Soil Compaction From Ground-based Thinning and Effects of Subsequent Skid Trail Tillage in a Douglas-fir Stand

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Abstract

Although soil tillage has been used successfully to alleviate compaction of forest soil after logging in a number of management contexts, little is known about the feasibility of tilling in residual stands. In an attempt to weigh the benefits of tillage against possible damage done to residual trees during tillage, a study was set up to look at both immediate and long-term effects of various treatments in a second-growth Douglas-fir thinning.

Designated skid trails were laid out 46 m apart prior to ground-based logging with a rubber-tired skidder and a small crawler tractor. Pre-logging analysis consisted of penetrometer transects used to obtain a general indication of soil strength; during logging, machine movements along trails and turn characteristics were recorded. After logging, four of seven trails were tilled and approximately 40 trees were selected as study trees in each of three populations: (1) trees near untilled trails, (2) trees near tilled trails, and (3) trees away from any trails (control). Bulk density changes were measured in soil near trees in each population using a dual probe nuclear densimeter. In addition, tree and site characteristics, root and stem damage from logging and adjacent competition were recorded for each tree.

Untilled trails showed average increases in soil bulk density over control of 17.8 and 11.2 percent for 10.2- and 20.3-cm depths, respectively, but a decrease of 2.7 percent at the 30.5-cm depth. Tilled trail average bulk density showed a difference of 6.1 percent greater than control at 10.2 cm and 2.2 and 3.6 percent less than control for 20.3 cm and 30.5 cm, respectively.

Stepwise multiple regression used to explore associations between slope, number of vehicle turns, cumulative ground pressure, slash characteristics on trails, and interactions of all these variables showed no significant associations with bulk density changes due to logging. Analysis of Variance did reveal greater mean bulk densities at the 10.2- and 20.3-cm depths near trees on untilled trails where slash did not exist as compared to where slash did exist.

Root damage due to tillage was assigned to low, moderate or high damage classes based on length and diameter of roots exposed above ground after tillage. Analysis by regression showed that these root damage classes had significantly different tree diameters, revealing a possible trend of higher root damage for larger trees along trails being tilled.

A rough economic analysis estimated tillage for this project cost the Bureau of Land Management approximately $600/mile or $400/acre of tilled trail area. These figures are unusually high due to several factors including the small amount of work done for high move-in costs, complications brought on by research demands, and operator inexperience.

Introduction

Soil physical productivity on forest lands in the Pacific Northwest of the United States is receiving more attention as management of second growth conifer stands emphasizes more partial cutting to maintain or enhance timber yields while also providing desirable ecological or aesthetic characteristics. Soil compaction and displacement can occur over large areas as a result of multiple entries into stands by ground-based harvesting equipment, especially where logging trails are not reused in subsequent entries. These soil impacts have been shown to significantly reduce seedling and tree growth of important conifer species in the region. Tillage provides a means of alleviating forest soil compaction impacts, but there has been little information gathered about the effects of tillage of skid trails following thinnings and selective cuts.

Literature Review

Increased soil bulk density is most often used as an index of soil compaction and is defined as the mass of dry soil per unit volume of solid, liquid and gaseous phase (Froehlich and McNabb, 1984). Most productive forest soils in the Pacific Northwest are characterized by relatively low bulk densities, ranging from about 0.5 g/cm^3 to 0.9 g/cm^3, and as a result have high macroporosity, high infiltration rates and low soil strength (Froehlich, 1976). These physical soil properties interrelate with soil moisture and soil texture in a complex manner, but most of these forest soils are vulnerable to compaction from ground based harvesting and machine site preparation (Froehlich and McNabb, 1984).

Thinning and clearcutting prescriptions using tractors are among the management procedures most likely to produce compaction (Greacen and Sands, 1980). Ground-based logging machinery can cause compaction by a combination of tire or tread pressure, kneading action, vibration, and scarification and pressure from a turn of logs being skidded (Froehlich, 1974).

Skyline logging has shown considerably less impacts to soil than tractor (Aulerich et al., 1974; Power, 1974), but may be twice as costly and less feasible on gently sloping ground (Aulerich et al., 1974). Similar cost and feasibility problems are associated with helicopter, balloon or horse logging as compared to tractor logging.

The percent of harvested area covered by skid trails with traditional ground-based logging generally ranges from 20 to 35 percent for a single entry (Adams, 1991) and up to 80 percent on tracts where several intermediate cuts require subsequent entries (Froehlich et al., 1981). The area impacted by tractor operations can be greatly reduced by the use of designated skid trails, felling to lead and winching logs to the trails (Adams, 1991; Garland, 1983; Froehlich et al., 1981). A reasonable goal for area covered by skid trails is less than 15 percent including landings (Garland, 1983).

Production studies have shown the advantages and disadvantages of designated skid trails. Froehlich et al. (1981) observed a two-thirds reduction in both area covered by skid trails and damage to residual trees by using designated skid trails, falling to lead and winching to the trails in a partial cut of young-growth Douglas-fir. Bradshaw (1979) found that preplanned skidding and winching had 11 percent less production and was 29 percent more costly per unit volume as compared to unplanned skidding, but the preplanned area disturbed only four percent of the area as opposed to 22 percent for the unplanned area. Bradshaw's preplanned skidding winched old growth logs (average diameter 22 inches) one at a time and an extra choker setter was used, which increased costs.

Olsen and Seifert (1984) studied four types of tractor logging equipment and found that although designated skid trails did raise costs of logging marginally, costs would be recovered by reduction of damage to advanced regeneration (by 10 percent) and area compacted (by almost 50 percent).

Degree and depth of compaction are often related to the number of trips over skid trails by logging equipment. Steinbrenner (1955) found that under dry soil conditions near Mt. St. Helens, Washington, four trips with a tracked vehicle reduced macropore space by 50 percent and infiltration rate by over 80 percent. Hatchell et al. (1970) found an average of 2.5 trips on various test sites and soil textures on the Atlantic Coastal Plain resulted in densities within 10 percent of maximum attained after nine trips. Similarly, Froehlich (1978) observed the greatest increase in soil density after the first few trips of a low ground-pressure, torsion-suspension logging vehicle, and density continued to increase slowly in amount and depth with added number of trips up to 20.

The pattern revealed in these studies shows that most compaction occurs within the first few trips after which density reaches a plateau, and continues to increase slowly in amount and depth with subsequent trips. At the inflection of this curve, where leveling off begins, the majority of macropores in the soil profile have been compressed by the downward compacting force, and soil strength has increased to the point of balance with the forces acting on it (Greacen and Sands, 1980; Froehlich et al., 1980). The ability of a soil to resist compaction (soil strength) is dependent on the soil physical properties of particle size distribution, particle roughness, moisture content and organic matter content (Froehlich et al., 1980). It is important to note that these properties may vary widely between soil types, and the susceptibility of each soil to compaction is unique and warrants its own attention.

There is evidence that a litter layer of logging slash on a skid trail may act as a buffer and reduce the amount and depth of compaction (Froehlich, 1978; Kairiukstis and Sakunas, 1989; Zaborske, 1989). In addition, Sidle and Drlica (1981) found that uphill yarding caused a greater increase in soil bulk density than downhill yarding (25 and 45 percent increases for downhill and uphill yarding, respectively). However, these studies confirm that associations found between soil compaction and variables like slope and slash characteristics are often difficult to establish due to small sample size of most experiments (Sidle and Drlica, 1981) and the inherent variability of soil.

Soil moisture can greatly affect the degree of soil compaction caused by ground based vehicles (Soehne, 1958; Moehring and Rawls, 1970). Froehlich (1974) states that continued action and vibration of vehicles on soil where there is abundant moisture to lubricate shear planes will lead to severe breakdown of soil structure or "puddling". Steinbrenner (1955), analyzing reductions in macropore space and infiltration rate in soil after ground-based logging, found that one trip with a tractor under moist soil conditions was equivalent to four trips when soil was dry. Turcotte et al. (1991) observed that exposed mineral soil and deep wheel ruts from mechanized logging occurred more frequently on somewhat poorly and poorly drained soils than on moderately well-drained soils in North-central Maine. However, it must be noted that regardless of whether a soil is classified as moisture sensitive or insensitive, substantial compaction from most logging vehicles can occur at any moisture content, and soil moisture should not be the sole criterion determining where and when ground-based operations should proceed (Froehlich and McNabb, 1984). Indeed, there are portions of the Oregon Coast Range which contain soils that rarely fall below 45% moisture content which makes these soils susceptible to damage year round (Sidle and Drlica, 1981).

Field and laboratory experiments have shown that seedling height, weight and root length all decline with significant increases in soil bulk density regardless of soil texture. Youngberg's (1959) analysis of Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) seedlings through two growing seasons showed reductions in the growth of seedlings planted on skid trails, due in part to reduced aeration, less organic matter, critical moisture conditions and a corresponding decrease in available nitrogen. Foil and Ralston (1967) found similar limiting factors of poor aeration, mechanical impedance to root growth and poor moisture relations for loblolly pine (*Pinus taeda* D. Don) seedlings planted in bulk densities greater than 0.9 g/cm^3. Dissimilarly, Sands and Bowen (1978) deduced that water availability and aeration were not growth limiting factors to roots of radiata pine (*Pinus radiata* D. Don) seedlings in laboratory experiments but limitation of root penetration was solely a product of increased soil strength.

Using regression equations, Heilman (1981) estimated upper limits of both bulk density (1.74 to 1.83 g/cm^3) and pore space (27-30%) above which root penetration by Douglas-fir seedlings would not occur and found that, in general, root penetration declined linearly with increase in soil bulk density. Over a five-year period, Froehlich (1979a) observed 8.5 and 13.9 percent less height growth in Douglas-fir seedlings on 6- and 10-pass skid trails, respectively, when compared to seedlings in undisturbed areas.

Zisa et al. (1980) experimented with germination and growth of three conifers commonly found in northeast United States and found that although germination percentage was high in soil of high bulk density (1.8 g/cm^3), subsequent downward root penetration and growth was limited. Power (1974), Zisa et al. (1980) and Heilman (1981) noted that increased lateral growth occurred in the surface three inches of the soil to partially compensate for restricted downward movement. Through hydraulic washing of white pine (*Pinus monticola* Dougl.) root systems, Olsen (1956) observed 50-foot lateral growth of feeding roots in the surface four inches of soil as a result of compaction.

The effects of compaction tend to carry on into latter stages of the rotation as well, causing marked reductions in stand growth and overall volume. **Table 1** summarizes studies done on four conifer species affected by different degrees of compaction. Power (1978) stressed the importance of recognizing topsoil loss from logging along with compaction, and in experiments with 12-year-old Douglas-fir, he found an 11 percent decrease in height growth due

Table 1. Summary of studies on the effects of compaction on stand growth and volume in the Pacific Northwest.

Study	Species	Stand Origin	Age	Soil	% Increase Bulk Density	% Decrease in volume/growth
Power, 1974 /1	Pseudotsuga menziesii [Mirb.] Franco	Natural	55	Loam	30%	40% vol. /2
Froehlich & Berglund, 1976	Pseudotsuga menziesii [Mirb.] Franco	Thinned	34-80	Loam Sandy Loam Clay Loam	8-19%	/3 Mod. Disturb.- 14% gr. Heavy Disturb.- 30% gr.
Wert & Thomas, 1981	Pseudotsuga menziesii [Mirb.] Franco	Natural	32	Clay Loam	5-13% /4	11.8% vol.
Clayton et al., 1987	Pinus contorta [Dougl.] Lat.	Natural	15	Loam Silt Loam	Heavy - 31% /5	Heavy Disturb.- 44% vol.
Froehlich, 1979a	Pinus ponderosa Laws.	Plantation	17	Loamy Sand	Heavy - 45%	Heavy Disturb.- 69% vol. /6
Froehlich, et al., 1986	Pinus ponderosa Laws.	Natural after Partial Salvage	9-18	Loam	15%	20% vol.
Froehlich, 1979b	Tsuga heterophylla [Raf.] Sarg.	Thinned	22	Clay Loam	31%	15-17% gr.

/1 internal publication, not peer reviewed

/2 "vol." represents a reduction in overall stand volume

/3 "gr." represents a reduction in overall stand basal area growth

4/ calculated from Table 3, Wert & Thomas, 1981

5/ calculated from Table 3, Clayton et al., 1987

6/ calculated from table 6, predicted volumes by regression, Froehlich, 1979a to topsoil loss. The effects of increased bulk density and topsoil loss on growth of seedings and young stands should not necessarily be treated as a cause and effect relationship but rather an association (Froehlich and McNabb, 1984). In addition, inconsistent findings by various researchers should not be surprising considering the complex interaction of increased soil strength, decreased root penetration and growth as well as the inherent variability of soil density in undisturbed soils (Greacen and Sands, 1980).

Changes in the liquid and gaseous phases due to compaction can also have effects on the microbial and biochemical parameters of soil which can in turn affect nutrient cycling (Dick, et al., 1988). Dick et al. (1988) conducted experiments on the effects of compaction from logging and subsequent tillage on microbial biomass and soil enzyme activities in a 4-year-old clearcut. They found that compacted skid trails had significantly lower biomass C (38% decrease) and lower enzyme activity (41-79% decrease) in the 10- to 20-cm depth of soil as compared to undisturbed areas. Dick et al. (1988) attributed the decrease in microbial activity to two factors: (1) changes in physical properties such as decreased total porosity, air content, water infiltration rate, and saturated conductivity, and (2) the restriction of root growth, as the rhizosphere is known to promote microbial activity.

The extent to which soil will naturally recover depends on soil type and initial degree of compaction (Greacen and Sands, 1980). Agricultural studies have documented partial amelioration in the surface 20-25 cm where freezing and thawing, and wetting and drying occur, especially in clay soils (Voorhees, 1983). In soil with 40 percent clay, Perry (1964) estimated 40 years for recovery. Hatchell et al. (1970) estimated by extrapolated regression that it would take at least 18 years for soils of medium to fine texture beneath log decks to recover to the density of undisturbed soil. Both Froehlich et al. (1985) and Wert and Thomas (1981) found slow rates of natural recovery restricted primarily to the surface 15 cm, and Wert and Thomas

(1981) observed that heavy compaction persisted at 20.3- and 30.5-cm depths.

In light of slow rates of natural amelioration, tillage of compacted skid trails is being used to alleviate adverse soil conditions. **Table 2** gives four components of a good forest soil tillage method.

Experiments with various implements used for tillage, such as disk harrows, rock rippers and brush blades, have shown that although some situations warrant their use, they are often inadequate on forest soils with regard to the criteria listed in **Table 2** (Froehlich and Miles, 1984; Andrus and Froehlich, 1983). Consequently, the development and improvement of a winged subsoiler has shown promising results on a wide range of soils. Clay soils, however, have not responded well to tillage by any single implement yet tested.

Figure 1a illustrates the difference in design between a conventional ripper and the winged subsoiler. Based on extensive research with both agricultural and forest soils, the geometry of the winged subsoiler tine and attached wings have been designed to produce maximum upward force for significant shattering of compacted soil while keeping draft requirements to a minimum.

When discussing tine geometry and tillage effectiveness, an understanding of the concept of "critical depth" of tillage is crucial. Depending on soil moisture, soil strength and tine geometry, there is a critical depth beneath which desirable upheaving and shattering of soil ceases and is replaced by channelized, plastic flow and compaction as the tine moves forward through the soil (Andrus, 1982). **Figure 1b** shows an example of the improved performance of winged subsoilers over conventional tines with regard to critical depth. As seen in the upper diagram of **Figure 1b**, the inadequate design of conventional tines can lead to tillage that ignores the concept of critical depth and creates plastic flow of the tine through soil, compressing rather than shattering soil.

Table 2. Four components of a good tillage method (after Andrus and Froehlich, 1983).

1. The implement should completely loosen soil to the entire depth of compaction and across the entire width of the skid trail.

2. The implement should minimize the amount of large clods left and should not displace soil to the edges of the skid trail.

3. The implement should be rugged enough to till on irregular forest surfaces where rocks, woody debris and roots are common.

4. For economical tillage, the implement should be compatible with available logging equipment and should require only one pass for relatively complete tillage.

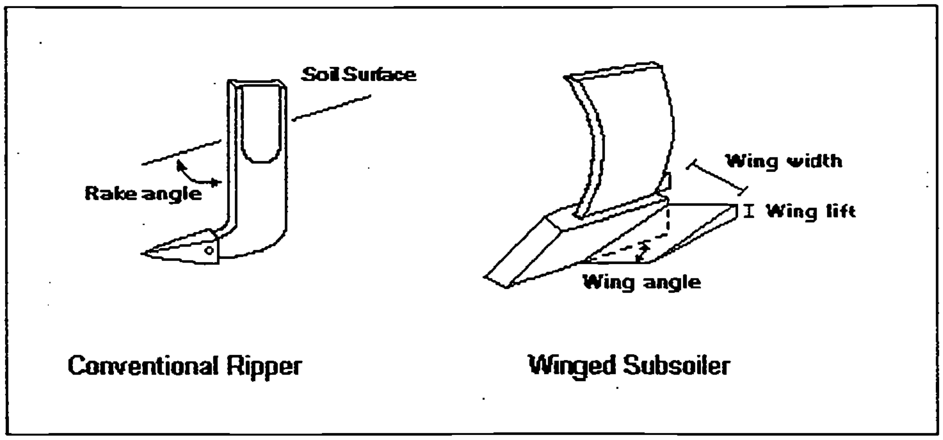

Figure 1a. Geometry of conventional and winged ripping tines (after Andrus and Froehlich, 1983).

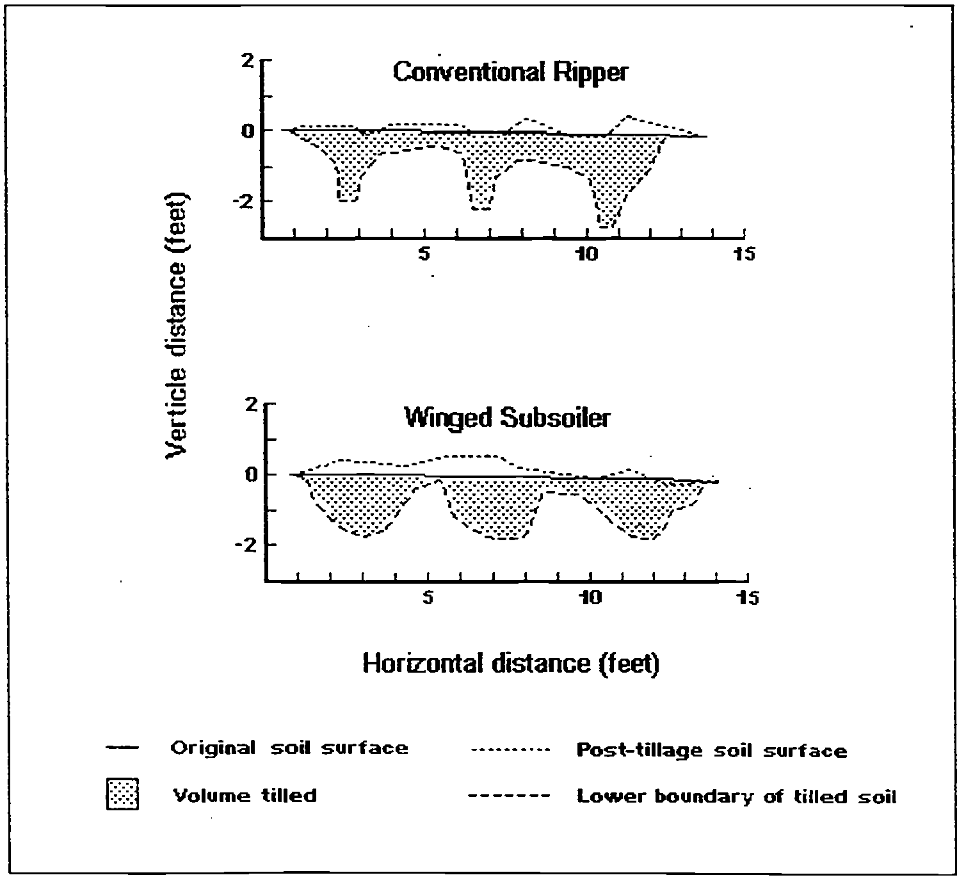

Figure 1b. Soil loosening patterns produced by conventional tines and winged subsoilers (after Andrus and Froehlich, 1983).

Eighty to 90 percent of compacted soil on a skid trail can be loosened with one pass of a winged subsoiler attached to a large crawler tractor when soil is dry or slightly moist (Froehlich and Miles, 1984; Andrus and Froehlich, 1983). Other methods such as disk harrows, brush blades and rock rippers have been shown to loosen only 20-45 percent of compacted soil volume. Improvements in the winged subsoiler such as individual shanks that release and reset hydraulically when encountering large obstructions, and hydraulically controlled tool bar lift have also contributed to its operability and compatibility with commonly used logging vehicles.

In addition to increases in aeration, water infiltration and root penetration as a result of subsoiling, research has also documented increases in microbial and biochemical parameters of soil. Dick et al. (1988) reported that subsoiling treatments of compacted primary and secondary skid trails significantly increased the biological activities, organic C concentrations, and total N concentrations to levels that were equal to undisturbed areas at depths of 10 to 60 cm. In a laboratory growth chamber experiment, Whitaker (1983) found that Douglas-fir seedlings growing in cores of tilled soil showed 44 percent improvement in height growth and 42 percent improvement in root biomass over seedlings planted in cores of compacted soil.

Although the winged subsoiler has been used effectively in clearcuts, questions exist over its potential use in stands where residual trees are at risk of root damage from tillage. The greatest proportion of water and nutrient absorbing surfaces for root systems are at a depth subject to changes produced by logging equipment (Froehlich, 1974; Burger et al., 1985). Roots damaged by logging can predispose trees to insect infestation (Moehring and Rawls, 1970), and in areas where root rot is a problem, wounded roots in contact with damp organic material pose an imminent threat (Olsen, 1956).

Study Objectives

This paper documents a study undertaken by Oregon State University for the USDI Bureau of Land Management of the effects of ground-based logging and tillage in a second-growth Douglas-fir thinning. Objectives of the study included the following:

1. Characterize soil strength on the study site prior to logging and relate to historical management of the site.
2. Observe both logging and tillage and document those factors that could adversely affect soil and residual trees on designated skid trails.
3. Characterize soil density around trees in compacted and tilled trails and compare to undisturbed soil conditions.
4. Designate and tag study trees in compacted, tilled and undisturbed areas that can be revisited in the future to analyze the effect of treatment on radial growth.

Site History

Agriculture was an important part of early settlement in this area, and grazing of dairy cows occurred on the study site from the early 1900s until approximately 1960. In the mid-1920s the site was logged, most likely using whipsaws or axes to fell the old growth. Spring board notches can still be seen on old growth stumps on the site where boards extended from the base of the tree and allowed timbermen better footing while chopping or sawing. Steam-powered engines or "steam donkeys" were used to yard logs downhill to a nearby railroad track where they were loaded on flatbed railroad cars and shipped to a local sawmill. Some reports suggest that old growth logs up to 2.5 m in diameter were skidded as far as 1.5 km or more before reaching loading areas, and trenches up to 2 m deep and 3 m wide are still visible on this study site and many other hillsides in the general vicinity. The clear presence of long trenches on aerial photographs from 1941 and 1952 substantiates these claims.

Shortly after the original logging occurred at this site, a mill was built near the southwest corner of the present-day unit. A large-scale wildfire burned through the area in 1927 and forced the closure of this sawmill. Judging from the current age of the stand, Douglas-fir naturally reseeded and became established in the area about eight years after the fire. On-site evidence suggests some minor salvage and firewood cutting has occurred in the past few decades but no records have been kept on these practices. Farming continues to a limited degree in this river valley today but grazing is now excluded from the site.

Site Description

The study site was chosen for its relative homogeneity of aspect, slope, soil and stand characteristics to allow feasible comparison between treatments. The area of analysis includes 7.5 hectares of a 9.6-hectare thinning unit managed by the USDI, Bureau of Land Management (Lat. 44 1'12", Long. 123 29'00", NE 1/4, NE 1/4, Sec. 11, T18S, R7W, Lane County, Oregon), located 25 km west of Eugene, Oregon (**Figure 2**). This area is located on the east side of the Coast Range of Western Oregon at an elevation of 190 m where weather is mild and temperate, receiving approximately 125 cm of precipitation per year, primarily as rain, between October and May.

At the time of thinning (summer, 1992) the stand overstory was 58 years old and contained nearly 100% second-growth Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) with small numbers of second-growth western hemlock (*Tsuga heterophylla* [Raf.] Sarg.). Thinning reduced stand density from 510 to 172 trees/hectare and trees removed consisted of both pulp and sawlogs averaging 25 cm in diameter. Total volume removed was approximately 300,000 board feet for an average of 31,380/hectare.

Slopes average about 14 percent with one small portion of the unit increasing to 30 percent. Based on deep soil cores taken on the site, it was found that two soil series are

Figure 2. Study site location

represented in the study area which include a predominance of the Jory series and a small amount of the Bellpine series on a knob at the top of the unit (both Clayey, mixed, mesic Xeric Haplohumults). According to the Lane County soil survey, these series are derived from sedimentary parent material (Tyee and Burpee formations) and are of silty clay loam texture near the soil surface increasing in clay content with depth (U.S.D.A. Soil Conservation Service, Sept., 1987). Average depth of litter layer on top of these soils ranges from 1.3 to 3.3 cm.

Understory species include heavy concentrations of vine maple (*Acer circinatum* Pursh) and salal (*Gaultheria shallon* Pursh), and lesser amounts of dwarf Oregon grape (*Berberis nervosa* Pursh), California hazel (*Corylus cornuta var. californica* [A. D.C.] Sharp), little wood rose (*Rosa gymnocarpa* Nutt.), cascara buckthorn (*Rhamnus purshiana* DC.), red huckleberry (*Vaccinium parvifolium* Smith) and ocean spray (*Holodiscus discolor* [Pursh] Maxim.). There are also approximately 10 Pacific yew (*Taxus brevifolia* Nutt.) trees that were flagged for protection during logging.

Methods and Procedures

PRE-LOGGING ANALYSIS

In early July, 1992, when weather was warm and dry, pre-logging analysis of soil on the site was conducted using a proving ring penetrometer to obtain a relative index of soil strength known as a "cone index" (Froehlich et al., 1980). A grid of east-west transects across the study area was laid out with transects 9 m apart, and penetrometer measurements were taken at 4.5 m intervals on these transects. At each measurement point, the penetrometer was pushed into the soil to a 30.5-cm depth and up to three readings were taken within a quarter-meter radius for an average value at each point. Readings taken from the dial indicator of the penetrometer are a measure of maximum deflection of the instrument's proving ring as the penetrometer shaft is being pushed into the soil to a consistent depth. The particular penetrometer used in this research was equipped with an LC-2B dial indicator which measures ten-thousandths of an inch deflection of a 250-lb capacity proving ring.

Field readings can then be applied to a calibration table (or equation) derived for the specific proving ring being used (see **Appendix 1**). The table provides the amount of force applied for any given deflection, which can be divided by the area of the cone (16°, 1.25 cm diameter in this case) at the bottom end of the shaft being pushed into the soil to obtain a cone index in kg/cm^2.

The results should only be used as a relative indication of soil strength, as numbers are highly influenced by soil moisture and the fact that soil strength varies tremendously, even within a small measurement area. In the end, the difference between the highest and lowest values for the entire range of measurements on this site was divided by three to establish low, moderate and high soil strength classes. **Table 3** shows the range of cone indices for each soil strength class and percent of the area covered by each class.

Also prior to logging, designated skid trails were laid out 46 m apart to reduce compacted soil area and ensure no more than 23 m winching distance from any given trail during logging (see **Figure 3a** for details).

LOGGING OF THE SITE

Logging began in late July, 1992, and continued through the third week in August. During this time, weather was hot and dry, lending to soil moisture less than 20% on all trails. Two small crawler tractors and a rubber-tired skidder were used in the logging (**Table 4**). One of the crawler tractors, a drive-to-tree, feller buncher equipped with a shear cutting head, was

Table 3. Estimated area covered by each cone index class in the study unit.*

Cone Index Class	Cone Index Range (kg/cm^2)	Percent Coverage
Low	< 25.2	4.7
Moderate	25.2 - 50.3	58.3
High	50.4 - 75.5	29.7
Inpenetrable	>75.5	6.1
Other**	-	1.2
		100.0

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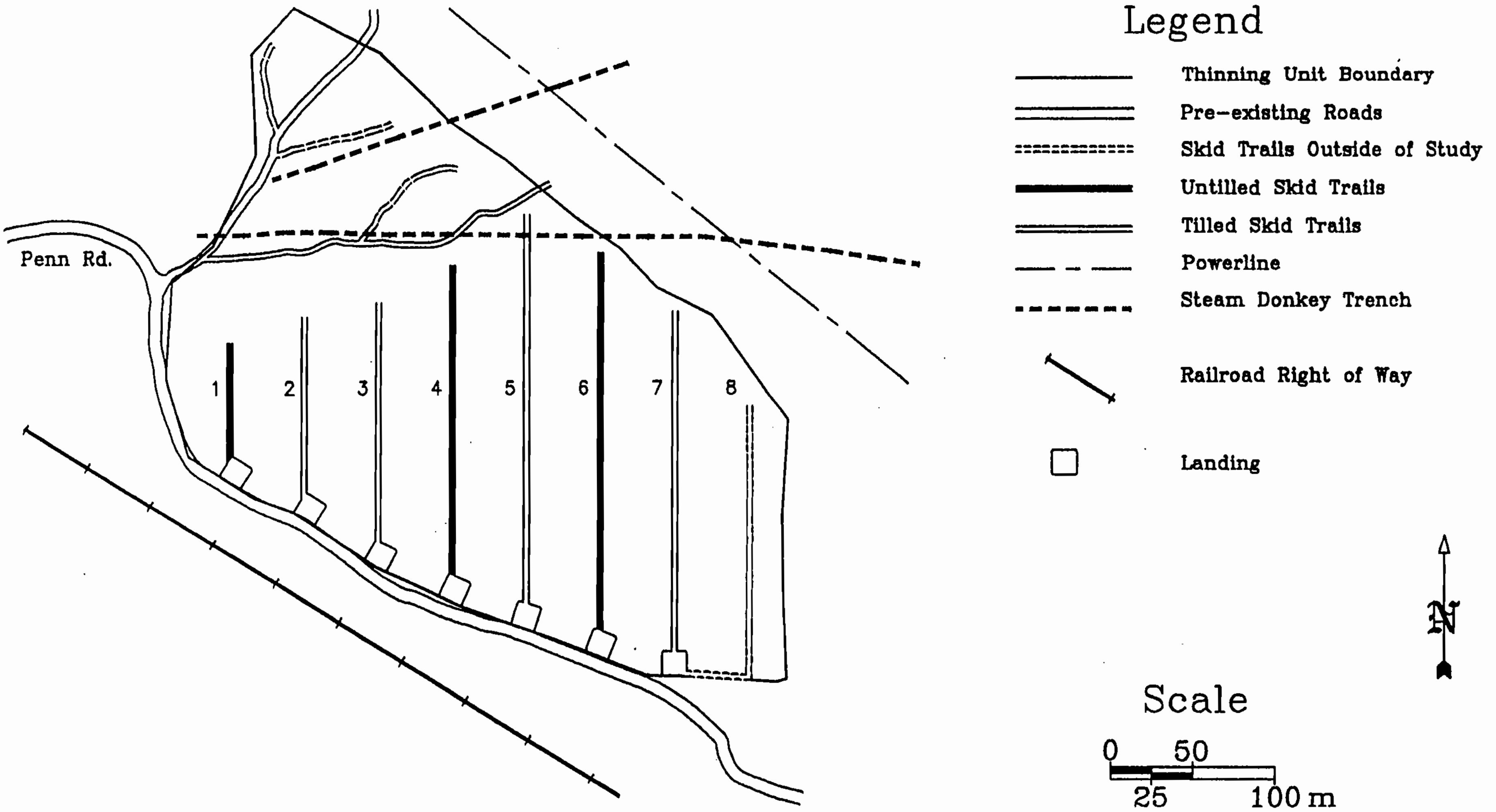
* Based on 10 samples covering the general area, soil moisture ranged between 13 and 20%.

** "Other" includes those areas where obstructions (i.e. large downed trees) precluded measurement.

Figure 3a. Lookout Unit 3 – Thinning



used exclusively to cut the designated skid trails. All other trees cut between designated skid trails were felled to lead by chainsaw. The second crawler decked logs on the landings at the base of each trail and did a minimal amount of skidding on the trails. The rubber-tired skidder did the majority of the skidding of whole trees and logs.

"Hot skidding" occurred during this operation where chainsaw felling was immediately followed by skidding. The rubber-tired skidder backed up the trail to reach each turn and then skidded the turn down the hill to a landing at the end of each trail (see **Figure 3a** for landing locations). Equipped with both grapple and drumline, the skidder would either grab easily reached pieces near the trail, or would winch pieces to the trail when needed. A sample of turn volumes and number of stems taken on two designated trails (**Appendix 2**) showed approximately 16 percent of the pieces skidded were saw logs (maximum 13.7 m, minimum 3.0 m) and the rest were whole trees (tops included) which were bucked at the landing into saw logs and pulp. Pulp and sawlogs were hauled together to a nearby mill where logs were separated for processing. As landings were relatively small, a self-loading log truck would pick up loads on a consistent basis to prevent large accumulations of wood on landings.

Table 4 gives approximate static weights and ground pressures for the logging equipment as well as estimated weight (and range of weights) of an average turn skidded to a landing. It must be noted that ground pressures of the logging vehicles were obtained by dividing unloaded vehicle weight by ground-surface contact area, which does not take into account dynamic pressure distribution during operation on various slopes. Mathematical models have been developed to determine theoretical ground pressure distribution under various conditions (Lysne and Burditt, 1983) and have been successfully used to predict soil compaction (Froehlich, et al., 1980). However, this study was not able to utilize these models for two main reasons. First, hot skidding only permits what has just been felled in between turn times to be skidded for each turn,

Table 4. Characteristics of three vehicles used in logging of the study site.

Machine Type	Rubber-tired Skidder	Tracked Crawler	Tracked Crawler
Manufacturer	John Deere 648D Turbo	Case 1150C with a Morbark 16" shear	Case 850D
Weight /1 Unloaded (kg)	12320	12690	7980
Tire/Shoe Size	30.5-32, 12 PR, steel-ply LS2	559mm	457mm
Ground Contact Area (cm)	25987 /2	24613	20164
Static Empty Ground Pressure (kPa)	/3 front - 53.9 rear - 39.1	50.6	38.8
Ave. turn weight (kg)	9310 (Range: 483-49874)	-	-

/1 Includes full tank of fuel and a 77 kg operator

/2 Ground contact at 5.1-cm penetration and recommended inflation

/3 Assumes weight distribution = 58% front, 42% rear which causes extreme variability in turn volumes and weights. One turn may include a single 50-cm diameter whole tree while the next includes seven 10-cm diameter whole trees. Secondly, interchangeable use of drumline and grapple during skidding confounds skidding line pull force and angle values needed for equations that predict theoretical ground pressure distribution. Given these and other problems, average ground pressure has been reported for this study, although higher dynamic pressures undoubtedly occurred. In addition, no effect of vehicle vibration, an important component of a machine's ability to compact soil (Cruse et al., 1980; Froehlich et al., 1980), is included in this study.

During the logging, movements of all three machines were recorded on each trail. 7.5-meter intervals were flagged along the trails and a machine pass was recorded when all four tractor tires of the skidder or the entire track of a crawler tractor passed a given 7.5-meter increment marker. One trip up hill and one back down past the same point was considered a turn by a vehicle. Turns by the rubber-tired skidder were usually easily recorded as it backed up the trail empty and returned back down the trail with a load of logs or whole trees. However, movements by the tracked crawlers tended to be less definite, including quick shifts back and forth, and quarter rotations which tended to knead and displace soil. At times, estimation of what was considered a turn was required and this became difficult at certain points along the trail, especially for the drive-to-tree feller buncher as it cleared the designated trails. Fortunately, the bulk of turns for each study tree were rubber-tired skidder turns as shown in **Appendix 3**.

In addition to machine turns, the number of skidder tires that left the trail while the operator was negotiating a turn of logs was sampled for a portion of the logging to ascertain how well the skidder operator stayed on designated trails (**Appendix 4**). Soil samples taken from skid trails after each day's logging and analyzed for gravimetric moisture content revealed soil moisture ranging from 16 to 20%. Also, post-logging analysis showed that approximately 7%

of the study area was covered by designated skid trails and 2% was covered by landings.

TILLAGE OF SELECTED TRAILS

In early September, 1992, after logging was completed, three of seven trails were chosen to be tilled (trails 2, 3, and 5). The three trails chosen were picked to provide an adequate number of tilled study trees (approximately 40) along these trails to compare to untilled and undisturbed residual trees. A winged subsoiler attached to a large tracked crawler was brought in to till the three trails. After some problems with logging slash obstruction and operator inexperience, a fourth trail (trail 7) had to be tilled as well to provide enough study trees for this treatment.

The hinderance of the tillage by logging debris on the first trails tilled quickly showed a need to clear the trails with a brush rake attached to the blade of the crawler tractor. Debris that accumulated in the tines of the subsoiler would displace surface soil, creating unwanted furrows. In addition, the inexperience of a first-time operator with the winged subsoiler proved to be an important factor, and trail areas next to some trees that had originally been chosen to demonstrate the tillage effect were not properly tilled. The most common error observed during the tillage was the lifting of the subsoiler shanks out of the soil to shake logging debris loose and not backing up to reenter the soil where the shanks had been lifted. This left certain stretches of trail either totally or partially untilled. The fourth trail was tilled after brushing of debris, and the combination of brush removal and experience gained from prior trails produced better results.

TREE SELECTION AND DATA COLLECTION

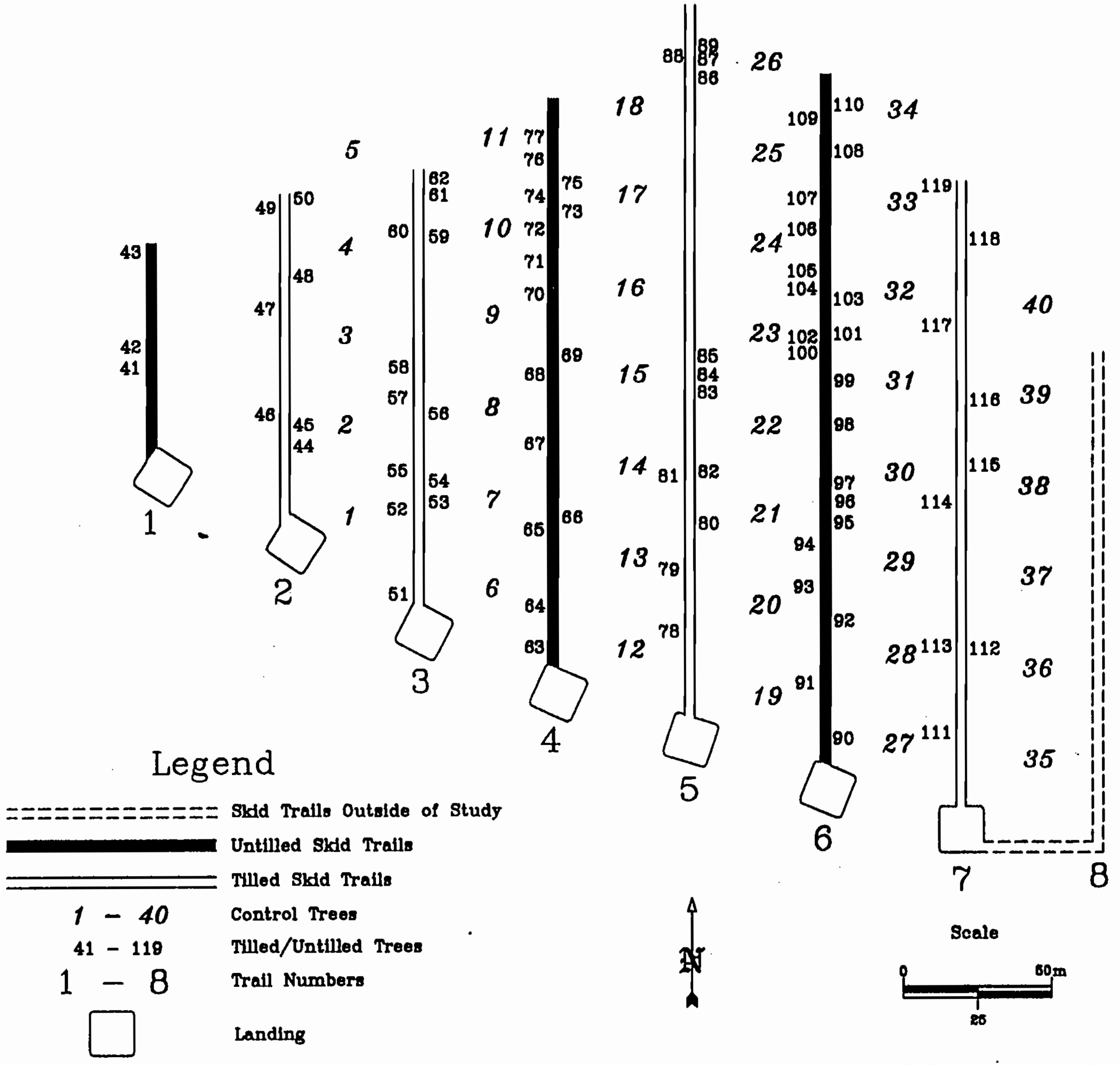
The next step in the study was to designate approximately 40 study trees in each of the two treatment areas (compacted and tilled) as well as 40 undisturbed trees. Trees chosen for each treatment were carefully evaluated to assure adequate proximity to the trail, adequate representation of the treatment in question and limited confounding effects from adjacent trees and stumps. General testing by penetrometer revealed inadequate tillage near many of the trees where slash raking had not occurred prior to subsoiling, and some of the trees deemed inappropriate to represent the tilled population were removed from the study.

Ultimately, 119 study trees were chosen which included 38 trees next to tilled trails, 41 trees next to trails left compacted by vehicles and 40 control trees located at 30-meter intervals in between skid trails (see **Figure 3b**). Each of these trees was tagged with a number on the north side to assure ease of relocation for future study. Eight months after logging and tillage, measurements of soil density as well as site and tree characteristics were taken at each of the 119 study trees. The short-term intent was to characterize the impacts of logging and tillage on the soil, and the long-term intent was to set up a growth study that could be monitored in years to come to see how growth is impacted by the treatments.

Soil wet bulk density was measured by a double-probe, portable nuclear densimeter (MC-1 Stratagauge, Campbell Pacific Nuclear, Martinez, CA). When probes are pushed into the soil to the same depth, the source and detector 30.5 cm apart count the number of gamma radiation particles that pass through a 6-cm wide swath of soil over a given amount of time. The amount of radiation that traverses the distance is inversely related to the density of the intervening material, and counts are applied to a calibration curve for the given depth of measurement to obtain wet bulk density. For each measurement, soil samples were taken to determine gravimetric moisture allowing calculation of dry bulk density in grams/cm^3 (see **Appendix 5** for details on probe calibration).

As seen in **Figure 4**, six soil density measurements were taken at tilled and untilled study trees (three on the trail and three off the trail) and three measurements were taken around

Figure 3b. Lookout Unit 3 Study Tree Locations



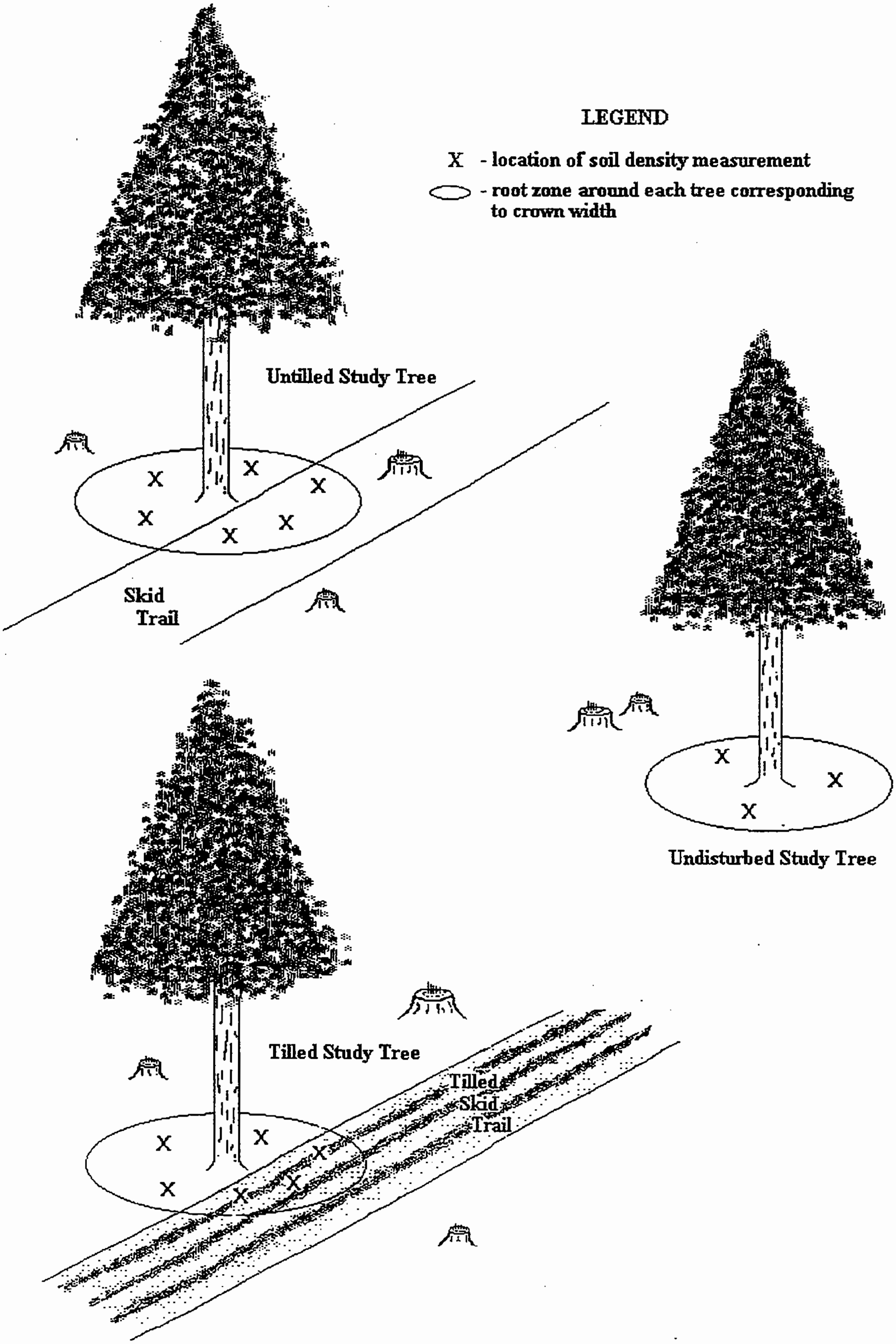


Figure 4. Examples of study trees in tilled, untilled and undisturbed populations.

undisturbed study trees. The measurements at each tree were confined to a circular root zone radius that corresponded to crown radius, based on the observation that the ratio of root spread to crown width averages from 1.1 to .9 in young Douglas-fir stands (McMinn, 1963; Smith, 1964). Ocular estimates of crown width were made on four sides of each tree and the maximum radius was used as the root zone radius for the tree.

Before each soil density measurement was taken, depth of slash and duff were measured and then removed to expose bare mineral soil. Holes 15.9 mm in diameter were prepared for the densimeter probes by pins driven through a steel guideplate. Both source and detector probes were then pushed into the soil to 10.2, 20.3 and 30.5-cm depths where counts were taken. From this data, an average density was determined at three depths for both the trail and non-trail sides of treatment study trees and an average density for three depths of undisturbed study trees (see **Appendices 6a** and **6b** for data and calculations).

Because future study on growth of these trees will seek to separate the thinning effect from treatment effects, comprehensive measures of tree and site characteristics were taken (**Appendices 7a-c**). Tree characteristics measured included tree diameter breast height, total height, crown class, crown length, crown area index and distance of each tree from the trail. Site characteristics included slope and aspect of the trail at each study tree. The diameter and distance of all trees and stumps influencing the study tree within a 12.2-m radius were recorded to calculate a diameter-based competitive stress index (CSI) (Arney, 1973). A CSI provides a relative index of competitive stress brought on by adjacent trees in a stand, and for this study, both a pre-thin and post-thin CSI were computed (**Appendices 8a** and **8b** give a sample calculation and CSI numbers for each study tree). A simple linear regression ($R^2 = 96.3\%$) based on measurement of diameter at both breast height and stump height of 603 standing trees in this CSI survey allowed estimation of diameter breast height for stumps needed to calculate pre-thin

CSI.

On the tilled trails of this study, an index of visible root damage from tillage was devised to analyze any possible association between tree or logging characteristics and root damage (**Appendix 7c**). At each tilled tree, the cumulative length of exposed and severed roots above ground was measured and an estimate of average diameter of these roots was made. Using these two numbers and subjective judgement, trees were placed into low, moderate or high root damage classes. Not only can these damage classes be tested for associations with other collected variables such as tree diameter or percent of root zone impacted by logging, but future growth information can eventually be collected on these trees and the data can be analyzed for differences between classes.

Any stem damage due to logging was measured for height above ground, length and width of the wound and a general description of wound severity. Wounds generally fell into three categories: superficial bark removal, wounds including cambium damage, and damage to the root collar at ground level (**Appendix 9**).

Results and Discussion

COMPARISON OF TREATMENTS

Figure 5 shows average bulk densities at three depths for tilled and untilled treatments and the control. The figure seems to indicate a unique pattern in bulk density change with depth for untilled, tilled and control populations. Multivariate repeated measures Analysis of Variance (ANOVA) revealed that the pattern with depth is indeed different for each treatment (Wilks' Lambda F-test, p=.0001). Furthermore, there is a significant difference between tilled and untilled average bulk densities at the 10.2 and 20.3-cm depths (ANOVA F-test, p=.0001 for both) but no significant difference at the 30.5-cm depth (ANOVA F-test, p=.3325).

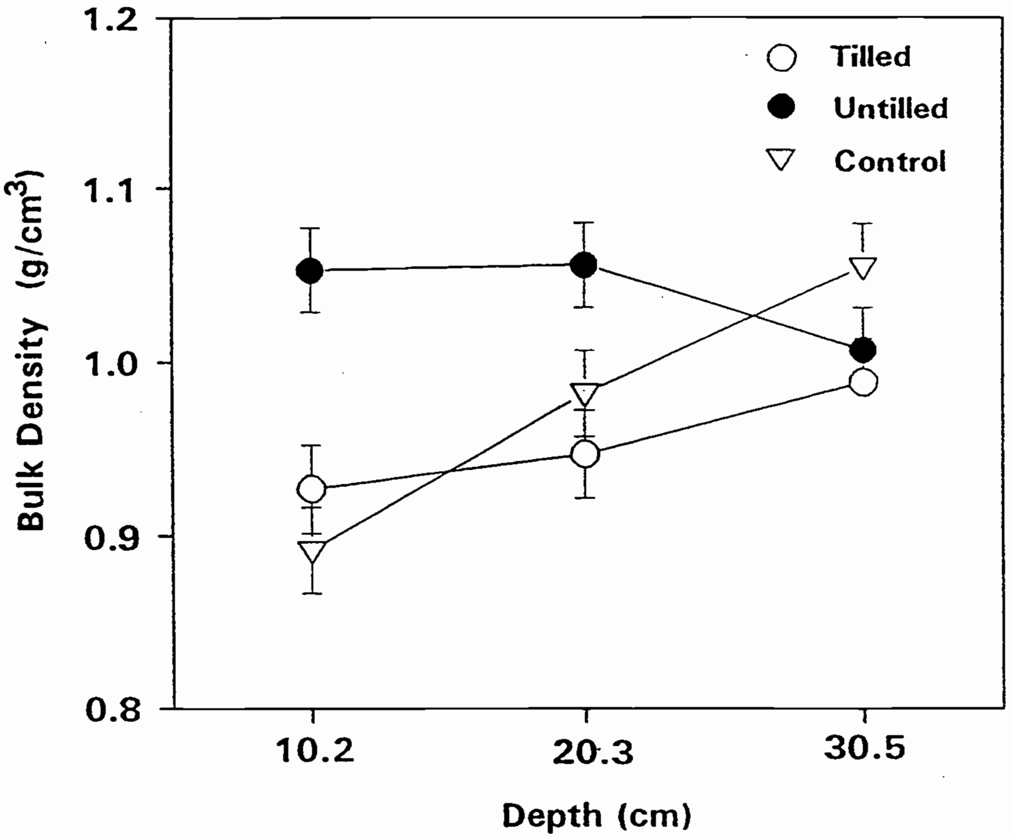


Figure 5. Average soil bulk density with standard error bars at three depths by treatment. Measurements at each depth are independent and error bars represent two standard errors above and below means.

The control population in **Figure 5**, representing trees undisturbed by logging trails, shows an increase in bulk density with depth which is characteristic of most undisturbed soils as the influence of organic matter, root penetration and soil fauna decreases with depth (Greacen and Sands, 1980; Froehlich and McNabb, 1984). In addition, soils of the Jory and Bellpine series characteristically increase in clay content with depth, as described earlier in this paper, and this would also lend to a greater bulk density with depth for the control population.

Untilled treatment means were compared to control means using Fisher's Protected Least Significant Difference test (LSD) for all three depths. The untilled population in **Figure 5** shows a significant increase in bulk density over the control at both the 10.2 and 20.3-cm depths (p=.0001 for both, .05 alpha level), but there is a significant decrease in bulk density from the control at the 30.5-cm depth (p=.0062, .05 alpha level). This anomalous decrease at 30.5 cm after logging is difficult to explain since one would expect either an increase or no effect from logging vehicles at this depth. One theory could be that vibration of logging vehicles loosens soil at lower depths, but more likely, this phenomenon may simply be a result of small sample size.

The tilled average bulk densities in **Figure 5** show the effect of tillage with the winged subsoiler. At 10.2 cm, the tilled bulk density is significantly different (greater) than the control bulk density (LSD, p=.0008, .05 alpha level). This implies that at the 10.2-cm depth, tillage did not loosen compacted soil to preharvest density. However, the density that was obtained by tillage (mean = .93 g/cm^3) is clearly an improvement over the untilled bulk density at this soil depth (mean = 1.05 g/cm^3). Average bulk densities are significantly different (lower) than control for both the 20.3 and 30.5-cm depths (LSD, p=.0479 and p=.0001, respectively, .05 alpha level), displaying the ability of the winged subsoiler to loosen compacted soil at lower depths. A corresponding increase in aeration, water infiltration and root penetration should be a result of tillage at all three depths.

As stated earlier, not only were independent control trees established for later growth analysis and comparison with treated trees, but each treatment tree has average bulk density measurements for both trail and non-trail sides (see **Figure 4**). By analyzing the difference between bulk densities on and off the trail, an adjustment is made for site specific differences that may have existed prior to treatment (see **Appendix 11** for data). A two sample t-test showed that mean non-trail bulk densities for both tilled and untilled populations generally were not significantly different than mean control tree bulk densities at all three depths (p=.7498, .2202, and .1381 for 10.2, 20.3 and 30.5-cm depths, respectively; .05 alpha level). Hereafter, differences between trail and non-trail bulk densities will be referred to as "adjusted bulk densities".

Figure 6 shows adjusted bulk densities, giving average differences between trail and non-trail sides of treatment trees at three soil depths. Multivariate ANOVA once again showed different patterns of density with depth for the two treatments (Wilks' Lambda F-test, p=.0001). A test for sphericity of this data revealed that a more powerful univariate analysis could be employed to confirm the multivariate ANOVA (Mauchly's Criterion, p=.2357), and once again showed a different pattern of bulk density with depth for each treatment (ANOVA F-test, p=.0001).

Adjusted bulk densities shown in **Figure 6** show the same statistical differences and similarities between treatments as discussed in **Figure 5** with one exception. The average difference between tilled bulk density and non-trail bulk density at the 20.3-cm depth is not significant (LSD, p=.0795, .05 alpha level). Essentially, what both **Figures 5** and **6** show statistically is that tillage creates a soil bulk density which is either very close to or less than original bulk density represented by the control. Future density measurements at tilled study trees can reveal if this condition persists with time.

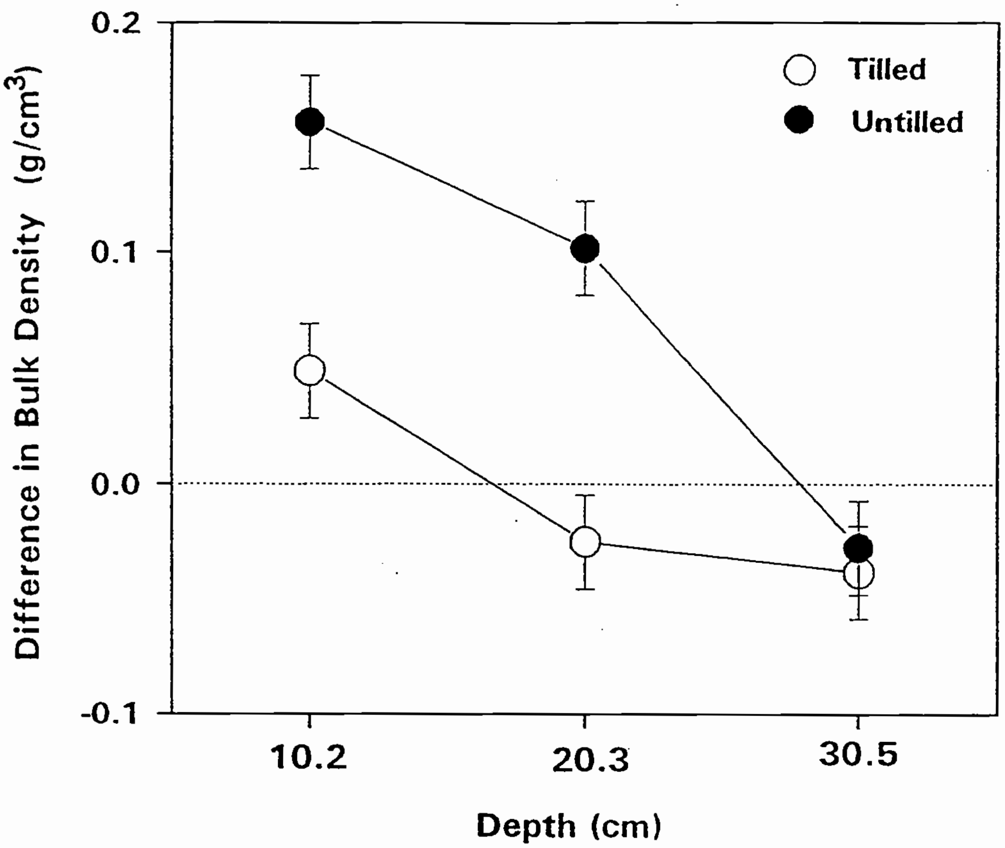


Figure 6. Average adjusted soil bulk density with standard error bars showing difference from control at three depths by treatment. Measurements at each depth are independent and error bars represent two standard errors above and below means.

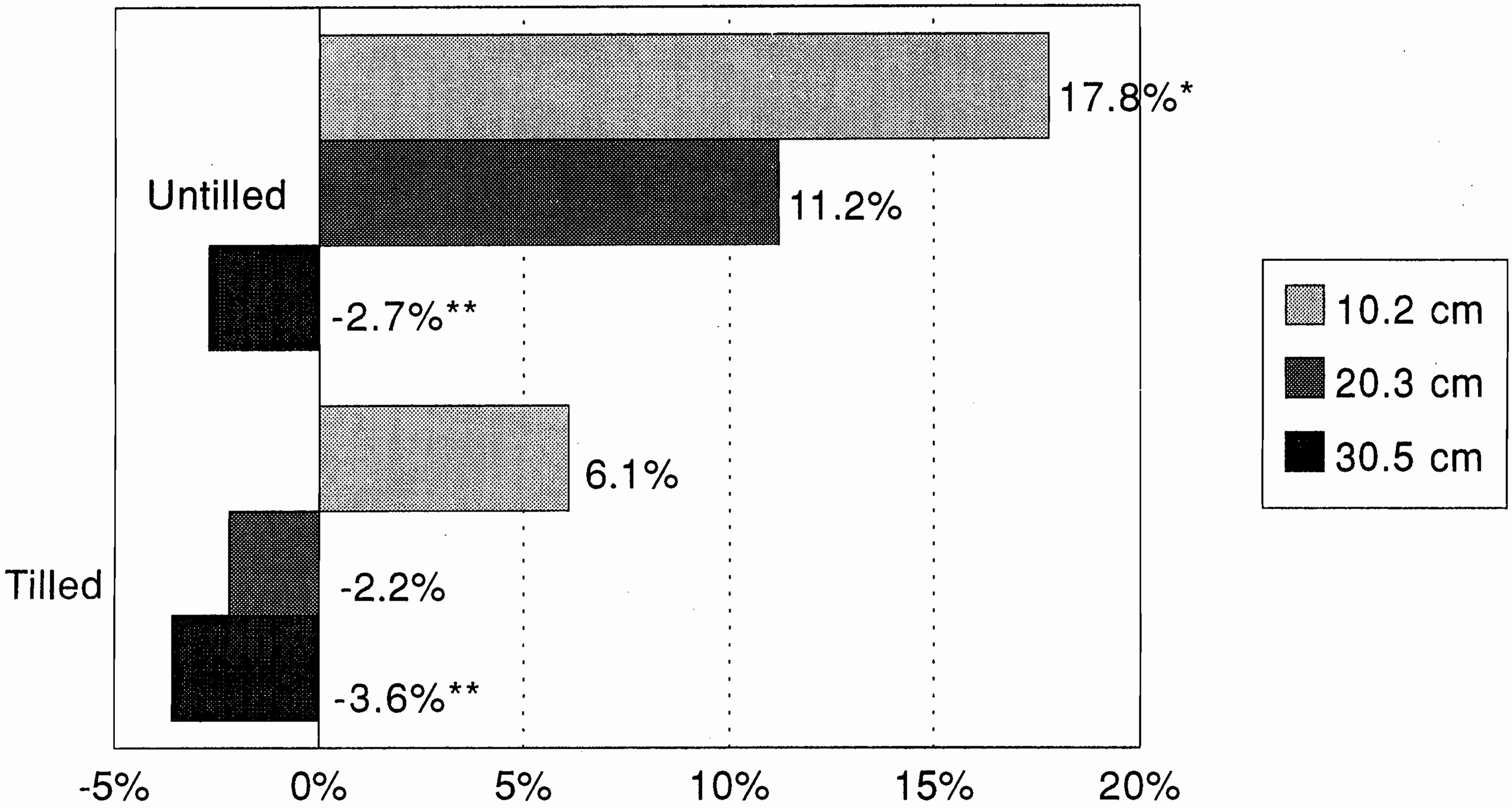
Figure 7 gives a final representation of the results in terms of an average percent increase or decrease in soil bulk density caused by treatment in comparison to undisturbed soil. As in **Figure 6**, percent difference is measured between trail and non-trail sides of trees along tilled and untilled trails. Some public forest managers use an upper threshold of 10% increase in soil bulk density as the definition of a detrimental impact for soils on the west side of the Cascades in Oregon (per conversations with USDA Forest Service and USDI Bureau of Land Management soil biologists, 1994). While both the 10.3- and 20.4-cm depths of the untilled population show an increase in soil bulk density above 10% (17.8% and 11.2% for the 10.3- and 20.4-cm depths, respectively), only the 10.3-cm depth is statistically greater than 10% (t-test, $p<.0001$, .05 alpha level). The tilled population shows percentages less than 10% at all depths. It must be noted that the use of percentages is highly dependent on the original bulk density of soil before disturbance, and inherent variability of soil as well as variability between soil types should lead managers to be cautious in extrapolating a percentage threshold to broad management areas.

TESTING FOR FACTORS RELATED TO COMPACTION

Stepwise multiple regression was used to explore what factors may be associated with compaction measured on untilled trails. Number of vehicle turns (one pass unloaded and one loaded), slash diameter and depth, slope, distance from the trailhead and interactions of all these variables were analyzed and no significant association was found between bulk density and any of the tested variables.

A machine-pass association with soil bulk density near 41 trees on untilled trails was tested in a number of ways. Past research has most often used a Log_{10} transformation of vehicle turns regressed against soil bulk density at each soil depth measured. This transformation as well as a number of root values of vehicle turns showed no association with either adjusted bulk

Figure 7. Average percent difference in soil bulk density between trail and non-trail sides of study trees along tilled and untilled skid trails.



* Percentage significantly greater than 10% at the .05 alpha level.

** Percentage significantly less than 0% at the .05 alpha level.

density or regular bulk density measurements (multiple regression R^2 values all less than 10%).

Another method of analysis took into account that all trails measured for bulk density change included the use of more than one type of vehicle and thus made the ground pressure effect at each study tree hard to quantify. By calculating a cumulative ground pressure index at each study tree, an attempt was made to negate the confounding effect of multi-vehicle pressures. The resultant index number represented a cumulative kilo-Pascal value representing all passes, both loaded and unloaded, and all vehicles that had impacted each study tree's root zone. Although this estimation was crude given that ground pressure distribution of machines varied tremendously with turn weight and slope of the trail, the index was an attempt to equilibrate machine passes between study trees. However, index numbers regressed against bulk density still showed no association and similar low R^2 values.

Although these results seem to contradict former research (Steinbrenner, 1955; Froehlich, 1978; Froehlich et al., 1980; Burger, 1985; Zaborske, 1989) there are notable differences in this study that may explain the discrepancy. As mentioned earlier in this paper, most prior research has shown that compaction occurs in the first 3-7 trips (turns) with change thereafter increasing at a much slower rate. As such, a theoretical curve would show a sharp initial increase in bulk density followed by a very gradual increase with a continued number of passes (Froehlich and McNabb, 1984). This study represents the far right of this theoretical curve where most of the trees analyzed (87%) near the trails received more than 10 vehicle turns. This is due mainly to the fact that designated skid trails, while protecting a major portion of a management area, will concentrate vehicle movement to a restricted area, causing a great number of turns to occur on each trail.

Past research has shown that logging slash of significant size and depth can serve as a buffer against compaction on trails (Froehlich, 1978; Froehlich et al., 1980; Kairiukstis and

Sakunas, 1989; Zaborske, 1989; Armlovich, unpublished), but no such trend appeared in the untilled trail data of this study analyzed by stepwise regression (**Table 5**). However, ANOVA did show that there was a significantly greater mean bulk density at both 10.2 cm (.05 alpha level) and 20.3 cm (.10 alpha level) for trees on untilled trails without slash than those trees with slash (p=.017 and .088 for 10.2 and 20.3, respectively). There was no significant difference in bulk density between slash and no slash trees at the 30.5-cm level (p=.8396).

Similar to this study, the absence of an association between slope and soil bulk density has been documented by other researchers (Sidle and Drlica, 1981). A fairly consistent slope throughout this study area precluded adequate comparison between various slope classes.

TESTING FOR FACTORS RELATED TO ROOT DAMAGE

Low, moderate and high root damage classes were analyzed by regression for any association with tree and logging characteristics. Independent variables tested included tree diameter, height, crown width and crown length, as well as percent of root zone affected by logging and competitive stress index. The analysis revealed an association between root damage class and tree diameter (p=.0027, .05 alpha level) and as shown in **Table 6**, mean diameters of the damage classes were significantly different at the .15 alpha level. This may indicate a trend of higher root damage for larger diameter residual trees, that have larger roots, than for smaller trees during tillage. Future growth analysis of these tilled trees may more clearly expose such a trend if it exists.

IMPACTS TO AREAS ADJACENT TO TRAILS

Prior research has shown that in the area three meters on either side of skid trails, a "transition zone" can be identified where tree growth following harvest is less than undisturbed

Table 5. Post-harvest slash characteristics on the trail side of 23 trees adjacent to untilled trails.

	Average	Minimum	Maximum	Regression p-value
slash depth	7.1 cm	1.3 cm	16.0 cm	.590
slash diam.	1.7 cm	1.3 cm	3.6 cm	.409

Table 6. Number and average tree diameters for three root damage classes on tilled trails.

Damage Class	Number of Trees	Average /1 Diam. (cm)
Low	18	38.7
Moderate	14	43.7
High	6	50.2

1/ Average diameters are all significantly different at the .15 alpha level.

areas but slightly greater than the skid trails themselves (Wert and Thomas, 1981). Observations made during logging of this study site revealed that the skidder would often have one, two, three or even four tires off the designated skid trail, either to protect residual trees while winching a turn or as just a commonly accepted operator practice. **Table 7** shows the results of a sample of 236 skidder turns which recorded the number of tires leaving the trail at the point of turn pickup (see **Appendix 4** for sampling data).

The results in **Table 7** suggest that over half the time, the skidder had at least one wheel off the trail, presumably in what has been referred to as the transition zone. Although soil density measurements were not made to verify the presence of a transition zone, at least a minor impact can be assumed in this area, especially where two rear tires were set off the trail and winching of logs shifted a majority of ground pressure to the rear of the skidder. However, the consequences of this impact should be weighed against the protection of residual trees, and in this study area, stem damage to residual trees was minimal. In addition, there were relatively little visible signs of soil disturbance in these transition zones aside from occasional soil exposure where the ends of logs being winched to the skid trail had scraped away slash.

Of the 79 trees analyzed along skid trails (38 tilled and 41 untilled), ten trees had some sort of stem damage due to logging. Five of these trees had wounds that cut into the cambium layer, three were superficial bark removal and two were damage to root collars at the ground level (**Appendix 9**). In future analysis, these trees can be tested for any possible effects on growth, although the small sample size is likely to preclude a rigorous analysis.

Table 7. Number and frequency of skidder wheels off designated skid trails at the point of turn pickup.

# of wheels off trail	# of turns observed	% occurrence
0	98	41.5%
1	62	26.3%
2	52	22.0%
3	18	7.6%
4	6	2.6%
	236*	100.0%

* This sample of 236 turns taken on trails #7 and #8 was only a subset of the total turns that occurred during logging.

Tips for Successful Tillage Within Residual Stands with a Winged Subsoiler

The following list includes some important points about tillage of skid trails using a winged subsoiler learned from this research:

1. Logging slash left on trails after harvest should be cleared to prevent obstructions during tillage. Slash caught in the tines of the subsoiler will build up, displacing soil and creating unwanted furrows in the tilled trail. Trail clearing with a brush blade is recommended where post-harvest slash has accumulated.

2. The most important goal of an operator is to maneuver the tractor on the trail while keeping the subsoiler tines fully submerged to allow tillage to the maximum depth with one continuous pass. Stopping to shift the tractor on the trail requires lifting of the subsoiler out of the soil and the length of trail needed for the tillage implement to re-enter the soil to maximum depth leaves sections of partially and totally untilled soil.

3. Regardless of whether or not the area being tilled has residual trees, stumps in the area will complicate tillage. Individually sprung tines of the winged subsoiler are designed to trip and reset to allow efficient tillage with these obstacles.

4. Operator experience is an important part of successful tillage. Even with past tillage experience in clearcut areas, an operator would have to gain new experience in what settings of the winged subsoiler work best (tripping pressure of tines; tine spacing; when to raise and lower tines) given the presence of residual trees, stumps and roots. With time an operator will gain an appropriate balance of experience and knowledge.

5. Once tillage has been completed, the only way to know if the ground has been properly treated is to push a penetrometer or long spade into the soil to the appropriate depth. A purely visual appraisal can not accurately and completely determine whether tillage was successful.

Economic Feasibility of Tillage

Stewart et al. (1988) devised an economic model that weighs the cost of tillage against projected losses of stand volume to see if tillage is a justifiable expenditure. The model takes into account factors such as skid trail density and related number of vehicle trips, changes in bulk density of soil, site productivity changes with multiple entries causing compaction, and production costs for various harvesting systems. Although the use of aerial harvesting systems to protect gentle terrain was not economically feasible, the model showed that tillage was costeffective under the most extreme compaction conditions created by various ground-based machines modeled. Using a 1984 tillage cost of $176/mile estimated by Froehlich and Miles (1984), Stewart et al. (1988) calculated that tillage would cost less than $20/acre and results of the model showed justifiable increases in yarding costs in the range of $86-$284 per acre depending on machinery, site index and discount rate used in the model. A re-evaluation of today's costs and benefits would most likely show the cost effectiveness of tillage, particularly in light of log prices which have more than doubled since 1984.

Circumstances surrounding the tillage done for this particular research project make economic analysis very difficult. The trails and landings tilled for this research totalled roughly 1/2 mile or approximately 2/3 of an acre. However, in undertaking tillage in this area with their own equipment for the first time, the Bureau of Land Management incurred costs for 3 1/2 days work, or about $3500. This included high move-in costs, extra mechanic labor to attach the subsoiler to a tracked vehicle and unexpected problems associated with the tillage such as having to bring in an additional vehicle equipped with a brush rake. Also, as mentioned previously, a learning curve must be assumed for operators attempting tillage for the first time.

The actual tillage itself lasted approximately 3 hours and the Bureau of Land Management uses two operators with their tillage vehicle (D6H Series II crawler tractor) at a rough estimate of $100 per hour ($40 for operators and $60 for machine). Using these numbers, tillage cost $600/mile or $400/acre. Undoubtedly, overall costs would decrease with increased operator experience, a larger amount of ground to till, and machinery set up to till on a regular basis.

Future Research on This Site

The eventual analysis of study tree radial growth and subsequent comparison between treatments in this study may provide the most compelling evidence for or against tillage in residual stands. At this time a judgement can not be made as to whether or not root damage from tillage does more harm to tree growth than the compaction that has been ameliorated. From this study, it was shown that approximately 1/3 of the root zone of each study tree was affected by a designated trail, depending on the distance of the tree from the trail. Questions to be answered by future research include whether the unaffected portion of the tree's root zone (2/3 of the root zone) can compensate for losses due to severed or damaged roots, if damaged roots will regrow, or if root damage will predispose tillage trees to disease.

In the final analysis, individual tree characteristics determining how trees will respond to thinning will be accounted for in order to identify how growth is affected by compaction, tillage or no disturbance. Some of the most crucial variables to account for are Competitive Stress Index, crown length and crown position in the stand. Radial growth will be measured by boring study trees on four sides and analyzing increment cores for the years since thinning.

Other possible areas of interest on this site would be to track any amelioration of trails and landings left compacted after this harvest, and remeasurement of tilled areas to see if loosened soil conditions have persisted or changed. Continued measurement of soil density over time will reveal if natural amelioration or resettling of soil is taking place in this temperate region where freezing and thawing are not prevalent.

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APPENDICES

Appendix 1 - Calibration Table for Proving Ring Penetrometer

Soiltest Inc., Evanston, Illinois

Proving Ring CN-970
Serial No.: 19936
Capacity: 250.00 lbs.
Calibration Date: Feb. 3, 1982

(POUNDS) = 0.315534922 * (DIAL INDICATOR READING * 100) - 0.1302874719

Correlation Coefficient = .9999850554

	Value in Pounds									
Dial Indicator X 100	0	1	2	3	4	5	6	7	8	9
80	26	26	26	27	27	27	28	28	28	28
90	29	29	29	30	30	30	31	31	31	32
100	32	32	33	34	33	34	34	34	34	35
110	35	35	36	37	36	37	37	37	38	38
120	38	39	39	40	39	40	40	40	41	41
130	41	42	42	43	43	43	43	44	44	44
140	45	45	45	46	46	46	46	47	47	47
150	48	48	48	49	49	49	50	50	50	51
160	51	51	51	52	52	52	53	53	53	54
170	54	54	55	56	55	56	56	56	57	57
180	57	57	58	59	58	59	59	59	60	60
190	60	61	61	62	62	62	62	63	63	63
200	63	64	64	65	65	65	65	66	66	66
210	67	67	67	68	68	68	69	69	69	69
220	70	70	70	71	71	71	72	72	72	73
230	73	73	74	75	74	75	75	75	75	76
240	76	76	77	78	77	78	78	78	79	79
250	79	80	80	81	81	81	81	81	82	82
260	82	83	83	84	84	84	84	85	85	85
270	86	86	86	87	87	87	87	88	88	88
280	89	89	89	90	90	90	91	91	91	92
290	92	92	93	93	93	93	94	94	94	95
300	95	95	96	97	96	97	97	97	98	98
310	98	99	99	100	99	100	100	100	101	101
320	101	102	102	103	103	103	103	104	104	104
330	104	105	105	106	106	106	106	107	107	107
340	108	108	108	109	109	109	110	110	110	110
350	111	111	111	112	112	112	113	113	113	114
360	114	114	115	116	115	116	116	116	116	117
370	117	117	118	119	118	119	119	119	120	120
380	120	121	121	122	122	122	122	122	123	123

Appendix 1 - Calibration table (cont'd)

	Value in Pounds									
Dial Indicator X 10	0	1	2	3	4	5	6	7	8	9
390	123	124	124	125	125	125	125	126	126	126
400	127	127	127	128	128	128	128	129	129	129
410	130	130	130	131	131	131	132	132	132	133
420	133	133	134	134	134	134	135	135	135	136
430	136	136	137	138	137	138	138	138	139	139
440	139	140	140	141	140	141	141	141	142	142
450	142	143	143	144	144	144	144	145	145	145
460	146	146	146	147	147	147	147	148	148	148
470	149	149	149	150	150	150	151	151	151	152
480	152	152	152	153	153	153	154	154	154	155
490	155	155	156	157	156	157	157	157	158	158
500	158	158	159	160	159	160	160	160	161	161
510	161	162	162	163	163	163	163	164	164	164
520	164	165	165	165	166	166	166	167	167	167
530	168	168	168	169	169	169	169	170	170	170
540	171	171	171	172	172	172	173	173	173	174
550	174	174	175	175	175	175	176	176	176	177
560	177	177	178	178	178	179	179	179	180	180
570	180	181	181	181	181	182	182	182	183	183
580	183	184	184	184	185	185	185	186	186	186
590	187	187	187	187	188	188	188	189	189	189
600	190	190	190	191	191	191	192	192	192	193
610	193	193	193	194	194	194	195	195	195	196
620	196	196	197	197	197	198	198	198	199	199
630	199	199	200	200	200	201	201	201	202	202
640	202	203	203	203	204	204	204	205	205	205
650	205	206	206	206	207	207	207	208	208	208
660	209	209	209	210	210	210	211	211	211	211
670	212	212	212	213	213	213	214	214	214	215
680	215	215	216	216	216	217	217	217	217	218
690	218	218	219	219	219	220	220	220	221	221
700	221	222	222	222	223	223	223	223	224	224
710	224	225	225	225	226	226	226	227	227	227
720	228	228	228	229	229	229	229	230	230	230
730	231	231	231	232	232	232	233	233	233	234
740	234	234	234	235	235	235	236	236	236	237
750	237	237	238	238	238	239	239	239	240	240
760	240	240	241	241	241	242	242	242	243	243
770	243	244	244	244	245	245	245	246	246	246
780	246	247	247	247	248	248	248	249	249	249
790	250	250	250	251	251	251	252	252	252	252
800	253	253	253	254	254	254	255	255	255	256

Appendix 2 - Sample of Turn Volumes and Composition

Samples were taken from trails #6 and #7. Large end diameters of whole trees and logs were estimated by eye during skidding. Volumes for whole trees were calculated using a simulated stand table (Pacific NW Region's Stand Projection System, v85.3) and log volumes were calculated using the Huber cubic foot rule (Dilworth and Bell, 1985).

Trail #6

# logs	# whole trees	Dbh	Total Volume (Cu. ft.)
1	3	1-12" log; 1-8", 2-4" whole trees	40.8
	4	ave. dbh = 6.0"	15.5
	2	1-14", 1-6"	43.5
	5	ave. dbh = 8.0"	52.5
	3	ave. dbh = 5.0"	7.4
	3	ave. dbh = 8.0"	31.5
	4	2-8", 1-10", 1-3"	40.0
	5	1-10", 4-6"	33.7
	5	ave. dbh = 7.0"	28.0
	3	1-10", 1-8", 1-6"	32.6
	3	1-6", 1-10", 1-12"	42.0
1	4	1-10" log, 4-6" whole trees	35.5
	1	20"	87.5
1	5	1-11" log; 2-6", 2-4" whole trees	34.5
	3	1-10", 2-6"	22.1
	3	1-24", 1-20", 1-6"	219.2
	4	1-10", 1-8", 2-6"	36.5
2	4	2-10" logs; 2-4", 2-6" whole trees	43.0
	3	1-25", 1-15", 1-12"	217.9
	3	2-25", 1-4"	289.4
	2	1-4", 1-25"	144.0
	2	8"	21.0
4		1-10"-36', 3-8"-25'	50.0
	4	1-12", 3-6"	39.2
	3	2-8", 1-6"	24.9
1	2	1-20" tree, 2-5"-10' logs	102.0
	3	2-12", 1-8"	65.6
	5	1-18", 2-8", 2-6"	98.8
	1	18"	70.0
	5	4-4", 1-6"	9.4
	4	3-4", 1-6"	8.0
	1	22"	107.5
	1	26"	153.0
	1	26"	153.0
	3	1-10", 2-8"	39.2
	5	3-8", 2-4"	34.3
	4	1-8", 1-6", 2-4"	15.8

Appendix 2, Trail #6 (cont'd)

# logs	# whole trees	Dbh	Total Volume (Cu. ft.)
	2	1-26", 1-24"	280.8
	4	1-12", 1-10", 2-8"	66.8
	2	10"	36.4
	5	1-12", 1-8", 3-4"	42.2
	2	10"	36.4
	1	12"	27.6
	4	2-10", 2-8"	57.4
	3	2-6", 1-8"	18.3
	3	1-20", 1-16", 1-6"	144.6
	3	2-6", 1-8"	18.3
	2	1-10", 1-26"	171.2
	5	3-4", 1-6", 1-20"	95.5
	4	1-25", 1-14", 2-8"	204.6
	4	1-14", 1-10", 1-8", 1-6"	72.2
	4	1-12", 1-10", 2-8"	66.8
2	4	2-10"-36' logs; 1-16", 3-6" whole trees	86.8

Trail #7

	3	1-10", 2-6"	26.0
	2	1-10", 1-8"	38.0
	2	1-10", 1-14"	57.8
1	1	1-8" log; 1-4" whole tree	15.8
	2	1-12", 1-6"	31.5
	3	1-8", 2-6"	18.3
	3	1-4", 1-6", 1-8"	15.8
	1	12"	27.6
	2	1-10", 1-22"	125.7
1	2	1-6" log; 1-4", 1-6" whole trees	9.3
3		2-22"-36', 1-16"-45'	205.0
	2	1-10", 1-5"	20.7
	6	1-8", 1-6", 4-4"	19.9
	3	1-10", 1-8", 1-4"	30.1
	3	2-10", 1-8"	46.9
	3	1-10", 1-8", 1-4"	30.1
	1	24"	127.8
	4	1-10", 1-8", 1-5", 1-4"	32.6
	2	1-20", 1-16"	140.7
	4	2-6", 2-4"	10.5
2		2-18"-45' logs	124.0
	4	1-16", 1-10", 2-6"	79.2
	3	3-4"	4.1
	2	2-14"	55.1
	4	1-10", 2-8", 1-6"	43.1

Appendix 2, Trail #7 (cont'd)

# logs	# whole trees	Dbh	Total Volume (Cu. ft.)
3		3-4"-25'	6.0
1	3	1-10"-35' log; 2-4", 1-6" whl trees	22.6
3	2	3-6"-35' logs; 2-4" whole trees	23.8
1	2	1-10"-35' log; 1-10", 1-8" whl trees	44.7
	5	ave. 6-8" whole trees	28.0
1	3	1-6"-36' log; 3-4" whole trees	11.1
2	3	1-10"-36', 1-10"-45' logs; 3-4" w t	60.1
4		1-12"-36', 1-12"-45', 2-6"-25' logs	63.0
4		1-16"-45', 3-16"-36' logs	179.0
	5	2-8", 3-4"	86.9
4	1	4-16"-45' logs; 1-4" whl tr	189.4
	2	6"	7.8
	5	2-8", 3-6"	32.6
	4	1-10", 1-6", 2-4"	24.8
	1	8"	10.5
	4	1-18", 1-10", 2-8"	109.2
	2	1-10", 1-6"	22.1
	3	1-12", 2-8"	48.6
1		1-10"-36' log	16.0
	1	1-10"	18.2
	1	1-8"	10.5
1	1	1-8"-36' log; 1-6" whole tree	13.9
2	1	1-12"-36', 1-8"-45' logs; 1-6" wt	42.9
2		1-10"-36', 1-8"-36' logs	26.0
1		1-14"-45' log	34.0
2	1	1-10"-36', 1-8"-20' logs; 1-4" wt	22.4
	1	1-18"	70.0
	2	1-8", 1-6"	14.9
2		1-8"-36', 1-6"-20' logs	12.0
	4	1-6", 3-4"	8.0
	2	2-10"	36.4
	2	2-8"	21.0
1	1	1-16"-36' log; 1-10" whole tree	62.2
	2	1-10", 1-8"	28.7
3	1	3-4"-10' pulps; 1-6" whole tree	9.9
1	1	1-10"-10' log; 1-10" whole tree	23.2
	2	12"	55.1
	2	6"	7.8
	3	1-8", 2-6"	15.9
	1	12"	27.6
1	1	1-10"-45' log; 1-6" whole tree	22.5
	3	1-10", 1-8", 1-6"	32.6
1	2	1-6"-35' log; 1-10", 1-8" whl trees	35.7
	4	2-10", 2-4"	39.2

Appendix 2, Trail #7 (cont'd)

# logs	# whole trees	Dbh	Total Volume (Cu. ft.)	
1	1	1-16"-36' log; 1-4" whl tree	39.4	
2	2	2-4"-20' pulps; 2-6" whl trees	11.8	
1	2	1-6"-25' logs; 1-10", 1-8"	33.7	
1	5	1-10"-45' log; 10", 8", 2-6", 4" wts	53.8	
2	1	2-12"-45', 1-14"-45' logs; 1-4" wts	83.4	
	3	2-12", 1-6"	59.0	
	2	2-6"	7.8	
	3	2-10", 1-6"	40.3	
	3	10"	18.2	
	3	1-8", 2-6"	18.3	
	5	10", 8", 6", 2-4"	35.3	
2		2-14"-45' logs	70.0	
	2	2-4" whole trees	2.8	
69	346	Average Volume	54.0	cu ft./turn
		Ave. Weight	20528.0	lbs/turn
		Max. Volume	289.4	cu. ft.
		Min. Volume	2.8	cu. ft.

Total from #6 & #7 = 424 pieces
% sawlogs skidded = 16.3%

Appendix 3 - Machine turns recorded for each study tree next to tilled and untilled trails for three vehicles used in logging. Trees 1-40 are control trees which have no vehicle activity near them. Turns include two machine passes, one trip up the trail and one trip back.

Tree Number	Trail Number	Tilled/ Untilled	Rubber-tired Skidder JD 648D	Feller Buncher Case 1150C	Landing Crawler Case 850D	Total # of Turns
41	1	U	42	5	5	52
42	1	U	42	5	5	52
43	1	U	0	0	8	8
44	2	T	52	1	1	54
45	2	T	53	1	1	55
46	2	T	49	2	1	52
47	2	T	28	3	1	32
48	2	T	24	3	0	27
49	2	U	7	4	0	11
50	2	U	7	4	0	11
51	3	T	106	1	4	111
52	3	T	76	4	0	80
53	3	T	76	4	0	80
54	3	T	73	2	0	75
55	3	T	64	1	0	65
56	3	T	55	1	0	56
57	3	T	48	2	0	50
58	3	T	45	2	0	47
59	3	T	10	3	0	13
60	3	T	10	3	0	13
61	3	T	4	1	0	5
62	3	T	4	1	0	5
63	4	U	48	3	0	51
64	4	U	39	4	0	43
65	4	U	27	2	0	29
66	4	U	27	2	0	29
67	4	U	16	3	0	19
68	4	U	12	4	0	16
69	4	U	12	4	0	16
70	4	U	9	3	0	12
71	4	U	6	13	0	19
72	4	U	5	8	0	13
73	4	U	3	3	0	6
74	4	U	3	9	0	12
75	4	U	2	4	0	6
76	4	U	1	1	0	2
77	4	U	1	2	0	3
78	5	T	145	1	0	146
79	5	T	114	5	0	119
80	5	T	106	5	0	111

Appendix 3 (cont'd)

Tree Number	Trail Number	Tilled/ Untilled	Rubber-tired Skidder JD 648D	Feller Buncher Case 1150C	Landing Crawler Case 850D	Total # of Turns
81	5	T	97	3	0	100
82	5	T	97	3	0	100
83	5	T	74	3	0	77
84	5	T	74	3	0	77
85	5	T	68	3	0	71
86	5	T	61	4	0	65
87	5	T	4	4	0	8
88	5	T	4	4	0	8
89	5	T	4	4	0	8
90	6	U	167	3	0	170
91	6	U	138	7	0	145
92	6	U	113	1	0	114
93	6	U	111	1	0	112
94	6	U	95	7	0	102
95	6	U	90	6	0	96
96	6	U	86	4	0	90
97	6	U	84	2	0	86
98	6	U	70	5	0	75
99	6	U	65	7	0	72
100	6	U	58	1	0	59
101	6	U	58	4	0	62
102	6	U	58	4	0	62
103	6	U	47	2	0	49
104	6	U	47	4	0	51
105	6	U	38	8	0	46
106	6	U	28	5	0	33
107	6	U	20	5	0	25
108	6	U	12	9	0	21
109	6	U	9	4	0	13
110	6	U	9	2	0	11
111	7	T	135	9	0	144
112	7	T	115	4	0	119
113	7	T	94	6	0	100
114	7	T	77	11	0	88
115	7	T	71	5	0	76
116	7	T	59	3	0	62
117	7	T	37	4	0	41
118	7	T	14	6	0	20
119	7	T	3	10	0	13

Appendix 4 - Sample of the number of skidder wheels that left the trail during turns on trails #7 and #8. Each individual number represents how many wheels have left the trail during a given turn and numbers assume rear tire(s) unless otherwise specified. Wheels leaving the trail impacted an area up to 10 feet wide.

Trail Position (feet)	Trail #7 (wheels)	Trail #8 (wheels)
50	2 (Landing)	(Landing)
75	0	0,0,0
100	0,2,0	0,0,0,2,3
125	2	0,0
150	2,0,1,0,3	0,1,0,1,1,0
175	1,1,0,1,2,0,1,1	1,1,2,0
200	0	2, [3,2,2,2]*, [2,3,2,2,2]*, 2,0,3,2,2
225	0,0,1,1,0	0,2,4,2,1,1,0,1,2(side)
250	0,1	0,3,2,0,0,4
275	1,0,3,0,0	4
300	1,2,0,1,0,2,1,1,0,1	0,4,2,1,1,2,1
325	0,0,0,0,3,1	0,0,0,0,1,2
350	0,1,1,2,0,3,3	0,0,3,0
375	2,0,3,2,1	2,0
400	0,1	0,1,0
425	1,1,1,1,1,2(side),0,0	0
450	2(front),2	1,2,1,0,2(side),2(side)
475	0,1,1	0,0,1,3,1,0,1,2,4(to reach windfall)
500	1,2(side)	0,1,0
525	1,2,1,0,1	0,0,1,2(side),0
550	1,4,2(side),0,0,1,2(side)	0,1
575	0,2,3,3,3,3,1	0,0
600	2,0	
625	1,0,1,0,1,0,0,0,2	0
650	1,0,2,0	
675	0,1,2(side)	
700	0,0,0	
725	0,0,0,0	
750	0,0,0,1,0,0,2,1,2,2,0,3	
775	2	

* bracketed values represent the turning around of the skidder on the trail here.

Appendix 5 - Calibration procedure for a double-probe, nuclear densimeter (MC-1 Stratagauge, Campbell Pacific Nuclear, Martinez, CA).

Proper calibration of a nuclear densimeter is essential to its use in the field. CPN, Inc. provides calibration equations with the densimeter upon purchase, but gradual decay of the densimeter's nuclear source eventually necessitates recalibration. The Oregon State University Department of Forest Engineering has purchased an aluminum calibration box of known dimensions (47.2 cm x 47.2 cm x 40.6 cm) from CPN to perform its own calibration. The following steps outline how the nuclear densimeter was calibrated for this study:

1. Buckets of forest soil were obtained from a nearby site for the calibration. Calibration is not exclusive to a single soil type, but rather a range of densities. As such, it was not essential to have soil from the study site for the calibration, but the wide range of densities used for the calibration included the general density of soil on the study site.

2. Soil was placed into the calibration box one layer at a time. Each layer was weighed to the nearest tenth of a gram so that once the box was filled, a total weight for the known volume could be obtained. The following variations provided a range of densities:

    1) Dry, loose soil
    2) Moist, loose soil
    3) Moist, compacted soil
    4) A separate concrete block of known density

    A sliding weight on a steel shaft welded to the back of a steel plate, 15.3 cm x 15.3 cm, was used to mechanically compact the soil, one layer at a time for medium #3. Once filled or compacted to the top, the lid with two probe holes was fastened on top of the calibration box and two 30.5-cm deep holes were prepared by a specially made guide plate and pins. Source and collector probes were then pushed into the soil to 10.2, 20.3 and 30.5-cm depths where counts (number of gamma radiation particles passing through medium between source and collector) were taken.

3. For each medium, weight of soil (grams) was divided by known volume of the calibration box (cm^3) to yield density in grams/cm^3. As prescribed by CPN for general use of the densimeter, counts at each depth were divided by a standard count (a count taken each day of operation to measure background radiation) to form a ratio for each depth. Using multiple linear regression, these variables of density and ratio of counts over a standard count, along with the natural log of the ratios were used to create calibration equations for each depth as follows:

    4" eqn: BULK DENSITY = 1.854 + .008(RATIO) - .725(LN RATIO)
    8" eqn: BULK DENSITY = 1.928 - .024(RATIO) - .687(LN RATIO)
    12" eqn: BULK DENSITY = 1.810 + .063(RATIO) - .824(LN RATIO)

Appendix 5 (cont'd) - Multiple linear regression information for wet bulk density calibration equations used with a CPN nuclear densimeter.

4-inch depth

BD	Ratio	LN Ratio
0.921	3.561	1.270
0.994	3.600	1.281
1.200	2.542	0.933
2.353	0.505	-.683

Regression Output		
Constant		1.854089
Std Err of Y Est		0.057075
R Squared		0.997566
No. of Observations		4
Degrees of Freedom		1
X Coefficients	0.007983	-0.72468
Std Err of Coef.	0.13339	0.206582

8-inch depth

BD	Ratio	LN Ratio
0.921	3.702	1.309
0.994	3.543	1.265
1.200	2.617	0.962
2.353	0.529	-.637

Regression Output		
Constant		1.928152
Std Err of Y Est		0.027840
R Squared		0.999421
No. of Observations		4
Degrees of Freedom		1
X Coefficients	-0.02436	-0.68694
Std Err of Coef.	0.066773	0.105853

Appendix 5 (cont'd) - Multiple linear regression information for wet bulk density calibration equations for a CPN nuclear densimeter.

12-inch depth

BD	Ratio	LN Ratio
0.921	3.616	1.285
0.994	3.814	1.339
1.200	2.589	.951
2.353	0.539	-.619

Regression Output		
Constant		1.809892
Std Err of Y Est		0.075402
R Squared		0.995751
No. of Observations		4
Degrees of Freedom		1
X Coefficients	0.062795	-0.8236
Std Err of Coef.	0.163116	0.265484

Appendix 6a - Dry soil bulk density measurements for 119 study trees.

Tree #	Pop'n*	Trail Soil Moisture Content**	Average Trail BD @ 4" (g/ccm)	Average Trail BD @ 8" (g/ccm)	Average Trail BD @ 12" (g/ccm)	Nontrail Soil Moisture Content**	Average Nontrail BD @ 4" (g/ccm)	Average Nontrail BD @ 8" (g/ccm)	Average Nontrail BD @ 12" (g/ccm)
1	C	N/A	N/A	N/A	N/A	0.25	0.91	0.97	1.02
2	C	N/A	N/A	N/A	N/A	0.31	0.88	0.98	1.09
3	C	N/A	N/A	N/A	N/A	0.26	1.01	1.18	1.18
4	C	N/A	N/A	N/A	N/A	0.32	0.85	1.10	1.17
5	C	N/A	N/A	N/A	N/A	0.30	0.81	1.05	1.11
6	C	N/A	N/A	N/A	N/A	0.28	0.78	0.77	0.92
7	C	N/A	N/A	N/A	N/A	0.23	0.92	1.00	1.09
8	C	N/A	N/A	N/A	N/A	0.23	0.89	0.94	1.06
9	C	N/A	N/A	N/A	N/A	0.23	0.82	0.92	0.95
10	C	N/A	N/A	N/A	N/A	0.28	0.92	0.98	0.98
11	C	N/A	N/A	N/A	N/A	0.22	0.88	1.02	1.03
12	C	N/A	N/A	N/A	N/A	0.31	0.84	1.04	1.14
13	C	N/A	N/A	N/A	N/A	0.27	0.87	0.94	0.90
14	C	N/A	N/A	N/A	N/A	0.25	0.92	1.01	1.08
15	C	N/A	N/A	N/A	N/A	0.29	0.87	0.94	0.90
16	C	N/A	N/A	N/A	N/A	0.22	0.96	1.12	1.16
17	C	N/A	N/A	N/A	N/A	0.25	0.91	1.02	1.12
18	C	N/A	N/A	N/A	N/A	0.26	0.92	0.95	1.12
19	C	N/A	N/A	N/A	N/A	0.25	0.88	0.97	0.97
20	C	N/A	N/A	N/A	N/A	0.21	1.03	1.12	1.15
21	C	N/A	N/A	N/A	N/A	0.22	0.89	0.76	1.07
22	C	N/A	N/A	N/A	N/A	0.21	0.89	0.98	1.10
23	C	N/A	N/A	N/A	N/A	0.21	0.71	1.05	1.11
24	C	N/A	N/A	N/A	N/A	0.24	1.03	1.04	1.10
25	C	N/A	N/A	N/A	N/A	0.21	0.90	1.11	1.16
26	C	N/A	N/A	N/A	N/A	0.19	1.00	1.02	1.16
27	C	N/A	N/A	N/A	N/A	0.22	0.95	1.04	1.04
28	C	N/A	N/A	N/A	N/A	0.22	0.80	0.90	1.00
29	C	N/A	N/A	N/A	N/A	0.20	0.89	0.90	1.01
30	C	N/A	N/A	N/A	N/A	0.22	1.00	0.95	0.97
31	C	N/A	N/A	N/A	N/A	0.22	0.90	1.02	1.16
32	C	N/A	N/A	N/A	N/A	0.20	0.89	0.92	1.00
33	C	N/A	N/A	N/A	N/A	0.19	0.86	0.88	1.01
34	C	N/A	N/A	N/A	N/A	0.21	0.98	0.96	1.04
35	C	N/A	N/A	N/A	N/A	0.22	0.80	0.93	0.95
36	C	N/A	N/A	N/A	N/A	0.21	0.73	0.90	0.92
37	C	N/A	N/A	N/A	N/A	0.22	0.86	0.96	1.02
38	C	N/A	N/A	N/A	N/A	0.21	0.88	1.03	1.12
39	C	N/A	N/A	N/A	N/A	0.19	0.98	0.95	1.08
40	C	N/A	N/A	N/A	N/A	0.20	0.86	0.96	1.03
41	U	0.37	1.00	0.99	0.93	0.32	0.80	0.82	0.97
42	U	0.38	1.13	0.92	0.94	0.26	0.92	1.02	1.03

Appendix 6a (cont'd)

Tree #	Pop'n*	Trail Soil Moisture Content**	Average Trail BD @ 4" (g/ccm)	Average Trail BD @ 8" (g/ccm)	Average Trail BD @ 12" (g/ccm)	Nontrail Soil Moisture Content**	Average Nontrail BD @ 4" (g/ccm)	Average Nontrail BD @ 8" (g/ccm)	Average Nontrail BD @ 12" (g/ccm)
43	U	0.33	1.02	1.11	0.87	0.31	0.86	0.86	0.88
44	T	0.31	0.98	1.07	1.06	0.30	0.84	0.97	1.07
45	T	0.32	0.83	0.94	1.00	0.36	0.72	0.87	0.97
46	T	0.36	0.90	0.85	0.89	0.36	0.82	0.88	0.89
47	T	0.36	0.84	0.90	0.96	0.22	0.88	1.02	1.08
48	T	0.28	0.91	0.97	1.00	0.27	0.82	0.88	1.01
49	U	0.34	0.85	0.95	0.98	0.32	0.78	0.83	0.99
50	U	0.34	1.05	1.02	1.08	0.31	0.94	0.97	1.10
51	T	0.30	0.89	0.87	0.92	0.33	0.79	0.82	0.90
52	T	0.31	0.90	0.93	0.85	0.25	0.82	0.91	0.88
53	T	0.33	0.93	0.90	0.96	0.30	0.85	0.90	0.98
54	T	0.32	0.89	0.91	0.93	0.29	0.84	0.87	0.95
55	T	0.38	0.86	0.87	1.04	0.26	1.02	1.13	1.13
56	T	0.29	0.91	0.91	0.86	0.25	0.77	0.87	0.89
57	T	0.30	0.86	0.91	1.04	0.24	0.86	0.94	1.09
58	T	0.33	0.88	0.78	1.01	0.23	0.80	0.97	1.09
59	T	0.30	0.96	1.08	1.08	0.22	0.99	1.06	1.15
60	T	0.32	1.05	1.00	0.95	0.26	0.85	1.05	1.00
61	T	0.31	0.97	0.94	1.08	0.28	0.93	1.09	1.10
62	T	0.33	0.94	0.93	0.94	0.27	0.96	1.00	0.98
63	U	0.38	1.01	1.05	1.01	0.28	0.87	0.99	1.08
64	U	0.38	0.97	0.96	0.99	0.30	0.96	1.02	1.05
65	U	0.31	1.10	1.07	0.93	0.24	0.88	0.93	0.99
66	U	0.28	1.06	0.98	0.94	0.25	0.92	0.91	0.96
67	U	0.31	1.19	1.09	1.06	0.35	0.92	0.96	1.02
68	U	0.26	1.12	1.09	0.94	0.24	0.89	0.91	0.96
69	U	0.25	1.05	1.00	1.15	0.22	1.04	1.03	1.18
70	U	0.31	1.07	0.99	0.95	0.26	0.83	0.93	0.99
71	U	0.30	1.16	1.09	1.00	0.29	0.92	1.01	1.01
72	U	0.36	1.08	1.05	0.96	0.27	0.91	1.07	1.03
73	U	0.35	1.14	0.95	1.08	0.32	0.91	0.99	1.10
74	U	0.27	1.01	1.06	1.19	0.24	0.84	0.93	1.22
75	U	0.31	1.07	1.17	0.97	0.24	0.88	0.95	1.02
76	U	0.28	1.06	1.11	1.04	0.30	0.89	0.87	1.02
77	U	0.22	1.00	1.09	1.10	0.23	0.93	1.01	1.09
78	T	0.34	0.91	0.81	0.91	0.30	0.83	0.91	0.95
79	T	0.32	1.02	0.98	0.95	0.28	0.84	0.95	0.98
80	T	0.31	1.07	1.06	1.12	0.33	0.88	0.95	1.10
81	T	0.34	0.91	0.84	0.87	0.24	0.90	0.85	0.93
82	T	0.30	0.98	0.92	1.13	0.27	0.85	1.02	1.16
83	T	0.33	0.83	0.91	0.95	0.27	0.89	0.93	0.99
84	T	0.31	1.00	1.02	0.99	0.28	0.83	0.93	1.02

Appendix 6a (cont'd)

Tree	Pop'n*	Trail Soil Moisture Content**	Average Trail BD @ 4" (g/ccm)	Average Trail BD @ 8" (g/ccm)	Average Trail BD @ 12" (g/ccm)	Nontrail Soil Moisture Content**	Average Nontrail BD @ 4" (g/ccm)	Average Nontrail BD @ 8" (g/ccm)	Average Nontrail BD @ 12" (g/ccm)
85	T	0.29	0.90	0.96	0.96	0.27	0.94	0.88	0.98
86	T	0.27	1.03	1.17	1.09	0.25	0.89	1.19	1.10
87	T	0.26	0.95	0.88	1.01	0.20	0.97	0.97	1.06
88	T	0.28	0.98	0.95	1.06	0.30	0.77	1.00	1.05
89	T	0.26	1.05	1.02	1.24	0.21	1.06	1.18	1.29
90	U	0.18	1.26	1.21	1.03	0.25	0.91	0.94	0.98
91	U	0.31	1.06	1.06	0.93	0.22	0.88	1.02	1.01
92	U	0.31	1.00	1.02	0.99	0.22	0.85	0.91	1.06
93	U	0.22	1.09	1.06	1.05	0.23	0.90	0.96	1.05
94	U	0.23	1.09	1.14	1.07	0.19	0.97	0.88	1.10
95	U	0.24	1.03	1.04	1.02	0.26	0.98	0.91	1.00
96	U	0.20	1.11	1.11	1.16	0.26	0.88	0.98	1.11
97	U	0.24	1.15	1.14	1.12	0.23	0.76	0.91	1.13
98	U	0.25	1.07	1.04	0.97	0.22	0.90	0.98	0.99
99	U	0.25	1.09	1.13	0.91	0.22	0.88	0.99	0.93
100	U	0.21	1.04	1.10	0.94	0.24	0.84	0.82	0.92
101	U	0.24	1.07	1.01	0.94	0.23	0.98	0.90	0.94
102	U	0.24	1.00	1.06	0.97	0.22	0.88	0.92	0.99
103	U	0.40	0.99	0.96	0.98	0.24	0.90	1.02	1.11
104	U	0.27	0.98	1.17	1.06	0.22	0.91	1.10	1.10
105	U	0.32	0.84	1.06	0.96	0.24	0.89	0.93	1.02
106	U	0.29	1.06	1.05	0.83	0.24	0.93	0.86	0.86
107	U	0.34	1.07	1.07	1.00	0.23	0.93	1.06	1.09
108	U	0.24	1.05	1.08	1.06	0.26	0.87	0.95	1.04
109	U	0.23	1.02	1.06	1.07	0.23	0.93	1.04	1.06
110	U	0.33	0.95	0.97	1.11	0.24	0.86	1.01	1.19
111	T	0.36	0.89	1.03	0.87	0.19	0.92	0.89	1.00
112	T	0.32	0.83	0.97	0.90	0.22	0.87	0.95	0.98
113	T	0.25	0.97	0.99	0.89	0.23	0.90	1.03	0.90
114	T	0.24	0.89	0.98	1.16	0.21	0.94	1.08	1.19
115	T	0.30	0.84	0.98	0.92	0.23	0.91	0.96	0.98
116	T	0.34	0.81	0.87	0.98	0.26	0.85	0.93	1.04
117	T	0.30	0.94	0.97	1.06	0.22	0.96	1.10	1.14
118	T	0.31	0.97	0.95	0.92	0.22	0.94	0.96	1.00
119	T	0.25	0.96	0.96	1.00	0.21	0.88	1.04	1.04

* C=Control, T=Tilled and U=Untilled

** Represents fractional moisture content at time of bulk density measurement.

Appendix 6b - Calculations for dry bulk density.

Fractional Moisture Content (MC):

$$\frac{\text{Wt. wet soil - Wt. dry soil}}{\text{Wt. dry soil - dish wt.}}$$

Soil wet bulk density:

$$\frac{\text{Ave. field count}}{\text{Standard Count}} = \text{Ratio}$$

Use ratio to calculate density from calibration equations for each depth (Appendix 5).

Soil dry bulk density:

$$\text{Dry bulk density} = \frac{\text{wet bulk density}}{1 + \text{MC}}$$

Appendix 7a - Tree and site characteristics for 119 study trees.

Tree #	Pop'n*	Skid Trail (on/betwn)	Side of Trail East/West	Dist from trailhead	Slope (%)	Aspect (azmuth)	dob @ 1.5' (in.)	dbh (in.)	Tree Ht. (ft.)
1	C	2/3	N/A	N/A	13	187	18.4	15.7	113
2	C	2/3	N/A	N/A	22	186	21.3	17.5	118
3	C	2/3	N/A	N/A	15	187	18.0	14.4	117
4	C	2/3	N/A	N/A	3	221	13.4	10.9	102
5	C	2/3	N/A	N/A	10	330	22.9	16.9	115
6	C	3/4	N/A	N/A	10	178	20.4	16.9	112
7	C	3/4	N/A	N/A	16	188	20.9	17.4	117
8	C	3/4	N/A	N/A	26	196	15.9	13.0	100
9	C	3/4	N/A	N/A	20	191	16.3	12.3	105
10	C	3/4	N/A	N/A	10	250	14.7	12.2	108
11	C	3/4	N/A	N/A	0	276	19.9	15.2	120
12	C	4/5	N/A	N/A	11	184	19.4	15.6	119
13	C	4/5	N/A	N/A	11	190	14.7	12.1	113
14	C	4/5	N/A	N/A	9	187	18.9	15.8	118
15	C	4/5	N/A	N/A	17	185	20.8	17.3	117
16	C	4/5	N/A	N/A	16	188	21.8	18.0	120
17	C	4/5	N/A	N/A	4	268	16.1	13.6	108
18	C	4/5	N/A	N/A	2	230	31.1	26.2	140
19	C	5/6	N/A	N/A	13	186	12.5	10.5	95
20	C	5/6	N/A	N/A	16	177	25.9	20.4	135
21	C	5/6	N/A	N/A	17	179	16.1	13.1	106
22	C	5/6	N/A	N/A	13	182	19.3	15.3	110
23	C	5/6	N/A	N/A	18	197	15.2	11.9	118
24	C	5/6	N/A	N/A	16	174	22.3	17.6	121
25	C	5/6	N/A	N/A	13	208	19.0	16.0	109
26	C	5/6	N/A	N/A	19	228	19.4	15.9	108
27	C	6/7	N/A	N/A	13	217	13.1	11.0	110
28	C	6/7	N/A	N/A	12	210	21.9	18.3	117
29	C	6/7	N/A	N/A	22	185	14.7	12.1	105
30	C	6/7	N/A	N/A	17	190	24.1	17.9	123
31	C	6/7	N/A	N/A	18	180	18.7	15.7	109
32	C	6/7	N/A	N/A	13	187	23.3	19.7	123
33	C	6/7	N/A	N/A	17	214	13.6	10.6	103
34	C	6/7	N/A	N/A	18	213	11.1	9.1	89
35	C	7/8	N/A	N/A	28	174	22.1	18.2	129
36	C	7/8	N/A	N/A	15	253	14.4	11.3	94
37	C	7/8	N/A	N/A	14	185	20.4	15.3	115
38	C	7/8	N/A	N/A	17	193	19.8	15.9	113
39	C	7/8	N/A	N/A	16	175	22.4	18.7	117
40	C	7/8	N/A	N/A	22	173	20.3	17.4	114
41	U	1	W	143	14	251	29.0	25.2	123
42	U	1	W	165	13	250	16.6	13.9	112
43	U	1	W	282	3	280	19.4	16.6	122

Appendix 7a (cont'd)

Tree #	Pop'n*	Skid Trail (on/betwn)	Side of Trail East/West	Dist from trailhead	Slope (%)	Aspect (azmuth)	dob @ 1.5' (in.)	dbh (in.)	Tree Ht. (ft.)
44	T	2	E	128	11	194	25.5	20.4	117
45	T	2	E	153	23	198	25.5	22.3	125
46	T	2	W	166	23	200	23.5	19.8	133
47	T	2	W	283	15	202	23.1	18.7	113
48	T	2	E	318	12	205	13.3	10.8	101
49	U	2	W	393	11	292	22.6	18.6	117
50	U	2	E	410	10	290	16.4	13.7	110
51	T	3	W	65	13	180	20.9	17.8	128
52	T	3	W	159	14	196	16.8	14.1	110
53	T	3	E	165	14	196	14.8	12.2	99
54	T	3	E	189	17	192	21.5	18.4	118
55	T	3	W	199	17	174	16.5	13.5	104
56	T	3	E	263	27	195	18.8	16.4	118
57	T	3	W	280	27	195	13.9	16.2	108
58	T	3	W	316	25	204	19.6	16.9	123
59	T	3	E	457	3	0	15.0	12.1	99
60	T	3	W	465	3	0	14.7	12.7	116
61	T	3	E	505	3	290	14.0	11.0	107
62	T	3	E	525	6	300	18.1	15.9	117
63	U	4	W	76	18	202	16.4	14.6	103
64	U	4	W	119	10	172	17.1	15.4	116
65	U	4	W	203	13	180	12.9	10.5	94
66	U	4	E	214	13	180	20.0	17.0	123
67	U	4	W	296	25	180	16.2	13.0	97
68	U	4	W	375	20	177	20.7	17.2	111
69	U	4	E	395	20	177	16.4	14.0	109
70	U	4	W	465	15	192	14.3	12.0	100
71	U	4	W	500	7	200	24.4	21.3	120
72	U	4	W	536	3	0	12.0	10.6	107
73	U	4	E	556	3	0	17.0	14.0	113
74	U	4	W	572	3	0	13.4	11.2	109
75	U	4	E	587	3	0	14.1	11.2	106
76	U	4	W	612	3	250	23.0	19.6	127
77	U	4	W	638	3	256	21.3	17.7	124
78	T	5	W	145	15	172	29.0	25.0	130
79	T	5	W	210	19	182	20.2	16.9	115
80	T	5	E	263	13	190	13.8	11.1	100
81	T	5	W	316	15	187	23.4	18.8	120
82	T	5	E	317	15	187	18.7	15.6	113
83	T	5	E	407	13	190	21.7	17.3	118
84	T	5	E	425	16	190	17.0	14.6	113
85	T	5	E	447	16	190	23.0	19.4	123
86	T	5	E	756	3	230	19.8	16.2	116

Appendix 7a (cont'd)

Tree #	Pop'n*	Skid Trail (on/betwn)	Side of Trail East/West	Dist from trailhead	Slope (%)	Aspect (azmuth)	dob @ 1.5' (in.)	dbh (in.)	Tree Ht. (ft.)
87	T	5	E	777	20	250	21.3	17.5	123
88	T	5	W	780	20	250	19.5	16.8	117
89	T	5	E	787	10	250	19.7	16.9	122
90	U	6	E	81	20	190	17.0	14.2	101
91	U	6	W	145	17	188	16.1	14.2	119
92	U	6	E	215	13	183	20.0	17.0	109
93	U	6	W	251	15	198	20.7	17.8	118
94	U	6	W	293	14	197	18.0	15.2	117
95	U	6	E	319	21	205	16.9	15.0	118
96	U	6	E	342	24	197	18.6	16.3	117
97	U	6	E	361	21	192	20.1	15.9	108
98	U	6	E	428	16	192	19.3	15.9	116
99	U	6	E	477	14	194	14.6	12.3	107
100	U	6	W	508	14	190	17.3	15.2	118
101	U	6	E	526	14	190	19.2	16.1	110
102	U	6	W	526	14	190	20.2	16.1	118
103	U	6	E	564	12	190	19.7	16.7	117
104	U	6	W	577	12	190	19.1	17.4	120
105	U	6	W	598	15	195	15.1	12.4	118
106	U	6	W	642	16	176	19.1	15.8	111
107	U	6	W	679	18	185	14.2	12.7	109
108	U	6	E	731	16	182	22.4	17.0	120
109	U	6	W	767	13	181	19.3	15.7	113
110	U	6	E	782	13	204	18.7	15.1	114
111	T	7	W	131	25	190	15.4	12.6	108
112	T	7	E	226	10	204	23.1	19.6	124
113	T	7	W	228	10	204	15.6	13.6	118
114	T	7	W	384	19	197	21.3	17.0	108
115	T	7	E	425	18	201	16.9	13.9	112
116	T	7	E	498	16	210	26.6	22.6	129
117	T	7	W	580	24	187	23.2	20.5	127
118	T	7	E	675	27	200	24.7	21.0	119
119	T	7	W	736	16	198	19.2	17.4	119
* C = Control			42 Ws	Averages:	14	193	18.9	15.8	114
U = Untilled			37 Es						
T = Tilled									

Appendix 7b - Tree crown characteristics for 119 study trees.

Tree #	Pop'n	Crown Class*	Crown Length (feet)	Spatial Crown Area (cu.ft.)	North Crown Radius (feet)	East Crown Radius (feet)	South Crown Radius (feet)	West Crown Radius (feet)	Ave. Crown Radius (feet)
1	C	C	42	5082	10	12	12	9	10.8
2	C	C	42	6599	14	12	12	11	12.3
3	C	C	46	7526	14	15	8	13	12.5
4	C	C	25	1472	7	10	6	7	7.5
5	C	C	45	8908	16	13	13	13	13.8
6	C	C	45	8908	13	14	10	18	13.8
7	C	C	57	13880	16	16	15	14	15.3
8	C	C	57	6580	8	10	13	11	10.5
9	C	C	40	3780	6	9	15	8	9.5
10	C	C	32	3185	10	10	9	10	9.8
11	C	C	41	6182	11	11	15	11	12.0
12	C	C	41	5678	10	12	12	12	11.5
13	C	C	45	4479	7	10	12	10	9.8
14	C	C	47	5955	9	7	14	14	11.0
15	C	C	44	10024	15	19	15	10	14.8
16	C	C	49	8341	9	13	15	14	12.8
17	C	C	28	2245	7	9	10	9	8.8
18	C	D	50	11390	13	18	13	15	14.8
19	C	I	22	2540	8	10	14	10	10.5
20	C	D	50	9192	12	13	13	15	13.3
21	C	C	49	6208	9	11	13	11	11.0
22	C	C	38	5262	10	10	13	13	11.5
23	C	C	29	3348	9	9	12	12	10.5
24	C	C	44	6634	12	13	9	14	12.0
25	C	C	38	4387	10	11	10	11	10.5
26	C	I	43	10471	16	14	15	16	15.3
27	C	I	24	2150	7	9	9	12	9.3
28	C	C	41	6442	13	11	15	10	12.3
29	C	C	37	3315	11	7	11	8	9.3
30	C	C	44	5831	14	11	9	11	11.3
31	C	C	33	3630	10	10	10	11	10.3
32	C	D	45	6505	10	10	16	11	11.8
33	C	I	27	2827	10	10	10	10	10.0
34	C	I	23	1951	7	10	11	8	9.0
35	C	C	45	6785	12	11	14	11	12.0
36	C	I	31	3751	11	10	12	10	10.8
37	C	C	46	5310	9	14	11	8	10.5
38	C	C	36	3053	8	8	8	12	9.0
39	C	C	39	4502	9	12	12	9	10.5
40	C	D	40	5301	8	13	14	10	11.3
41	U	D	43	11526	14	12	17	21	16.0
42	U	C	42	4849	10	5	13	14	10.5

Appendix 7b (cont'd)

Tree #	Pop'n	Crown Class*	Crown Length (feet)	Spatial Crown Area (cu.ft.)	North Crown Radius (feet)	East Crown Radius (feet)	South Crown Radius (feet)	West Crown Radius (feet)	Ave. Crown Radius (feet)
43	U	C	48	7238	7	12	14	15	12.0
44	T	D	63	14843	14	11	19	16	15.0
45	T	D	80	18225	15	15	15	14	14.8
46	T	C	41	8414	15	17	15	9	14.0
47	T	C	37	4477	11	10	10	12	10.8
48	T	C	27	1924	9	8	7	9	8.3
49	U	C	42	4398	9	9	8	14	10.0
50	U	C	25	2363	13	9	6	10	9.5
51	T	D	45	8587	12	12	16	14	13.5
52	T	C	33	3455	7	10	13	10	10.0
53	T	C	32	3872	12	9	11	11	10.8
54	T	C	45	7963	13	16	13	10	13.0
55	T	C	24	2268	7	12	13	6	9.5
56	T	C	40	5068	10	13	13	8	11.0
57	T	C	31	2629	6	9	11	10	9.0
58	T	C	47	5426	8	14	13	7	10.5
59	T	C	29	2325	6	8	12	9	8.8
60	T	C	29	2598	7	11	9	10	9.3
61	T	C	28	2245	9	10	6	10	8.8
62	T	C	33	3810	10	10	9	13	10.5
63	U	D	33	3993	11	10	13	9	10.8
64	U	C	37	5579	12	13	12	11	12.0
65	U	C	24	1924	9	7	8	11	8.8
66	U	C	50	7539	9	10	15	14	12.0
67	U	C	31	3579	12	9	10	11	10.5
68	U	C	34	5127	11	14	10	13	12.0
69	U	C	41	4961	9	12	11	11	10.8
70	U	C	30	3630	11	9	11	12	10.8
71	U	D	44	6634	10	13	14	11	12.0
72	U	I	31	2629	9	10	9	8	9.0
73	U	C	38	4387	10	10	12	10	10.5
74	U	C	26	3446	11	9	12	13	11.3
75	U	I	31	1950	10	5	9	7	7.8
76	U	C	42	6872	11	15	12	12	12.5
77	U	C	30	2986	10	10	10	9	9.8
78	T	D	49	8341	13	13	16	9	12.8
79	T	C	30	4908	12	14	12	12	12.5
80	T	I	18	991	7	8	7	7	7.3
81	T	C	38	5730	10	10	15	13	12.0
82	T	C	32	4241	14	9	10	12	11.3
83	T	C	44	6634	11	10	14	13	12.0
84	T	C	38	5493	10	12	12	13	11.8

Appendix 7b (cont'd)

Tree #	Pop'n	Crown Class*	Crown Length (feet)	Spatial Crown Area (cu.ft.)	North Crown Radius (feet)	East Crown Radius (feet)	South Crown Radius (feet)	West Crown Radius (feet)	Ave. Crown Radius (feet)
85	T	C	45	7660	13	12	13	13	12.8
86	T	C	29	3037	9	10	10	11	10.0
87	T	C	37	5814	9	13	12	15	12.3
88	T	C	43	7035	17	11	7	15	12.5
89	T	C	37	4070	13	10	7	11	10.3
90	U	I	21	1407	9	8	9	6	8.0
91	U	C	29	2887	11	10	9	9	9.8
92	U	C	33	3993	8	8	15	12	10.8
93	U	C	30	3463	12	11	11	8	10.5
94	U	C	37	6547	14	12	15	11	13.0
95	U	C	31	3410	8	9	12	12	10.3
96	U	C	40	7078	12	16	14	10	13.0
97	U	C	29	2460	7	10	11	8	9.0
98	U	C	31	3928	12	7	12	13	11.0
99	U	I	34	3384	10	6	11	12	9.8
100	U	C	27	2419	8	7	14	8	9.3
101	U	C	30	4154	9	12	14	11	11.5
102	U	C	32	4241	10	12	14	9	11.3
103	U	C	42	5321	11	10	11	12	11.0
104	U	C	37	3138	10	8	10	8	9.0
105	U	C	32	3694	11	10	10	11	10.5
106	U	C	35	4638	12	9	12	12	11.3
107	U	C	33	3455	11	9	9	11	10.0
108	U	C	38	6217	13	11	13	13	12.5
109	U	C	30	2688	8	9	10	10	9.3
110	U	C	34	4506	11	11	12	11	11.3
111	T	I	34	3046	7	9	14	7	9.3
112	T	C	31	3751	10	13	11	9	10.8
113	T	C	34	2278	7	8	9	8	8.0
114	T	C	35	4638	13	13	9	10	11.3
115	T	C	29	3843	13	8	10	14	11.3
116	T	D	50	13825	14	16	18	17	16.3
117	T	C	33	6533	12	20	17	6	13.8
118	T	D	30	3976	10	9	15	11	11.3
119	T	C	39	5168	12	13	8	12	11.3
	Averages:		37	5188					11.1

* D = Dominant (13), C = Codominant (94), I = Intermediate (12)

Appendix 7c - Root zone characteristics for 119 study trees (radii, distances and widths in feet).

Tree #	Pop'n	Root Zone Radius	Root Zone Area Index (sq.ft.)	Dist. Tree to Trail, Near edge	Dist. Tree to Trail, Far edge	Width of Trail	% Root Zone Affected	Root Damage Class*
1	C	12	452	N/A	N/A	0.0	0	-
2	C	14	616	N/A	N/A	0.0	0	-
3	C	15	707	N/A	N/A	0.0	0	-
4	C	10	314	N/A	N/A	0.0	0	-
5	C	16	804	N/A	N/A	0.0	0	-
6	C	18	1018	N/A	N/A	0.0	0	-
7	C	16	804	N/A	N/A	0.0	0	-
8	C	13	531	N/A	N/A	0.0	0	-
9	C	15	707	N/A	N/A	0.0	0	-
10	C	10	314	N/A	N/A	0.0	0	-
11	C	15	707	N/A	N/A	0.0	0	-
12	C	12	452	N/A	N/A	0.0	0	-
13	C	12	452	N/A	N/A	0.0	0	-
14	C	14	616	N/A	N/A	0.0	0	-
15	C	19	1134	N/A	N/A	0.0	0	-
16	C	15	707	N/A	N/A	0.0	0	-
17	C	10	314	N/A	N/A	0.0	0	-
18	C	18	1018	N/A	N/A	0.0	0	-
19	C	14	616	N/A	N/A	0.0	0	-
20	C	15	707	N/A	N/A	0.0	0	-
21	C	13	531	N/A	N/A	0.0	0	-
22	C	13	531	N/A	N/A	0.0	0	-
23	C	12	452	N/A	N/A	0.0	0	-
24	C	14	616	N/A	N/A	0.0	0	-
25	C	11	380	N/A	N/A	0.0	0	-
26	C	16	804	N/A	N/A	0.0	0	-
27	C	12	452	N/A	N/A	0.0	0	-
28	C	15	707	N/A	N/A	0.0	0	-
29	C	11	380	N/A	N/A	0.0	0	-
30	C	14	616	N/A	N/A	0.0	0	-
31	C	11	380	N/A	N/A	0.0	0	-
32	C	16	804	N/A	N/A	0.0	0	-
33	C	10	314	N/A	N/A	0.0	0	-
34	C	11	380	N/A	N/A	0.0	0	-
35	C	14	616	N/A	N/A	0.0	0	-
36	C	12	452	N/A	N/A	0.0	0	-
37	C	14	616	N/A	N/A	0.0	0	-
38	C	12	452	N/A	N/A	0.0	0	-
39	C	12	452	N/A	N/A	0.0	0	-
40	C	14	616	N/A	N/A	0.0	0	-
41	U	21	1385	2.0	13.0	11.0	31	-
42	U	14	616	2.0	17.0	15.0	41	-
43	U	15	707	2.0	11.0	9.0	34	-

Appendix 7c (cont'd)

Tree #	Pop'n	Root Zone Radius	Root Zone Area Index (sq.ft.)	Dist. Tree - to Trail, Near edge	Dist. Tree to Trail, Far edge	Width of Trail	% Root Zone Affected	Root Damage Class*
44	T	19	1134	1.0	11.0	10.0	31	2
45	T	15	707	4.0	14.0	10.0	32	3
46	T	17	908	4.0	15.0	11.0	33	1
47	T	12	452	3.0	12.0	9.0	34	1
48	T	9	254	3.0	14.0	11.0	29	1
49	U	14	616	4.0	14.0	10.0	32	-
50	U	13	531	4.0	14.0	10.0	31	-
51	T	16	804	2.0	14.0	12.0	39	2
52	T	13	531	1.5	12.0	10.5	41	1
53	T	12	452	3.0	12.0	9.0	34	2
54	T	16	804	2.5	13.0	10.5	35	1
55	T	13	531	4.5	16.5	12.0	28	1
56	T	13	531	0.5	11.0	10.5	44	2
57	T	11	380	2.0	14.0	12.0	38	2
58	T	14	616	3.0	14.0	11.0	36	2
59	T	12	452	2.0	12.0	10.0	39	1
60	T	11	380	2.0	12.0	10.0	38	3
61	T	10	314	3.0	12.0	9.0	31	1
62	T	13	531	5.0	17.0	12.0	26	1
63	U	13	531	4.0	16.0	12.0	31	-
64	U	13	531	2.0	13.0	11.0	40	-
65	U	11	380	1.5	13.0	11.5	41	-
66	U	15	707	2.0	15.0	13.0	42	-
67	U	12	452	3.0	12.0	9.0	34	-
68	U	14	616	2.5	12.0	9.5	36	-
69	U	12	452	1.5	11.5	10.0	42	-
70	U	12	452	3.0	12.5	9.5	34	-
71	U	14	616	1.5	12.0	10.5	40	-
72	U	10	314	2.0	14.0	12.0	37	-
73	U	12	452	3.0	13.0	10.0	34	-
74	U	13	531	2.0	13.0	11.0	40	-
75	U	10	314	2.5	13.0	10.5	34	-
76	U	15	707	7.0	17.0	10.0	21	-
77	U	10	314	2.0	10.0	8.0	37	-
78	T	16	804	2.0	16.0	14.0	42	2
79	T	14	616	3.0	15.0	12.0	36	1
80	T	8	201	1.5	13.0	11.5	38	2
81	T	15	707	2.5	14.0	11.5	38	1
82	T	15	707	3.5	15.0	11.5	35	1
83	T	14	616	2.0	13.0	11.0	40	2
84	T	13	531	2.0	13.0	11.0	40	1
85	T	13	531	2.0	13.0	11.0	40	3
86	T	11	380	2.0	13.0	11.0	38	2

Appendix 7c (cont'd)

Tree #	Pop'n	Root Zone Radius	Root Zone Area Index (sq.ft.)	Dist. Tree to Trail, Near edge	Dist. Tree to Trail, Far edge	Width of Trail	% Root Zone Affected	Root Damage Class*
87	T	15	707	2.0	15.0	13.0	42	2
88	T	17	908	5.0	17.0	12.0	32	2
89	T	13	531	2.0	13.0	11.0	40	1
90	U	9	254	3.0	19.0	16.0	29	-
91	U	11	380	3.0	15.0	12.0	33	-
92	U	15	707	2.0	13.0	11.0	39	-
93	U	12	452	3.0	13.0	10.0	34	-
94	U	15	707	2.0	15.0	13.0	42	-
95	U	12	452	1.0	11.0	10.0	43	-
96	U	16	804	1.5	13.0	11.5	39	-
97	U	11	380	2.0	11.0	9.0	38	-
98	U	13	531	2.0	13.0	11.0	40	-
99	U	12	452	6.0	17.5	11.5	20	-
100	U	14	616	5.0	15.0	10.0	28	-
101	U	14	616	3.0	15.0	12.0	36	-
102	U	14	616	3.0	14.0	11.0	36	-
103	U	12	452	6.5	17.5	11.0	17	-
104	U	10	314	4.0	14.0	10.0	25	-
105	U	11	380	5.0	15.0	10.0	22	-
106	U	12	452	2.0	12.0	10.0	39	-
107	U	11	380	5.5	21.0	15.5	20	-
108	U	13	531	2.0	12.5	10.5	40	-
109	U	10	314	1.5	10.5	9.0	41	-
110	U	12	452	3.5	16.0	12.5	32	-
111	T	14	616	2.0	14.0	12.0	41	1
112	T	13	531	2.0	12.0	10.0	39	2
113	T	9	254	2.0	13.0	11.0	36	1
114	T	13	531	3.0	15.0	12.0	35	1
115	T	14	616	3.5	14.0	10.5	34	1
116	T	18	1018	3.0	16.0	13.0	37	3
117	T	20	1257	3.0	15.0	12.0	33	3
118	T	15	707	2.0	12.0	10.0	36	3
119	T	13	531	3.0	14.5	11.5	35	2
Averages:		13	564			11.0	35	

* Root damage class only applies to tilled study trees.
1 = Low damage (18), 2 = Moderate damage (14), 3 = High damage (6)

Appendix 8a - An example of a competitive stress index calculation.*

Estimation of Dbh from stump Dob is based on the following regression equation:

Dbh = .855731(Stump Dob) - .530787
n = 603   R-Squared = 96.33

Study Tree #1

Residual Competition		**Harvested Competition**					
Stump Dob	Dbh	Stump Dob	Estimated Dbh	Distance From Subject Tree	Azmuth	**Prethin CSI	**Postthin CSI
20.9	18.1			25	360	16	16
		19.0	15.7	31	65	1	
		16.0	13.2	15	71	34	
22.2	18.3			22	159	25	25
		18.8	15.6	15	165	43	
19.7	16.7			14	271	50	50
		13.2	10.8	16	299	31	
27.9	21.4			17	337	50	50
		13.5	11.0	24	349	6	
			Subject Tree Dbh = 15.7"			100	100
						356	241

* For future use of CSI during analysis of treatment effects on radial growth, refer to Arney (1973), Froehlich (1979) and Smith and Bell (1983).

**Individual CSI numbers are taken from tables developed by Arney (1973) which quantify the relative stress placed on a tree by its neighbors based on dbh and distance of each competitor.

Appendix 8b - Competative stress index (CSI) numbers for 119 study trees.

Tree #	Pop'n	Prethin CSI	Postthin CSI	Change in CSI
1	C	356	241	115
2	C	296	237	59
3	C	474	265	209
4	C	404	199	205
5	C	268	206	62
6	C	312	165	147
7	C	193	191	2
8	C	270	139	131
9	C	350	163	187
10	C	337	223	114
11	C	379	212	167
12	C	359	148	211
13	C	258	145	113
14	C	352	198	154
15	C	354	203	151
16	C	261	192	69
17	C	386	257	129
18	C	418	252	166
19	C	408	218	190
20	C	326	183	143
21	C	186	135	51
22	C	309	202	107
23	C	448	238	210
24	C	427	254	173
25	C	373	226	147
26	C	305	277	28
27	C	371	279	92
28	C	377	284	93
29	C	340	242	98
30	C	321	218	103
31	C	325	208	117
32	C	330	225	105
33	C	330	229	101
34	C	284	156	128
35	C	329	319	10
36	C	256	233	23
37	C	341	246	95
38	C	372	235	137
39	C	330	251	79
40	C	299	197	102
41	U	241	174	67
42	U	337	183	154
43	U	380	221	159
44	T	259	186	73

Appendix 8b (cont'd)

Tree #	Pop'n	Prethin CSI	Postthin CSI	Change in CSI
45	T	218	195	23
46	T	385	283	102
47	T	363	196	167
48	T	328	234	94
49	U	401	209	192
50	U	411	200	211
51	T	272	172	100
52	T	429	210	219
53	T	377	166	211
54	T	233	172	61
55	T	349	256	93
56	T	420	245	175
57	T	415	251	164
58	T	373	243	130
59	T	380	208	172
60	T	316	194	122
61	T	477	146	331
62	T	332	194	138
63	U	338	150	188
64	U	348	164	184
65	U	271	160	111
66	U	450	174	276
67	U	350	196	154
68	U	284	225	59
69	U	231	199	32
70	U	370	204	166
71	U	345	161	184
72	U	347	201	146
73	U	317	156	161
74	U	404	160	244
75	U	280	150	130
76	U	471	168	303
77	U	444	284	160
78	T	286	174	112
79	T	279	168	111
80	T	358	191	167
81	T	311	196	115
82	T	399	178	221
83	T	327	187	140
84	T	484	198	286
85	T	353	133	220
86	T	469	255	214
87	T	446	280	166
88	T	351	259	92

Appendix 8b (cont'd)

Tree #	Pop'n	Prethin CSI	Postthin CSI	Change in CSI
89	T	417	256	161
90	U	364	271	93
91	U	374	162	212
92	U	406	198	208
93	U	314	159	155
94	U	302	187	115
95	U	295	169	126
96	U	412	157	255
97	U	425	179	246
98	U	380	200	180
99	U	448	228	220
100	U	401	222	179
101	U	382	164	218
102	U	439	243	196
103	U	281	164	117
104	U	360	199	161
105	U	325	169	156
106	U	330	166	164
107	U	338	150	188
108	U	392	228	164
109	U	377	254	123
110	U	372	212	160
111	T	374	286	88
112	T	350	211	139
113	T	395	291	104
114	T	262	212	50
115	T	347	212	135
116	T	334	209	125
117	T	348	282	66
118	T	330	192	138
119	T	322	172	150
Averages		350	207	143

Appendix 9 - Recorded stem damage for 10 study trees along skid trails.

Damage Type	Tree #	Description	Area
Cambium Cut	44	Skidder blade cut into cambium	3" x 3"
Cambium Cut	52	Wound on South side of bole	3" x 3"
Cambium Cut	56	Deep blade cut, 1.7 feet off ground	10" x 4", .75" deep
Cambium Cut	59	2 bark wounds and a cambium cut	2" x 2"
Cambium Cut	79	Wound on West side, 12" off ground	6" x 5" (oval)
Bark Removal	54	Bark scratch, no cambium damage	
Bark Removal	74	Dry wound, 3" from ground, mostly lost bark	6" x 6"
Root Collar	61	Root collar wound w/ cambium cut	6" x 2.5"
Root Collar	112	Soil removal & root collar damage in 2 places	2"x 2" & 2"x 5"
Root Collar	118	On top of root collar @ ground level	5" x 7"

Appendix 10 - Slash characteristics for 38 study trees near untilled trials.

Tree #	Slash Depth (in.)	Slash Diameter (in.)	
41	0.0	0.0	
42	0.0	0.0	
43	0.0	0.0	
49	2.0	0.8	
50	4.0	1.0	
63	3.0	0.5	
64	6.3	0.5	
65	0.0	0.0	
66	1.3	0.5	
67	0.0	0.0	
68	1.3	0.5	
69	0.0	0.0	
70	1.3	0.5	
71	0.0	0.0	
72	4.0	0.8	
73	3.0	0.5	
74	2.0	0.5	
75	2.2	0.5	
76	0.0	0.0	
77	0.0	0.0	
90	0.0	0.0	
91	2.5	0.5	
92	1.0	0.5	
93	0.0	0.0	
94	0.0	0.0	
95	0.0	0.0	
96	0.5	0.5	
97	0.0	0.0	
98	3.2	0.5	
99	0.0	0.0	
100	0.0	0.0	
101	0.0	0.0	
102	0.0	0.0	
103	3.7	0.5	
104	6.2	0.5	
105	2.0	1.0	
106	4.5	1.0	
107	3.0	0.8	
108	1.3	1.0	
109	3.3	1.4	
110	2.7	0.5	
	1.6	0.4	(Averages for all 38 trees, slash and non-slash)
	2.9	0.7	(Averages for just the untilled trees with slash)

Appendix 11 - Percent difference between trail and nontrail soil dry bulk densities for tilled and untilled study trees.*

Tree #	Pop'n	Difference @ 4" (g/ccm)	Difference @ 8" (g/ccm)	Difference @12" (g/ccm)	% Change @ 4"	% Change @ 8"	% Change @12"
41	U	0.199	0.167	-0.036	25.1	20.4	-3.7
42	U	0.207	-0.099	-0.093	22.6	-9.7	-9.0
43	U	0.162	0.254	-0.012	18.7	29.6	-1.4
44	T	0.145	0.105	-0.005	17.4	10.9	-0.4
45	T	0.111	0.062	0.031	15.3	7.1	3.2
46	T	0.075	-0.034	-0.000	9.1	-3.8	-0.0
47	T	-0.036	-0.118	-0.117	-4.1	-11.6	-10.8
48	T	0.091	0.096	-0.005	11.2	11.0	-0.5
49	U	0.076	0.127	-0.015	9.8	15.4	-1.5
50	U	0.112	0.055	-0.024	11.9	5.7	-2.2
51	T	0.094	0.041	0.026	11.9	5.0	3.0
52	T	0.084	0.022	-0.038	10.3	2.4	-4.3
53	T	0.075	0.003	-0.022	8.9	0.4	-2.2
54	T	0.052	0.037	-0.022	6.2	4.3	-2.3
55	T	-0.157	-0.263	-0.093	-15.4	-23.2	-8.2
56	T	0.141	0.035	-0.029	18.3	4.0	-3.2
57	T	0.004	-0.029	-0.052	0.5	-3.1	-4.8
58	T	0.073	-0.196	-0.080	9.1	-20.1	-7.3
59	T	-0.033	0.016	-0.073	-3.3	1.5	-6.4
60	T	0.202	-0.046	-0.043	23.8	-4.4	-4.3
61	T	0.043	-0.143	-0.025	4.6	-13.2	-2.3
62	T	-0.016	-0.064	-0.044	-1.7	-6.4	-4.5
63	U	0.135	0.058	-0.078	15.6	5.9	-7.2
64	U	0.011	-0.063	-0.060	1.2	-6.1	-5.7
65	U	0.219	0.137	-0.051	25.0	14.7	-5.1
66	U	0.139	0.065	-0.022	15.1	7.2	-2.3
67	U	0.266	0.127	0.033	28.9	13.2	3.2
68	U	0.224	0.175	-0.018	25.1	19.2	-1.8
69	U	0.009	-0.025	-0.030	0.8	-2.4	-2.5
70	U	0.246	0.068	-0.034	29.7	7.4	-3.4
71	U	0.233	0.080	-0.012	25.2	7.9	-1.2
72	U	0.172	-0.013	-0.068	18.9	-1.2	-6.6
73	U	0.230	-0.043	-0.028	25.2	-4.3	-2.5
74	U	0.176	0.126	-0.031	21.0	13.4	-2.6
75	U	0.195	0.220	-0.048	22.2	23.1	-4.7
76	U	0.166	0.246	0.015	18.6	28.4	1.5
77	U	0.069	0.080	0.009	7.4	7.9	0.8
78	T	0.075	-0.096	-0.034	9.0	-10.5	-3.6
79	T	0.183	0.026	-0.032	21.8	2.7	-3.3
80	T	0.183	0.107	0.022	20.7	11.2	2.0
81	T	0.010	-0.010	-0.065	1.1	-1.2	-7.0
82	T	0.130	-0.099	-0.028	15.3	-9.8	-2.4

Appendix 11 (cont'd)

Tree #	Pop'n	Difference @ 4" (g/ccm)	Difference @ 8" (g/ccm)	Difference @12" (g/ccm)	% Change @ 4"	% Change @ 8"	% Change @12"
83	T	-0.060	-0.021	-0.040	-6.8	-2.3	-4.0
84	T	0.175	0.087	-0.025	21.1	9.4	-2.4
85	T	-0.034	0.081	-0.022	-3.6	9.2	-2.2
86	T	0.133	-0.018	-0.016	14.9	-1.5	-1.4
87	T	-0.021	-0.084	-0.044	-2.1	-8.7	-4.1
88	T	0.209	-0.054	0.018	27.2	-5.4	1.7
89	T	-0.015	-0.158	-0.051	-1.4	-13.4	-4.0
90	U	0.347	0.272	0.057	38.2	29.0	5.8
91	U	0.178	0.042	-0.071	20.2	4.1	-7.1
92	U	0.146	0.111	-0.070	17.0	12.2	-6.5
93	U	0.182	0.103	0.003	20.2	10.7	0.3
94	U	0.117	0.259	-0.035	12.0	29.5	-3.2
95	U	0.049	0.129	0.016	5.0	14.3	1.6
96	U	0.230	0.126	0.050	26.2	12.8	4.5
97	U	0.390	0.231	-0.013	51.3	25.3	-1.2
98	U	0.171	0.056	-0.024	19.0	5.7	-2.4
99	U	0.205	0.137	-0.024	23.2	13.9	-2.6
100	U	0.203	0.281	0.021	24.3	34.3	2.3
101	U	0.084	0.113	-0.007	8.5	12.6	-0.7
102	U	0.121	0.131	-0.016	13.8	14.2	-1.6
103	U	0.089	-0.063	-0.131	9.9	-6.2	-11.8
104	U	0.079	0.071	-0.042	8.7	6.4	-3.8
105	U	-0.052	0.127	-0.064	-5.8	13.6	-6.2
106	U	0.128	0.189	-0.032	13.8	22.0	-3.7
107	U	0.139	0.010	-0.083	14.9	1.0	-7.7
108	U	0.178	0.132	0.018	20.4	13.9	1.7
109	U	0.091	0.015	0.002	9.7	1.4	0.2
110	U	0.091	-0.047	-0.085	10.6	-4.6	-7.1
111	T	-0.028	0.145	-0.124	-3.1	16.3	-12.5
112	T	-0.046	0.020	-0.080	-5.3	2.0	-8.2
113	T	0.079	-0.043	-0.016	8.8	-4.2	-1.8
114	T	-0.055	-0.095	-0.029	-5.8	-8.8	-2.4
115	T	-0.079	0.021	-0.051	-8.6	2.2	-5.2
116	T	-0.036	-0.061	-0.063	-4.3	-6.5	-6.1
117	T	-0.023	-0.132	-0.074	-2.3	-12.0	-6.5
118	T	0.034	-0.014	-0.074	3.6	-1.4	-7.4
119	T	0.082	-0.079	-0.038	9.3	-7.6	-3.7
				Averages:	T=6.1% U=17.8%	T=-2.2% U=11.2%	T=-3.6% U=-2.7%

* Negative percentages represent locations where trail bulk density is lower than non-trail bulk density.