The Effect of Soil Compaction

by Logging on Forest Productivity

Henry A. Froehlich

Forest Engineering Department

Oregon State University

Corvallis, Oregon

Contents

Douglas-fir and Ponderosa Pine

Seedling Growth in Skid Trails

Several studies have shown that increasing soil density generally reduces seedling growth of both planted and natural seedlings. Youngberg (1959) found that seedling growth in severely compacted trails was reduced as much as 50 percent. The measurements made on the Eugene District, BLM[1] also showed that leader growth was reduced as soil density increased. The undisturbed soil had an average bulk density of 0.84 gcm^{-3}. Growth reductions ranged from 11 percent at 0.94 gcm^{-3} to 35 percent at 1.24 gcm^{-3}. Two greenhouse studies have also shown significant reductions in growth of seedlings grown in pots of soil compacted to various densities (Pearse, 1958; Hatchel, Ralston and Foil 1970). The purpose of this study is to quantify the level of impact on seedling growth by tractor logging in managed young-growth stands.

Methods

Three sites were located in western Oregon, one on a gravelly loam soil on the west side of the Oregon Coast Range (Alsea Plot), one on a clay loam soil on the east side of the Oregon Coast Range (Dunn Forest Plot), and the third on a sandy loam soil on the west side of the Cascade Range (Molalla Plot). At each site a series of parallel skid trails was made with a small crawler tractor skidding a turn of logs typical of young-growth logging. Two trails were made for each specified number of passes. Possible skid trail routes were marked and numbered and random numbers drawn to select

[1] From unpublished paper on file at Bureau of Land Management, Eugene Distrcit, Eugene, Oregon.

the treatment to be applied to each set of trails. The treatments consisted of 0, 1, 3, 6 and 10 passes with the tractor and its turn of logs. Prior to the treatment sections of the test site were covered with plastic sheets to keep the soil at a minimum soil moisture level, one section was irrigated to raise the moisture level to near saturation level and a third was allowed to receive rainfall to bring the soil moisture to an intermediate level. Also prior to treatment soil samples from these sites were analyzed for particle size distribution, organic matter content and bulk density. Bulk density was measured with a two-probe nuclear soil density gage calibrated to materials of known density and containers of soil from these sites.

Following the treatment each site was planted with tubeling Douglas-fir seedlings supplied by the BLM Horning Nursery. Sets of 30 seedlings were selected and assigned a number. Each sub-plot within the site was randomly assigned a number to select the set of tubelings to be planted in it. Planting was done with a solid dibble. The planted seedlings were mapped and initial height was recorded. Seedling height and any mortality or damage was recorded at the end of each growing season. Each seedling was protected for the first few years by a vexar net tube to reduce animal damage. As the leaders grew above the tubes, a double tube was placed higher on the tree. During later growing seasons the trees were sprayed with a deer repellant. In spite of these precautions numerous trees were damaged by browsing and some leaders were seriously damaged by the protective tubes. Atrazine was applied the first two years to control grasses. The fourth year a treatment of Roundup was applied to control berries, shrubs and forbs.

Results

This report will include only the results from two plots as the third was damaged by a spray and burn treatment applied to lands adjacent to the plot. A fourth site was selected to study the effect on ponderosa pine seedlings and will be described later in this report.

Dunn Forest Plot

The soils on this plot, on the east side of the Oregon Coast Range, is a Jory clay loam and has an organic matter content of 19 percent as determined by ashing in a muffle furnace. Inititial bulk density of the site was 0.92 gcm^{-3}. The tractor and logs did not cause significant increases in bulk density in the one and three trip skid trails. The average density of the 6 and 10 trip strips was 1.01 gcm^{-3}. The difference in density between the 6 and 10 trip trails was not statistically significant. Density along the skid trails was highly variable and ranged from 0.72 to 1.51 gcm^{-3}.

The high variability in soil density also obscured the differences in density which may have been produced by the different soil moisture conditions at the time of skidding. Moisture contents ranged from 20 percent on the driest section to 44 percent on the irrigated section. According to Proctor curves of this soil we expected to see differences in soil density within treatments. However, the high variability within treatments masked any difference which may have occured as a function of the variations in soil moisture. The 10 percent increase in soil density in the 6- and 10-trip trails stopped between 6 and 9 inches in depth.

Air permeameter measurements (Steinbrenner 1959) were taken after all the treatments had reached equal soil moisture content. Significant differences were found in permeability of the surface inch as shown in Table 1.

Table 1. Differences in surface soil permeability with repeated trips

No. of Trips	Backpressure Reading
0	6.92 lbs/in^2
1	8.34 "
3	11.02 "
6	12.76 "
10	13.40 "

Four years after the treatment, there was no significant difference in permeability between treatments. The surface at this clayey soil cracks readily upon drying and this may allow for a fairly rapid recovery of porosity in the surface inch of soil.

Seedling growth did not appear to be affected for the first year after planting. Growth was significantly less on the 6 and 10 trip trails than on the 0, 1, and 3 trip trails in subsequent years. Over the next three years, small differences in growth between 0, 1 and 3 trip trail seedlings were not significant nor were the differences between 6 and 10 trip trails. The difference in leader growth between the two groups for the next 3 years was 11, 12 and 25 percent. The largest growth reduction was associated with a severe drought year. In the final analyses we dropped the data from the three-trip trail as it had begun to be severely shaded by an adjacent plantation. In this analysis 0 and 1 trip growth data is combined. All data is based on seedlings which have escaped any damage or browsing over the five year period.

The height growth of the seedlings (present height minus planting height) over the five year period shows that the seedlings grown on the trail with six trips is 8.5 percent less than the 0 and 1 trip plantings and is 13.9 percent less on the 10 trip planting, significant at the 0.05 level. Table 2 gives the

height increment associated with each treatment. This compares with the data reported by the BLM where a 12 percent increase in density was associated with an 11.1 percent decrease in leader growth.

Mortality was slightly higher on the 6 and 10 trip plantings the first year. Subsequent mortality in the remainder of the plot has increased slightly and at the end of the fifth year there is no significant difference between treatments in survival of seedlings. The average survival over all treatments is 90 percent.

Table 2. Height growth of seedlings planted in skid trails with varying degrees of usage on a clay loam soil.

Treatment	No. in Sample	Height Growth cm
0 trips	42	173.7^{*} ⎤
		⎥ 178.1
1	49	181.9^{*} ⎦
6	52	164.2^{+} **
10	51	156.3^{+} **

$^{*+}$Adjacent values followed by the same symbol are not significantly different.

**Significantly different from the 0- and 1-trip plots at the 0.05 level.

Molalla Plot

This site in the western Cascades is mapped as a McCully sandy loam. It has an organic matter content of 17.6 percent as measured by ashing in a muffle furnace. Initial bulk density of the site was 0.87 gcm^3. Densities after treatment were 0.92, 0.93, 0.95, and 0.99 after 1, 3, 6 and 10 trips respectively. Mositure content at the time of treatment of the dry section was 27 percent. The soils of the two wetted sections were at 43 percent moisture

content during the log skidding. The differences in moisture were not associated with a statistically significant difference in soil density after the treatment. It is possible that at 27 percent, soil moisture is high enough to allow compaction to proceed so that it differs little from higher moisture levels. The 9 and 14 percent increase in densities at 6 and 10 trips are comparable to those found on the Dunn Forest Plot. Density increases did not appear to penetrate below 6 to 9 inches depth.

Seedling growth was measurably affected at the 6 and 10 trip level of treatment beginning with the first growing season. The height growth was most strongly affected during the driest year.

Table 3 shows the results of height growth measurement after the fourth growing season.

Table 3. Height growth of seedlings planted in skid trails with varying degrees of usage on a sandy loam soil

Treatment No. of trips	No. in Sample	Height Growth cm
0	40	83.6
1	54	73.5^{*}
3	27	76.8^{ns}
6	67	69.3^{**}
10	66	61.3^{**}

78.0

*Different from 0-trips at the 5 percent level
** Different from 0-trips at the .05 percent level
^{ns} Not significantly different from 0-trips

The 6 and 10 trip plots combined are significantly different at the 0.05 level from the 0, 1 and 3 trip plots combined. There is a 16 percent difference in growth between the seedlings on the more heavily used trails as compared to the untraveled or lightly used trails.

Compaction, at the level produced by these treatments, did not appear to affect seedling survival. The overall survival of the tubelings planted in this plot was 87 percent. There is some evidence that greater usage affects survival. As the tractor was required to turn outside of the test plots, there was an area which received at least 20 trips adjacent to the plot. This was planted as part of a buffer zone around the study plots. A check on survival in the turning zone showed only 74 percent survival. The growth of the survivors is comparable to that of the seedlings in the 10-trip plot.

Summary of Dunn Forest and Mollala Plot results

The small crawler tractor and turns of logs produced a 9 and 14 percent increase in soil density with 6 and 10 trips respectively on the Mollala plot. On the Dunn Forest plot the difference in soil density was not significantly different between 6 and 10 trips where it averaged 9.7 percent higher than the undisturbed soil.

The depth of compaction on both plots was limited to the surface 6 to 9 inches. Some loosening of the surface inch is apparent from the air permeameter readings, but there is no significant reduction in density in the surface 6 inches over the 4 and 5 that the plots have been installed.

Seedling survival was good on both plots and at all levels of skid trail usage up to 10 trips. An area receiving 20 trips appeared to sustain higher seeding mortality rates.

Height growth of the seedlings is affected by increasing soil density. Six and ten-trip trails on the Dunn Forest plot had 8.5 and 13.9 percent less height growth than the 0 and 1 trip plots. On the Molalla plot the 6 and 10 trip trails produced seedlings with 11 and 21 percent less height growth over the four years of observation. Roughly, each percent increase in soil density is associated with a 1.3 percent decrease in height growth over the period of observation.

Soil Compaction and Ponderosa Pine Seedling Growth

In lieu of the work that would have been expended on the damaged Douglas-fir plot, the project was modified to include a study of the effect of soil compaction on the growth of young ponderosa pine. The first objective is to quantify the relationship of increasing soil density on growth of ponderosa pine seedlings. A second objective is to learn more about the longevity of the compacted condition and its effect on growth over a longer period of time than was possible in the Douglas-fir seedling study.

A plantation of 17-year old ponderosa pine was located in the west fork of the Evans Creek drainage near Medford, Oregon. Two-year old pine had been planted on an area clearcut logged in 1963. The logging had been done in 1961 using large crawler tractors. The soils are coarse textured, of granitic origin. Generally less than 10 percent of the surface foot of soil is finer than sand this fine material is almost entirely clay. Texturally the soil is classed as sand to loamy sand. The soil moisture at the time of logging is not known.

Methods

A sample of thirty trees were selected which were growing on an array of soil conditions ranging from little or no disturbance to heavily used skid trails. No trees were selected which were growing on seriously eroded skid trails or on sites where soil was deeply excavated from the trail. The trees were all selected within a small area to minimize differences in slope position, aspect, and soil type.

Soil density measurements were taken at three points about the base of each tree. The measurements were made with a single-probe nuclear soil density meter to obtain the density of the surface 6 inches and also the surface foot of soil. A number of similar density measurements were made in recently developed skid trails in a nearby cutting unit and also in a small area where no cutting has been done. These values were taken to provide a comparison with the 17-year old trials in the study area.

Stem diameter and total height were taken on each sample tree and the crown extension sketched on a map. All adjacent competing shrubs and trees were also sketched on the map to provide an estimate of competition for each tree. The stem volume of each subject tree was computed from a volume equation for young ponderosa pine (Brackett, 1973) as follows:

Volume of Stem (ft^3) = $10^{-2.730}$ x DBH $^{1.909}$ x Ht$^{1.086}$.

The level of competition is expressed as a decimal of the percent of overlap of competing canopy over a circle with a 6.5 foot radius about the sample tree. This radius is one and a half times the average crown extension and is assumed to be the average root extension for these trees. Multiple regression equations were run with stem volume and tree height as the dependent variable. The average soil density of the surface 6 inches of soil, the density of the 0-12 inch layer of soil, a location variable, and competition index were used as independent variables. It appeared from plots of the data that stem volume and tree height were curvilinearly related to soil density. Therefore a curve fitting program was run utilizing an equation of the form: Tree Volume or Height = b_1 (soil density^{-b2}) -b_3 (Competition Index).

Results

The soil density measurements were grouped into three skid trail use classes; non to lightly disturbed, moderately used trails and heavily used trials. Table 4 summarizes the data from the .97 soil density points.

Table 4. Soil densities produced by various levels of tractor usage.

Location	n	Density (g cm^{-3})	
		0-6"	0-12"
Plantation area			
Non to lightly used	32	0.90	0.97
Moderately used	31	0.98	1.11
Heavily used	24	1.18	1.26
Adjacent area			
Undisturbed forest	5	0.75	0.91
Recently made, heavily used trail	5	1.54	1.60

It appears that there may be some recovery of porosity over the 17 years as the soil density of the plantation trails are significantly lower than the data from recently made, heavily used skid trails. This interpretation must be made with caution as it is not possible to know the exact degree of usage of each trail nor the soil moisture content at the time of logging. Qualitatively it appears that the surface few inches of soil has improved somewhat and possibly some improvement exists with depth. It is discouraging to find that the soil compaction has persisted at this level for 17 years. Table 5 summarizes the tree and soil measurements made on the 30 sample trees.

To quantify the influence of the soil compaction on growth of the planted ponderosa pine two curvilinear regression equations were developed. The significant variables were found to be soil density over the 0-12 inch depth and the competion index. The equations read as follows:

Table 5. Summary of data from 30 ponderosa pine trees included in
          the study.

	Average	Range
Tree height (ft.)	14.76	6.62 - 24.10
D B H (inches)	3.77	1.34 - 5.07
Volume (ft^3)	0.52	0.03 - 1.31
Soil density - 0-6" (gcm^{-3}) Average of 3 points/tree	1.00	0.74 - 1.38
Soil density, 0-12" (gcm^{-3}) Average of 3 points/tree	1.09	0.74 - 1.74
Competition Index	0.33	0.00 - 0.76

$$\text{Volume (ft}^3） = 0.770 \ SD^{-2.381} - 0.436 \ CI \qquad (1)$$

$$R^2 = 0.53$$

$$\text{Height (ft)} - -134.529 + 152.143 SD^{-0.091} -4.865 \ CI \qquad (2)$$

$$R^2 = 0.38$$

where SD = average soil density 0 - 12 inch depth, (gcm^{-3})
and CI = Competition index (dimensionless)

Solving equations (1) and (2) while holding the competition index
at the average value of 0.33 shows the predicted effect of an increase
soil density. Table 6 lists the predicted volume and height growth
of the seedling for a variety of soil densities.

Table 6. Predicted decreases of 17-year old ponderosa pine seedlings volume and height growth with increasing soil density.

Soil Density gcm^{-3}	Stem Volume ft^3	Total Height ft
0.84	1.02	18.4
0.94	0.75	16.9
1.06	0.53	15.2
1.15	0.41	14.1
1.24	0.32	13.1
1.34	0.24	12.0

The table shows that a 12 percent increase above a density of 0.84 gcm^{-3} is associated with an 8 percent decrease in height. The average density of the heavily used skid trials was close to 1.24 gcm^{-3} and this is associated with a 29 percent reduction in height growth. Roughly, each percent increase in density is associated with about 2/3 percent decrease in height growth.

Volume growth is affected to a greater extent than is height growth. A 12 percent increase in soil density above 0.84 gcm^{-3} is associated with a 26 percent decrease in stem volume. Trees planted on heavily used skid trails averaged only about one-third the volume of those growing on non to lightly compacted soils. We can compare these results, at least qualitatively, with the work by Perry (1964). He compared the height and volume growth of loblolly pine planted in compacted "woods roads" to those planted in adjacent fields. After 26 years he found a 13 percent reduction in height, but a 53 percent reduction in volume in the trees on the compacted sites. The differences in soil density were not reported.

The effect of soil density increases on volume reduction also appears in very small seedlings. Minore (1969) found that 2-year old Douglas-fir seedlings grown on soils with densities of 1.32, 1.45, and 1.59 gcm^{-3} had shoot weights of 6.17, 3.50 and 2.58 grams. Thus a 10 percent increase in soil density above 1.32 gcm^{-3} resulted in a 43 percent decrease in shoot weight. A 20 percent increase in density produced a 58 percent decrease in weight. We can probably assume that weight is roughly proportional to volume. In the present study an increase from 1.15 gcm^3 to 1.34, a 16.5% increase, is associated with a 41.5 percent decrease in volume.

Field Applicability

Degree of Compaction

The small crawler tractors used in the young-growth logging produced markedly lower soil compaction than the larger equipment used in old growth logging. Not only were higher densities produced by the larger equipment but the compaction extended at least through the surface foot of soil. With the smaller equipment the compaction was measurable through the surface 6 inches, but was not found at a depth of 9 inches. This suggests that the smallest equipment capable of doing the work should be used to keep the soil impact to its lowest level.

With larger equipment, it appears that about 90 percent of the compaction is produced by the 2nd or 3rd trip. The small crawlers used in preparing the Dunn Forest and Molalla plots produced relatively little compaction the first three trips and added a small but significant increase as the usage increased to 6 and 10 trips. This implies that with smaller equipment the impact may be lessened by dispersing the trails while with larger equipment it would be beneficial to concentrate the impact on as few trails as possible as the heavy equipment affects the soil to a greater extent the first few trips.

Longevity of Compacted Condition

The little, if any, recovery of soil porosity in 4 or 5 years on the Dunn Forest and Molalla plots and the relatively little recovery on the Evans Creek site in 17 years means that when soil compaction occurs under western Oregon conditions it is likely to be a long term impact. If the difference in density between the recently used skid trails and the 17-year old skid trails on the Evans Creek plot represent a trend towards recovery, and if the recovery rate is linear, it would suggest that the soils will take from 35-40 years to recover by natural forces.
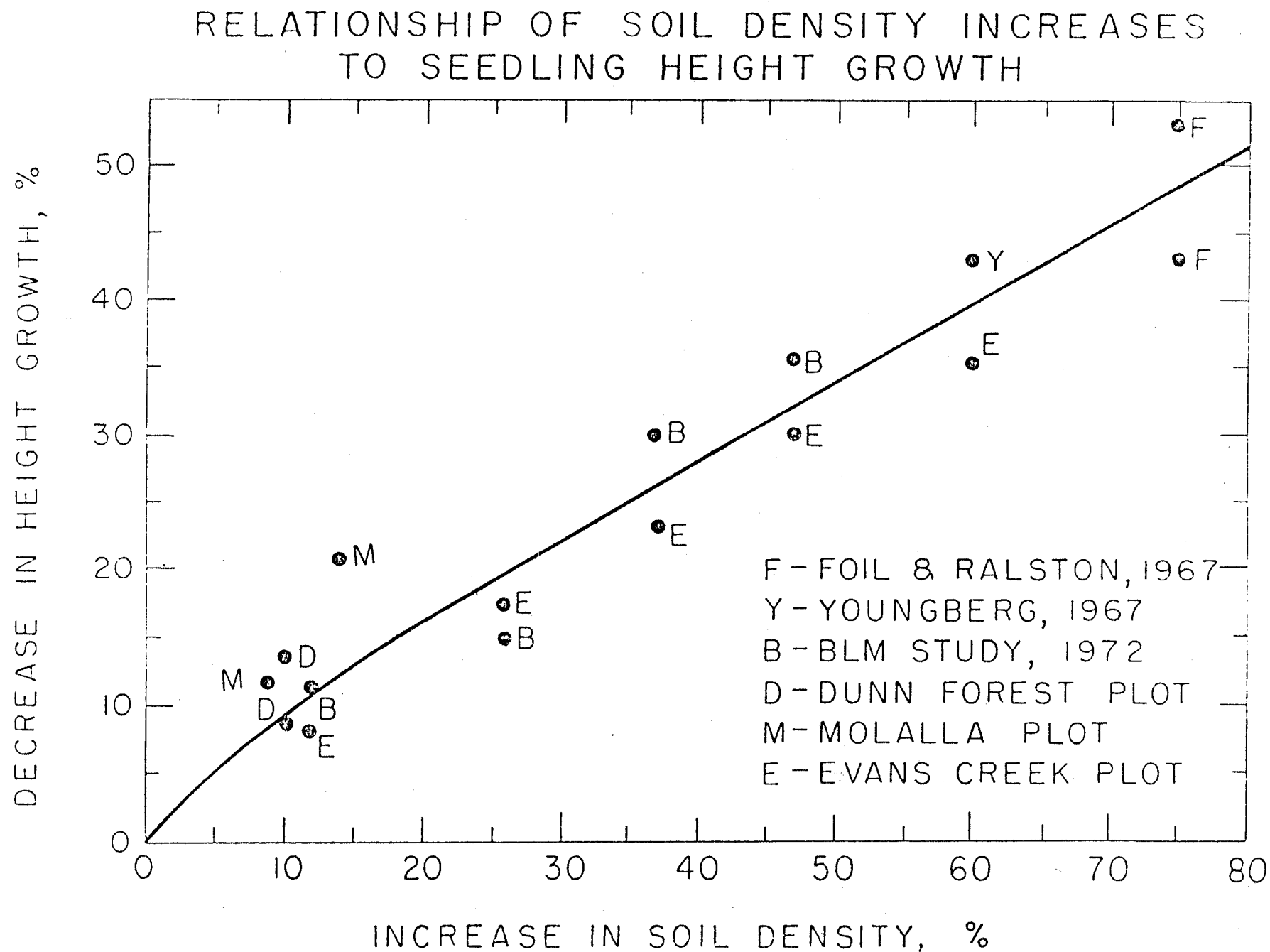
Seedling growth reduction

Soil compaction significantly reduced the height growth of both the 4- and 5-year old Douglas-fir and the 17-year old ponderosa pine. Figure 1 illustrates the results from the three plots in this study as well as results from three earlier studies. The results, in terms of percent decreases in height growth with percent increases in soil density, are remarkably similar. The points represent studies on three species and at least five different types of soil. The seedlings studied ranged in age from 2-years in the Foil and Ralston study to 17-years on the Evans Creek plot of the present study.

If the reductions in growth are assumed to represent a reduction in site class we now have a basis for quantifying the effect of various levels of soil impact.

The percent of volume growth reduction is greater than the height growth reduction for a given percent increase in soil density. There is less data available on reductions in stem volume due to compaction than is available concerning seedling height, but it appears that percent volume reduction is two or more times that of seedling height.

An approximation of the effect on growth over an area may be estimated as follows: Assumptions: 1) 25 percent of the area is covered by skid trails, 48% of the trails are heavily used, 40 percent are moderately impacted and 12 percent are lightly impacted; 2) these classes may be defined as having 50, 32, and 15 percent increases in soil density respectively; 3) the initial soil bulk density is 0.84 gcm^{-3}; and 4) trees are equally spaced over the area. Calculation: 1) determine the densities of each class; 2) determine the growth

Figure 1.

RELATIONSHIP OF SOIL DENSITY INCREASES
TO SEEDLING HEIGHT GROWTH

F — FOIL & RALSTON, 1967
Y — YOUNGBERG, 1967
B — BLM STUDY, 1972
D — DUNN FOREST PLOT
M — MOLALLA PLOT
E — EVANS CREEK PLOT

associated with each density and calculate the percent reduction of this volume, 3) multiply the percent reduction times the percent of the whole area in each skid trail class and sum for the weighted percent decrease. Solving the question by the above assumptions and methods shows that the expected growth reduction due to compaction is 14.8 percent. The calculated height growth reduction for the site averages about 6 percent.

Literature Cited

Brackett, Michael. 1973. Notes on tarif tree volume computations. State of Washington, Dept. of Nat. Resources, Resource Mgt. Report No. 24, 26 pp.

Foil, R. R. and Ralston, C. W. 1967. The establishment and growth of loblolly pine seedlings on compacted soils. Soil Sci. Soc. Amer. Proc. 31:565-568.

Froehlich, Henry A. 1973. The impact of even-age forest management on physical properties of soils. IN: Even-age Management, Proceedings of a Symposium Aug. 1972, Oregon State University. ed. by Richard K. Hermann and Denis P. Lavender. p. 199-220.

Hatchel, G. E., C. W. Ralston, and R. R. Foil. 1970. Soil disturbances in logging. J. Forestry 68:772-775.

Minore, Don, C. E. Smith and R. F. Woollard. 1969. Effects of high soil density on seedling root growth of seven Northwestern tree species. USDA, Forest Serv. Research Note PNW-112. 6 pp.

Pearse, P. H. 1958. A study of the effects of soil compaction on the early development of seedlings of Douglas-fir and western hemlock. Univ. British Columbia For. Club Res. Com. Res. Note 16, 7 pp.

Perry, T. O. 1964. Soil compaction and tree growth. Tree Planter Notes 67:9.

Steinbrenner, E. C. 1959. A portable air permeameter for forest soils. Soil Sci. Soc. Amer. Proc. 23:478-481.

Youngberg, C. T. 1959. The influence of soil conditions following tractor logging on the growth of planted Douglas-fir seedlings. Soil Sci. Soc. Amer. Proc. 23:76-78.

Part II

The Impact of Soil Compaction

During Thinning on Growth Rate

of Residual Trees

The following three papers are reports on the research concerning soil compaction effects on the growth of residual stands. As each study was completed they were submitted to journals for publication. Each are under review at this time. The papers are submitted here to provide a complete picture of the research project and its results. The species examined were Douglas-fir, western hemlock and ponderosa pine.

THE EFFECT OF SOIL COMPACTION DURING THINNING
ON THE GROWTH OF RESIDUAL TREES

Henry A. Froehlich and Erwin R. Berglund
Forest Engineering Department
Oregon State University

Track and wheeled skidders and the mass of the turn of logs have been shown to markedly increase the density of soils in skid trails. Forest managers are concerned about how the impact of this change in the soil properties may alter the growth of residual trees as well as the longevity of the compacted condition.

Soil compaction beyond a certain threshold depresses the growth of many plant species. Agricultural crops varying from sugar beets to citrus fruit are sensitive to increases in soil density in their root zones. Fewer observations have been made in forestry but reports consistently show that there is a reduction in growth rates due to increasing soil densities.

Extensive areas of young-growth timber in Oregon need thinning and much of the area is suited for ground-based logging systems. Soil compaction problems can be greatly reduced in these stands by the use of cable systems. Unfortunately, current costs of cable thinning are likely to be much higher than that of thinning by tractors (Aulerich, Johnson and Froehlich, 1974). The objective of this study was to quantitatively evaluate growth differences in thinned, young-growth Douglas-fir [Pseudotsuga menziesii (Mirb.) Franco] due to various degrees of soil compaction in their root zones.

Previous Work

Soil compaction problems on forest lands have not been emphasized at the same level as with agricultural crops. This is largely due to timber being a slowly maturing crop. Consequently, the effects of forest soil compaction are more subtle and not as apparent. Methodologies for measuring forest productivity are less precise than that for measuring the yield of an annual crop. Lull (1959) provides a comprehensive review of the broad field of soil compaction as to its causes and effects. Froehlich (1973) also provides a summary review of the causes and effects of soil compaction dealing primarily with coniferous seedlings and young trees. Both reviews report numerous studies on the physical changes that take place in the soil but relatively few studies which quantify the growth differences due to compaction.

As early as 1944, Dambach reported changes in the productivity of sugar maple woods after intensive grazing. Other studies have shown the effect of tractor logging on hardwood stands (Herrick and Deithschman, 1966) and softwood stands (McCulley, 1950). Recently, Perry (1964) studied the effect of soil density on 26-year old Loblolly pine trees growing on compacted soils. Perry found approximately 50 percent less cubic volume in the trees growing on the compacted sites. Power (1974) reported on a case study involving the growth of 55-year old Douglas-fir trees on severely compacted sites. He predicts a growth reduction of about 40 percent due to high soil density. Both Perry's and Power's studies compared tree growth on compacted sites from the time they were seedlings. Moehring and Rawls (1970) conducted an experiment to measure the effect of various levels of

soil compaction on 40-year old loblolly pine. In their study the soil was compacted with a small tractor pulling a load of three 10-foot logs passing six times near the subject tree. The treatment was applied during wet weather. The results were measured by determining the differences in the cubic volume of growth over a five-year period. Growth was found to be affected only slightly when compaction was limited to one side of a tree. Compaction on two, three and four sides of a tree produced 13.7, 36.3 and 43.4 percent less volume added during the 5-year period.

It is apparent that reduced growth due to soil compaction is likely, but previous studies do not provide predictive capabilities for tree growth response on soils compacted during a thinning operation. Further work is needed to more precisely determine what growth reduction, if any, would occur under conventional thinning programs.

Experimental Procedure

This study was designed to determine: 1) the impact of various degrees of soil compaction on the growth of residual trees following thinning young Douglas-fir stands by crawler tractors or rubber-tired skidders and 2) the longevity of compacted soil condition within thinned stands.

Stand and tree selection:

Five different stands of Douglas-fir were located which had a record of only one ground-based thinning (Figure 1). These stands were thinned five to fifteen years before measurement and gave a range of stand ages and diameter classes. Ninety three sample trees were selected within these stands. Table 1 summarizes stand conditions from which the sample trees were selected. The soils of these stands were all loamy soils, ranging from

Table 1. Descriptive data of sites included in study.

	Site Number				
	1	2	3	4	5
Approximate elevation (m)	730	730	730	730	610
Year of thinning	1961	1958	1967-68	1966-67	1958-62
Year of measurement	1973	1973	1973	1973	1974
Years since thinning	12	15	5	6	12

Clay-loam to sandy loam (Table 2). The study trees were selected primarily on the basis of their uniformity of crown spacing after thinning. No trees were included which had significant stem wounds which might influence growth response. Each sample tree was measured for a number of variables (Table 3). A map was made of each tree site showing the projection of the tree crown, the location of adjacent trees and all areas of soil disturbance within the site. These maps were the basis for the estimation of the percentage of soil disturbance at each tree and as an aid in classifying the level of impact. An assumption for this study was that the tree crown extension roughly coincided with the root extension of the tree. Previous studies have shown that the roots of young Douglas-fir occupy a space ranging from 0.9 to 1.1 times the crown extension (McMinn, 1963; Smith, 1964).

Basal area ratio calculation:

The primary dependent variable used in this study is the ratio of basal area growth after thinning to the basal area growth before thinning for an equal period of time. The objective in selecting this ratio was to reduce the variability due to individual tree elements such as genetic differences, micro-site differences and other growth affecting factors. Four increment cores were taken at DBH on each sample tree. One core was taken to determine the age of the tree while the other three, taken at 90° intervals, were taken to accurately estimate pre- and post-logging basal area growth. Growth rings that occurred during thinning were omitted for the calculation of the post-logging basal area growth. On sites 1 and 2, one year's growth was omitted while on sites 3 and 4, the thinning was spread over two years and on site 5, four years.

Table 2. The percent sand, silt, and clay and textural class of the
soil between 0 and 30 cm for each study site.

Texture	Site				
	1	2	3	4	5
Sand (2-0.02 mm)	44	62	44	45	53
Silt (0.02-0.002 mm)	38	27	31	25	32
Clay (<0.002 mm)	18	11	25	30	15
Textural class	Loam	Sandy loam	Loam	Clay loam	Sandy loam

Table 3. Descriptive parameters of the sample trees with respective means ($\bar{x}$) and standard deviations (s).

	Site Number									
	1		2		3		4		5	
No. of sample trees (n)	28		10		11		19		25	
	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s
Age (years)	77	8.7	80	7.1	76	5.1	67	5.2	34	2.8
Diameter (cm)	51.7	6.1	55.5	6.1	56.6	4.9	51.4	8.9	32.3	5.3
Height (m)	40.5	3.6	47.1	2.5	46.3	2.1	41.4	3.1	26.5	2.0
Crown length (m)	15.6	4.1	15.8	3.2	14.6	3.6	16.3	2.8	13.7	1.8
Crown Area (m^2)	45.0	11.9	49.9	14.5	47.1	9.3	34.6	8.7	25.0	5.3
Crown Volume (m^3)	531.3	245.5	591.0	251.9	514.9	211.6	419.6	134.6	255.7	72.0
Basal Area Ratio [3]/	1.172	0.292	1.110	0.274	1.276	0.266	0.944	0.159	1.619	0.323
Competitive Stress Index [1]/	259	52	2/		290	60	322	58	251	26

[1]/ Determined by a system using competitive tree diameters and distances from each study tree. See: Arney, James D. 1973. Tables for quantifying competitive stress on individual trees. Dept. of the Environ., Can. For. Serv., Pac. For. Res. Can., Info. Rpt. BC-X-78. 10p + tables.

[2]/ A second thinning in 1973-74 removed most of the study trees before this measurement could be taken.

[3]/ Basal area Ratio = Basal area of growth after thinning divided by the basal area of growth for an equivalent period of time before thinning.

∞

Other tree factors:

Descriptive variables for each sample tree were recorded to aid in determining tree similarity and to test for possible effects on residual tree growth. Table 3 gives the means of each of the sample tree parameters measured within the five stands. The competitive stress index indicates in a general way the relative degree of release with the lowest index value indicating the greatest growing space. The degree of release within a thinned stand was assumed to be a major factor in determining the acceleration of growth. As a result of sample tree selection for near equal degree of release, the range of competitive stress index values was found to be relatively low over the five study stands.

Other tree related variables measured or computed were diameter breast height, total tree height, crown length, crown area and crown volume.

Soil properties and compaction classification:

A portable nuclear soil density instrument was used to measure soil density in both disturbed and undisturbed soils under each sample tree. All soil density measurements were taken within the assumed root zone of the tree. Concurrent soil samples were used for soil moisture determinations for the calculation of dry bulk density and for textural analyses by the hydrometer method.

Textural analyses are reported in Table 2. It is assumed that limited differences in soil texture are not a major factor in influencing the growth response to thinning. Texture differences could influence the amount of initial compaction and the rate of recovery.

Soil related factors assumed to be the most important in influencing the ability of a tree to respond to thinning were, 1) the percent of the root zone compacted, 2) the percent increase in soil density above undisturbed

soils, and 3) the distance from the stem to the major impact. Three compaction or disturbance classes were defined and each tree site was assigned to one of the three classes. The basis for the classification is shown in Figure 2. A light impact was considered as: 1) when less than 10 percent of the root zone was affected by compaction, and 2) when the disturbance covered up to 40 percent of the root zone and the increase in soil density ranged from zero to 10 percent. A heavy compaction classification was assigned to sites with greater than 10 percent increase in density and with more than 40 percent of the area compacted. These classes were slightly modified by the distance from the stem to the major impact. Thus when a sample fell along the border of "heavy" compaction but the impact was two or more meters from the stem it would be classed as "moderate."

Results

Growth response:

Preliminary regression analyses showed that the tree factor most strongly related to the basal area ratio was tree diameter at time of thinning. Crown volume and crown length, normally important growth prediction parameters, had a limited range for the selected trees and, consequently, were of limited value in predicting growth responses. The smaller diameter stems typically increased in basal area at a higher relative rate than larger stems. It appears that the use of a ratio of growth after thinning to growth before thinning did reduce the variability due to individual tree and site differences. The diameter at time of thinning was associated with 40 percent of the variation in the basal area ratio. A multiple linear regression was run to determine the relationship between the three disturbance

classes, the diameter at time of thinning and the basal area ratio. An analysis of variance technique was used to test the hypothesis that there was no difference between the means of the basal area ratios associated with each disturbance class. In a procedure described by Draper and Smith (1966) the three disturbance classes were represented by dummy variables as follows:

Disturbance class	Independent variables X_1	X_2
Light	1	0
Moderate	0	1
Heavy	0	0

The third independent variable, X_3, was diameter at time of thinning in inches.

The resultant regression equation was:

$$Y = 1.596 + 0.433 \ X_1 + 0.226 \ X_2 - 0.036 \ X_3 \qquad \text{Eq. (1)}$$

where Y was basal area response. The correlation coefficient of equation (1) is 0.60, highly significant at the 1 percent level. Substituting the constants of the dummy variables for each disturbance class results in the three equations:

Light disturbance, $Y = 2.029 - .036 \ X_3$ Eq. (2)

Moderate disturbance, $Y = 1.822 - 0.036 \ X_3$ Eq. (3)

Heavy disturbance, $Y = 1.596 - 0.036 \ X_3$ Eq. (4)

An analysis of variance shows that the means of equations (2), (3), and (4) are highly significant. Thus, for a diameter at thinning of 16.0 inches, the predicted growth response ratio for light, moderate, and heavy disturbance is 1.45, 1.25, and 1.02 respectively.

These differences in response ratios indicate that a reduction of basal area growth of 14 percent is associated with moderate disturbance and a 30 percent reduction is associated with heavy disturbance. These average responses apply only to stands within the limits of the sampled conditions and species. It is likely that species with different rooting patterns will respond differently to soil impacts. It is also possible that younger trees are more sensitive to compaction than older trees of the same species.

Soil density changes:

Skid road and undisturbed soil bulk densities were statistically compared within each site at 0-15 cm and 0-30 cm depths (Table 4). The 0-15 cm depth skid road bulk densities at sites 4 and 5 were significantly greater (5% and 1% levels, respectively) than undisturbed soils. Site 4 showed 7 percent increase while site 5 was 16 percent greater. There were no significant differences between skid trail and undisturbed 0-15 cm soils at sites 1, 2, and 3.

The 0-30 cm depth skid road bulk densities were significantly greater than undisturbed soils at all sites. Significance at sites 1, 2, and 3 was at the 5 percent level while sites 4 and 5 were at the 1 percent level. Skid road bulk densities at sites 1-5 were 8, 11, 10, 12, and 19 percent greater, respectively, than adjacent undisturbed soils.

It appears that soil density is tending to return to normal on the skid roads on three of the five sites. The lack of significant higher densities in the surface layer of sites 1, 2 and 3 may indicate that recovery is progressing from the surface downward. However, individual sample points were found to have very high densities even after 12 to 15 years since thinning. Most of the variation is likely due to the degree of compaction at the time

Table 4. Statistical comparison of the soil bulk density
measurements of the five study sites.

0-30 cm depth

	Undisturbed		Skid Trails	
Site	Average Density (g/cc)	s	Average Density (g/cc)	s
1	0.908	0.128	0.991*	0.127
2	0.958	0.052	1.073*	0.112
3	0.885	0.106	0.981*	0.089
4	1.025	0.124	1.166**	0.097
5	0.841	0.064	1.036**	0.093

0-15 cm depth

	Undisturbed		Skid Trails	
Site	Average Density (g/cc)	s	Average Density (g/cc)	s
1	0.956	0.119	0.994	0.089
2	1.001	0.052	1.068	0.110
3	0.948	0.128	0.986	0.089
4	1.095	0.099	1.178*	0.092
5	0.945	0.084	1.119**	0.077

(s) Standard deviation
 * Significantly greater at 5% level
 ** Significantly greater at 1% level

of thinning. Highly compacted points along a skid trail are likely to have a much slower recovery rate than lightly compacted areas. The compacted condition, especially at the 15-30 cm depth, is still strongly present after 15 years. Our data does not provide a means of predicting rate of recovery but it appears that it will take at least another decade for soil densities to return to normal.

Discussion and Conclusions

It is evident that soil compaction will reduce the growth rate of residual trees. The interactions of the various tree and soil factors with growth response are still not well understood. However, the reasonably strong correlation of the compaction classification method with growth response is strong evidence of the approximate degree of basal area growth reduction. Previous work has shown a significant reduction in height and growth. In this study we did not reconstruct three heights at time of thinning and thus could not determine if a similar reduction in height growth had occurred. If there is little or no change in height growth then the actual volume growth reduction should be approximately proportional to the basal area differences. If there was also some reduction in height growth, then the cubic volume growth reduction on heavy impact sites would appear to fall within that reported by Moehring and Rawls (1970). Their two most heavily compacted areas showed 36.3 and 43.4 percent reductions in growth. Power (1974) also estimates a 40 percent reduction in volume growth on heavily compacted sites.

Sixty percent of the trees growing on heavily compacted sites had lower growth rates after thinning than before thinning. Fourteen percent of the trees in the moderate compaction class also had lower growth rates after

thinning than before thinning. Only 4% of the lightly disturbed trees had reduced growth rates. These trees may be the most logical trees to take in the next thinning so as to maximize site productivity. This would tend to create skid road corridors since all of these trees are adjacent to skid trails.

In making the first entry in a thinning with tractors or skidders, the growth reduction could be significantly reduced by using fewer skid trails and winching logs to the trail. Preplanned trails with trees felled for most efficient skidding would aid in reducing the amount of area compacted.

Since the growth reduction is shown to be greatest on the heavily impacted sites, it is desirable to continue the development of low ground pressure thinning equipment. The trend towards recovery of the soil bulk density on some of the sites is encouraging. However, mechanical treatment may be needed if the soil is to be favorable for root expansion to achieve accelerated growth rates. Skid trail scarification shows promise in improving the soil recovery rate and other methods of ameliorating the compacted condition should also be examined. More research is needed to evaluate scarification of skid trails in residual stands without causing detrimental root damage. Further research is also needed to determine if the results of this study are applicable to other tree species.

References

Aulerich, E., Johnson, N. and Froehlich, H. 1974. Tractors or skylines: What's best for thinning young-growth Douglas-fir? Forest Industries Magazine, Vol. 101(12):42-45.

Dambach, Charles A. 1944. Comparative productiveness of adjacent grazed and ungrazed sugar-maple woods. Journal of Forestry 42:164-168.

Draper, N. R. and Smith, H. 1966. Applied Regression Analyses. John Wiley & Sons, Inc., New York, N.Y. 407 p.

Froehlich, Henry A. 1973. The impact of even-age management on physical properties of soils. In: Even-age Management, Symposium Proceedings, Ed. by Hermann, R. K. and Lavender, D. P., Oregon State University, Corvallis. pp. 199-220.

Herrick, David E. and Deitschman, Glenn H. 1956. Effect of tractor logging upon hardwood stands. Forest Products Journal 6:403-408.

Lull, H. W. 1959. Soil compaction on forest and range lands. U. S. Department of Agriculture Miscellaneous Publication 768. 33 p.

McCulley, Robert D. 1950. Wet-weather logging may damage seed trees. Virginia Forests 5:6.

McMinn, R. G. 1963. Characterisitcs of Douglas-fir root systems. Canadian Journal of Botany 41(1):105-122.

Moehring, D. M. and Rawls, I. K. 1970. Detrimental effects of wet weather logging. Journal of Forestry 68(3):166-167.

Perry, T. O. 1964. Soil compaction and loblolly pine growth. Tree Planter's Notes 67:9.

Power, Willima E. 1974. Effects and observations of soil compaction in
    the Salem District. USDA, Bureau of Land Management Technical Note
    256. 12 p.

Smith, J.H.G. 1964. Root spread can be estimated from crown width of
    Douglas-fir, lodgepole pine, and other British Columbia tree species.
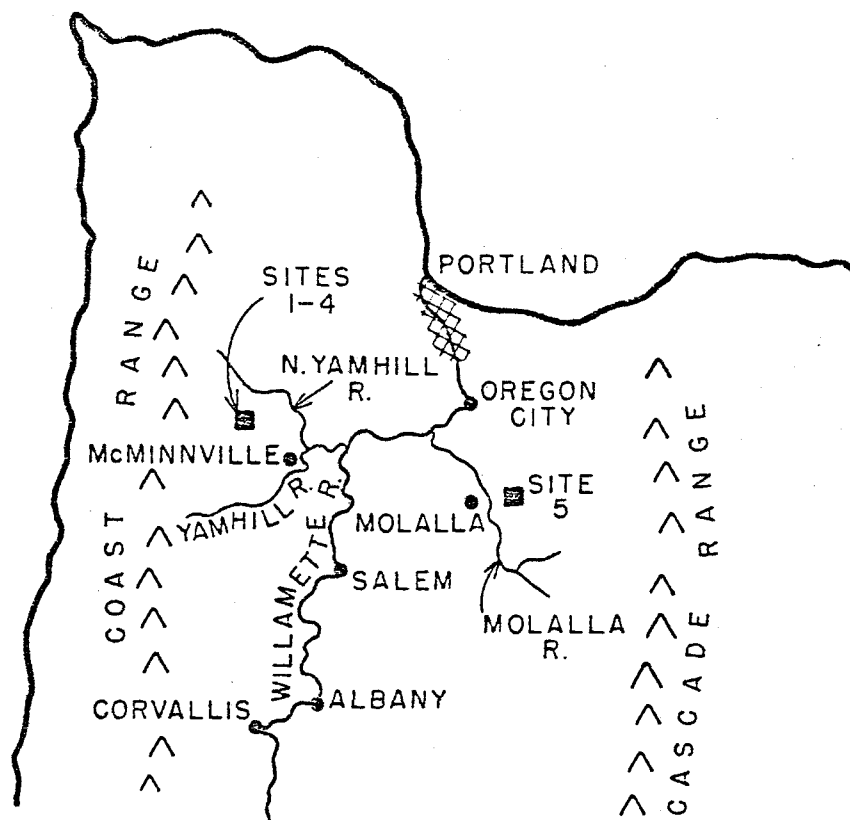   Forestry Chronicle 40(4):456-473.

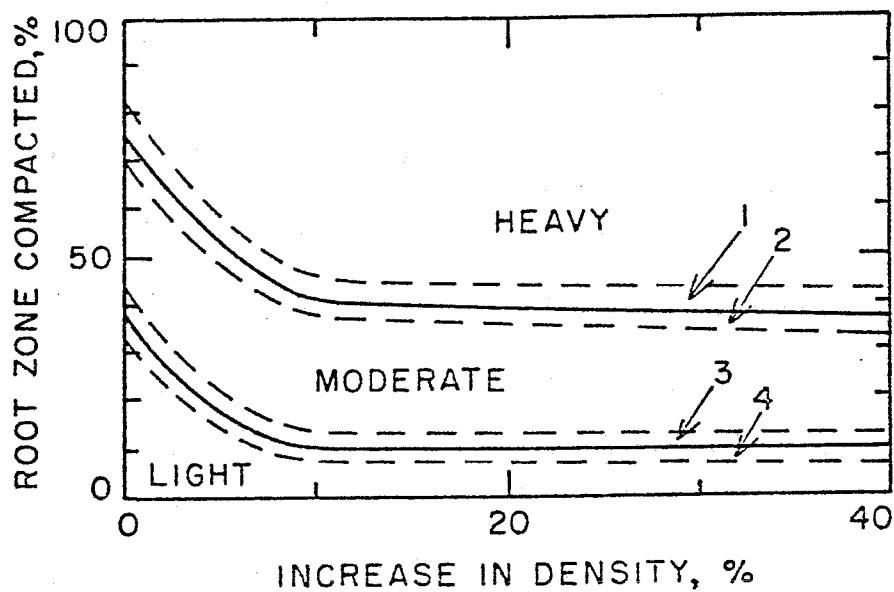Figure 1. Location of Study Sites in Northwest Oregon.

Figure 2. Basis for assigning compaction classes
to disturbed soil.

[1] Place in Moderate class if major impact is more
than two meter from the stem.

[2] Place in Heavy class if major impact is less
than one meter from the stem.

[3] Place in Light class if major impact is more
than two meter from the stem.

[4] Place in Moderate class if major impact is less
than one meter from the stem.

Skid Trails and Competition Reduce

Growth Rate of Residual Western Hemlock

Henry A. Froehlich

ABSTRACT--Growth rates of 22-year-old western hemlock (Tsuga heterophylla
(Raf.) Sarg.) were found to be affected by skid trails produced by commer-
cial thinning with small tractors. Growth response averaged 15 percent less
for trees with moderate soil impact in their root zone. Degree of release
was also a major factor in determining the response to thinning.

The goal of intensive forest management is to manipulate a forest stand to produce the maximum amount of usable forest products in a short time. Reaching this goal may require that a stand be entered several times in one rotation for thinning and other silvicultural treatments. If the thinning system requires tractors or rubber-tired skidders, the area will be disturbed to some degree by skid trails. This study was made to determine if measurable impact on the growth rate of western hemlock (Tsuga heterophylla (Raf.) Sarg.) could be associated with the impact of equipment on soils.

Study Description

The study site was located near Seaside, Oregon in an area cable logged in 1949. A dense stand of western hemlock became established over the area, with an excess of 2,000 trees per acre. A portion of this stand was thinned by Crown Zellerbach Corporation as part of a long-term research project to determine management prescriptions for young-growth western hemlock. The portion used in this study was thinned to reduce the stand to 300 trees per acre at 15 years. Trees were cut and left on the site. At 22 years of age, trees were thinned commercially with small crawler tractors. Crown Zellerbach researchers kept accurate records of diameter growth of individual trees on several small plots within the thinned stand.

This study used as many trees in the study plots as possible and additional selected trees to make a sample of 37 trees. Each tree stem, crown projection, and skid trail was mapped. Estimates were made of crown length, competition from adjacent trees, and the degree of release during the commercial thinning. Soil densities were measured in skid trails and in adjacent undisturbed points around each subject tree with a double-probe nuclear densitometer. Densities were measured at 4-inch and 10-inch depths.

Basal-area growth of each subject tree was computed from growth data furnished by Crown-Zellerbach for trees in the study plots and from four increment cores taken at breast height on trees outside the study plots. Basal-area growth was calculated for the prethinning period 1965-1971 and for the post-thinning period 1971-1976.

The soils on the site are a well-drained clay loam containing about 30 pecent organic matter in the surface 10 inches. The surface soils have very low densities, averaging only 0.41 gram per cm^3 when undisturbed.

Soils in the skid trails are 31 percent denser than the undisturbed soils at 4 inches depth and 17 percent denser at 10 inches depth, a significant increase, but the trails are still of very low density. This may be due to the relatively light usage given the trails, the high organic matter of the soils, and the amount of support given by the dense network of roots in the surface few inches. The level of impact on the root zone of the 17 trees affected by skid trails was very similar. For analysis by stepwise multiple regression, a value of 1 was assigned if the tree had a skid trail in its rooting zone and a value of 0 if it had none.

The sample trees were not all given equal release at thinning. For the analysis, a value of 1 was assigned if the subject tree had release on two or more sides and a value of 0 if it had less release.

The diameter of each competing tree and its distance from the subject tree were measured to obtain an additional expression for the degree of competition. These values were converted to a Competition Index with the method designed by Arney (1973). Table 1 summarizes the data on the 37 sample trees.

Results and Conclusion

Two stepwise linear regressions were run. The dependent variable of the first is the growth ratio (growth after thinning divided by growth before thinning). The second dependent variable is the basal-area growth for the post thinning period 1971-1976. Independent variables were crown length in percent of tree height, competition index, soil impact class, release class, and diameter at time of thinning. Crown length did not prove to be significant, possibly because the variation of crown length among the sample trees was too small. Tree diameter at the time of thinning is a significant variable. The equation developed is:

Growth (in ^{2}/yr) = $3.519 + 1.288X_1 - 0.021X_2 - 1.69X_3^3 + 0.994X_4$

X_1 = Diameter at time of thinning, in inches

X_2 = Competition index

X_3 = 1 if skid trail was present
      0 if release was poor

X_4 = 1 if release was good
      0 if release was poor

Each variable was significant at the 0.05 level except X_4 which is significant at the 0.10 level. The equation has an R^2 of 0.64, significant at the 0.05 level.

The product of the equation shows that a tree with a diameter breast height of 10.28 inches at time of thinning, a competition index of 154, and good release would grow at a rate of 11.0 square inches per year. If a skid trail were present, its rate would be expected to be 9.31 square inches per year or 15 percent less. For trees with poorer release, the difference due to skid trail impact is 17 percent. Table 2 provides a summary of growth response.

The 15 to 17 percent reduction in growth compares favorably with the reduction in growth on loblolly pine (Pinus taeda Law.) noted by Moehring and Rawls (1970). In their study, the soil was compacted with a small crawler tractor pulling a load of three 10-foot logs passing six times near the subject tree. Compaction of two, three, and four sides of a tree produced 13.7, 36.3 and 43.4 percent less volume added during the 5-year period after treatment. The impact made by commercial thinning in the hemlock stand is relatively moderate and probably lighter than the compaction on two sides in the Moehring and Rawls study. The shallow rooting pattern of hemlock possibly makes the species more sensitive to soil impacts than loblolly pine.

The results have also been compared with earlier work by Froehlich and Berglund[1] which found that moderately impacted Douglas-fir trees averaged 14 percent less basal-area growth than trees without soil compaction. Trees with a heavy impact in their root zone (over 40 percent in skid trails) produced 30 percent less basal-area growth than undisturbed trees.

Repeated entry probably will increase the impact by densification of the soil and by affecting additional trees in the stand as skid trails are added to the area. Additional study is needed to define the exact economic impact on a stand over time. The results show clearly that the tractor trails can have a negative impact on the growth of residual trees. Economically feasible techniques of harvesting and thinning should be developed that will produce the least compaction on the smallest amount of skid trail within a thinned stand.

Literature Cited

ARNEY, J. D. 1973. Tables for quantifying competitive stress on individual

    trees. Can. Dep. Environ. Can. For. Serv., Pac. For. Res. Cent. Inf.

    Rep. BC-X-78. 10 p.

MOEHRING, D. M., and I. W. RAWLS. 1970. Detrimental effects of wet weather

    logging. J. Forestry 68:166-167.

Footnote

[1]Froehlich, H. A., and E. R. Berglund. Soil compaction during thinning af-

    fects growth rate of residual trees. (In preparation for publication.)

Table 1. Summary of data from 37 western hemlock trees.

Variable	Range	Mean
Growth response ratio	0.71 – 1.57	1.16
Growth rate 1971–1975 (in^2/yr)	3.87 – 13.62	7.91
Diameter in 1971	8.2 – 12.0	10.28
Crown length/tree height	0.50 – 0.90	0.68
Competition index	87 – 254	154

Table 2. Summary of growth response ratio for young-growth western hemlock when competition index is 154.

Condition	Growth response ratio
No soil impact, good release	1.42
Soil impact, good release	1.21
No soil impact, poor release	1.15
Soil impact, poor release	0.93

THE IMPACT OF LOGGING EQUIPMENT ON
GROWTH OF YOUNG PONDEROSA PINE

Henry A. Froehlich

Henry A. Froehlich is Associate Professor, Forest Engineering Department, Oregon State University, Corvallis, Oregon.

GROWTH OF YOUNG PONDEROSA PINE

Several studies have measured the changes in physical soil proper-
ties due to logging equipment. The amount of area affected, the relative
increase in soil density with repeated trips, reduction in infiltration
and porosity have been documented under a variety of conditions. It is
commonly found that tractor trails cover 25-35 percent of a tractor-
logged site (5,9,13,14). Additional studies have shown the reduction
in establishment and reduction in growth of seedlings on skid trails
(6,12,15). Reductions of 40 percent and up in growth and a reduction
of established seedlings by two-thirds when compared to adjacent cutover
lands were recorded. The effect of soil compaction in skid trails on
growth of residual trees has also been observed. Moehring and Rawls (11)
showed that the degree of growth reduction of 40-year old loblolly pine
(Pinus taeda b.) is strongly related to the severity of the impact on soils
in the root zone of the tree and could be as much as 40 percent less for
heavily impacted trees. This potential for growth reduction led to a study
on the impact of soil compaction on growth of residual young ponderosa pine
(Pinus ponderosa Laws) in stands thinned by conventional logging methods.
A second objective was to estimate the rate of reduction of soil compaction
in skid trails under the climatic and soil type common to the region.

Methods

A site on the Ochoco National Forest in central Oregon was located
where a heavy partial cut of old-growth ponderosa pine removed most of
the overstory from a stand of young pine. The harvest took place in 1961

and a year later the young stand was thinned by hand to provide a release

for selected crop trees. Trees were fell by hand and not yarded. At

the time of this study in 1977, the average age of the stand, at breast

height, was 64 years. The original logging was done with large crawler

tractors common to the logging industry at that time. No logging equipment

has entered the stand since the overstory removal.

Soil and Site Measurements

A sample of 75 trees was selected which included a wide range of soil

disturbance in the root zone about each tree.

Soil densities were measured with a two-probe nuclear densitometer.

Densities were measured at two or more points in the skid trails and one or

more points in the undisturbed areas about each sample tree. A total of

254 points were measured, 120 in skid trails and 134 in undisturbed locations.

At each point, soil densities were measured 3, 6, 9 and 12 inches (7.6,

15.2, 22.9, 30.5 cm) below the soil surface. The crown extension and skid

trail locations were mapped for each tree. It was assumed that the root zone

of the tree was equivalent to a circle with a radius 1.5 times the average

crown radius of the tree (3,4). The percent of root zone in skid trail was then

measured on the map.

Each tree was then assigned to one of three disturbance classes; light,

moderate or heavy. Light disturbance was assigned when less than 10 percent

of the root zone was disturbed, moderate impact was assigned when from 11

to 40 percent of the area was disturbed and the disturbance had more than

10 percent increase in density. A tree was classed as heavily disturbed

when more than 40 percent of the root zone was disturbed and the disturbed soil

had a 10 percent or greater increase in density.

Cattle have used the area since 1965. It was not possible to determine the exact amount of cattle usage, but each tree was subjectively assigned into one of three separate cattle impact classes on the basis of the present evidence of cattle activity. Some trees were protected by the slash from the logging and the precommercial thinning and were assumed to have little or no impact from cattle. Others showed signs of considerable cattle usage by close cropping of the grasses and sedge, cattle trail patterns and signs of bedding around the tree and were assigned to the moderate or heavy impact classes.

The soil at this site is a sandy clay loam which became stoney at 9 to 12 inches (22.9 to 30.5 cm) depth. Rooting depth appeared to be generally less than 18 inches. The terrain is gently rolling with slopes ranging from 5 to 25 percent. On the basis of the height and age of the 16 tallest trees in the sample, the site is classed as Site V for ponderosa pine (10).

Tree Measurements

Several variables were recorded for each sample tree to aid in determining growth rates before and after logging. Four increment cores were taken at DBH to determine age and basal area growth rates before and after the overstory removal and subsequent thinning. Other variables included height, crown length, crown width, distance to and diameter of competing trees. From these variables the growth response ratio was calculated. Growth response ratio is an expression of the basal area added since logging divided by the basal area added prior to logging over an equal number of years. Other calculated variables include crown/height ratio, crown volume, and competitive stress index (2). Trees with stem wounds, broken tops or other visible defects were excluded from the sample. Table 1 provides a summary of the variables considered in the study.

Table 1. Description of variables tested in the statistical analysis,
including the mean ($\bar{x}$), range, and standard deviations(s).

Variable	$\bar{x}$ Range s	Description
Growth Ratio	3.46 0.74 - 7.05 1.46	Basal area added during 15 years prior to release divided by the basal area added during and equal period of time after release. Measured from four increment cores.
Growth Rate	1.57 0.19 - 3.37 0.69	Average basal area added per year during the 15-year period after release; measured from four increment cores per tree; in^2/yr.
Tree height	39.0 21-58 8.5	Height to nearest foot
Crown length	24.1 11-38 5.89	Length of live crown to nearest foot
Crown width	11.2 8-15 1.72	Average width of crown projection to nearest foot
Crown volume index	8.7 4-14 2.90	Computed from equation $CV = \Pi \times dia. \times length/100$
Crown/height ratio	62.6 34-79 8.75	Crown length divided by tree height x 100
Competitive Stress Index	73.6 1-250 55.7	Computed from distance to and diameter of all competing trees; after Arney, 1973
Diameter of Thinning	4.41 2.01 - 8.17 1.32	Measured from four increment cores per tree; nearest 0.01 inch
Cattle Impact Class	-	Light = 1, Moderate = 2, Heavy = 3
Compaction Class	-	Light = 1, Moderate = 2, Heavy = 3

Results and Discussion

Effect of Logging on Soil Density

The effect of logging equipment on soil density was readily measurable 16 years after logging. Soil density at the three and six inch (7.62 and 15.2 cm) depths in the skid trails average 18 percent higher than the undisturbed soils. The variability of soil density in the skid trails is quite high. Variability increases at the 9 and 12 inch (22.9 and 30.48 cm) depths probably due to the increased stoniness. The skid trails at the 9 and 12 inch depths (22.9 and 30.48 cm) had an average density nine percent greater than the same depth in undisturbed soils. From the data collected we are unable to explain the reason for the slightly higher density at 3-inches (7.6 cm) as compared to the 6-inch (15.2 cm) depth at non-skid trail sites. Table 2 summarizes the soil density values.

That the skid trails are this dense 16 years after logging is surprising. Six density measurements made in the skid trails of an active logging operation nearby showed essentially the same densities at each level as in the 16-year old trails. Thus little recovery is evident over this period of time.

Compaction from cattle using the area was thought to play a small part in keeping the surface layers more dense, but this impact is not clear. Alderfer and Robinson (1) found that compaction due to cattle was mostly limited to the surface 1 or 2 inches (2.5 or 5.0 cm). In our study, soil densities at the 3-inch (7.62 cm) and 6-inch (15.2 cm) depth of 30 sample points rated as currently having heavy cattle usage were compared with an equal number of points having little or no current usage. There was no statistical difference between the two treatments, and as might be expected, the cattle usage classification was not a significant variable in predicting growth.

Table 2. Soil density in skid trails and adjacent undisturbed areas with respective means ($\bar{x}$) and standard deviations (s).

| | Soil Density g/cm | | | |
| | Undisturbed | | Skid Trail | |
Depth	$\bar{x}$	s	$\bar{x}$	s
3	0.97	.09	1.14**	.12
6	0.91	.11	1.07**	.15
9	1.01	.16	1.10*	.19
12	1.03	.15	1.12**	.20

**Significantly different from undisturbed, α = .05
*Significantly different from undistrubed, α = .10

Effect of Logging on Residual Tree Growth

Two regression equations were run to test the effect of the tree and soil parameters on the two dependent variables: Growth Ratio and Growth Rate.

The three tree variables most strongly related to the Growth Ratio were the Diameter at time of release, Crown Volume and Competitive Stress. The equation shows that a smaller diameter tree with a relatively large crown was able to respond to the release more effectively in percent increase in growth. Although not specifically designed for use with ponderosa pine, the Competitive Stress Index as computed from Arney's (2) method was also a highly significant factor affecting the Growth Ratio.

Soil compaction, as reflected by the assigned equation classes, was a much less significant variable than Diameter, Crown Volume or Competition. The equation for predicting growth ratio has an R^2 of 0.56** and is as follows:

Ratio = 5.256**

-0.979 x Diameter at release**

+0.294 x Crown volume**

-0.146 x Compaction class*

-0.005 x Competitive stress index**

**Significant at α = .01

*Significant at α = .15

The equation for predicting the Growth Rate of the released trees, in square inches per year, has an R^2 of 0.64** and is as follows:

Growth Rate = 0.131

> +0.168 x Crown volume**
>
> -0.102 x Compaction class*
>
> -0.004 x Competitive stress index**

**Significant at α = .01

*Significant at α = .05

Crown volume apparently indexes growth response very well; no other tree variable was as useful in explaining the variation in growth after release. The Competitive Stress Index also was highly significant in explaining the difference in rate of basal area growth. As might be expected, a tree with a relatively larger crown released the most completely from its competitors responded with the greatest acceleration in growth. Skid trail compaction had a negative effect on the Growth Rate. However, the soil impact, as reflected by the assigned compaction classes, is less significant than either crown volume or competition.

Solving the prediction equation, holding crown volume and competition at their mean value, shows that the average tree with little or no compaction in its root zone grew at 1.64 in^2/yr (10.58 m^2/yr). Trees in the moderate and heavy soil impact classes grew at 1.54 and 1.44 in^2/yr (9.93 and 9.29 cm^2) respectively, a 6 and 12 percent reduction in growth rate for the moderate and heavily impacted trees. This is appreciably less than was found in our previous work on Douglas-fir [Pseudotsuga menziesii (Mirb.) Franco] where there was a 14 and 30 percent reduction in growth rate for moderately and heavily impacted trees (7). In western hemlock [Tsuga heterophylla (Raf.) Sarg.], Froehlich (8) found a 14 percent reduction in growth of moderately impacted trees. Thus, in spite of the persistence of the compacted condition of the skid trails, its effect on growth of the residual ponderosa pine trees at this site is relatively light.

Some interesting questions are raised by these results. Does the relatively wide spacing of residual trees allow the trees to compensate by extending roots away from the skid trails? Are the other stresses on the trees so high that soil density is not a major additional factor? Perhaps the most important question is, what is the effect of similar soil impacts on higher site ponderosa pine stands?

The reduction in growth caused by compaction is large enough to indicate that the existing skid trails should be utilized to the greatest extent practicable in any future harvests. Our experience has shown that typically, repeated entries into a stand increases the area covered by skid trails markedly and the impact is accumulated. It also appears that on low site class areas such as this the potential growth loss is not so high as to exclude ground-based logging, especially if the area in skid trails is kept to an economic minimum.

References

1. Alderfer, R.B. and R.R. Robinson. 1947. Runoff from pastures in relation to grazing intensity and soil compaction. J. Amer. Soc. Agron. 39:948-958.

2. Arney, James D. 1973. Tables for quantifying competitive stress on individual trees. Dept. of the Environ., Can. For. Serv., Pac. For. Res. Can., Info. Report BC-X-78. 10p. + tables.

3. Berndt, Herbert W. and Robert W. Gibbons. 1958. Root distribution of some native trees and understory plants growing on three sites within ponderosa pine watersheds in Colorado. USDA, Forest Serv. Rocky Mtn. Forest and Range Exp. Sta., Sta. Pap. 37, 14pp.

4. Curtis, James. 1964. Roots of a ponderosa pine. USDA Forest Serv. Res. Paper INT-9. 10pp.

5. Dyrness, C.T. 1965. Soil surface condition following tractor and high-lead logging in the Oregon Cascades. J. Forestry 63:272-275.

6. Foil, R.R. and C.W. Ralston. 1967. The establishment and growth of loblolly pine seedlings on compacted soils. Soil Sci. Soc. Amer. Proc. 31:565-568.

7. Froehlich, Henry A. and Erwin R. Berglund. ____ Soil compaction during thinning affects growth rate of residual trees. (In preparation for publication.)

8. Froehlich, Henry A. ____ Skid trails and competition reduce growth rate of residual western hemlock. (In preparation for publication.)

9. Lull, Howard W. 1959. Soil compaction on forest and range lands. U.S. Forest Serv., Misc. Pub. 768. 33p.

10. Meyer, Walter H. 1934. Growth in selectively cut ponderosa pine forests of the Pacific Northwest. USDA, Tech. Bul. No. 407, 64pp.

11. Moehring, David M. and Ike W. Rawls. 1970. Detrimental effects of wet weather logging. J. Forestry 68:166-167.

12. Pomeroy, K.B. 1949. The germination and initial establishment of loblolly pine under various surface soil conditions. J. Forestry 47:541-543.

13. Steinbrenner, E.C. 1955. The effect of tractor logging on physical properties of some forest soils in southwest Washington. Soil Sci. Amer. Proc. 19:372-376.

14. _____ and S.P. Gessel. 1955. Effect of tractor logging on soils and regeneration in the Douglas-fir region of southwestern Washington. Soc. Amer. Foresters Proc. 1955:77-80.

15. Youngberg, C.T. 1959. The influence of soil conditions, following tractor logging, on the growth of planted Douglas-fir seedlings. Soil Sci. Soc. Amer. Proc. 23:76-78.

Field Applicability

Each of the three species studied shows a negative response to soil compaction. The reduction in growth is roughly proportional to the degree of impact, including the percent of root zone affected and the percent increase in soil density. It appears that Douglas-fir and hemlock are more sensitive to compaction than ponderosa pine. The results of the three case studies can be summarized as follows:

Percent reduction in basal area growth
of study trees

	Moderately Impacted	Heavily Impacted
Douglas-fir	14	30
Western hemlock	15	-
Ponderosa pine	6	12

Applying the individual tree response to compaction to an estimated percentage of trees in each compaction class a weighted average for the stand can be calculated. The net result depends heavily on the percent of area in skid trails. Using this method on some of the thinned stands of Douglas-fir it appears that from 8 to 10 percent less basal area is added than if the area had been thinned without the soil impact. The basal area growth reduction on the low-site ponderosa pine stand is less than 5 percent. The total stem volume growth reduction may be somewhat greater when effects of height growth are also considered.

The rate of recovery of soil porosity under natural conditions is still not well defined, but it appears that the compacted condition will persist for at least a few decades.

The results of the study indicate that to maintain maximum productivity of forest lands the area devoted to skid trails should be kept to an economic minimum. Existing trails should be reused for future thinnings or salvage operations. With planned skid trail locations it would appear that the per-cent of area in skid trials could be reduced by half of what is now commonly produced.

Further research is needed to develop feasible means of speeding the recovery of compacted soils. The costs of treatment and the degree of recovery that can be accomplished with various mechanical means needs to be studied. Additional work is also needed to develop a methodology for predicting what degree of compaction will be produced by various types and sizes of equipment.