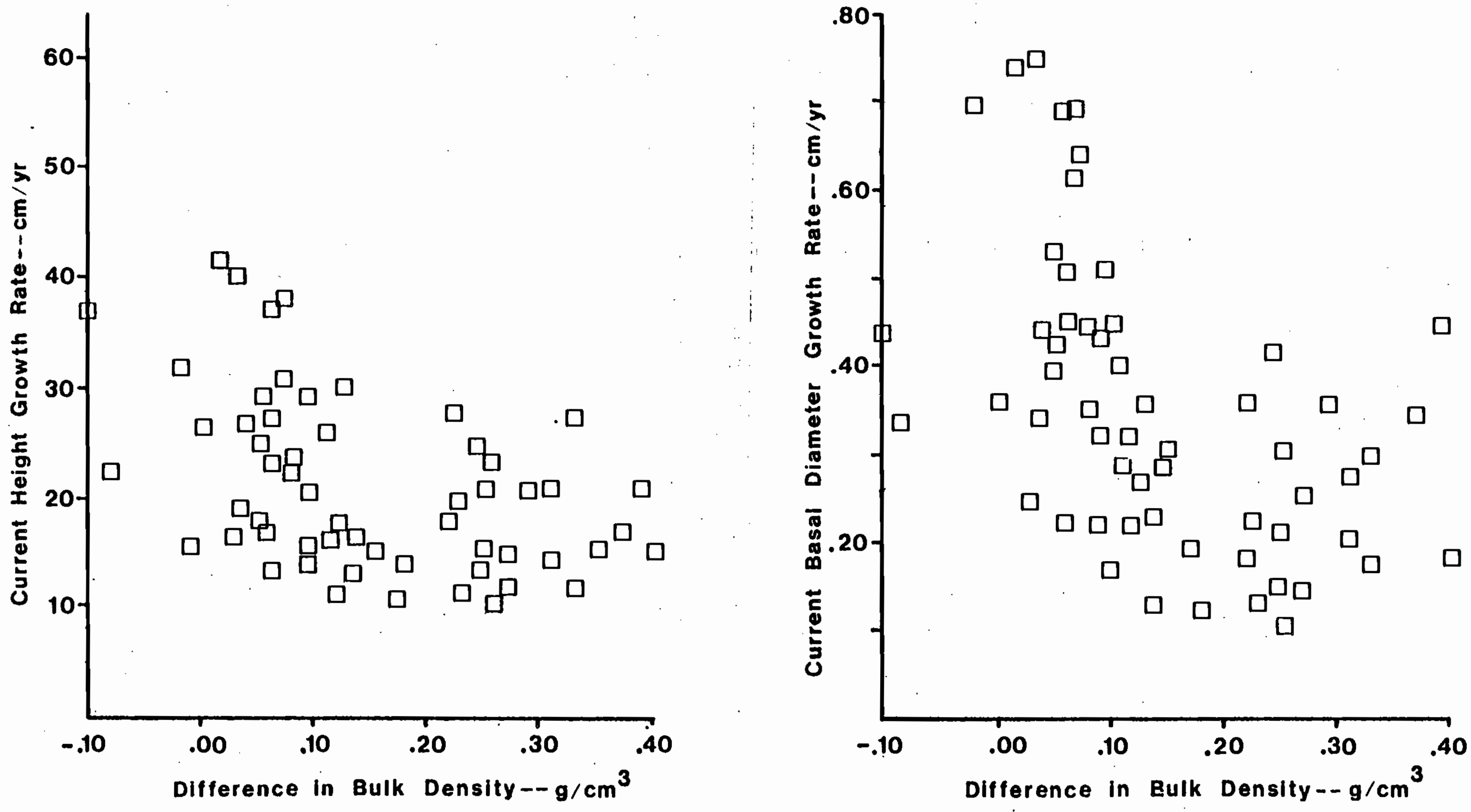

Figure 12. Current annual growth-bulk density relationships for ponderosa pine.

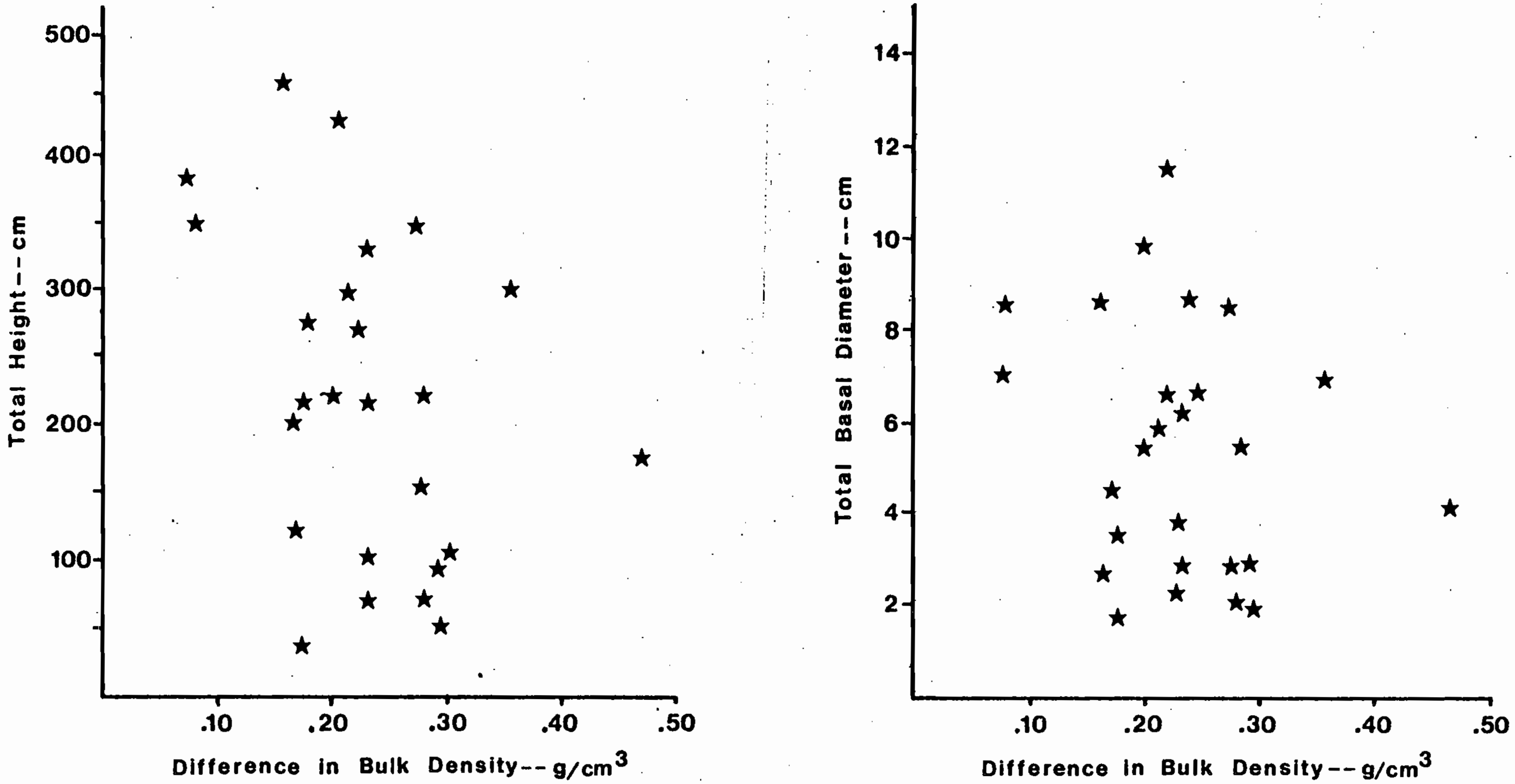

Figure 13. Total growth-bulk-density relationships for lodgepole pine.

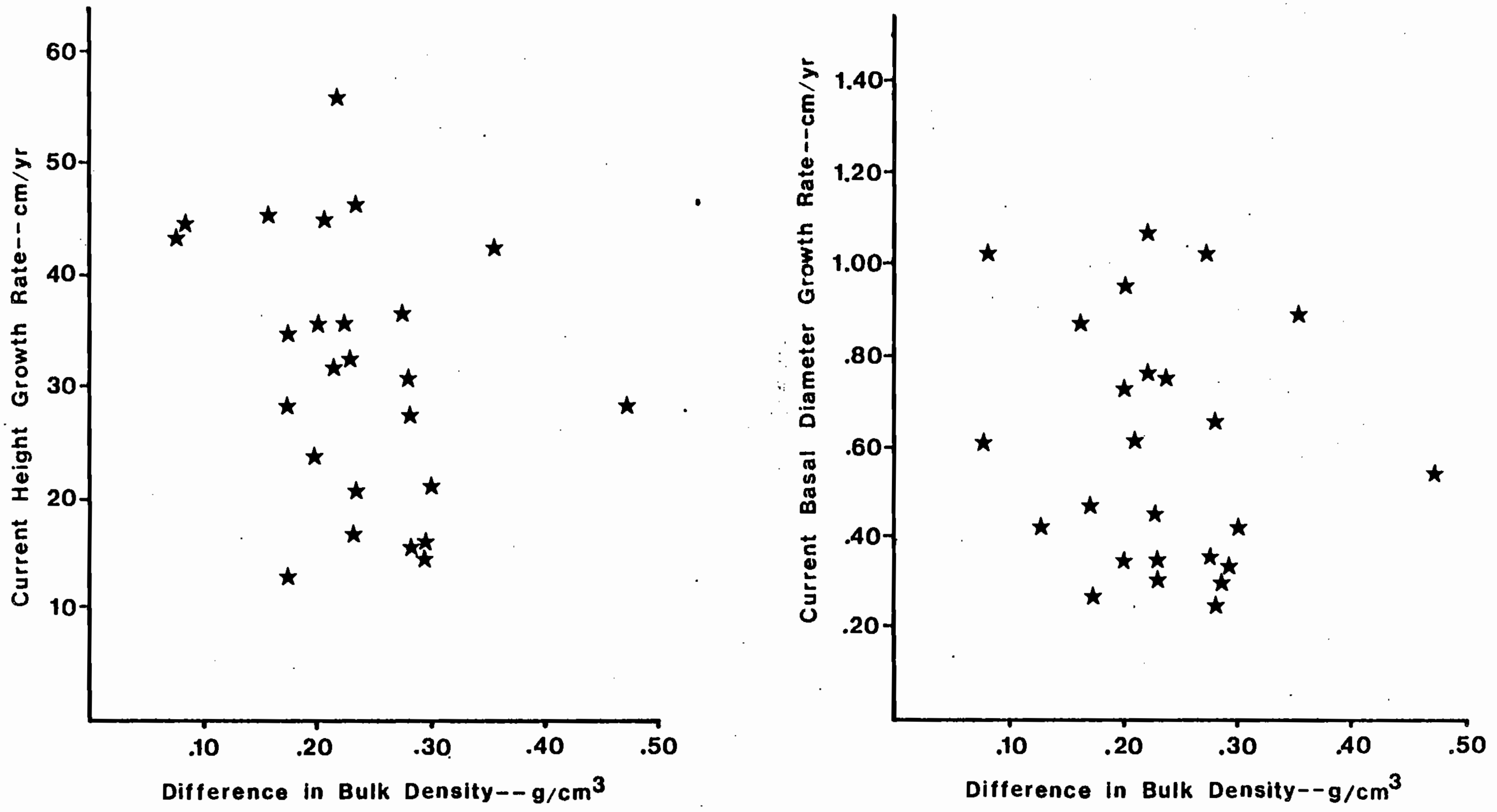

Figure 14. Current annual growth-bulk density relationships for lodgepole pine.

variables. A stepwise selection procedure was used to test the significance of the independent variables at the $\alpha = .05$ level. Variables included in the analysis were: age (AGE), site index (SI), overstory basal area (BA), understory conifer competition index (CI), number of trees per hec. (TPH), percent difference in bulk density of the 0 to 30.5 cm depth ($\%\Delta D_b$), and percent total organic matter (%OM) in the surface 30.5 cm.

The equations predicting total growth for ponderosa pine are shown in Table 5. The maximum likelihood method (Draper and Smith, 1966) and residual plot analysis determined that natural log transformations of the growth parameters provided the best fit with the set of independent variables. Of the factors tested, site index, age, and basal area were the most strongly correlated with total growth. Since basal area provided an index of overstory canopy cover, the highly significant correlation with the independent variables suggest that tree growth was quite sensitive to the effects of shading and perhaps competition for soil moisture and nutrients from the residual stand. The slowness with which the reproductive stand develops in selectively cut ponderosa pine forests was noted by Meyer (1934), who found the rate of development for shaded clumps of reproduction to lag far behind the rate normal for open-grown seedlings and saplings. A wide range in age class structure of the ponderosa pine regeneration noted earlier is of course responsible for the significance of this variable in the model. Inclusion of site index in the model indicates that differences in climate or soil productivity may underlie some of the variation in tree growth.

Table 5. Total growth regression equations for ponderosa pine.

Model	Mean ln(Y)	Regression coefficients 1/					R^2	MSE
		β_0	β_1	β_2	β_3	β_4		
$\ln(HT) = \beta_0+\beta_1 SI+\beta_2 AGE+\beta_3 BA$	5.2270	.9766	.0320 (.000)	.0792 (.000)	-.0144 (.005)	--	.53	.0657
$\ln(HT) = \beta_0+\beta_1 SI+\beta_2 AGE+\beta_3 BA+\beta_4 \%\Delta D_b$	5.2270	1.2029	.0304 (.000)	.0764 (.000)	-.0126 (.016)	-.0032 (.238)	.54	.0652
$\ln(DIA) = \beta_0+\beta_1 SI+\beta_2 AGE+\beta_3 BA$	1.1522	-4.2383	.0394 (.000)	.1128 (.000)	-.0209 (.000)	--	.65	.0706
$\ln(DIA) = \beta_0+\beta_1 SI+\beta_2 AGE+\beta_3 BA+\beta_4 \%\Delta D_b$	1.1522	-3.8696	.0368 (.000)	.1081 (.000)	-.0181 (.001)	-.0052 (.0612)	.67	.0674
$\ln(VOL) = \beta_0+\beta_1 SI+\beta_2 AGE+\beta_3 BA+\beta_4 \%\Delta D_b$	6.9681	-4.5272	.0845 (.000)	.2519 (.000)	-.0427 (.002)	-.0148 (.037)	.64	.4405

1/ Numbers in parentheses indicate the significance of the regression coefficients.

The next variable which entered the regression equations was the percent increase in bulk density. A significant relationship of this compaction measurement with total height could not be established, but the coefficient and p-value are shown for the equation which includes this variable. A nearly significant correlation was established for basal diameter (p=.06), which suggests that radial growth is affected to a greater degree than height growth. The pair of regression equations for height and diameter shown in Table 5 therefore represent two cases: (1) where models developed from the stepwise selection procedure include only the independent variables significant at the $\alpha = .05$ level, and (2) where models allow the inclusion of the non-significant bulk density coefficient for descriptive and predictive purposes. The regression equation for total stem volume determined that the percent increase in density bears the strongest relationship (p = .037) to volume growth.

Similar equations were derived for the last five year growth (Table 6). The same four independent variables most related to total growth were also good predictors of recent incremental growth. However, the strong effect of age differences was reduced somewhat in this analysis. Soil density was strongly correlated with periodic diameter growth (p=.005), and nearly significant at the α=.05 level for height (p=.053) and volume growth (p=.066). The low coefficient of determination values for both groups of equations, which ranged from .53 to .70, are not surprising in light of the many physical, biological, and climatic factors that potentially affect plant growth. The MSE (mean square error) values in the table were used as

Table 6. Last five year growth regression equations for ponderosa pine.

Model	Mean $\ln(Y)$	Regression coefficients [1]					R^2	MSE
		β_0	β_1	β_2	β_3	β_4		
$\ln(HT) = \beta_0+\beta_1 SI+\beta_2 BA+\beta_3 \%\Delta D_b$	4.5909	2.0534	.0270 (.000)	-.0157 (.001)	-.0048 (.053)	--	.60	.0538
$\ln(HT) = \beta_0+\beta_1 SI+\beta_2 BA+\beta_3 \%\Delta D_b+\beta_4 AGE$	4.5909	1.7689	.0281 (.000)	-.0157 (.001)	-.0046 (.065)	.0122 (.520)	.60	.0530
$\ln(DIA) = \beta_0+\beta_1 SI+\beta_2 BA+\beta_3 \%\Delta D_b+\beta_4 AGE$	.4429	-3.6943	.0369 (.000)	-.0233 (.000)	-.0082 (.005)	.0534 (.018)	.70	.0730
$\ln(VOL) = \beta_0+\beta_1 SI+\beta_2 BA+\beta_3 \%\Delta D_b+\beta_4 AGE$	6.7892	-6.0388	.0988 (.000)	-.0456 (.002)	-.0136 (.066)	.2391 (.000)	.65	.4832

[1] Numbers in parentheses indicate the significance of the regression coefficients.

correction factors recommended when a log transformation is applied to the dependent variable. An approximate correction for log bias is obtained by adding one-half the residual variance to the log scale estimate before making the transformation back to the natural scale (Stage 1975; Flewelling and Pienaar, 1980).

Multicolinearity among the independent variables presented some problems in the regression analysis for ponderosa pine. This became apparent during the stepwise regression procedure, when changes in partial F-values occurred following the addition or deletion of certain variables to the model. These were also accompanied by changes in the regression coefficients when interaction existed among the independent variables. A case in point is the colinearity between overstory basal area (BA) and the percent differences in bulk density ($\%\Delta D_b$). Although no biological relationship occurs between the two variables in the natural environment, the group of trees for which the greatest difference in bulk density was recorded were located in a partial-cut stand with the highest residual stocking. This association affected the significance of the soil density variable by increasing the probability of a type I error and decreasing the magnitude of the regression coefficient.

Some degree of colinearity was also evident between bulk density and organic matter content. When the soil density variable was included in the model, the entering F-value for the percent organic matter coefficient became less significant. Soils high in organic matter content are characterized by low bulk density, and the interaction reflected the tendency for both predictor variables to explain similar variation in the growth parameters.

Regression equations developed for total and periodic growth of lodgepole pine differ markedly from the ponderosa pine equations. Results of the regression analyses are presented in Tables 7 and 8. Age and percent organic matter are the only variables significantly related to the six growth parameters. No relationship between bulk density and tree growth could be found for this sample, since p-values commonly exceeded .50 for this variable. Partial F-values for the regression coefficients were generally insensitive to the order of variable inclusion, indicating that multicolinearity was not a problem in the regression analysis.

The strong negative correlation with organic matter content may indicate that growth reductions have occurred due to the effect of soil displacement during harvesting and slash disposal at this site. A strong negative response of lodgepole pine seedling height and weight to soil disturbance from windrowing was also noted by Perry et al. (1981) in a greenhouse bioassay. Large differences in bulk density were found in skid trails at the lodgepole pine study area, but trees were apparently more sensitive to reductions in fertility caused by physical removal of the nutrients in the upper soil horizons.

As in the case of ponderosa pine, the regression relationships developed for lodgepole pine apply specifically for conditions found in the sample area. Caution should be exercised in extrapolating results to a variety of site conditions without validation, since

Table 7. Total growth regression equations for lodgepole pine.

Model	Mean ln(Y)	Regression coefficients [1/] β_0	β_1	β_2	R^2	MSE
$\ln(HT) = \beta_0+\beta_1 AGE+\beta_2 \%OM$	5.4341	1.2577	.2638 (.003)	-.1986 (.020)	.56	.1249
$\ln(DIA) = \beta_0+\beta_1 AGE+\beta_2 \%OM$	1.5116	-3.0613	.2980 (.002)	-.1997 (.027)	.57	.1400
$\ln(VOL) = \beta_0+\beta_1 AGE+\beta_2 \%OM$	7.6602	-4.0821	.7588 (.002	-.5251 (.022)	.58	.9004

[1/] Numbers in parentheses indicate the significance of the regression coefficients.

Table 8. Last five years growth regression equations for lodgepole pine.

Model	Mean ln(Y)	Regression coefficients [1]			R^2	MSE
		β_0	β_1	β_2		
$\ln(HT) = \beta_0+\beta_1 AGE+\beta_2 \%OM$	4.9685	1.9489	.1669 (.024)	-.1897 (.012)	.42	.1162
$\ln(DIA) = \beta_0+\beta_1 AGE+\beta_2 \%OM$	.9937	-2.3144	.1999) (.020)	-.1748 (.041)	.45	.1281
$\ln(VOL) = \beta_0+\beta_1 AGE+\beta_2 \%OM$	7.6105	-4.2761	.7573 (.002)	-.5826 (.021)	.57	.9771

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[1] Numbers in parentheses indicate the significance of the regression coefficients.

lodgepole pine occupies a large geographic range and a broad ecological amplitude (Pfister and Daubenmire, 1975). In addition, our knowledge about nutrient relations in lodgepole pine forests and the effects which various silvicultural treatments have on them is incomplete[2]. Predicting the response of lodgepole pine to soil disturbance under a range of site conditions may be difficult, since as Lotan and Perry (1983) concluded, the species "may occupy a low nutrient niche and that too much fertility may favor competitive species to the detriment of lodgepole pine."

Differences in site conditions between the two areas and lack of experimental control complicate any direct comparisons of the effect of compaction on lodgepole pine and ponderosa pine. Lodgepole pine occurred under more open-grown conditions, which reduced any potential effects of shading from the residual stand. This would presumably offer a better opportunity to focus on the effect of soil density on growth. The limited sample size for this species was initially considered to be responsible for the lack of any compaction-related growth impacts. However, the sample areas in the ponderosa pine zone with a comparable sample size and bulk density range showed significant relationships between density and growth for at least two growth variables. Limited information is available from compaction studies on lodgepole pine, but the root growth study by Minore (1969) ranked lodgepole among the highest of several species tested for root

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[2] D. A. Perry. Personal communication.

penetration through artificially compacted cores. If the higher precipitation received at this elevation reduces the period of severe moisture stress, then growth-limiting effects from compaction may be less pronounced than for more xeric moisture regimes. However, the growth losses reported for highly productive sites in the Douglas-fir region confirm that mesic climatic conditions alone do not provide a means to overcome the effect of compaction.

The competition index used to quantify the level of competition from other sapling-aged trees and from brush and grass vegetation in the skid trails was not successful in explaining growth reductions. In fact, the index was positively correlated with growth for both lodgepole pine and ponderosa pine. The index apparently reflected the relative site quality by taking on lower values in microsites where the combination of factors which controlled tree growth (e.g. site index, soil density, organic matter content, overstory cover, etc) were at growth-limiting levels. Conversely, more favorable microsites characterized by minimum site degradation supported high levels of plant biomass but were assigned high competition index values as well. When included in the regression analysis, this variable naturally "explained" a substantial part of the variation in tree growth, but was also highly correlated with other independent variables. The index therefore added little information concerning growth of skid trail regeneration and was omitted from the final regression analysis.

Predicted Growth Impacts from Compaction

The regression equations developed for height, diameter, and volume growth were used to predict the effect of soil compaction on the growth of young ponderosa pine. By sampling trees growing under a wide array of bulk densities, the influence of this variable on tree growth could be investigated further. The growth response was predicted by allowing the percent difference in bulk density to vary between no impact (0%) and the maximum difference obtained for the sample (44%), while holding the other independent variables in the model at their mean values. The predicted growth was then expressed as a percent reduction in growth relative to the mean response for no measurable compaction.

The projected values of total growth are presented in the form of growth reduction curve shown in Figure 15 and predict a curvilinear response due to the logarithmic transformation of the growth (dependent) variables. The models indicate a greater reduction in diameter growth than for height growth, at a given level of bulk density increase. The projected decrease in total stem volume is even more severe, and corresponds to a nearly 1:1 ratio of percent growth reduction to percent density increase. The greater relative effect of compaction-induced stress on radial growth is consistent with observations by plant physiologists, who report that meristematic tissues receive a greater relative supply of resources than supportive tissue when the distribution of photosynthate is less than optimum. The even greater relative impact on stem volume reflects the

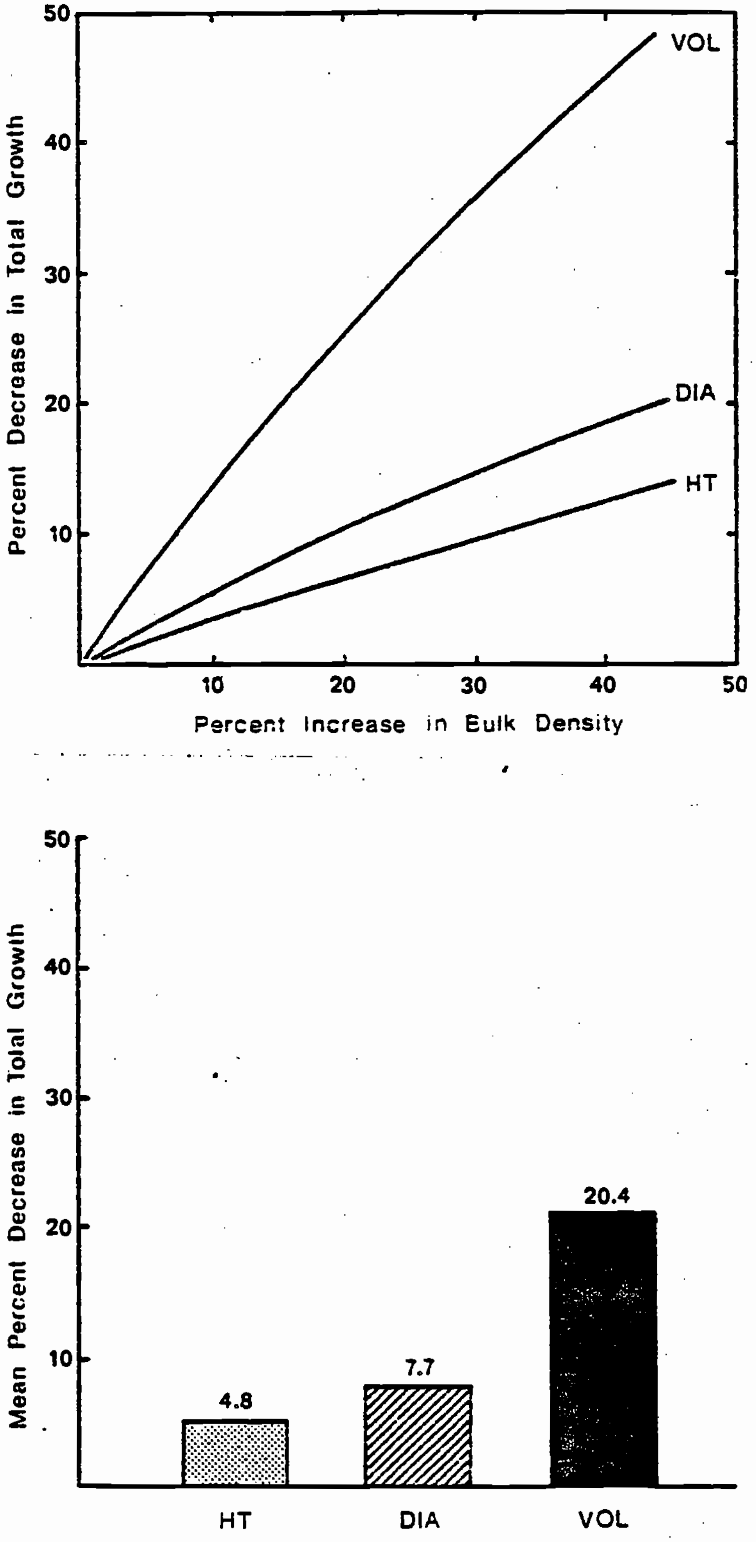
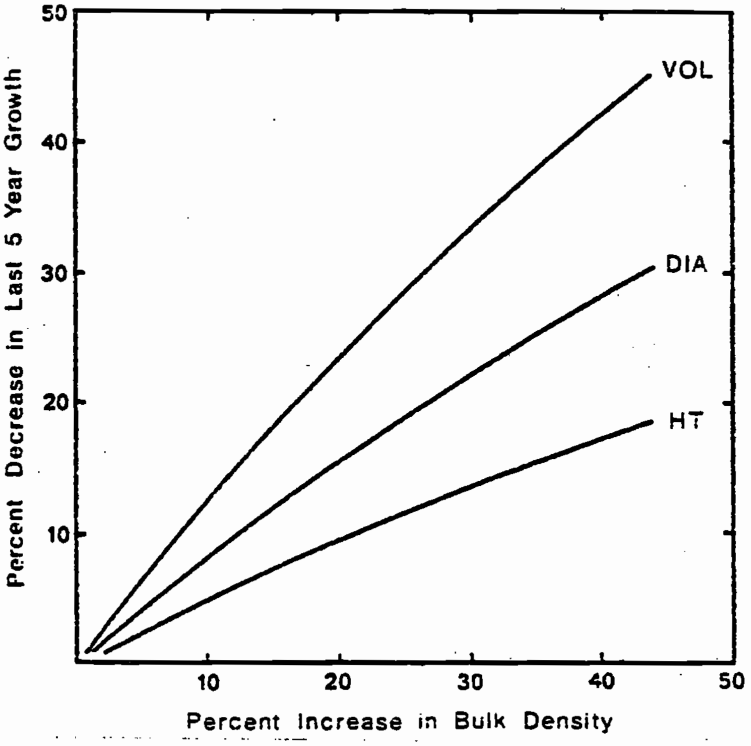


Figure 15. Predicted reductions in total growth for ponderosa pine.

exponential relationship of volume with diameter, and may represent the moist meaningful measure of productivity losses due to compaction.

The mean reductions in total height, diameter, and volume for ponderosa pine are shown in the bar graph portion of Figure 15. Those values are based on a 15.4 percent increase in density-the mean values obtained for the sample. The reductions of 4.8, 7.7, and 20.4 percent for total height, diameter, and volume are probably conservative estimates, since the sample included several trees growing in soil densities comparable to undisturbed soil. The upper 95 percent confidence limit for the mean density increase in skid trails corresponds to a 19.1 percent increase in bulk density. Projected growth impacts for this level correspond to reductions of 5.9, 9.4, and 24.6 percent for height, diameter, and volume, and are probably more realistic estimates given the sampling conditions for the study.

Growth impacts for the last five year period showed a similar pattern of growth reductions for height, diameter, and volume (Figure 16). This is not surprising since periodic growth is strongly related to total size. However, height and diameter growth over this most recent period shows a stronger correlation with density, with mean reductions of 7.1 and 11.8 percent predicted for ponderosa pine. Comparison of the height and diameter curves in Figures 13 and 14 suggests that compaction has a more substantial impact on growth as trees develop from seedlings to saplings and exert greater demands for moisture and nutrients required for stemwood production. A mean reduction in periodic volume growth of almost 19 percent is predicted



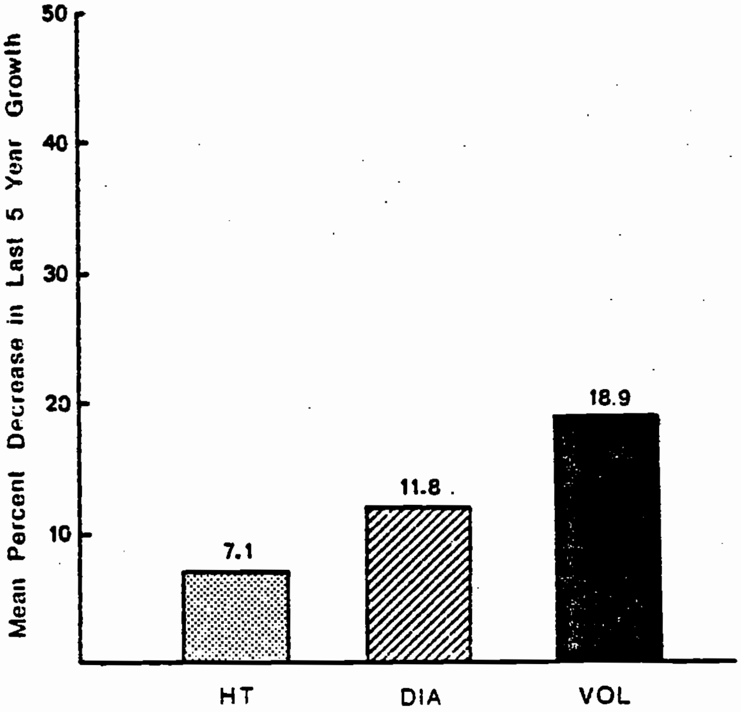


Figure 16. Predicted reductions in last five year growth for ponderosa pine.

for skid trails. Given the greater relative impact on the other two parameters, the reduction in volume growth is probably underestimated and perhaps reflects differences in the nature of the dependent variables. The periodic volume increments were based on regression predictions while height and diameter growth were accurately measured in the field of laboratory. Projected impacts on periodic growth based on the upper 95 percent confidence limit for the mean density increase correspond to reductions of 8.7, 14.4, and 22.9 percent for height, diameter, and volume.

Chronological Growth Trends

Measurements of annual height and diameter growth provided an opportunity to examine chronological growth development for each of the sample trees. This analysis was done to remove any possible bias introduced by differences in age class within the sample. Growth trends were analysed only for ponderosa pine, since significant correlations between growth and soil density were obtained only for this species.

The sample was stratified into "low impact" and "high impact" groups to facilitate growth rate comparisons. Trees whose root systems occupied soil with less than a 10 percent increase in bulk density were placed in the low impact group, while those associated with an increase equal or exceeding 10 percent were defined as high impact. This provided sample sizes of 27 and 34 trees, respectively. The mean height, diameter, and projected volumes for the first through the final year of growth were computed for the two groups. Mean and standard error values for the cumulative growth through year 14 (average stand age) are presented in Tables 9, 10, and 11.

When these values are plotted to construct the curves shown in Figures 17 and 18, a marked contrast in chronological growth trends can be seen. With increasing age the high impact group appears to lag further below the heights and diameters attained by trees in the low impact group. The growth curves also indicate that diameter growth is affected to a greater extent than height growth, which reconfirms the results of the regression analysis discussed earlier. The difference in projected volume growth rate for the two classes is even more dramatic (Figure 18). For example, the estimated cumulative volume attained by age 14 in the low impact group is nearly six times the mean stem volume estimated for trees in the high impact sample.

Two points should be emphasized about the contrast between the two impact groups. First, the curves shown are not based on regression, but are merely a series of linear segments used to connect adjoining mean values and provide a visual presentation of the data. A statistical comparison of two regression equations with impact group used as a covariable would be influenced by the strong tendency toward heteroscedasticity with increasing age. Logarithmic transformation of the dependent and independent variables would only partially stabilize the increasing degree of error variance. Second, the colinearity noted between overstory basal area and bulk density probably enhances the contrast in growth trends to some degree. A

Table 9. Cumulative height of ponderosa pine by compaction class.

	Cumulative Height Low impact ($<10\%\ \Delta D_b$)			Cumulative Height High impact ($\geq 10\%\ \Delta D_b$)		
Year	n	$\bar{X}$---cm---	$S\bar{x}$	n	$\bar{X}$---cm---	$S\bar{x}$
1	27	6.12	.68	34	4.93	.46
2	27	6.96	1.40	34	10.85	.74
3	27	25.58	1.85	34	18.31	1.04
4	27	38.58	2.87	34	25.86	1.32
5	27	52.30	3.76	34	34.98	1.91
6	27	69.06	5.36	34	44.91	2.39
7	27	84.30	6.10	34	54.99	2.74
8	27	99.29	7.54	34	68.12	3.71
9	27	123.52	9.19	34	82.32	4.55
10	26	148.31	11.07	34	96.14	5.51
11	25	174.55	13.36	32	112.09	6.22
12	23	198.68	15.77	32	127.86	7.09
13	22	222.48	18.01	30	143.51	7.85
14	15	257.73	26.11	25	156.87	8.48
β_0[1]	27	2.316a	.225	34	1.776b	.152
β_1	27	1.434a	.045	34	1.306b	.035

[1] Regression constants for logarithmic growth models computed through year 10: $HT = \beta_0\ YR^{\beta_1}$. Mean values followed by the same letter are not significantly different based on the Students-t range of the LSD test ($\alpha = .05$).

Table 10. Cumulative basal diameter of ponderosa pine by compaction class.

	Cumulative Diameter Low impact ($<10\%\ \Delta D_b$)			Cumulative Diameter High impact ($\geq 10\%\ \Delta D_b$)		
Year	n	$\bar{X}$---cm	---$S\bar{x}$	n	$\bar{X}$---cm	---$S\bar{x}$
1	27	.23	.03	34	.20	.00
2	27	.43	.05	34	.33	.02
3	27	.61	.08	34	.43	.02
4	27	.79	.09	34	.56	.03
5	27	1.04	.10	34	.71	.04
6	27	1.32	.12	34	.86	.05
7	27	1.60	.13	34	1.04	.06
8	27	1.96	.15	34	1.98	.07
9	27	2.36	.18	34	1.24	.08
10	26	2.77	.23	34	1.68	.09
11	25	3.23	.28	32	1.91	.10
12	23	3.68	.33	32	2.16	.12
13	22	4.14	.36	30	2.44	.13
14	15	4.80	.53	25	2.57	.15
β_0[1]	27	.080a	.009	34	.070a	.004
β_1	27	1.062a	.029	34	.918b	.029

[1] Regression constants for logarithmic growth models computed through year 10: $DIA = \beta_0 \ YR^{\beta_1}$. Values followed by the same letter are not significantly different based on the Students-t range of the LSD test ($\alpha = .05$).

Table 11. Cumulative stem volume in cubic cm for ponderosa pine by compaction class.

	Cumulative Volume Low impact (<10% ΔD_b)			Cumulative Volume High impact ($\geq$10% ΔD_b)		
Year	n	$\bar{X}$---cm	---$S\bar{x}$	n	$\bar{X}$---cm	---$S\bar{x}$
1	27	.3	.2	34	.2	.0
2	27	3.3	.8	34	1.1	.2
3	27	12.9	3.6	34	3.6	.5
4	27	28.5	7.0	34	8.4	1.1
5	27	62.1	14.3	34	17.0	2.5
6	27	121.7	26.7	34	32.1	4.6
7	27	207.6	44.7	34	55.4	8.2
8	27	352.3	75.1	34	94.9	14.9
9	27	584.2	118.3	34	152.7	24.7
10	26	919.5	185.8	34	233.8	38.2
11	25	1404.9	282.2	32	325.8	50.1
12	23	2017.4	412.6	32	457.0	69.2
13	22	2737.0	575.5	30	585.5	90.9
14	15	4195.1	1037.8	25	718.6	103.2

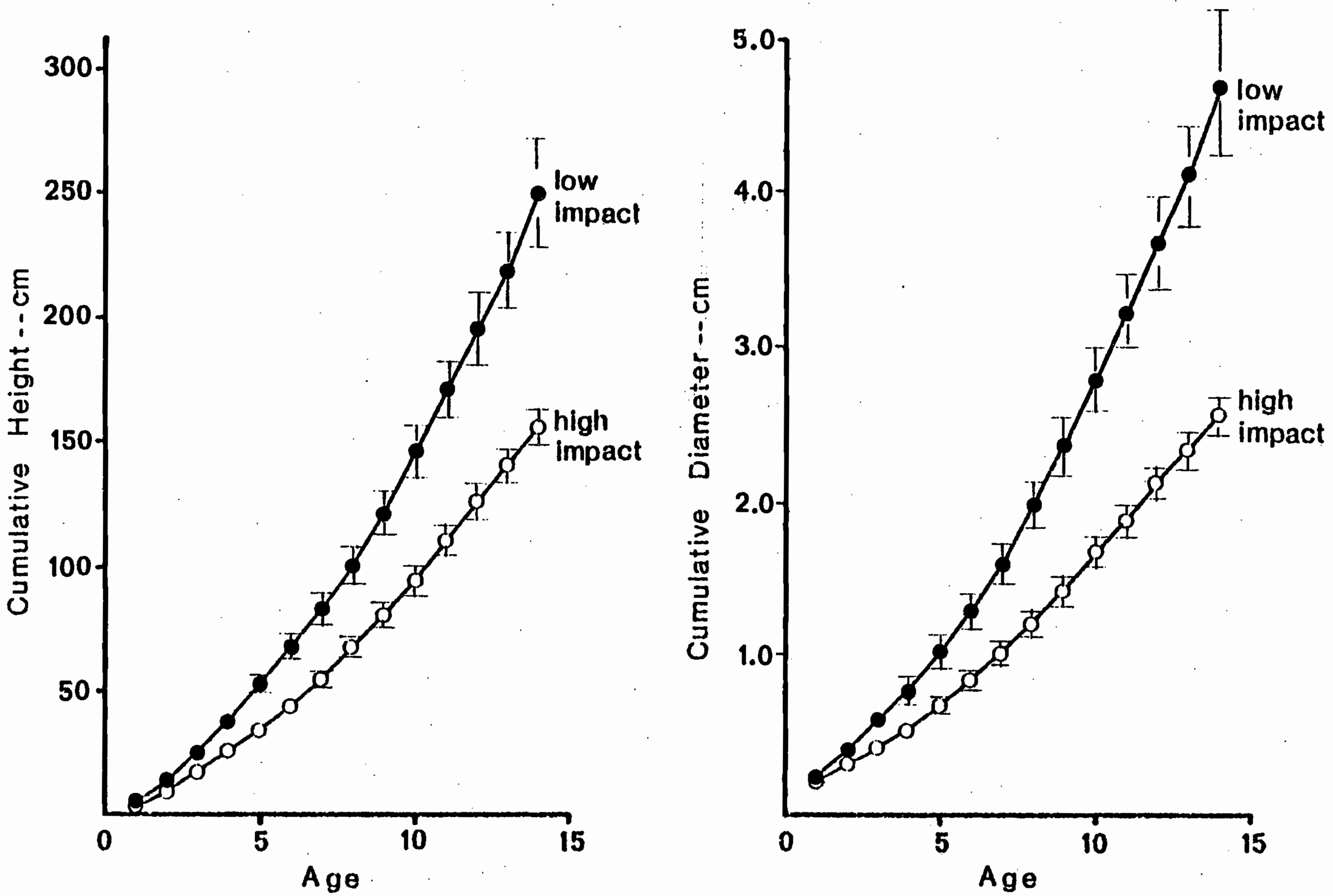


Figure 17. Cumulative height and diameter growth for ponderosa pine by compaction class.

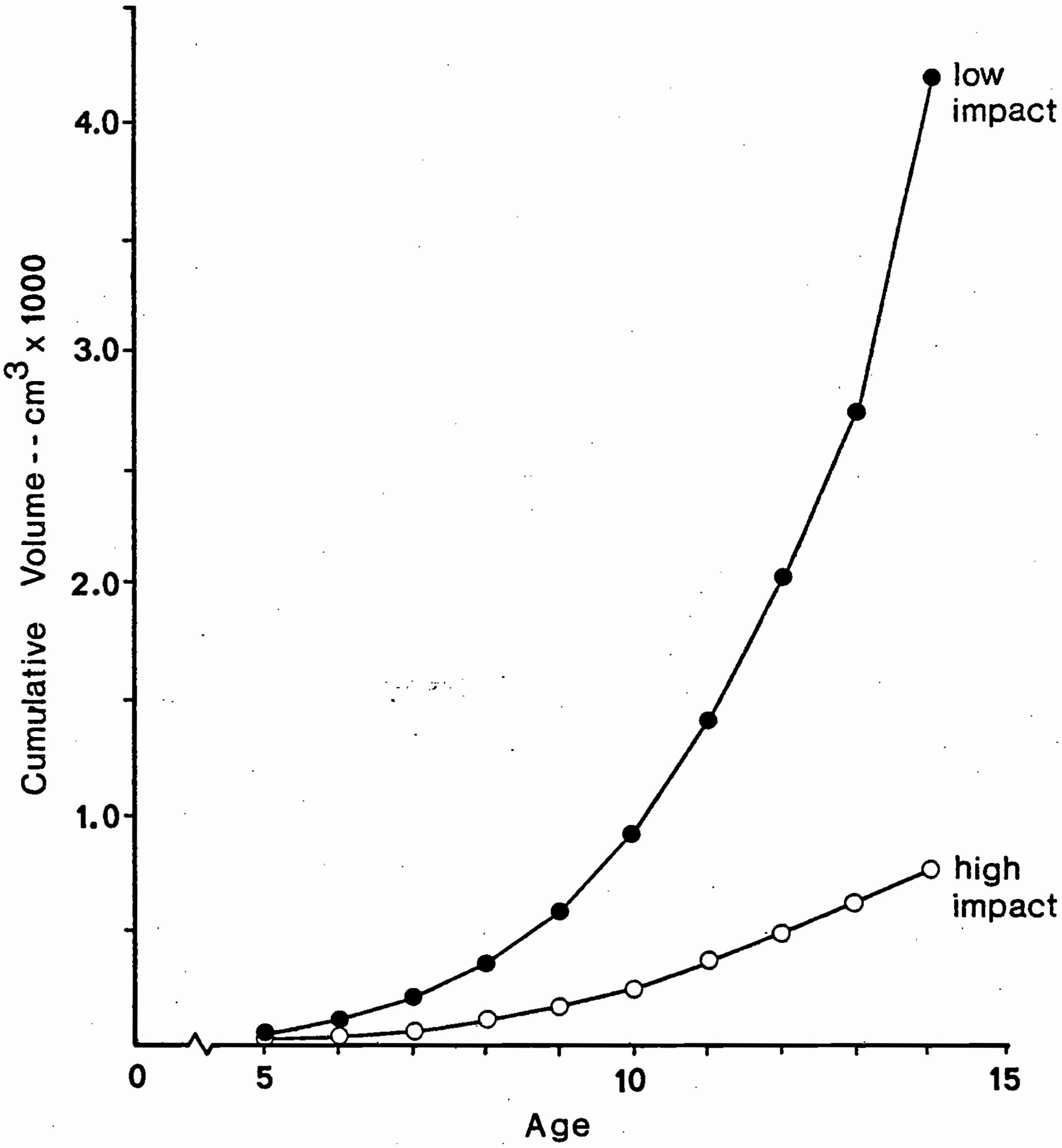


Figure 18. Cumulative volume growth for ponderosa pine by compaction class.

truly unbiased comparison of growth rates can only be made with more rigid experimental control over treatments and interacting factors.

A procedure was devised to statistically test for differences in the early growth rate for the two compaction classes. Since all but one of the ponderosa pine sample trees were at least 10 years of age at the time of sampling, the exponential rate of growth for this early period could be compared. The sectioned height and diameter data for year 1 through 10 were used to develop separate height-age and diameter-age equations for each tree- a total of 122 regressions. A simple logistic function of the general form:

$$Y = \beta_o X^{\beta_1}$$

modeled the growth for this early period very closely. The β_1 constant is a measure of the rate of exponential growth for diameter or height as a function of age. Since the contrast was done on an _a posteriori_ basis and involved unequal sample sizes, the least significant difference (LSD) test based on the Students-t range was used to test for differences between the mean β_1 values for the two groups (Snedecor and Cochran, 1980). As shown in Tables 9 and 10, the test found that both the height and diameter growth rates for the two groups were significantly different at the $\alpha = .05$ level. Comparisons were also made for the intercept (β_o) values, which represent the first year height and diameter. First year heights were significantly different, but initial basal diameters were not. However, these are of secondary importance to the comparison of growth rate coefficients.

Chronological changes in the magnitude of the bulk density-growth correlation coefficients were noted for ponderosa pine. Correlation coefficients between the percent increase in bulk density and cumulative height, diameter, and volume growth for ages 5 through 12 for this species are shown in Figure 19. A general trend toward increasing strength of negative correlation is evident for this period, as trees develop from seedlings to saplings and exert greater demands for soil moisture and nutrients. Incremental changes in the magnitude of the coefficient is greatest for diameter growth, followed by volume and height. The association between soil density and cumulative height growth is initially the highest, but increases only slightly between the fifth and twelfth year. The reason for the decline at age 8 is unknown, but may reflect a lack of correlation due to favorable soil moisture conditions during a wet year that minimized differences in water availability among compaction levels. Examination of changes in the value of correlation coefficients does not allow definitive statistical tests of the data. However, the technique is useful in illustrating the relative importance of soil density increases in explaining some of the variation in tree growth during the early years.

An interesting finding is that diameter growth is affected to a greater extent by increases in soil density than is height growth. This was confirmed by both the regression analysis and from the stem analysis data. It is not clear whether this same differential impact on meristematic development and cambial activity applies to a variety of species, age classes, and site conditions. For the ponderosa pine

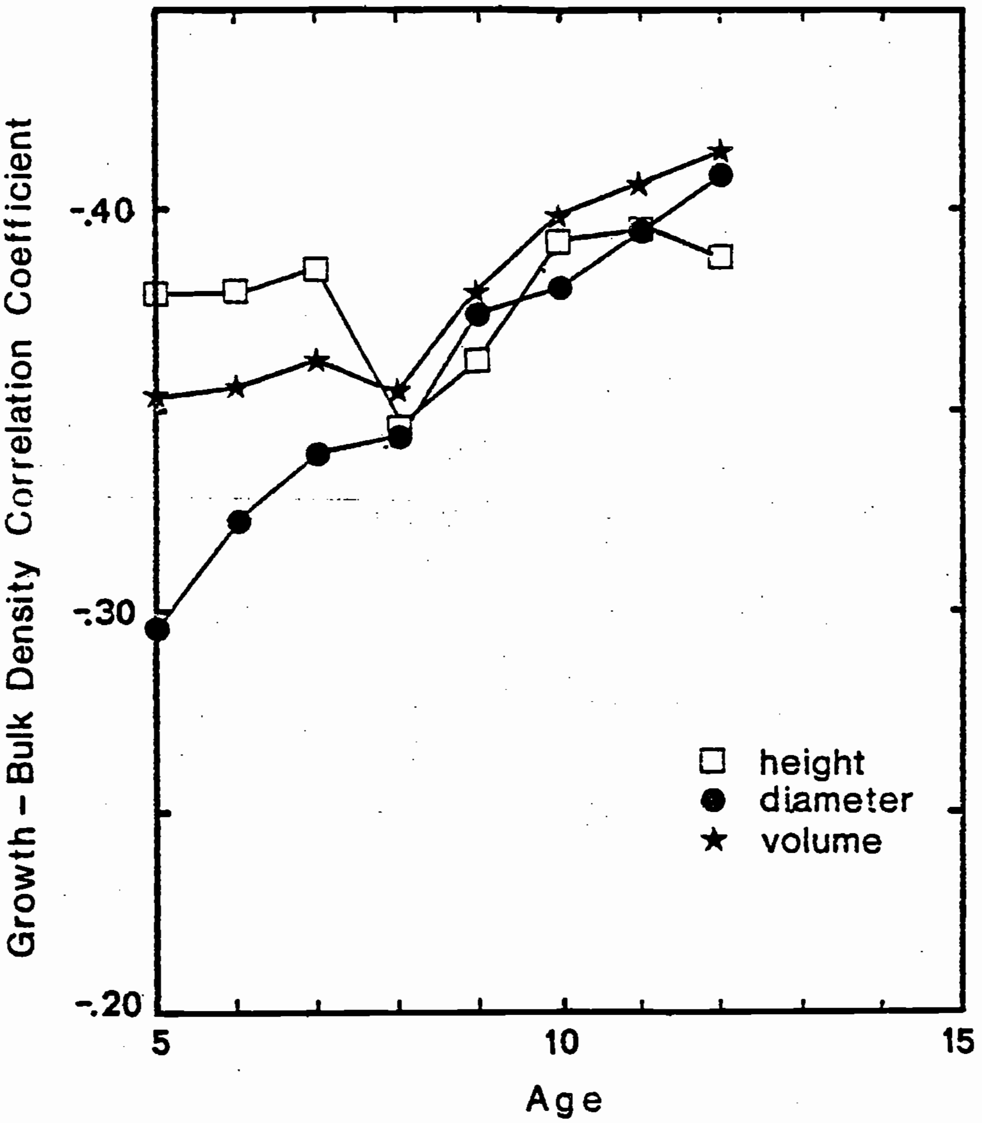


Figure 19. Chronological changes in growth-bulk density correlation coefficients for ponderosa pine.

regeneration in this study, it appears that bud formation and shoot elongation were assigned a higher priority than cambial growth under conditions of compaction-induced plant stress. The exponential relationship between volume and diameter is responsible for the substantially greater losses in volume growth reported here and in the few studies in which this variable was measured.

Conclusions about differences in species response to compaction are difficult to draw from the study. Dissimilarities in sample size, soil characteristics, climate, competition influences, and disturbance history for the two areas preclude any direct comparisons between ponderosa pine and lodgepole pine. Although a link between bulk density increase and tree growth could be established for ponderosa pine, the strong correlation between organic matter content and lodgepole pine growth suggests that soil displacement was the most significant form of soil disturbance for this site.

Field studies designed to examine the effect of soil compaction on productivity must deal with the difficult task of separating out the influence of compaction from other forms of soil disturbance. A more extensive study carried out with greater experimental control may be necessary to objectively assess the relative effect of compaction for these higher elevation sites, where lodgepole pine readily colonizes disturbed zones on cutover areas. The wide array of physiographic and biological factors that interact to control growth in natural stands are difficult if not impossible to completely account for. The fact that the amount of unexplained variation in the regression models ranged from 30 to 47 percent for ponderosa pine and from 43 to 55 percent for lodgepole pine illustrates the complexity of heterogeneous biological systems.

CONCLUSIONS

The study confirms that there is a strong association between soil bulk density and reduced early growth of natural reproduction established on skid trails from tractor logging. Reductions in total height, basal diameter, and stem volume of 5, 8, and 20 percent are predicted for young ponderosa pine, based on an average increase in soil bulk density of 15.4 percent relative to undisturbed conditions. Reductions in height and diameter growth rates over the last five year period were 7 and 12 percent respectively. Regression relationships between recent periodic height and radial growth were more significantly related to bulk density increases than were total height and basal diameter. Differences in the date of establishment for the seedlings accounted for a substantial source of variation in the sample.

The average reductions in growth determined here are probably conservative estimates and should be considered as the minimum impact expected for moderately to highly compacted skid trails. Natural regeneration was primarily confined to skid trails and other areas of soil disturbance where adequate scarification and light intensity were required for successful establishment and growth of shade-intolerant seedlings. The partial cut stand conditions found throughout the study area therefore precluded any objective comparison of seedling growth on compacted skid trails with those growing in undisturbed soil. Based on the growth curves computed for seedlings growing on sites with high and low soil density, a negative growth response to compaction is clearly evident through the first 14 years. The low soil density samples approximate the undisturbed or lightly impacted soil condition.

Regression relationships between the dependent growth variables and the set of independent site characteristics were influenced by the high sample variability of the natural stands and by multicolinearity among the predictor variables. The lack of experimental control over a wide range of soil and microclimatic influences which govern plant growth allowed a substantial proportion of the sample variation to be unexplained. Colinearity between an index of overstory canopy leaf area and the increase in soil bulk density influenced the significance and magnitude of the regression parameters for ponderosa pine. As a result, the projected growth reductions derived from the regression models underestimate the effect of soil compaction on young tree growth. Future studies of compaction-site productivity relationships should concentrate on areas where it is possible to isolate the influence of soil compaction from other growth-limiting factors.

The duration of impacts from soil compaction on site productivity is ultimately a function of soil recovery rates. Average bulk density differences of 15.4 percent were found for skid trails established 23 years ago in the ponderosa pine study area, and 27.5 percent differences were detected in the lodgpeole pine study area 14 years after logging. While it is not possible to clearly identify the dominant recovery mechanism for the sample areas the large differences detected after these time periods suggest that natural recovery will require more than two decades.

A first approximation of area-wide impacts can be made by applying the reductions determined for skid trail regeneration to the stand level using a conservative estimate of skid trail coverage. Assuming 20 percent of the land area in the ponderosa pine zone is occupied by the skid trail network, the 20.4 percent reduction in average stem volume of the 14 year old regeneration is equivalent to a 4 percent reduction in site productivity on an area-wide basis. More precise estimates of stand-level impacts should consider potential reductions in growth and mortality of mature residual trees that border the skid trails in selectively cut stands.

Soil compaction and soil displacement have been shown to have a negative impact on tree growth. The exact influence of each factor is unknown. The strong correlation between organic matter content and the growth of young lodgepole pine, however, suggests that removal of the surface soil and litter affected site productivity by reducing the contribution of organic matter in nutrient cycling, mycorrhizal development, and moisture storage. From the perspective of the land manager, determination of whether soil displacement or compaction is the primary cause of growth reductions is subordinate to the more general concern of how various forms of soil disturbance collectively influence the productivity of forest soils.

The growth impacts observed in this study appear to warrant concern for minimizing compaction from ground-based logging systems. Some degree of soil compaction and soil disturbance is unavoidable, but careful planning of the skid trail network can effectively reduce the percentage of the compacted area. Frequent stand entries required under an all-aged management regime has the potential for increasing the area in skid trails during each harvest. By restricting vehicles to designated trails that are used during each successive entry, the areal extent of growth impacts on regeneration and the residual stand can be minimized. Post-harvest treatment of compacted skid trails by tillage may partially restore site productivity by improving soil structure and porosity. Additional study is necessary to adequately define the relationship between the quality of the tillage operation and the degree of long-term restoration in productivity.

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APPENDICES

APPENDIX A

SOIL PROFILE DESCRIPTIONS[1]

Location:	Cedar Valley area
Soil Classification:	medial over loamy-skeletal, mixed frigid Andic Xerochrept
Soil Series:	unmapped
Parent Material:	mixed loess and basalt

Horizon	Depth	Description
0	1.5-0	duff and litter layer
A1	0-7	dark brown (7.5YR 3/3) moist; sandy loam; very fine subangular blocky structure; soft, friable, nonsticky, nonplastic and weakly smeary; strongly acid (pH 5.5); NaF pH 10.6; clear, smooth boundary.
A2	7-16	dark brown (7.5YR 3/4) moist; sandy loam; very fine subangular blocky structure; soft, friable, nonsticky, nonplastic and weakly smeary; strongly acid (pH 5.5); NaF pH 10.5; clear , smooth boundary.
B	16-27	dark brown (7.5YR 3/4) moist; gravelly sandy loam; very fine subangular blocky structure; slightly soft, friable, nonsticky, slightly plastic and weakly smeary; medium acid (pH 6.0), NaF pH 10.1; abrupt, wavy boundary.
IIB	27-60	strong brown (7.5YR 4/6) moist; very cobbly loam; massive structure; slightly soft, slightly sticky, plastic; medium acid (pH 6.0); NaF pH 10.1.

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[1] Soil profile descriptions were done by J. Bodura and T. John, Soil Scientists, Yakima Nation.

Location:	McCreedy Creek Area
Soil Classification:	medial-skeletal, Andic Cryochrept
Soil Series:	unmapped
Parent Material:	mixed loess and basalt

Horizon	Depth	Description
0	3-0	duff and litter layer
E	0-2	dark gray brown (10YR 4/2) moist; loamy sand; granular structure; loose, loose, nonsticky, and nonplastic; broken, wavy boundary.
B_s	2-5	reddish brown (5YR 4/3) moist; sandy loam; very fine subangular blocky structure; loose, loose, nonsticky, nonplastic and smeary; strongly acid (pH 5.5); NaF pH 10.5; abrupt, wavy boundary.
B1	5-13	strong brown (7.5YR 4/6) moist; sandy loam; fine granular structure; loose, loose, nonsticky nonplastic and smeary; strongly acid (pH 5.5); NaF pH 10.5; clear, wavy boundary.
B2	13-24	reddish brown (5YR 4/4) moist; cobbly loam; very fine subangular blocky; soft, very friable, slightly sticky, nonplastic and smeary; medium acid (pH 6.0); NaF pH 10.5; clear , wavy boundary.
B3	24-58	strong brown (7.5YR 4/6) moist; very cobbly loam; very fine subangular blocky; soft, very friable, slightly sticky, nonplastic and smeary; medium acid (pH 6.0); NaF pH 10.5.

APPENDIX B

STEM VOLUME COMPUTATION PROGRAM

```
      PROGRAM VOLCOM (TAPE1.TAPE2.TAPE3.TAPE4.TAPE5)
C
C     THIS PROGRAM READS TWO FILES AND CALCULATES THE THEE VOLUME AND CI
C
C     TAPE1 IS THE INPUT FILE FE011. CARD TYPE 2.
C     TAPE3 IS THE OUTPUT FILE FE011. CARD TYPE 2.
C     TAPE2 IS THE INPUT FILE FE011. CARD TYPE 3.
C     TAPE4 IS THE OUTPUT FILE FE011. CARD TYPE 3 WITH CI COMPUTED.
C     TAPE5 IS THE OUTPUT FILE FE011. CARD TYPE 3 CONDENSED WITH SUM OF CI.
C
      CHARACTER *4 DIAM(10). DBH
      CHARACTER *9 DCODE, DCODE2
      CHARACTER *10 HATT. HATT2
      CHARACTER *12 BUKORG, BUKORG2
C
      REAL RHF. RHI. RCOVER, RCD, DIA1, DIA2. THT,
     1   VOL, TVOL. CI. TCI
      INTEGER K, TN, HF. HI, HT. HT2, NEXT. COVER, CD, RATIO. TN2
C
      TN2 = 0
      TCI = 0
 10   READ(1,1000.END=30)DCODE,TN,DBH.HF,HI,DIAM
      RHF = FLOAT(HF)
      RHI = FLOAT(HI)
      THT = (RHF * 12) + RHI
      CHT = 24.0
      TVOL = 0.0
      NEXT = 0
      K = 1
C
C     CALCULATE THE VOLUME PER SEGMENT
C
 20   IF (DIAM(K+1).EQ.@   . @) THEN
           DIA1 = DIA2
           DIA2 = .2
           CHT = THT - (24.0 * (K-1))
           NEXT = 1
      ELSE
           READ(DIAM(K),FMT=@(F4.1)@) DIA1
           READ(DIAM(K+1).FMT=@(F4.1)@) DIA2
      ENDIF
      K = K +1
      VOL = ((CHT * ((DIA1*DIA1) + (DIA2*DIA2))) / 2)
      TVOL = TVOL + VOL
      IF (NEXT.NE.1) GOTO 20
      TVOL = TVOL * (3.1415926 / 4)
      HT = AINT(THT)
C
C     PRINT TO FILE
C
      WRITE(3.1010)DCODE,TN,DBH.HT,DIAM(1),TVOL
      GOTO 10
C
C     READ IN SECOND FILE AND CALC CI PRINT OUT RESULTS TO TWO FILES
C
 30   READ(2.1020.END=2000)DCODE,TN,BUKORG,HF,HI.BATT.COMPS.COVER.COMPH.
     1RATIO,CD.FD
      RCOVER = FLOAT(COVER)
      RCD = FLOAT(CD)
      HT = (HF * 12) + HI
      IF (TN.EQ.TN2) THEN
           CI = ((RCOVER * COMPH)/ 1000) * ((1/RCD) - (1/FD))
```

```
          TCI = TCI + CI
          WRITE(4,1030)DCODE,TN,BUKORG,HT,BATT,COMPS,COVER,COMPH,
     1    RATIO,CO,FD,CI
          DCODE2 = DCODE
          TN2 = TN
          BUKORG2 = BUKORG
          HT2 = HT
          BATT2 = BATT
       ELSE
          WRITE(5,1040)DCODE,TN2,BUKORG2,HT2,BATT2,TCI
          TCI = 0
          CI = ((RCOVER * COMPH)/ 1000) * ((1/RCD) - (1/FD))
          TCI = TCI + CI
          DCOOE2 = DCODE
          TN2 = TN
          BUKORG2 = BUKORG
          BATT2 = BATT
          HT2 = HT
          WRITE(4,1030)DCODE,TN,BUKORG,HT,BATT,COMPS,COVER,COMPH,
     1    RATIO,CD,FD,CI
       ENDIF
C
C      FORMATS
C
 1000 FORMAT(A9,I2,A4,2I3,10A4)
 1010 FORMAT(A9,I2,A4,I6,A4,F7.2)
 1020 FORMAT(A9,I2,A12,2I3,A10,A6,I2,F5.1,I3,I2,F4.1)
 1030 FORMAT(A9,I2,A12,I6,A10,A6,I2,F5.1,I3,I2,F4.1,F5.2)
 1040 FORMAT(A9,I2,A12,I6,A10,F7.2)
      GOTO 30
 2000 STOP *NORMAL EXECUTION  OF VOLCOM*
      END
```

APPENDIX C

STEM VOLUME EQUATIONS AND BARK FACTORS FOR PONDEROSA PINE AND LODGEPOLE PINE

Species	Volume Equation	r^2	n	DOB/DIB Ratio
Ponderosa pine	$V = 5.883D^{1.723}H^{1.021}$	.995	61	1.286 (.079)
Lodgepole pine	$V = 2.032D^{1.488}H^{1.313}$	.991	25	1.153 (.074)