AN ABSTRACT OF THE THESIS OF

Carol Anne Whitaker for the degree of Master of Science in Forest Engineering presented on March 17, 1983

Title: Restoring Productivity of Compacted Forest Soils with Tillage

Abstract approved: Henry A. Froehlich

Tillage of forest soils compacted by ground-based logging systems is a practice that is becoming widely accepted in the Pacific Northwest. However, past research has failed to adequately define the conditions and specifications that particular tillage operations should meet in order to produce the maximum growth response from planted seedlings. The objective of this study is to quantify the early growth response of conifer seedlings to altered soil conditions produced by conventional ripping practices.

To achieve the stated objective, a field study and a growth chamber study were implemented. A small tractor equipped with two 58-cm long ripper teeth spaced 140 cm apart performed the tillage on compacted gravelly loam soils in the Cascade Mountains of southwestern Oregon. Conditions for both studies included undisturbed soil, compacted soil in skid trails, and ripped soil in skid trails. Fifty-nine soil cores (15 cm in diameter by 32 cm long) were extracted from each treatment as growth media for the growth

chamber study.

Preliminary results from the field study showed no significant differences in height growth or diameter growth of planted 2-0 bare root Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) seedlings after two years, even though soil bulk density and strength were significantly different and depth of compaction extended to 40 cm. It is possible that improper handling of seedlings either in the nursery or during planting has retarded development to the point that planting shock is overriding any effects due to soil treatment. This phase of the study will be continued for another four years, so treatment effects may yet appear.

The growth chamber study included observations on Douglas-fir and white fir (Abies concolor) seedlings grown from seed for 226 days. At 148 days, the Douglas-fir seedlings growing in tilled soil showed a 44 percent improvement in height growth compared to seedlings growing in compacted soil. Differences between means were statistically significant at $p = 0.051$ level. Differences between means for white fir were statistically significant at $p = 0.074$ level. Significant differences in root development were evident for both species at the end of 226 days. Dry root weight found in the top 20 cm of tilled soil for white fir was 61 percent greater than for trees growing in compacted soil. For Douglas-fir, a 42 percent increase was noted. These differences reflect the influence of aggregate strength rather than bulk density since the latter values for soil in the cores were not significantly different as a result of disturbance from sampling and handling. It was postulated that seedlings growing in tilled soil with their more extensive root systems would fare better under stressed conditions than seedlings growing in compacted soil.

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RESTORING PRODUCTIVITY OF COMPACTED FOREST SOILS WITH TILLAGE

by

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RESTORING PRODUCTIVITY OF COMPACTED FOREST SOILS WITH TILLAGE

INTRODUCTION

Ground-based logging systems commonly used on much of the forested terrain in the western United States provide an efficient, economical method to transport felled and bucked logs within forest environments. The equipment is readily available, reasonably dependable, and adaptable to perform many timber harvest-related tasks such as road building and maintenance, skidding, stump grubbing, brush piling, and soil scarification. However, severe impacts can and have resulted from the use of such machinery under the wrong conditions. An estimated 2.5 million hectares of potentially productive timberland in southwestern Oregon and northern California are presently nonstocked or poorly stocked as a result of harsh summer climate, soil conditions, and competition by noncommercial vegetation. Tractor skidding in this region has resulted in a dense network of compacted skid trails following thinning and clearcut harvesting operations which only tend to compound an already serious regeneration problem. Steinbrenner and Gessel (1955), Pomeroy (1949), Perry (1964), Foil and Ralston (1967), Froehlich (1979), and Wert and Thomas (1981) have demonstrated that both short term and long term reductions in growth and survivial of trees growing in compacted skid trails can be directly linked to changes in soil properties, specifically increased soil bulk density, following logging.

Other changes in soil properties associated with the compaction process include: breakdown of natural soil structure with the accompanying increases in micropore space at the expense of macropore space, increases in soil strength, and decreases in gaseous diffusion rates and water infiltration rates (Greacen and Sands, 1980). Decreased infiltration rates may, in turn, lead to greater volumes of surface runoff and erosion. In some instances, the litter layer and the nutrient-rich A horizon may be partially or totally removed (Youngberg, 1959). Moehring (1970) notes that mechanical disturbance, through its interference with the air-water regime and strength properties of soil, may indirectly alter chemical and microbiological conditions of the soil and thus adversely affect plant growth.

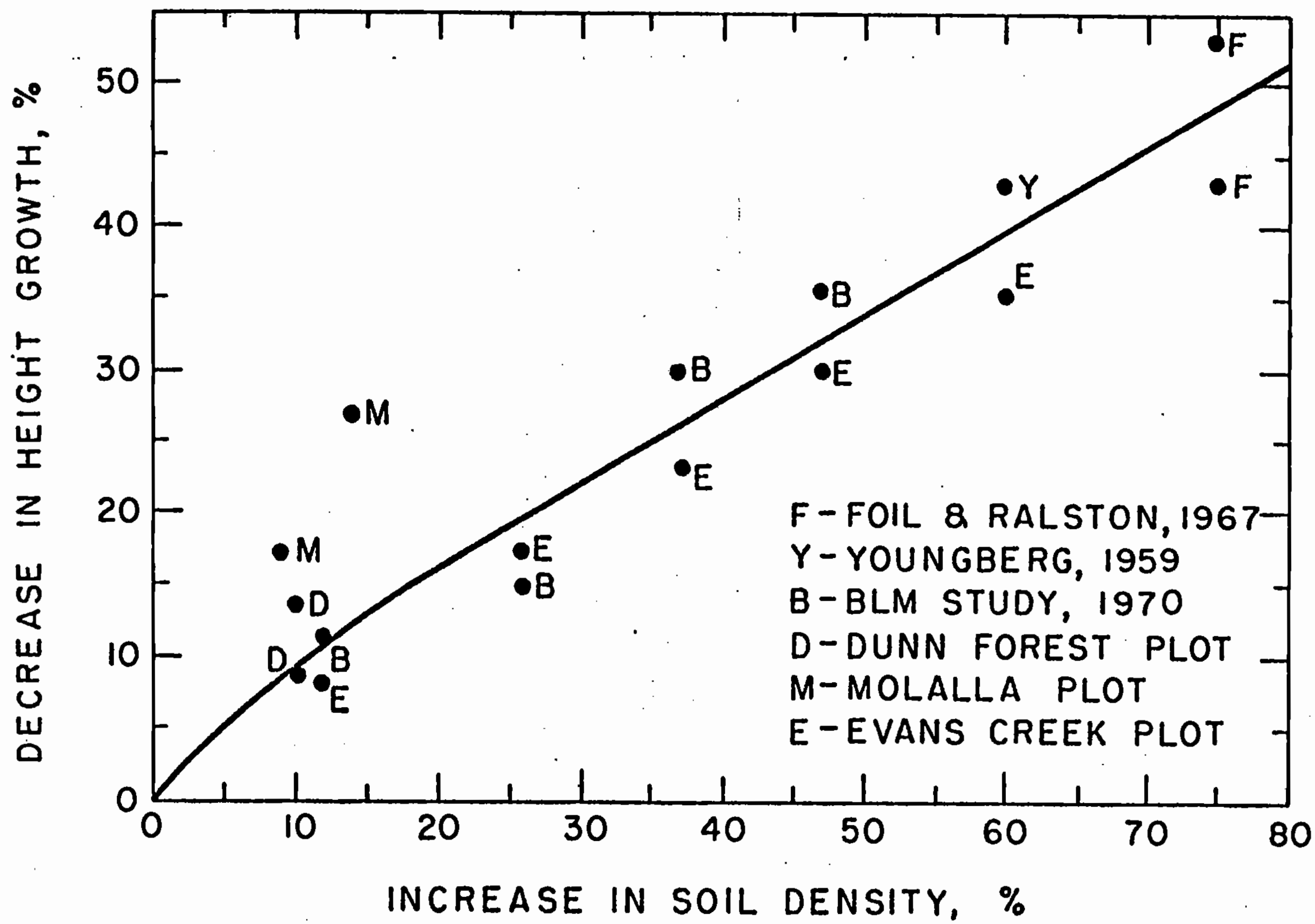
Plant Response to Compaction

Greacen and Sands (1980), in their review of the compaction process and consequences, point out that increases in soil strength may accompany compaction, yet predictions of "growth limiting" values for particular soil types become difficult because of the complexity of the interactions involved. For example, a plant root system might occupy less soil volume following compaction, but if air, water, and nutrients are plentiful and root lengths are sufficient to satisfy the needs of the developing shoot, then top growth need not be limited. Conceivably, compaction can be beneficial under these circumstances since available water retention, hydraulic conductivity, and nutrient ion uptake are enhanced. Conversely, when water and/or nutrients within the soil volume occupied by plant roots become limiting, shoot growth will be inhibited and will not recover unless further exploration of the soil mass by new roots can take place.

Furthermore, Wiersum (1957) notes that root penetration through pores smaller in diameter than themselves can occur only by overcoming the strength of the soil. Greacen and Sands (1980) state that elongation rates decrease exponentially with increases in soil strength. Significant reductions in seedling establishment and growth have been linked to relatively small increases in soil bulk density. This phenomenon has been described by Froehlich (1976) and is illustrated in Figure 1. It is apparent from the above discussion that both good judgment and accurate measurements are required to determine the potential for success of reforestation efforts, and it is misleading to discuss the effects of compaction in terms of threshhold values of one soil physical concept such as bulk density since plant stresses created by compacted soil are additive and highly interdependent.

Increases in physical resistance of soil to root penetration may cause nutrient deficiencies to occur in the seedling since the volume of soil available to roots for the extraction of nutrients becomes limited. The decrease in total porosity and increase in the proportion of smaller pores that accompanies compaction will cause an increase in soil water potential for a given moisture content (Hillel, 1971). This, in turn, causes more energy to be exerted by the plant in establishing a sufficient water potential gradient to

FIGURE 1. Relationship between increase in soil bulk density and seedling height growth. (After Froehlich, 1976.)



supply shoot meristems with the nutrients essential to growth (Gill, 1961).

Some land managers would argue that the application of fertilizer prior to planting may allow the seedling to overcome the resistance presented by compacted soil. Craig, Bren, and Hopmans (1977), in their study of establishment techniques on radiata pine, found that the major reduction in mortality was due to mechanical site preparation treatments and not to fertilizer applications. Although mean height on fertilized control plots was improved by 40 percent over unfertilized control plots, the authors point out that the interaction between blocks and fertilizer was significant ($p < 0.01$) such that the effect of the fertilizer was different within different blocks. Hatchell (1981) notes that survival actually decreased with fertilizer application and postulates that competition from other plants was enhanced. Stand height at the end of four years was improved to a greater extent by mechanical site preparation than by fertilization. Survival decreases noted by Berg (1975) agree with Hatchell's findings, and height after three years was comparable between trees growing in ripped, nonfertilized plots and those growing in nonripped, fertilized plots where the optimum fertilizer treatment was used. All of these authors conclude that fertilizer treatment alone was insufficient in allowing seedlings to overcome the effects of compaction in most cases, but that some combination of fertilizer and mechanical site preparation produced the best results.

Tillage of Forest Soils

What optimum combination of factors, then, contribute to what is generally termed "soil tilth", and what types of strategies are available to either preserve tilth during logging or restore it once compaction has occurred? Loosely defined, tilth is "the physical conditions of the soil as related to its ease of tillage, fitness as a seedbed, and its impedance to seedling emergence and root penetration" (Hausenbuiller, 1972). Since natural recovery from the compacted condition is excessively long under climatic conditions existing in the west (Vanderheyden, 1980; Froehlich, 1979), other methods of preserving or restoring soil tilth have been explored. Three philosophical approaches have been taken: (1) employ cable yarding systems where feasible, (2) lessen the impact of heavy machinery by using low ground pressure vehicles and/or reducing skid road area, and (3) ameliorate compacted soil through the use of mechanical site preparation equipment, such as rock rippers, brush blades, harrows, and disks.

Many private and public timberland managers have utilized tillage methods in an attempt to rehabilitate compacted soil in skid trails and landings with varying degrees of success. Power (1978), through the collection of information on skid trail ripping within the Salem District of the Bureau of Land Management, has compiled a guide to determining the objective of a ripping treatment in terms of the physical appearance of tilled soil and the conditions and equipment specifications needed to achieve the objective. Andrus

(1982) has examined changes in soil physical properties using different tillage implements and discusses the factors which control the degree of soil shattering and the cost of the operation in relation to a given set of soil conditions.

The ultimate objective of any tillage operation, as described by Kuipers (1963), is to provide a well pulverized soil surface with a clod size distribution that permits adequate air and water circulation. The final product should be able to retain water, yet still possess adequate hydraulic conductivity (McKyes, et al., 1979). Hewitt and Dexter (1979) found greater nutrient availability per unit length of root in small size aggregates. Nutrient availability was also inversely related to aggregate strength. Coarse tillage may leave large voids among the clods producing excessively high hydraulic conductivity and diffusion rates and poor soil contact with the seedling root mass. Too fine a tillage operation may pulverize the soil unduly and result, eventually, in a recompacted surface (Hillel, 1971). Minko (1975), although not specifically concerned with the effects of deep ripping in his study of plant-soil relationships in nursery beds, notes that surface soil layers along ripped areas contained one percent more moisture than in adjacent nonripped areas. The final quality of the tilled soil (i.e., volume of soil shattered per unit length of surface, or aggregate size distribution) is not discussed. Ultimately, each set of climatic and soil conditions will dictate the timing (i.e., moisture content) at which the operation is to take place, the depth to which the soil should be tilled, and the quality of the final product.

It must be remembered that descriptions of the quality of tillage using concepts such as bulk density, clod size distribution, homogeneity, and the like will bear no direct relationship to plant growth. Kuipers (1963) stresses the need to include changes in properties related to moisture, temperature, aeration, and strength (which directly affect root vigor and expansion) in arriving at a causative relationship between tillage and plant growth. The relationship is an extremely complex one, and it may be many years before isolation of each of the variables can be achieved (Foil and Ralston, 1967).

Evaluating results from past studies is always difficult because of varying objectives and experimental approaches towards solving the perceived problem. Many tillage studies, for instance, combine tillage and fertilization in order to achieve optimum growth. Much of the work done in the southeastern United States has been primarily designed to provide for improved drainage, debris disposal, and reduction of vegetative competition. Very little has been done to explore means of alleviating compaction until very recently.

Additionally, differences in implements and differences in soil conditions result in vastly different qualities of tillage. Andrus (1982) points out marked differences in volumes of soil shattered as a result of these two variables. Few studies describe the quality of the soil medium either before or after tillage.

Despite these problems, an attempt has been made to condense the results from available literature. Table 1 lists results from field studies. The data seem to indicate that some improvement in early

TABLE 1. Comparative results of field trials in evaluating growth response from tillage.

Treatment Description	Tree Species	Soil Type	Time Span	Results	Reference
Ripped to 60 cm (1) landings (2) hard clay ridges	radiata pine	clay	3 yrs	(1) 25% increase in height over untilled control; 22% increase in survivial (2) 52% increase in height over control; 10% increase in survival	Berg, 1975
Triple disked to 12.5 cm	loblolly pine	clay	4 yrs	21% decrease in height over control; 8% increase in survival (controls had herbicide treatment)	Hatchell, 1981
Ripped to 60 cm	radiata pine	skeletal alluvium	2 yrs	13% increase in height over control; 70% increase in survival	Guild, 1971
Ripped to 100 cm	radiata pine	gravelly loam over clay	2 yrs	4% increase in height over control; 21% increase in survival (56% increase on poorly drained sites)	Craig, et al., 1977
Ripped to: (1) 45 cm (2) 120 cm	radiata pine	stony silty clay loam	11½ yrs	(1) 4% increase in height; (2) 5% increase in height (no information on survival)	Somerville, 1979
Contour ripped to 45 cm	radiata pine	eroded glacial	2 yrs	69% increase in height; 66% increase in survival	Ritchie, 1965
Ploughed: (1) 18 cm (2) 38 cm	Scots pine Lodgepole pine Jap. larch W. hemlock D. fir Sitka & Norway spruce	peaty gley podzol with hardpan	20 yrs	Douglas-fir: 35% greater height in deep ploughed plots after 15 yrs; 20% greater after 20 yrs Western hemlock: 15% greater height in deep ploughed plots after 15 yrs; 6% greater after 20 yrs (No nonploughed control)	Thomson and Neustein, 1973

growth and survival can be anticipated with tillage. However, Craig, Bren, and Hopmans (1977) report only a 4 percent improvement in height over the nonripped control while Ritchie (1965) reports a 69 percent improvement. Increases in seedling survival range from 8 percent (Hatchell, 1981) to 70 percent (Guild, 1971). Indeed, the range of values reported is quite large, and a decision whether to till and under what conditions based on information presented in the literature would be tenuous at best. Additionally, Thomson and Neustein (1973), in one of the few long term tillage studies existing to date, observe that the early improvement in growth rates on "deep" tilled versus "shallow" tilled plots decreases with time and that the early benefits derived from deep tilling were lost by the 15th to 20th year.[1] Unfortunately, Somerville (1979), in another long term study, did not include periodic measurements of height over the 11.5 year time span since the objective of that study was to assess windthrow resistance, and it was not revealed if similar reduction in growth rates with time were observed. It is unclear whether the favorable early growth response from tillage is one that will persist

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[1] The authors state that 33 cm depth of cultivation and 50 percent rupturing of the ironpan achieved on their study plots was considered adequate and represented the limit to what could be achieved with the equipment available at the time (1952). By today's standards, they admit, such a level of shattering would be deemed unacceptable, especially in light of the indurated conditions existing at the site. They hypothesize that the most vigorous trees may have fully exploited the shattered soil volume and may be limited by some other physical factor, e.g., summer drought or winter waterlogging, and that deeper cultivation might alleviate the problem. Unfortunately, a nontilled control treatment was not included in the design making it difficult to draw any further conclusions from the data they present.

through an entire rotation, and only careful, long term observation will reveal the answer.

Information gathered from greenhouse studies (Table 2) was as difficult to interpret as was that from the field studies. The difficulty was further confounded by the fact that only two of the studies used actual loosening of compacted soil as a treatment. Most used containers in which soil had been artificially compacted to different bulk densities thus destroying any effects due to aggregation. None used samples of tilled and nontilled soil collected in the field. Nevertheless, the inverse relationship between growth (either shoot or root) and bulk density is pronounced, although response varied greatly with soil type and tree species (Figure 2).

Study Objective

The objective of this study was to explore responses of tree seedlings to the changes in soil properties produced by conventional ripping practices. Information gathered on soil physical properties was reported as part of a parallel tillage study completed by Andrus (1982).

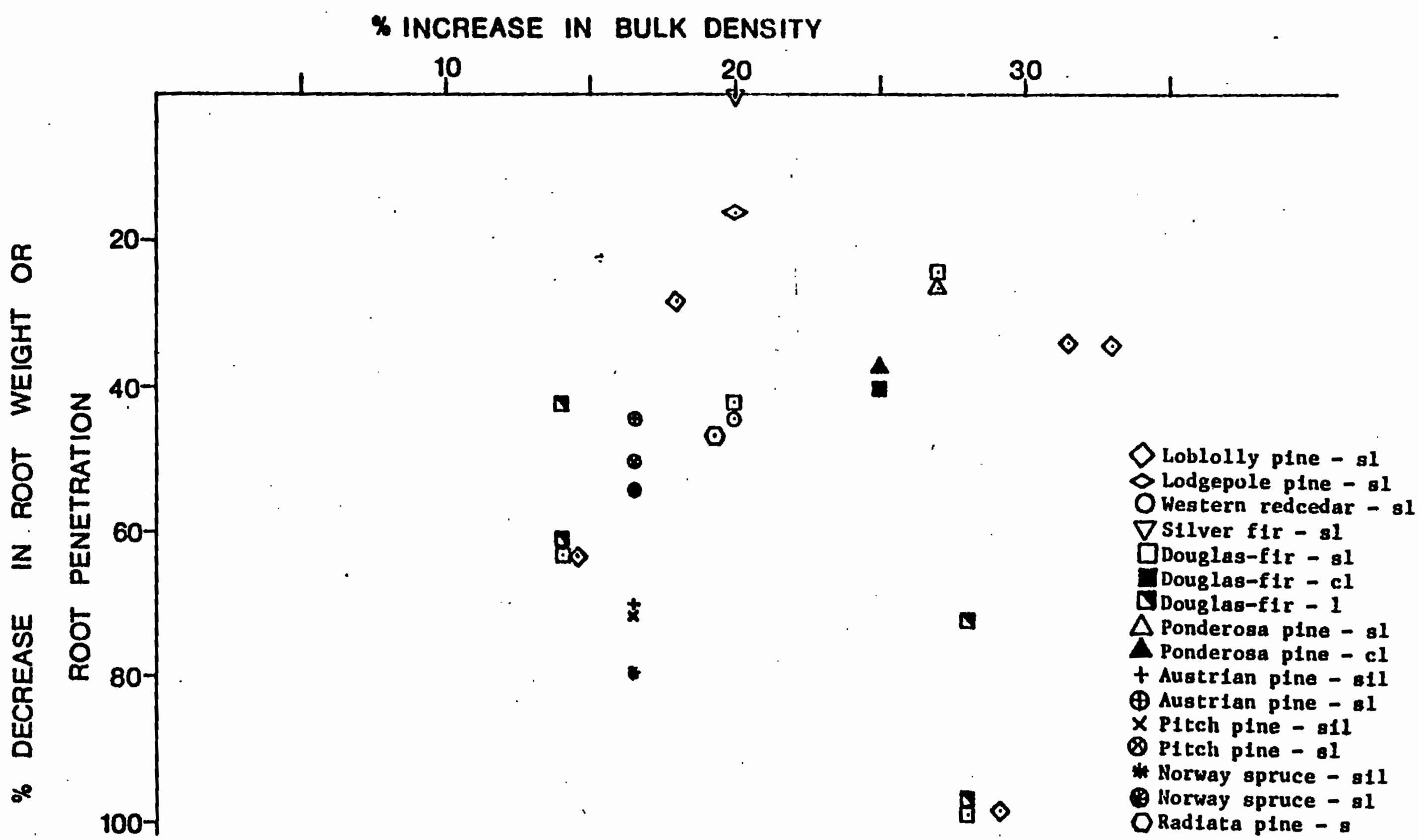
TABLE 2. Comparative results of greenhouse trials in evaluating growth responses to changes in soil bulk density.

Treatment Description	Tree Species	Soil Type	Time Span	Results (% change over control)	Reference
4 levels of bulk density in cores 6.3 cm (diam) x 22.6 cm (len) artificially created densities	pitch pine (1) Austrian pine (2) Norway pine (3)	silt loam sandy loam	4 mos.	species soil Δ root len. Δ bulk density (1) sil -71 +16.6 sl -50 " (2) sil -70 " sl -44 " (3) sil -79 " sl -54 "	Zisa, et al., 1980
field collected cores of undisturbed soil 10 cm (diam) x 13 cm (len); artificially created densities	loblolly pine	loam loamy sand clay	one growing season (?)	soil Δ root len. Δ bulk density loam -61 +44 loamy sand -44 +50 clay -64 +67	Foil and Ralston, 1967
3 levels of bulk density in 5 gallon cans; artificially created densities	Douglas-fir ponderosa pine	clay loam sandy loam	variable (11 to 40 wks.)	species soil Δ root wt. Δ bulk density fir cl -40 +27 sl -24 +27 pine cl -37 +25 sl -26 +25	Singer, 1981
3 levels of bulk density in 4½ gallon cans; artificially created densities	Douglas-fir W. hemlock	sandy loam	13 wks.	species Δ root len. Δ bulk density Douglas-fir +11 +44 -31 +74 W. hemlock +34 +44 -50 +74	Pearse, 1958
3 levels of bulk density in cores 10.2 cm (diam) x 36.6 cm (len) artificially created densities	radiata pine	sand	5 mos.	root wt Δ root vol. Δ bulk density -46.4 -47.8 +18.5 -12.5 -16.9 +9.6	Sands and Bowen, 1978

TABLE 2. Continued.

Treatment Description	Tree Species	Soil Type	Time Span	Results (% change over control)					Reference
3 levels of bulk density in cores 10 cm (diam) x 37 cm (len); artificially created densities	red alder (1) W. redcedar (2) lodgepole pine (3) Douglas-fir (4) Sitka spruce (5) Pacific silver fir (6) W. hemlock (7)	sandy loam	16 mos.	species	Δ root wt.		Δ bulk density		Minore, et al., 1969
				(1)	-25		+20		
				(2)	-44		"		
				(3)	-16		"		
				(4)	-42		"		
				(5)	+107		"		
				(6)	0		"		
				(7)	+267		"		
field collected cores of compacted soil 10 cm (diam) x 15 cm (len); loosening treatments: (1) 0 cm, (2) 7.5 cm, (3) 15 cm	loblolly pine	loamy sand (1) loam (2) silt loam (3) sandy clay loam (4) clay loam (5)	5 mos.		Δ root wt.		Δ bulk density		Hatchell, 1970
				treatment	7½ cm	15 cm	7½ cm	15 cm	
				soil					
				(1)	+152	+120	-13	-16	
				(2)	+67	+56	-18	-19	
				(3)	+2	0	-17	-20	
				(4)	-39	-46	-16	-17	
				(5)	+6	+12	-22	-17	
3 levels of bulk density (2 moisture levels) in cores 8 cm (diam) x 10 cm (len); artificially created densities	Douglas-fir	loam (2) sandy loam	1½ mos.	soil	Δ root len.		Δ bulk density		Heilman, 1981
				loam (1)	-42		+14		
					-72		+28		
				loam (2)	-61		+14		
					-98		+28		
				sandy loam	-63		+14		
					-98		+28		
5 levels of bulk density in cores 44 cm (diam) x 30 cm (len); artificially created densities	loblolly pine	gravelly fine sandy loam	19 wks.	Δ root wt.			Δ bulk density		Mitchell, et al., 1982
				-34			+33		

FIGURE 2. Reported changes in root configuration with increases in soil bulk density. (Data sources listed in Table 2.)



METHODS

The purpose of the research reported here was to determine the degree to which seedling growth and survival on compacted forest soils was improved by tilling the soil before planting. A twofold approach was utilized. The first study consisted of a field planting using 2-0 Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) seedlings in ripped and nonripped skid trails. The second study consisted of seedlings grown in a controlled environment. Douglas-fir and white fir (Abies concolor) were grown from seed in 15 cm diameter cores of soil extracted from ripped and nonripped portions of compacted skid trails and from adjacent undisturbed ground.

Site Description

The site chosen to conduct both the outplanting study and the soil core extractions for the growth chamber study was located within the Rogue River National Forest about 56 kilometers east of Medford, Oregon, in the Cascade Mountains. Elevation was 1,370 meters. Located atop a smooth, gently rounded basaltic plateau, the young residual soils within the 21 hectare harvest unit were moderately deep and loamy in texture (gravelly loam—USDA; GM--Unified), well drained, contained between 10 and 30 percent coarse fragments throughout the profile, and fell within Dunning's Site Class III. The unit had been logged during the fall and winter of 1979 under a shelterwood silvicultural prescription (approximately 55 percent of 1,050 m^3/ha removed). Crawler tractors and skidders were used to yard cut logs to landings located in the center of the unit.

Vegetation consisted of Douglas-fir, sugar pine (Pinus lambertiana), and white fir in the overstory and western red cedar (Thuja plicata), Pacific yew (Taxus brevifolia), chinquapin (Castanopsis chrysophylla), and several other deciduous shrubs in the understory. Grasses and thistle occupied bare soil surfaces.

Field Study Description

Study plots were grouped into three blocks and treatments within blocks consisted of compacted soil in skid trails, tilled soil in skid trails, and undisturbed soil adjacent to skid trails. Approximately 40 trees were planted in each plot (Table 3).

TABLE 3. Field trial sample information.

	No. of Trees Block		
	A	B	C
Treatment			
Compacted	40	42	40
Tilled	40	42	40
Undisturbed	40	43	40

Individual plots were chosen with the following criteria in mind: (1) uniform degree of shading, (2) plots within a block spaced within 15 to 23 meters from each other, and (3) relatively uniform ground surface on skid trails (i.e., no rutting or signs of puddling in compacted plots, evenly ripped trenches in tilled plots, and no "boulder fields" in tilled plots). In addition, (4) undisturbed plots could not show evidence of disturbance by logging activities. No litter displacement, vehicle track marks, bark scars on residual trees, or debris piles could be present.

The subsoiling operation took place in late August of 1980. A 53-horsepower tractor equipped with two 58-cm long ripper teeth spaced 140 cm apart performed the tillage in two offset passes. Measurements of soil bulk density and strength, as well as depth and volume of shattered soil, were taken on all plots. Bulk density was measured using a double probe nuclear densitometer and soil strength with a recording cone penetrometer. Bulk densities within the tilled plots were measured immediately after tillage and again the following spring at time of planting.

Approximately 40 2-0 bare root Douglas-fir seedlings were planted in each plot in March 1981. The trees were planted in a 60 cm by 60 cm spacing arrangement in order to maximize space utilization, especially within the undisturbed plots which tended to be irregularly shaped. Trees planted in the tilled plots were planted directly in the center of the tilled swath or fracture zone. "Vexar" tubes were placed over each tree after initial height measurements were recorded in order to reduce animal damage. It was planned to return to the site once a year for five years to record seedling height and overall condition. At the end of the fifth year, surviving trees will be extracted. At that time, shoot dry weight, leaf area, and root dry weight distribution will be measured.

Growth Chamber Study Description

Fifty-nine cores of soil were extracted from areas adjacent to those used for the field study plots. The extraction device used is similar in design to one developed by the Forestry Research Department of Crown-Zellerbach Corporation and works in the same fashion as coring devices used to sample soil for bulk density determinations. An inner plastic core, 15 cm in diameter and 32 cm long, is designed to fit snugly within the outer steel cylinder which has a sharp, case-hardened lower edge to aid penetration. Full penetration could only be achieved through the force exerted by a backhoe. The flat side of the bucket was placed against the top of the coring device and forced into the ground in a single downward motion. Care was taken to avoid excessive rocking of the bucket to prevent shattering of the soil mass within the cylinder. After removal of the plastic cylinder containing the core of soil, the bottom was planed smooth. Several layers of cheesecloth and a piece of wire mesh were secured to the bottom. The cores were transported to the Forest Research Laboratory on the Oregon State University campus.

The growth chamber used in the experiment was equipped with adjustable clock-driven temperature and light controls. Temperature settings of 24°C daytime and 18°C nighttime and a photoperiod of 18 hours were used in accordance with past research at the laboratory identifying temperature-photoperiod optima for maximum conifer growth.[2] The cores were arranged within the growth chamber in a

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[2] D. P. Lavender. Personal communication.

randomized block design and were systematically shifted within each of the blocks throughout the growth period. In addition to light and temperature controls, the chamber was retrofitted with a drip irrigation system. Individual small-diameter tubes fed water to each core at very slow rates. Vacuum gage tensiometers were installed in three randomly selected cores, one within each treatment, to determine when watering was necessary. In addition to the efficiency and labor savings, the system produced more uniform wetting of the soil mass, less tendency of creating surface puddling in the compacted cores, and required less handling of the cores.

Seed was obtained from Douglas-fir and white fir cones collected by Forest Service personnel. After sorting, stratifying, and germinating, the seed was sown at a rate of sixteen viable germinants per core, the two species being randomly assigned to cores within each of the three treatments. Three weeks after planting, newly emerged seedlings were thinned to four per core. Final numbers of cores and numbers of seedlings within each treatment are summarized in Table 4. Height measurements were taken 4 times during the 226-day growth period.

At the end of the growth period, the cores were removed from the

TABLE 4. Growth chamber trial sample information.

	No. of Cores		No. of Seedlings	
Treatment	White fir	Douglas-fir	White fir	Douglas-fir
Compacted	9	11	36	43
Tilled	10	10	37	37
Undisturbed	10	8	39	32

growth chamber. Stem diameter at the root collar and seedling height measurements were made prior to the placement of the cores in a cold room to await the destructive measurement phase of the experiment. Final processing and measurements were made swiftly to prevent any discrepancies between the first measurements and the last.

Each core was weighed and height of soil within the cores determined before the soil-plant mass was removed. Soil strength for the upper 10 cm of soil was measured using a ring penetrometer with a small diameter cone. The dry weight of soil was determined by removal of a sample of soil from the interior of the core volume for moisture content by gravimetric method. The tare weight of the plastic cylinder and accoutrements was deducted from the total weight and volume calculated from the height and circumference of soil to determine dry bulk density. (Weight of the seedlings was assumed to be negligible in comparison to the weight of soil.)

Roots growing down the space between the container wall and the soil was perceived as a potential problem early in the design phase of the experiment since roots growing in this zone of least resistance are not being subjected to the effects of the treatment being applied. The problem was alluded to by Minore, et al. (1969), but no mention was made of how best to alleviate the problem. Attempts to control the problem by planting seed in the center of the core and maintaining soil moisture at or near field capacity were futile. Hence, at the time the soil and seedlings were removed from the container, these "side roots" were marked with a soilution of rhodamine dye so that they could be distinguished and separated from the rest of the root mass.

The soil mass, with seedling shoot and root masses intact, was impaled on a nailed washing surface, and the soil was gently washed away from the roots. The seedlings were photographed against a grid background. Shoot parts were severed from roots at ground level and dry weights of needles and stems were determined. A simple regression between leaf dry weight and leaf area was determined for each species using a leaf area meter and samples of needles from several of the seedlings. It was then a relatively easy task to calculate leaf area from total needle dry weights. The root mass was severed at three depth increments--0 to 10 cm, 10 to 20 cm, and 20 to 30 cm. Side roots (dyed) were separated from the total root mass and dry weights determined for all samples.

RESULTS AND DISCUSSION

Field Study

A typical shattering pattern for ground tilled with two passes of the tractor on ground adjacent to the plots is shown in Figure 3. About 36 percent of the compacted soil mass was shattered assuming a compacted depth of 40 cm. The average depth of soil shattering was 14 cm, and very little shattering took place between tilled swaths as can be seen in Figure 3. Soil dry bulk density and strength values are illustrated in Figures 4 and 5 and in Table 5. Differences between treatments were tested statistically using analysis of variance and Tukey's Honestly Significant Difference test (Steele and Torrie, 1980).

Significant differences in bulk density were present at the 10 cm depth--the layer of soil most critical to water uptake and nutrition. However, reconsolidation of soil following tillage is likely to occur as a result of gravitational effects, animal activity, and precipitation. Precipitation, especially, plays an important role in the reconsolidation process by breaking down large aggregates through raindrop impact and slaking. Small aggregates or particles that become dislodged may form a surface crust or they may be carried downward with infiltrating water to either fill voids or coalesce with larger aggregates. The latter phenomenon was observed by Dexter (1976) who found that voids tend to become larger near the surface and smaller deeper down. It follows that the probability of any

FIGURE 3. Typical shattering pattern of soil in tilled skid trails.

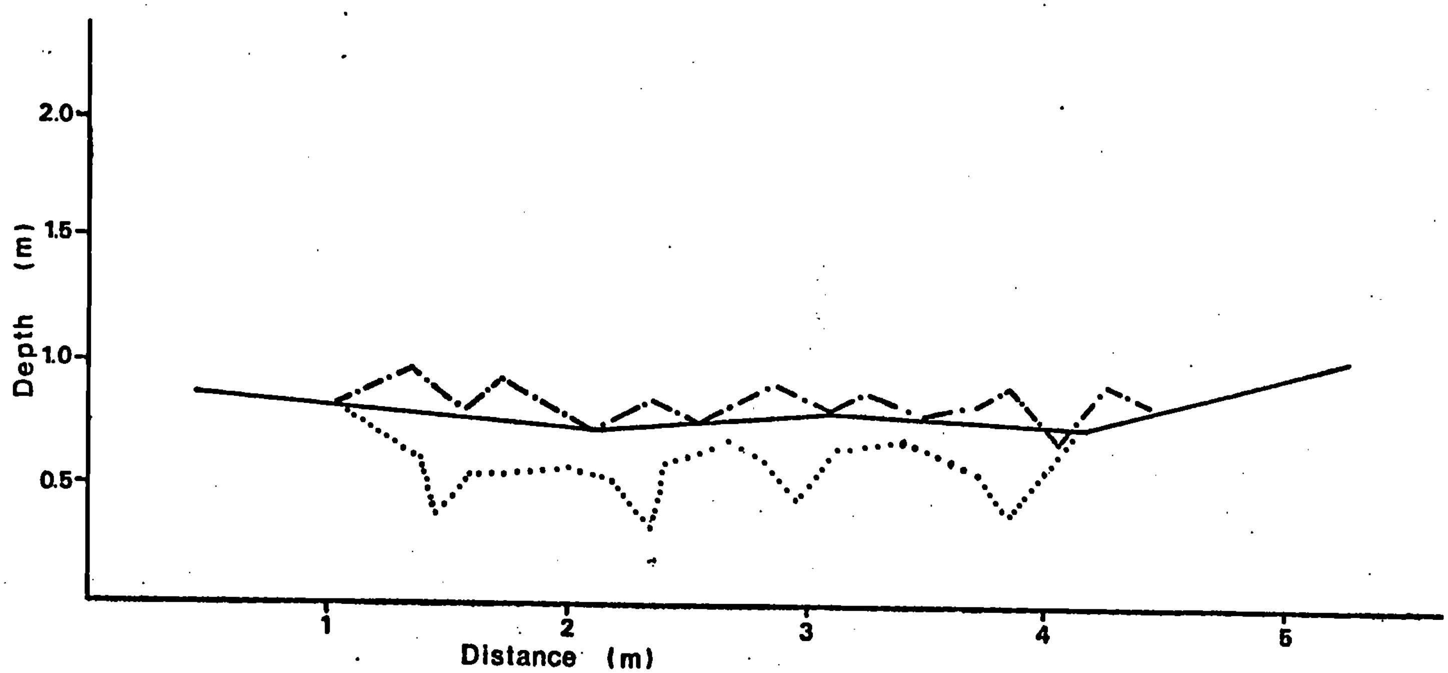

FIGURE 4. Bulk density profile for outplanting study plots.

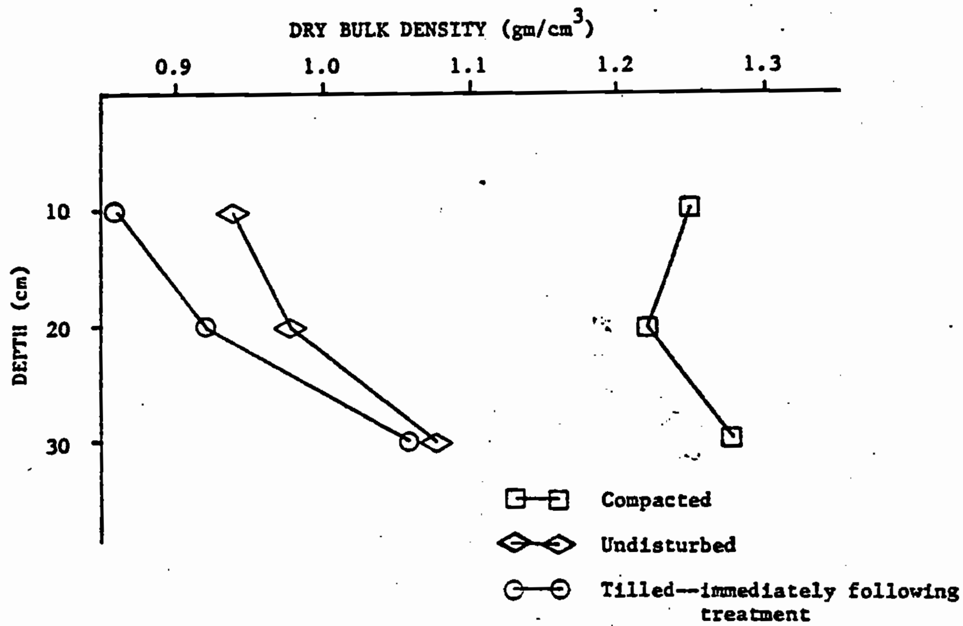

FIGURE 5. Soil strength profile for outplanting study plots.

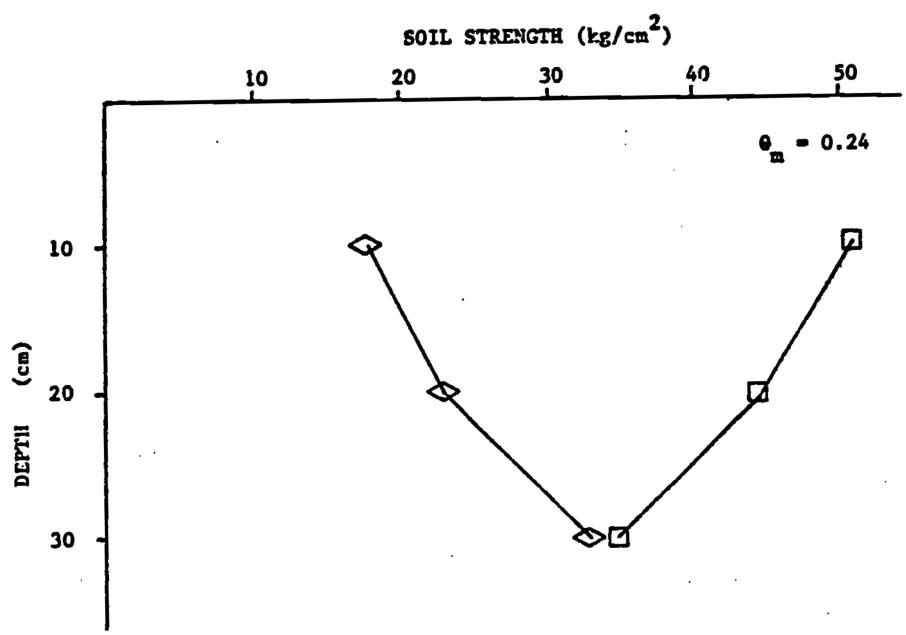

TABLE 5. Bulk density and strength of soil in outplanting study plots. Values within depth classes followed by the same letter are not significantly different using Tukey's Honestly Significant Difference test ($p < 0.05$). Insufficient information was available to test for differences in strength. (Standard deviations in parentheses.)

Depth	Bulk Density 10 cm	Bulk Density 20 cm	Bulk Density 30 cm	Strength ($\theta_m = 0.24$) 10 cm	Strength ($\theta_m = 0.24$) 20 cm	Strength ($\theta_m = 0.24$) 30 cm
	gm/cc			kg/cm^2		
Compacted	1.25a (.06)	1.22a (.07)	1.28a (.07)	51	45	36
Tilled	0.86b (.08)	0.92b (.07)	1.06b (.07)			
Undisturbed	0.94b (.01)	0.98b (.02)	1.08b (.02)	18	23	33

subsurface aggregate being larger than 5 mm increases with time (155 days) while the probability of any aggregate being larger than 1 mm decreases in both the surface and subsurface soil layers. Dexter also observed that the smaller aggregates tend to be sorted towards the bottom of the tilled layer. Thus, it is likely that reconsolidation of the tilled soil has occurred during the time since the original bulk density measurements were taken, and slightly higher values for tilled plots should be expected when bulk density measurements are retaken in the future.

Height and diameter growth measurements for the first two seasons after treatment are listed in Table 6. Table 7 lists absolute height and diameter measurements. Differences between treatments were not statistically significant ($p < 0.05$) for either height growth or diameter growth, although the analysis of variance indicated significant differences due to blocking for the first year's height growth only ($p < 0.02$). This would indicate that some other factor, perhaps rockiness, had intensified the planting shock or moisture stress experienced by the seedlings during that first year. However, problems with leader constriction within the "Vexar" tubes were observed making it difficult to get an accurate height increment due to the malformed stems. The tubes were removed at the time the second year growth measurements were taken. Percent survival likewise was not significantly different between the three treatments.

Reasons for the poor performance of seedlings in the undisturbed plots are unclear. Any residual vegetation within 2 meters of the

TABLE 6. Mean cumulative growth (present measurement - initial measurement) of outplanted seedlings for the first and second year after planting. Values followed by the same letter are not significantly different using Tukey's Honestly Significant Difference test ($p < 0.05$). (Standard deviations in parentheses.)

	1st Year		2d Year	
	Ht. Growth	Diam. Growth	Ht. Growth	Diam. Growth
	cm	mm	cm	mm
Compacted	8.85a	2.08b	21.11c	4.67d
	(.66)	(.19)	(2.55)	(1.28)
Tilled	9.35a	2.02b	20.56c	4.36d
	(1.07)	(.17)	(2.88)	(.88)
Undisturbed	8.17a	1.98b	17.01c	3.72d
	(.62)	(.44)	(4.90)	(1.34)

TABLE 7. Mean absolute growth measurements and percent survival of outplanted seedlings for the first and second years after planting. (Standard deviations in parentheses.)

	Year							
	0		1			2		
	Ht.	Diam.	Ht.	Diam.	Surv.	Ht.	Diam.	Surv.
	cm	mm	cm	mm	%	cm	mm	%
Compacted	24.20	4.71	33.05	6.79	99	45.31	9.38	98
	(1.82)	(.41)	(1.75)	(.25)		(4.28)	(1.43)	
Tilled	23.26	4.50	32.61	6.52	100	43.72	8.94	92
	(1.86)	(.41)	(1.39)	(.24)		(4.07)	(1.06)	
Undisturbed	24.30	4.73	32.97	6.71	100	41.31	8.35	96
	(1.43)	(.31)	(1.23)	(.13)		(3.48)	(1.04)	

plots was carefully removed. It was noted at the time the second set of growth measurements were taken that not all trees were planted in mineral soil, and, in some cases, a thick mycelial mat oftentimes penetrated mineral soil to a considerable depth. A large proportion of live roots from adjacent competing vegetation were also present near the surface in the undisturbed plots. This competition for water and nutrients could well explain the stressed appearance of seedlings in these plots. Further, seedlings growing in cores of undisturbed soil collected in the same area and having no such competition from surrounding vegetation showed none of the stressed characteristics noted in the field plots (See Figure 6a). If the root systems of these seedlings can manage to penetrate below this highly active layer to tap moisture deeper in the profile, their rates of development might improve to the point of overtaking growth rates of trees in the other two treatments.

Several researchers have noted distinct differences in sensitivity to poor handling techniques with older seedlings as compared to younger seedlings.[3] The use of containerized younger seedlings is becoming more popular because of their greater resistance to the effects of improper handling, but research directed at confirming these observations has yet to be undertaken. If these observations are correct, the effects of poor handling or planting of the 2-0 bare root stock used in this study could well be overriding any effects due to soil treatment.

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[3] D. P. Lavender. Personal communication.

Continued monitoring of the site over the remaining three years of the study will reveal whether the trends noted above will persist. Information on root form and morphology will be especially valuable in evaluating the reasons for the trends observed thusfar. Additional planting sites were installed the following year in which the effective shattering of soil was greatly improved by the use of more appropriate equipment. Data gathered from these areas will also aid in the interpretation of trends noted in this first study.

Growth Chamber Study

Variables measured in the growth chamber study were tested statistically using analysis of variance and Tukey's Honestly Significant Difference test. Mean bulk density and strength for soil cores are listed in Table 8. Treatment means and alpha levels of significance are recorded in Tables 9 and 10 for Douglas-fir and white fir, respectively.

Bulk Density and Strength. Soil bulk density measured in the containers after the growth period varied only slightly between the three treatments (Table 8). The values reported for the tilled cores fall within the range of bulk densities reported for the tilled outplanting plots after one year. Values reported for the undisturbed cores also fall within range of bulk densities measured in the field. However, the low levels of bulk density measured in the compacted cores compared to the measured field values are difficult to explain. The most likely source of error exists in the sampling procedure. If, at the time of sampling compacted soil,

TABLE 8. Mean bulk density and strength for soil cores. (Soil strength was measured for the surface 10 cm of soil only.) Values followed by the same letter are not significantly different using Student's t-test (α = .05). (Standard deviations in parentheses.)

	Bulk density	Strength (0 - 10 cm)
	g/cm^3	kg/cm^2
Treatment		
Compacted	1.05a (.05)	23.3a (θ_m = .20) (10.32)
Tilled	1.02a (.04)	12.6b (θ_m = .19) (5.26)
Undisturbed	0.98a (.03)	6.6c (θ_m = .19) (2.79)

TABLE 9. Means for measured variables in growth chamber study -- Douglas-fir. Values followed by the same letter are not significantly different using Tukey's Honestly Significant Difference test ($\alpha = 0.05$). (Standard deviations in parentheses.)

Alpha level	Variable	Compacted		Tilled		Undisturbed	
.25	Height - 27 days (cm)	2.80a	(.08)	3.09a	(.29)	2.89a	(.15)
.04	Height—74 days (cm)	4.90a	(.31)	5.70ab	(.06)	6.16b	(.66)
.05	Height—148 days (cm)	11.67a	(3.63)	16.76a	(.25)	17.52a	(.39)
.22	Height—226 days (cm)	18.47a	(2.93)	21.98a	(1.08)	21.64a	(1.24)
.03	Diameter (mm)	2.73a	(.29)	3.26ab	(.09)	3.38b	(0.0)
.07	Total Root Weight (gm)	1.29a	(.31)	1.77a	(.14)	2.05a	(.26)
.03	Root Weight* 0-10 cm (gm)	0.61a	(.09)	0.79ab	(.05)	0.95b	(.12)
.01	Root Weight* 10-20 cm (gm)	0.23a	(.06)	0.40ab	(.05)	0.45b	(.04)
.19	Root Weight* 20-30 cm (gm)	0.27a	(.12)	0.39a	(.05)	0.48a	(.11)
.05	Root Weight 0-10 cm (gm)	0.66a	(.10)	0.83ab	(.06)	1.02b	(.16)
.05	Root Weight 10-20 cm (gm)	0.30a	(.08)	0.50ab	(.03)	0.52b	(.07)
.37	Root Weight 20-30 cm (gm)	0.34a	(.14)	0.45a	(.07)	0.51a	(.12)
.27	Shoot Weight (gm)	1.23a	(.45)	1.77a	(.45)	1.96a	(.33)
.11	Stem Weight (gm)	0.39a	(.19)	0.69a	(.18)	0.75a	(.11)
.42	Leaf Weight (gm)	0.83a	(.27)	1.08a	(.27)	1.21a	(.26)
.41	Leaf Area (cm^2)	61.42a	(19.53)	79.59a	(19.98)	88.79a	(19.21)
.91	Shoot/Root Ratio	0.93a	(.12)	0.99a	(.18)	0.95a	(.10)
.94	Side Root Weight (gm)	0.18a	(.06)	0.19a	(.04)	0.17a	(.08)

*Excluding side roots.

TABLE 10. Means for measured variables in growth chamber study -- white fir. Values followed by the same letter are not significantly different using Tukey's Honestly Significant Difference test ($\alpha = 0.05$). (Standard deviations in parentheses.)

Alpha level	Variable	Compacted		Tilled		Undisturbed	
.83	Height—27 days (cm)	3.35a	(.08)	3.44a	(.34)	3.41a	(.13)
.34	Height—74 days (cm)	3.87a	(.14)	4.24a	(.48)	3.86a	(.09)
.07	Height—148 days (cm)	5.14a	(1.26)	7.46a	(1.57)	5.33a	(.39)
.21	Height—226 days (cm)	8.38a	(3.40)	11.64a	(.84)	8.49a	(.82)
.05	Diameter (mm)	2.26a	(.49)	2.93b	(.26)	2.33ab	(.07)
.11	Total Root Weight (gm)	0.58a	(.36)	1.06a	(.22)	0.66a	(.15)
.32	Root Weight* 0-10 cm (gm)	0.33a	(.15)	0.45a	(.10)	0.32a	(.07)
.02	Root Weight* 10-20 cm (gm)	0.11a	(.07)	0.26b	(.05)	0.16ab	(.03)
.03	Root Weight* 20-30 cm (gm)	0.08a	(.08)	0.30b	(.06)	0.16ab	(.06)
.33	Root Weight 0-10 cm (gm)	0.34a	(.15)	0.46a	(.10)	0.32a	(.07)
.03	Root Weight 10-20 cm (gm)	0.14a	(.09)	0.29b	(.06)	0.17ab	(.03)
.07	Root Weight 20-30 cm (gm)	0.11a	(.12)	0.32a	(.07)	0.17a	(.06)
.14	Shoot Weight (gm)	0.52a	(.24)	0.88a	(.17)	0.50a	(.16)
.38	Stem Weight (gm)	0.24a	(.13)	0.34a	(.08)	0.21a	(.08)
.08	Leaf Weight (gm)	0.28a	(.12)	0.54a	(.11)	0.29a	(.08)
.08	Leaf Area (cm^2)	25.91a	(11.59)	50.05a	(10.09)	28.36a	(5.74)
.28	Shoot/Root Ratio	0.95a	(.23)	0.83a	(.08)	0.74a	(.07)
.51	Side Root Weight (gm)	0.06a	(.06)	0.05a	(.02)	0.03a	(.01)

*Excluding side roots.

the edge of the device hits a small rock or root causing a momentary angular deflection in the downward path of the cylinder, the brittle soil mass within could shatter laterally creating a larger volume per unit weight. Thus, "compacted" soil cores could have artificially low bulk densities, while vibration of the cores during transport to Corvallis plus the consolidation produced by percolating water could artificially densify the tilled soil cores. A means of measuring soil bulk density within the cores at time of sampling would have been preferrable. Strength measurements taken in the cores were less than measured field values. (See Table 4.) This, however, is more easily explained since intensive root exploration would tend to loosen the soil. The root mass within nearly all the cores was concentrated in the upper 10 cm. Absolute strength differences between compacted and undisturbed treatments remained proportionally the same as they existed in the field indicating that the soil treatments were, in fact, distinct. Differences between treatments were significant and $p < 0.05$ using Student's t-test. It is interesting to note that the cone penetrometer was able to detect differences between treatments by recording the degree of resistance of some impeding layer of soil or clod which may be limiting normal root penetration. Thus, the strength of soil in field-collected cores may be a more sensitive index of soil conditions limiting plant growth than bulk density.

Cumulative Growth. Cumulative heights for Douglas-fir and white fir are recorded in Table 11 and illustrated in Figures 6a and 6b. It can be seen from the two growth curves that the response of the two species to treatments was distinctly different. In the first

TABLE 11. Mean height growth over time for seedlings in pots. Values followed by the same letter are not significantly different using Tukey's Honestly Significant Difference test (α = .05).

	Cumulative Height Growth			
	27 days	74 days	148 days	226 days
	cm			
Douglas-fir				
Compacted	2.80 (.08)	4.90a (.31)	11.67a (3.63)	18.47 (2.93)
Tilled	3.05 (.29)	5.70ab (.06)	16.76a (.25)	21.98 (1.08)
Undisturbed	2.89 (.15)	6.16b (.66)	17.52a (.39)	21.64 (1.24)
White-fir				
Compacted	3.35 (.08)	3.87 (.14)	5.14 (1.26)	8.38 (3.40)
Tilled	3.44 (.34)	4.24 (.48)	7.46 (1.57)	11.64 (.84)
Undisturbed	3.41 (.13)	3.86 (.09)	5.33 (.39)	8.49 (.82)

FIGURE 6a. Cumulative growth for Douglas-fir seedlings in pots.

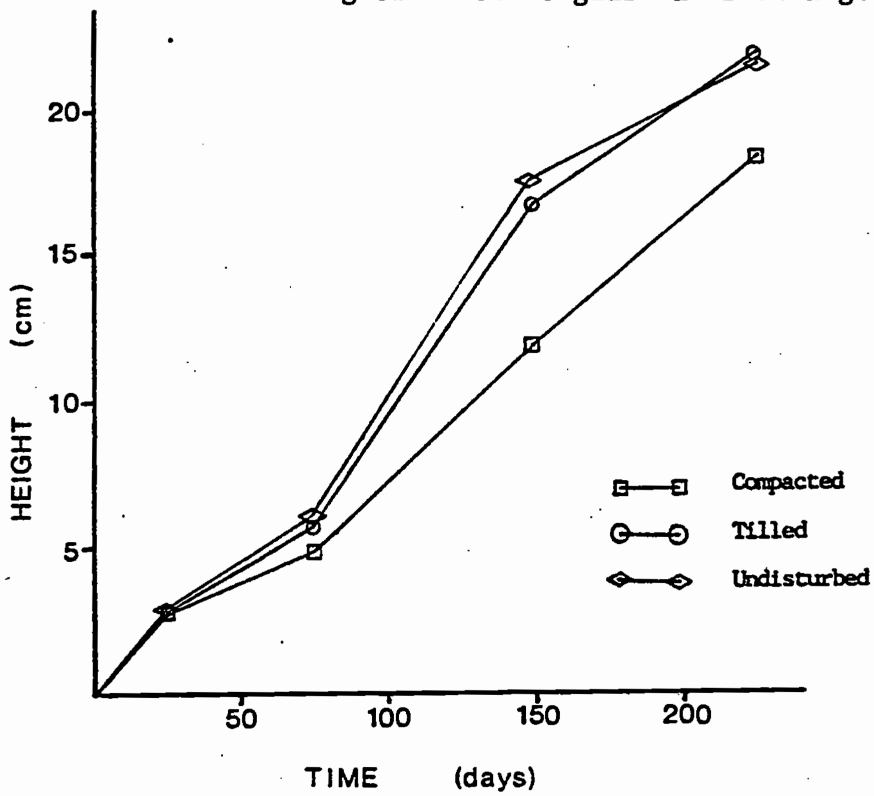
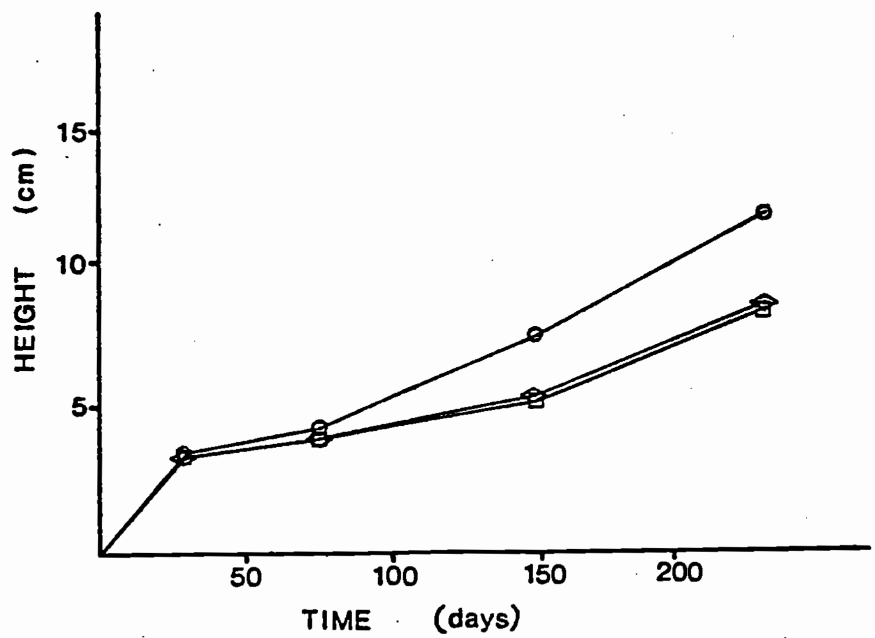


FIGURE 6b. Cumulative growth for white fir seedlings in pots.



place, the development of white fir is about half of that for Douglas-fir. More time was needed for the white fir seedlings to show differences due to treatments than was necessary for Douglas-fir, but none of the treatment means within each time increment were statistically different for white fir. Differences between treatments for Douglas-fir were present at 74 days and were still apparent after 148 days although differences between means were not significant at $p < 0.05$ level. Height differences at 226 days were no longer significant for Douglas-fir.

Stem Diameter. Mean stem diameters were significantly different for both species, and in both cases seedlings growing in compacted soil had smaller diameters than either of the other two treatments. However, white fir seedlings growing in tilled cores had the larger mean stem diameter of the remaining two treatments. Douglas-fir seedlings growing in undisturbed cores had the larger mean stem diameter. Again, varying species response to the treatments is apparent.

Root Weight. Separating side roots from the remainder of the root mass increased the precision of the analysis by intensifying the differences between means and thereby increasing the alpha level of significance, even though absolute values of side root weight were not significantly different. Species differences were again apparent as Douglas-fir seedlings exhibited differences higher in the profile (0 to 10 cm and 10 to 20 cm) while differences in root weight for white fir seedlings appeared in the lower portions of the profile (10 to 20 cm and 20 to 30 cm).

Means for other measured variables were not significantly different.

It is difficult to make any conclusive statements about the effects of the treatments on growth in this study since soil bulk density values indicate some change of the soil bulk density from its original condition took place during core extraction or handling. However, if the differences in soil strength are any indication of the true density of the soil aggregates in the cores, then certain statements can be made with respect to the overal success of this experiment. It was obvious during the washing process that in many cases the seedling root mass had occupied virtually all the available space in the core by the end of the experiment, especially in the case of Douglas-fir. The abrupt change in slope of the growth curve which takes place at 148 days (Figure 6a) indicates that root proliferation had peaked at this point for seedlings in the tilled soil and further growth was limited by pot constraints and not by soil constraints. Had the laboratory analyses for the Douglas-fir seedlings taken place at this point (after 148 days rather than 226 days), it is possible that more noticeable differences could have been observed. Significant differences in diameter growth and root mass lend support to this theory.

CONCLUSIONS

The information gathered from the growth chamber study indicate that soil tillage has the potential for enhancing the critical early stages of seedling development.

1. In both species, root biomass production in the top 20 cm was shown to have benefitted from soil loosening. Certainly under stressed conditions, seedlings with the greatest amount of absorbing root surface will fare better than those which have inferior root systems. Since moisture was maintained at or near field capacity during this experiment, seedlings in this study were not subjected to the stresses encounted under field conditions. Dyeing the roots growing in soil-pot interfaces provied to be an effective means of increasing the precision of total root biomass measurements.
2. Height growth at 148 days for both species indicated some improvement in growth of seedlings in tilled soil over those growing in compacted soil even though statistically significant differences were lacking at $p < 0.05$ level. The levels of significance were 0.051 for Douglas-fir and 0.074 for white fir.
3. For the size of pots used, growth of Douglas-fir seedlings should have been halted at around 150 days rather than the 226 days that growth was allowed to continue. This was discovered as a result of the final shape of the growth curves and by the extensive degree of root proliferation that had taken place.
4. As indicators of soil conditions, none of the above-ground meas-

urements were as effective as root biomass. A means of assessing growth response nondestructively would be preferable, and perhaps some other shoot feature such as internodal length or needle length would have been a more effective index.

The problems encountered during both phases of this study have been alluded to previously. To summarize they include:

1. Statistical variability. As with many other studies designed to measure biological responses, natural variability was responsible for many of the problems encountered in the statistical analysis. The fact that a 44 percent greater height of Douglas-fir seedlings growing in tilled soil over those growing in compacted soil (at 148 days) was not significant ($p < 0.05$) is evidence of the problems natural variability can cause. If the experiment were to be run again, in order to detect a difference in height of 5 cm at the $p < 0.05$ level, a sample size of 25 pots per treatment would be required.
2. Characterization of soil properties most limiting to plant growth. Soil bulk density in field-collected cores was discovered to be an inadequate means of representing conditions encountered by growing roots since disturbance during sampling, transporting, and handling, is virtually unavoidable. Soil strength, as measured by the cone penetrometer, was shown to be a more sensitive index to soil conditions within the cores. It was able to detect resistant layers or clods irregardless of the planes of weakness produced by sampling and subsequent handling.
3. Quality stock and planting technique. Results of the outplanting

study emphasize the importance of ensuring that quality planting stock and good planting technique are employed.

Differences between treatments were not observed in the field plots after two years, although differences may appear in the final years of the outplanting phase of the study. Information gathered from the two more recent study sites in which the extent of the tillage operation was superior to this first site will shed more light on plant-soil interactions taking place in tilled soil.

Careful monitoring of changes in soil properties through time on tilled soils represents an important key to future investigations. Measurements of other soil physical, chemical, and microbiological properties, such as heat and vapor transfer, nutrient availability, and mycorrhizal formation would also aid in the interpretation of growth responses noted in the field and in the laboratory.

Finally, the persistence of benefits gained from tillage, as pointed out earlier, is a topic that has yet to be explored. Continued funding support, personnel changes, and changes in research objectives will continue to hamper efforts to carry out long term studies into this and other areas. Yet, if improved timber yield and quality at the time of final harvest are deemed worthwhile objectives, then a strong commitment towards continued support for tillage studies and other related reforestation research will be necessary.

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