Soil Compaction and Disturbance Following a Thinning of Second-Growth Douglas-fir with a Cut-to-Length and a Skyline System in the Oregon Cascades

by

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Abstract

Soil bulk density and disturbance were measured before and after a commercial thinning of 30-50 year-old Douglas-fir using a cut-to-length (CTL) and a skyline system on the Willamette National Forest in the Oregon Cascades. A dual-probe nuclear densimeter was used to measure bulk density at four and eight inches. Slash depth after thinning and disturbance category were determined at bulk density measurement points in all units. Data were analyzed using paired t-tests, Tukey-Kramer multiple comparison tests, and multiple linear regression.

Data were collected in two CTL units pre-thinning but one unit post-harvester and post-thinning (after both harvester and forwarder). During the sampling period thinning was completed only in the northeast corner of one unit (approximately 25 acres) before operations were ended due to concerns about soil moisture conditions and damage to hauling roads. Thus post-harvester and post-thinning data and conclusions apply only to that portion of the CTL units. In this harvested portion, slopes ranged from 0-10 percent and equipment traffic levels were estimated to range from three passes at the end of skid trails, to 30 passes on secondary trails and well over 40 passes on primary trails. These values are considered characteristic of most of Unit 82 except for areas near streams with steeper slopes.

Plot centers were located using an incomplete, offset grid system. A sub-sample of bulk densities in old skid trails was also taken. The effects of harvester-only and the combined effect of harvester-forwarder traffic on the bulk density of old skid trails and previously undisturbed soils was assessed. In the three skyline units, bulk density was

measured in the center, edge and halfway between skyline roads both before and after thinning. In addition, detailed maps of soil disturbance were created from transects located both directly on top of and halfway between a sub-sample of skyline roads within each unit.

From the randomly located plots in the CTL units, it was determined that old skid trails covered approximately 27 and 13% of the two units, respectively. In the portion of the one unit where thinning was completed, it is estimated that an additional 27% of the area was disturbed, for a total of 40% disturbance post-harvester. Further, the harvester was estimated to have left exposed soil on 4% of the area and mixed the mineral and organic horizons on 9%. Post-thinning (both harvester and forwarder), new disturbance was estimated at 25%, for a total combined disturbance of 38%. Exposed or mixed soil was not observed at this time. The discrepancy between post-harvester and post-thinning disturbance estimates is thought to be due to different surveyors, slightly different data sets, redistribution of slash during forwarding or sampling error.

In the skyline units, the maximum unit-wide disturbance was 1.8%, though greater than 10% of some units were in skyline roads. Mixing accounted for most of the disturbance, with exposure and rutting never reaching 0.5% on a unit-wide basis. The areas of exposure and rutting were small, discontinuous and usually occurred within 150 feet of the landing.

In comparison to undisturbed soil, bulk density was still significantly elevated on the fifty-year-old skid trails sampled in the CTL units. The old skid trail center was 10-16% more dense than undisturbed soil at the four inch depth in both units, but only ruts in Unit 81 were also greater in density (+8%) at the same depth. At eight inches, old skid trail ruts in both units were consistently more dense (13-15%), as well as the center of trails in Unit 82 (+15%). In neither unit was the bulk density of old skid trail berms statistically different from undisturbed soil. Overall, it is estimated that 4 and 10% of Unit 81 (4 and 8 inch depth) and 6 and 4% of Unit 82 was already in a compacted state prior to this thinning entry. It is important to note, however, that elevated bulk densities on old skid trails may also be explained by measurements being made on naturally more dense subsoils exposed after scalping of the surface soils during the initial harvest entry.

The harvester alone was not found to significantly compact either undisturbed soil or old skid trails ($p>0.10$). Harvester-forwarder traffic significantly increased the bulk density of previously undisturbed soil by an average of 12 (4 inch depth) and 11% (8 inch depth, $p=0.04$ and 0.05), but did not change the bulk density of old skid trails. Compaction levels as a result of this entry were comparable with those of old skid trails. Overall, it is estimated that this new entry contributed an additional 25% (4 and 8 inches) to the compacted area, for an estimated total compacted area of 29-31%. The estimate of total compaction due to this thinning is based on the estimated area in new skid trails and an average of all observed compaction values across the width (both ruts and center) of the skid trail.

The bulk densities of the center, edge and zone between skyline roads after thinning were compared to pre-thinning values, but revealed no evidence that a significant difference existing between the four categories (90% level). There was some evidence that mixed soil with ruts greater than six inches deep were approximately 40 and 45% (4 and 8 inch depth) more dense than undisturbed soil ($p=0.0006$ and 0.0002). Also, points along the skyline roads where over 16000 ft^3 were yarded were found to be significantly associated with a reduction in bulk density of approximately 16 and 18% at four and eight inches in depth (p=0.022 and 0.008).

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1. Introduction

Accompanying the change from a timber base consisting of large, old trees to smaller, second-growth stands has been a decrease in average tree diameter and increase in harvesting costs per-unit volume in the Pacific Northwest. Long-term soil productivity and minimization of timber-harvest related disturbance also remain a concern for forest managers. Practices such as leaving limbs and tops in the stands as a nutrient source and avoiding soil compaction are some of the ways managers have sought to deal with these concerns. Mechanized harvest may provide an economical tool for implementing such practices (Kellogg and Brink 1992, Kellogg et al. 1992). The benefits of mechanized harvest[1] have been said to include (Gingras 1994, Howe 1994, Lanford and Stokes 1995):

- Minimization of soil disturbance and compaction
- Improved safety by having most workers within protective equipment cabs during felling operations
- Better transport scheduling ensured by the delivery of evenly spaced loads
- Direct harvester/mill linkage via computerized tree measuring programs
- Improved utilization of marketable timber
- Optimization of log lengths as required by the mill.

While these advantages do not apply equally to all mechanized harvesting systems, it is believed that both the cut-to-length (CTL) and cable harvest systems have great potential to help forest managers meet their economic and site productivity and disturbance goals. Little technical

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[1] Operations with at least one single or multi-function machine for manufacturing (felling, delimbing, bucking or chipping), or operations where trees or logs are placed in bunches prior to primary transport, or operations where primary transport is able to handle multiple stems." (Kellogg et al. 1992)

information is available, however, about the effects these systems have on soil (Bettinger et al. 1993). The objective of the two case studies presented is to increase our knowledge of the effects these systems have on soil. Specifically, I sought to quantify the degree and extent of soil compaction and disturbance incurred during thinning operations with a harvester/forwarder pair and a small-wood cable yarder in second-growth conifer stands in the western Oregon Cascade Mountains.

2. Literature Review

2.1 General

High organic matter contents, soil fauna activity, the presence of old root channels and other properties make many Pacific Northwest forest soils low in bulk density, high in porosity, and low in strength. Those properties make these soils particularly susceptible to compaction from harvest machinery (Froehlich and McNabb 1983). Bulk density, "...defined as the mass of dry soil per unit bulk volume of the solid, liquid, and gaseous phase", is the most common measure of soil compaction (Froehlich and McNabb 1983).

There are two general ways to assess soil compaction concerns. First is the edaphological approach, which relates the vegetative response to soil compaction. Second is the pedological approach, which focuses on the study of soil physical properties (Walker and Chong 1986). This literature review discusses soil compaction as it affects both the edaphological and pedological realms, although the field research focuses on the latter.

2.2 The Soil Compaction Process

The inherent bulk density of a soil is determined by its particle size distribution, gradation, particle roughness, organic matter content, mineralogy of the clay fraction, and structure (Froehlich and McNabb 1983). When a sufficient load is applied to a soil, the particles are rearranged and brought closer together, increasing soil strength and reducing total porosity at the expense of the large voids (Greacen and Sands 1980). In turn, volumetric water content and field capacity can be increased, while air content, infiltration rate and saturated hydraulic conductivity can be reduced. The consequences may include elevated risk of surface runoff and lower tree growth associated with a diminished water supply (if runoff increases), restricted root growth and poor aeration.

It is commonly thought that the compactability of a soil is affected largely by the moisture content at time of compaction and soil texture. For this reason, logging equipment is often restricted to operating on dry or frozen soils. It is important to note that some soils compact to similar bulk densities almost regardless of moisture content, thus the optimum compaction/moisture content relationship should be determined on a site specific basis (Froehlich and McNabb 1983). Soils with a broad distribution of particle sizes are usually considered most compactible, though fine textured soils have also been found to compact to relatively high bulk densities (Page-Dumroese 1993, Geist et al. 1989, Sullivan 1987). Sandy soils or soils with very high organic matter contents have proved to be resistant to compaction in some locations (Graecen and Sands 1980) and susceptible in others (Froehlich et al. 1980).

Natural processes that act to reduce bulk densities include freeze/thaw cycles, shrinking and swelling of clays, soil fauna activity, plant root growth, and windthrow. Coarse-textured soils have been noted to regain undisturbed levels of bulk densities more quickly than fine-textured soils. Unfortunately, the combination of soil types and climate in the Pacific Northwest impede the progress of these ameliorative processes, making compaction a rather long-lived phenomenon (Adams and Froehlich 1981). Studies in this region have found soil compaction to still be present up to several decades after machine-caused compaction (Froehlich 1979, Froehlich and Berglund 1979, Geist et al. 1989, Vanderheyden 1980, Wert and Thomas 1981).

2.3 Equipment, Skid Trail Layout and Design, and the Compaction Process

In addition to the inherent soil properties previously discussed, the degree and extent of soil compaction incurred depends on the amount and type of machine pressure and vibration applied, wheel slip, tree size and suspension, number of equipment passes, skid trail slope and curvature, and the experience of the machine operators (Adams and Froehlich 1981, Ryder et al. 1994, Wingate-Hill and Jakobsen 1982).

A study conducted at four sites in the Sierra Nevada mountains compared the compaction due to a crawler tractor, rubber-tired skidder, and a flexible-track, torsion-suspension vehicle in controlled skidding tests (Froehlich et al. 1980). For all three machines, 60% of the soil density achieved after 20 passes was present by the sixth trip, with minimal increases in density after further machine passes. This asymptotic relationship between bulk density and number of passes has been noted in many studies (Armlovich 1995, Froehlich 1978, Ryder et al. 1994, Zaborske 1989). The crawler tractor, however, produced greater increases during the first ten trips than either the rubber tired skidder or the torsion suspension vehicle. In addition, the crawler tractor produced 60% greater bulk densities than the skidder or the torsion suspension vehicle ($p<0.01$).

Another comparison between the soil impacts due to a flexible and rigid tracked skidder operating over a protective slash mat was conducted in a mountain ash stand (Eucalyptus regnans) in Australia (Jakobsen and Moore 1981). Soil textural analysis revealed a composition of 33% clay, 22% silt and 45% sand. While measured soil properties did not significantly differ between the two pieces of equipment, the flexible tracked skidder exhibited a superior ability to traverse the slash mat without disturbance.

In order to quantify the relationship between soil disturbance and skid trail characteristics, measurements of parallel and side-hill skid trail slope, curvature and traffic density were made on 5.6 miles of trails in north central Maine (Ryder et al. 1994). Textural analysis of a soil sample from the study site revealed a composition of 36.21% sand, 45.98% silt and 17.81% clay. The results of regression analysis suggested that skid trail curvature and the number of equipment passes explained most of the soil disturbance. Side-hill and skid trail slope contributed little to the regression.

Flexible track machines have lower ground pressures and better traction than rigid-tracked or rubber-tired skidders (Sirois et al. 1985). On the other hand, the flexible-track vehicles may have greater cost and lower versatility (Wingate-Hill and Jakobsen 1982). Static machine pressure, however, may not be as accurate in predicting post-traffic bulk density as dynamic vehicle pressure which accounts for log load and ground slope (Lysne and Burditt 1983). Models of theoretical ground pressures for a crawler tractor, torsion-suspension vehicle and rubber-tired skidder revealed substantial differences between the leading and trailing track or tire when up- or downhill skidding. Static ground pressures do not account for such changes in weight distribution over the machine footprint.

2.4 Slash as a Protective Layer Against Compaction

Mechanized harvesting may provided an opportunity for managing logging slash as a protective cushion against machine weight and thus soil compaction. Froehlich (1978) suggested that the presence of a litter layer reduced the degree and depth of compaction following skidding with a torsion-suspension vehicle in sites throughout Oregon, though no formal analysis of the two parameters was conducted. It is possible, however, that the different characteristics between logging slash and the litter layer would affect any role that each played in protecting against soil compaction.

In order to examine the potential protection offered by slash, soil bulk density measurements were taken before and after forwarder traffic (loaded) at two levels (1 and 5 passes), three slash densities (0, 10, and 20 kg/ m^2), and two moisture contents ("dry" and "wet") over loamy sands in Alabama (Seixas et al. 1995). For both the dry and wet soils, the increase in bulk density was the same at all slash densities after one pass. After five passes over the dry soil, the no-slash treatment had significantly higher bulk densities than either slash treatment, between which there were no differences. For the wet soil data, the heavier slash treatment (20 kg/ m^2) exhibited lower bulk density than the 10 kg/m^2 slash treatment, although this difference was not significant at the 95% level. The 20 kg/m^2. treatment was, however, significantly lower than the bare plot treatment. Thus, slash appears to protect against increased bulk density as the number of passes increases, and wet soils may benefit more than dry from a slash layer.

In a study conducted in the Oregon Coast Range, the results of a stepwise regression did not suggest a trend of decreased compaction with increasing slash depth or diameter following skidding with a rubber-tired skidder and a small crawler tractor (Hogervorst 1994). Results from an analysis of variance did show a significantly greater mean bulk density for skid trails without slash as compared to slash covered trails (10.2 and 20.3 cm depths, $p<0.05$).

After logging with a harvester-forwarder pair in the Cascades of Oregon, measurements of O-horizon depth, slash depth, density, and average slash diameter were collected in addition to bulk density data (Armlovich 1995). Measured characteristics of slash and the O-horizon depth were greatest at less than four equipment passes, remained at a constant level from five to 20 passes, then reached their lowest values at the greater than 30 passes strata. It was found that as the amount of slash diminished bulk density increased, suggesting that a factor of protection is presented by the slash layer.

Zaborske (1989) measured bulk density, slash depth and number of passes by a tracked feller-buncher and rubber-tired skidder on volcanic ash soils in eastern Oregon. The findings of this study were similar to Armlovich in that slash depth was significantly reduced with the first few passes, remained constant at intermediate levels of traffic, then decreased again at greater than 50 passes. A negative relationship was found to exist between bulk density and slash depth at a given number of passes ($p<0.01$).

The effect of skidder traffic (torsion-suspension vehicle and Caterpillar D-7) on the bulk density and cone index of bare or slash-covered soils (18 kg/m^2) was tested in Australia by Jakobsen and Moore (1981). Some protection was provided by the slash mat but only for a few logging cycles. No difference between the two skidders was observed.

Another Australian study (Wronski 1990) concluded that apparent soil strength increased by 25% for every additional 10 kg/m^2 of slash placed above a slash base of 10 kg/m^2. A noticeable reduction in rut formation was another observed benefit of slash placement.

It is important to note that the quantity and depth of slash normally diminishes (mechanically removed or crushed) with increasing number of equipment passes. These changes confound the identification of specific causal factors related to bulk density. However, the available findings support further study of relationship between slash and changes in bulk density.

2.5 Soil Disturbance Associated With Forest Harvest

Soil disturbance due to harvest activities remains a concern to forest resource managers. Disturbance covers a wide variety of soil conditions such as mixing (mixing of mineral and organic horizons), exposure, rutting, puddling, displacement, and scalping. It is important to note that disturbance, as a commonly used term in studies of forest harvest effects on soils, does not necessary imply a negative impact. For the purpose of this study, disturbance was defined as "...any direct movement or compression of soil or surface litter during mechanised thinning and harvesting operations" (Wingate-Hill and Jakobsen 1982). Abeels (1995) distinguished between several terms; disturbance, alteration, change and damage to soils. Disturbance only represents visible evidence of harvest activities. An alteration, like compaction, implies a change. "An effective change implies a substitution or an essential modification that adds to the alteration...like a modification of the pH or of the chemical composition" (Abeels 1995). Finally, damage corresponds to a loss, such as reduced productivity or erosion.

As compaction has been strongly tied to the reduced growth of conifers located adjacent to or in compacted areas in the Pacific Northwest, it can imply damage, given a sufficient spatial context and relative increase in bulk density. The other disturbance categories do not have as clear a direct relationship as a causal factor in reduced site productivity or losses. Thus, they are best referred to as disturbances or alterations, and in a few cases damage as discussed below.

Puddling, the shearing and destruction of soil aggregates in wet conditions, reduces soil permeability and increases the risk of erosion (Sirois et al. 1985). Pomeroy (1949) attributed poor germination rates of loblloly pine (Pinus taeda) to puddling after wet-weather logging in Virginia.

Rutting can disrupt natural drainage patterns and increase the incidence of surface ponding (Sirois et al. 1985). In addition, severe rutting may decrease tree growth. Though no significant differences in bulk density, porosity, or saturated hydraulic conductivity were identified between undisturbed and disturbed soils in an Arkansas logging unit, loblloly pine (Pinus taeda) growing within 12 feet of skid trails with ruts greater than six inches deep experienced reduced diameter growth (-5%) and periodic annual increment (Reisinger et al. 1992). Trees growing adjacent to ruts 0-3 and 3-6 inches deep showed no significant differences in growth. Six inches corresponds to the depth of the A-horizon found in the study area. Tiarks (1990) also found rutting to be associated with decreased height growth of slash pine (Pinus elliottii var. elliottii Engelm.) seedlings in Louisiana. Wet-weather logging resulted in different areal extents of rutting in growth plots ranging from low (<25%) to moderate (25-75%) and high (75%+). Tree heights in the low disturbance category were not significantly different from the undisturbed condition, but trees in the moderate and high disturbance categories were significantly shorter (2.4 m and 1.9 m vs. 2.8 m).

Removal of the O-horizon (exposure) can result in reduced availability of nutrients. Zabowski et al. (1994) subjected soil plots in New Zealand to one of three treatments: O-horizon preserved (OP), O-horizon hand removed, no compaction (OR), and O- and A-horizons removed with heavy compaction from eight passes of a loader (COAR). Maximum summer temperatures of the OR and COAR treatments increased by approximately 10°C, and minimum winter temperatures were reduced by 5°C. The increased temperatures are suggested as being a causal factor in the observed decrease in fine-root and mycorrhizal-root biomass observed in the OR and COAR treatments, which were five and ten times lower than the OP condition, respectively. Radiata pine (Pinus radiata D. Don) seedlings planted on the OR and COAR plots had growth rates of 70 and 20% as compared to the OP plots. As productivity losses occurred in both the OR and COAR treatments, it appears that a mechanism other than compaction is significant.

Significant displacement of surface organic matter was found to occur during cable logging over silt loams and during both cable and ground skidding over a sandy loam soil in southwestern Mississippi (Miller and Sirois 1986). Overall, the fertility of the sandy loam was most effected by harvesting, with significant reductions in phosphorus and calcium. Exposure of the clay containing subsoil resulted in increased magnesium concentrations for both harvest methods.

Based on the studies examined above, there is some evidence to suggest that soil ruts extending through the depth of the A horizon may qualify as damage according to Abeels'(1995) definition when associated with decreased conifer growth. Puddling, as it was linked to poor germination rates of loblloly pine (Pinus taeda), may be considered a damaging disturbance as well. Without a stronger tie to a significant loss to site productivity, exposure or mixing disturbances are best considered an alteration.

2.6 Soil Compaction and Disturbance Associated With Ground-based Mechanized Harvest

Using conventional "logger's choice" harvesting with tractors or rubber tired skidders,up to 18-36% of a unit can be covered by skid trails (Froehlich et al.1981). Additional entries can increase that area up to 80%. Bulk density increases in these trails can range from 10-80% (Froehlich et al. 1981). Less information is available on soil compaction and disturbance due to ground-based, highly mechanized harvest systems. Wingate-Hill and Jakobsen (1982) state that there is a consistent pattern of 1-3% of the harvest unit area having heavy disturbance (landings), a larger area in moderate disturbance (primary skid trails,3-20%) and light disturbance occurring over 8 to 45% of the area as secondary trails. Table 1 presents a summary of soil disturbance and compaction as the result of different mechanized harvest systems.

Feller-buncher systems, which require that equipment without booms drive to the base of every tree, have raised concerns about soil impacts. Table 1 shows that feller-buncher systems (feller-buncher and grapple skidder) may disturb 9 to 54% of total unit area. The low 9% level noted in Hogervorst (1994) is most likely due to the fact that the feller-buncher was only used to clear main skid roads while the trees between trails were manually felled. Excluding those results, these systems average 36% disturbance, with approximately 15% attributed to only the feller-buncher. Increases in bulk density ranged from 0 to 25% in the surface soils.

In contrast, single-grip harvesters paired with either a crawler tractor or forwarder averaged total disturbance levels of 21% with a maximum of 38 and minimum of 16%. Interestingly, the pairing of a single-grip harvester with cable yarding increased the level of disturbance to approximately 40% (Hogervorst and Adams 1995). Over half of this disturbance, however, was defined as “light use”, and only 4 to 9% was described as “heavy use”.

With the harvester/forwarder system, bulk density was noted to increase by 20% with less than four equipment passes (4 inch depth, Armlovich 1995), though only a 12% increase (2 inch depth) was noted in a harvest unit in Alabama (Lanford and Stokes 1995). It is difficult to compare these two numbers, however, as the first study is based on specific equipment pass categories while the latter is based on a soil disturbance category probably averaged across many pass categories.

Location	Method	Bulk Density Changes	Area Disturbed	Reference
Lyons, OR. West Cascades	SGH, F	<4 Passes: 4": +20% , 8": +5% 12": +9% 7-8 Passes: 4": +17% , 8": +16% 12": +11% 30+Passes: 4": +29% , 8": +23% 12": +20%	Total: 23.2%	Armlovich 1995
Manitoba Model Forest, Canada	SGH, F	NA	Total: 25%	Gingras 1994
Eugene, OR. Eugene Dist. BLM, Coast Rng.	Tracked FB, RTS	4": +17.8% , 8": +11.2% 12": +2.7%	Designated skid trails: 7% Landings: 2% Total: 9%	Hogervorst 1994
A) Deerhorn, Ukiah, OR. E. Oregon B) Enterprise, OR.	A) SGH, cable yarding B) (1) Tracked FB, RTS (2)SGH, CT	A) 4": 0 to +8%* 8": 0 to +8%* B) 4 & 8": No significant differences (90%), but limited sample size. *Range for sites with and without rock.	A) Avg: 40% B) (1) Avg: 28-33% (2) Avg: 16-26%	Hogervorst and Adams 1995
Baldwin County, Alabama	SGH, F	2″: +12%* 6″: 0%	Total: 38%	Lanford and Stokes 1995
Burns, OR. Malheur NF	Tracked FB, CT	+0.047 Mg/m^3	FB: 11% Designated Skid Trails: 18% Total: 29%	McNeil 1996
Oakridge, OR. W. Cascades, Willamette NF	Rubber-tired FB, RTS	Avg: +25%	FB: 14% RTS: 20% Landings and Roads: 4% Total: 38%	Murdough & Jones 1984
LaGrande, OR. Willowa-Whitman NF	2*Tracked FB, 2*RTS	After FB: 0-4": +2.6% , 0-8": +8.7% , 0-12": +8.8% After RTS (1-4 Passes): 0-4": +0.69%, 0-8": +6.6% , 0-12": +9.3%	FB: 19% RTS: NA DST: 12% Total: 54%	Zaborske 1989

Table 1: Summary of soil disturbance and bulk density after mechanized commercial thinning operations. RTS = Rubber-tired skidder, SGH = Single-grip harvester, FB = Feller Buncher, CT = Crawler tractor, F = Forwarder, DST = Designated skid trail.

2.7 Soil Compaction and Disturbance Associated With Cable Harvest

The difficult terrain, large tree size, and stand density of the Pacific Coast made cable logging "...a direct leap from oxen and horse logging.." (Silversides 1984). Thus, cable logging has a long history of use in the Pacific Northwest. Recent concerns about soil impacts and logging in environmentally sensitive areas, plus the advent of smaller, trailer-mounted yarders, has served to emphasize the benefits of cable harvest despite its generally higher cost over ground based yarding and mechanized systems. Studies in various locations show that cable harvest does not disturb the soil to the extent that ground based harvesting systems do, and can still be cost effective. Factors controlling the degree of damage following harvest with a cable system include the degree of deflection, terrain shape, log size, soil moisture content, rigging heights, use of intermediate supports, and winter logging over snow.

With long convex slopes and hummocky relief, a clearcut cable logging unit in the Mangatu Forest, New Zealand, resulted in 62% of the unit experiencing only shallow disturbance (disturbance of litter layer and some mixing of litter and topsoil, McMahon 1995). Twelve percent of the area experienced deep disturbance, mostly on mid span ridges. Of that 12%, most of the area had topsoil removed, with 3% in ruts or in a puddled or unconsolidated condition. Only 1% of the area was compacted.

In a similar study in North Carolina, three units with differing harvest intensities (conventional shelterwood, irregular shelterwood, and commercial thinning) were cable yarded with a 37 ft tower and a Christy Carriage (Baumgras et al. 1995). After harvest, visual observations of soil conditions were made, placing plots in categories of undisturbed, deeply disturbed, or deeply disturbed and compacted. No significant differences between silvicultural treatments were noted. The average of all treatments found 70% of the total area to be undisturbed and 10.3% to be deeply disturbed or deeply disturbed and compacted. Outside of cable roads, 6.1% of the area was deeply disturbed, as compared to 43.7% within cable roads. Only 14.6% of the area in cable roads was undisturbed. Poor deflection was suggested as the major factor in soil damage.

A Bell TH120 with a single-grip harvesting head was paired with a 30 foot trailer-mounted tower in order to examine alternative means of clearcut harvesting Eucalyptus grandis on sensitive flat terrain in Zululand, South Africa (Howe 1994). In addition to being cost effective, soil disturbance on the site was so minimal that the author "...deemed it unnecessary to quantify."

In contrast, a harvester/cable combination used in northeastern Oregon thinning resulted in 41 and 38% of the soils in two units being disturbed, with 6-10% exposed and 4-9% displaced (Hogervorst and Adams 1995). Further, ruts up to one foot deep were formed in the ash soils in a few locations. Measurements with a nuclear densimeter did not identify compaction to be a significant impact of this harvest system ($p>0.10$). It was suggested that soil disturbance could have been reduced in some locations with better use of intermediate supports.

Bulk density measurements were taken before and after summer high-lead clearcut logging in the Cascade Mountains in Washington (Purser et al. 1992). Unlike Hogervorst and Adams (1995), increases in bulk density in cable roads were found to be significant ($p<0.025$), with a resulting 32.7% reduction in available water storage. Skid trails covered 5-7% of the unit and were mostly exposed. While the northeast Oregon study involved small diameter pine, this study took place in a 250 to 500 year-old stand of western hemlock (Tsuga heterophylla), Pacific silver fir (Abies amabilis), and western redcedar (Thuja plicata), which may partly explain the higher bulk densities.

Another study of old-growth, high-lead logging in the Cascade Mountains found that across three clearcut units, 51-63% of the area was undisturbed, 19-25% was slightly disturbed, 6-14% was deeply disturbed, and 7-11% was compacted (Dyrness 1965). In comparison to a nearby tractor unit, all disturbance classes were comparable except for compaction, where the tractor unit had three times the degree of change in bulk density compared with the high-lead units. Pre-logging bulk densities were in the range of 0.71 g/cm^3, increasing to 0.95 g/cm^3 in compacted areas.

2.8 Affects of Compaction on Conifers

2.8.1 Establishment

Except for at very high bulk densities, compaction seems to have little or no impact on conifer germination or establishment. In the Oregon Cascades, Youngberg (1959) found survival rates of Douglas-fir (Pseudotsuga menziesii) 2-0 seedlings after one year to be above 90 percent regardless of whether they were planted on tractor roads, the adjacent berms, or undisturbed soil. No significant difference was found in the first year survival of loblloly pines (Pinus taeda) planted on and off of skid trails in Georgia (Campbell 1973). Only a bulk density of 1.8 g/cm^3 was found to reduce the establishment of pitch pine (Pinus rigida), Austrian pine (Pinus nigra), or Norway spruce (Picea abies (L.) Karst) in silt loam soils (Zisa et al. 1980). Establishment was not affected on sandy loams up to the same bulk density in greenhouse experiments. Compaction created by wooden mallets during planting actually significantly improved the establishment of jack pine (Pinus banksiana) in northwestern Ontario (VanDamme et al. 1992). "Seed germination was not affected by soil type or treatment, but seedlings became established with difficulty on clay cores and on heavily compacted cores of lighter texture" in South Carolina (Foil and Ralston 1967). Seedling survival of 15 week-old lodgepole pine (Pinus contorta) and 24 week-old White spruce (Picea glauca) was not affected by bulk densities equivalent to post-ground equipment logging on loamy aeolian soils in west-central Alberta (Corns 1988).

2.8.2 Seedling Growth

The affects of compaction on seedling growth have been variable, but the majority of studies show a consistent trend of decreased growth with increasing bulk density. Heilman (1981) grew Douglas-fir (Pseudotsuga menziesii) seedlings for 35 to 45 days in compacted soil cores with bulk densities ranging from 1.3 to 1.77 g/cm^3. Though seedling heights were not significantly affected by bulk density, this experiment found a linear decline in rooting with increasing bulk density ($p<0.0001$). It was also noted that the bulk density at which root penetration was restricted for most seedlings varied by soil texture. Rooting penetration in a loam topsoil (19% clay, 27% silt) was limited at a bulk density of 1.83 g/cm^3, another loam topsoil (24% clay, 29% silt) at 1.75 g/cm^3, and a sandy loam weathered subsoil (14% clay, 30% silt) at 1.75 g/cm^3.

In a study for the Eugene District of the Bureau of Land Management, Froehlich (1979) planted Douglas-fir (Pseudotsuga menziesii) seedlings in skid trails with a specified number of tractor passes (0, 1, 3, 6, and 10). After four years, seedlings planted on a clay loam soil with six and ten passes had 8.5 and 13.9% less height growth than the zero and one pass plots. Reductions of 11 and 21% were noted for the six and ten passes class as compared to the zero and one classes on a sandy loam soil.

In the Oregon Cascades, Youngberg (1959) found that the heights of 2-0 Douglas-fir (Pseudotsuga menziesii) seedlings grown for two years on skid trails with clay textures were significantly reduced ($p<0.01$). The clay content of the undisturbed soils was considerably lower than that of the skid trails.

Seedlings of seven tree species (Pinus contorta, Pseudotsuga menziesii, alnus rubra, Abies amabilis, Tsuga heterophylla, Picea sitchensis, and Thuja plicata) were grown in compacted sandy loam soil cores (1.32, 1.45, and 1.59 g/cm^3) and observed for 1.3 years (Minore et al. 1969). Only western redcedar (Thuja plicata) showed significant effects in total, root, and shoot weights between density treatments. The roots of all species grew through the 1.32 g/cm^3 cores, though cores of 1.45 g/cm^3 prevented rooting of western redcedar (Thuja plicata), Sitka spruce (Picea sitchensis), and western hemlock (Tsuga heterophylla). Red alder (Alnus rubra), lodgepole pine (Pinus contorta), and Douglas-fir (Pseudotsuga menziesii) roots completely penetrated the 1.45 g/cm^3 core, but the root growth of these species were severely restricted by the 1.59 g/cm^3 core.

Pearse (1958) grew Douglas-fir (Pseudotsuga menziesii) and western hemlock (Tsuga heterophylla) from seed in soil cores compacted to levels of 0.586, 0.842, and 1.017 g/cm^3. Measurements of average green weight, root length, top length, and top:root ratio were taken after eight and 13 weeks of growth. Seedlings grown in the intermediate compaction had roots that were slightly longer than the lowest compaction, but the roots of seedlings grown in the highest compaction were substantially shorter. The affects on seedling height were not as pronounced, but a trend of decreasing height with increasing bulk density was identified.

Conifer species of other areas of the United States had similar growth reductions associated with compaction. Foil and Ralston (1967) grew loblloly pine (Pinus taeda) seedlings for one season in compacted cores (loamy sand, loam, and clay textures) and found "negative linear relationships between root weight and penetration and densities ranging from 0.8 to 1.4 g/cm^3 and that compaction at all rates "greatly reduced seedling size and weight." The weight of seedlings grown in clay were also observed to be significantly less than in other textures.

Pitch pine (Pinus rigida), Austrian pine (Pinus nigra), and Norway spruce (Picea abies (L.) Karst.) were grown from seed for 120 days in silt loam and sandy loam soils compacted to bulk densities of 1.2, 1.4, 1.6, and 1.8 g/cm^3 (Halverson and Zisa 1982). This experiment discovered that "...root penetration depth is highly correlated with soil compaction stress." None of the other growth response variables were well-related to soil compaction stress ($p<0.01$). Soil type and seedling species were significant factors affecting growth, but partitioning the variance among the main effects showed compaction to be the most important variable.

Mitchell et al. (1982) performed a greenhouse experiment of how loblloly pine (Pinus taeda) seedling growth was affected by differing compaction levels in a gravely fine sandy loam (1.2, 1.4, 1.6, 1.8, and 2.0 g/cm^3). Seedling height was measured weekly for nineteen weeks (week fourteen omitted). Root growth, mass, and surface area were measured at final harvest in addition to a qualitative evaluation of mycorrhizal infection. The poorest root growth and mycorrihzal infection occurred at bulk densities of 1.8 and 2.0 g/cm^3, and improved as bulk densities decreased. Root mass was also negatively correlated with bulk density. Above 1.4 g/cm^3, the relative root surface area decreased with increasing bulk density, reducing "...the abilities of the trees to exploit the available soil volume for both water and nutrients." Tree heights were substantially reduced by increased bulk density starting at week seven. For the entire period, "trees in soil of BD [bulk density] 1.2 grew 280 mm during the measurement period while trees in soil of BD 2.0 grew only 120 mm."

In contrast, Campbell et al. (1973) found that loblloly pine (Pinus taeda) seedling heights in Georgia were not affected by being planted on skid trails (loams, sandy loams, and clay loams) after one year ($p<0.05$).

Pinus taeda establishment from seed was not found to differ between secondary skid trails and undisturbed loamy sand and sandy loam soil (Hatchell et al. 1970). However, shoot growth was retarded for two years on both primary and secondary trails. Reduced stocking and height growth were especially pronounced on the finer textured soil. In a second part of this study, seedlings were grown in a greenhouse in compacted soils due to three applied pressure treatments of 50, 100, and 150 lbs/in^2. "Root weight was negatively correlated with bulk density over a range in density from 0.8 to 1.4 grams per cubic centimeter." Compaction was not noted to affect germination, but "...even the smallest pressure applied greatly reduced seedling height and weight."

Radiata pine (Pinus radiata) seedlings grown for 151 days in compacted soils (Mt. Burr Sand) in south Australia showed reduction in fresh and dry weights of roots and tops, root volume, and top height as bulk density increased in the order of 1.35>1.48>1.60 g/cm^3 (Sands and Bowen 1978). In all parameters, a 10-17% reduction occurred between 1.35 and 1.48 g/cm^3, and a 37-48% reduction between 1.48 and 1.60 g/cm^3 ($p<0.05$).

In Alberta, Corns (1988) observed lodgepole pine (Pinus contorta) and white spruce (Picea glauca) seedlings grown for 15 and 24 weeks, respectively, in soil cores (silty clay, clay loam, sandy loam, silt loam) compacted to three levels characterized as; "(1) clear-cut block roads immediately after logging and site preparation, (2) clear-cuts 5-10 years after logging and site preparation, and (3) undisturbed control [$p<0.05$]." The results indicated that "seedling growth differences...were generally more evident in lodgepole pine... [and] growth was generally poorer and mortality higher on the... [clay loam] soil than on the other soils at similar bulk densities." Rooting was impaired at bulk density of 1.3 for the sandy loam, 1.35 in the silty clay, and 1.4 g/cm^3 in the clay loam. Of the nine factors reviewed (maximum root depth, maximum root depth within soil, total weight, shoot weight, root weight, stem diameter, shoot height, seedling survival, shoot:root ratio), at least one showed a significant reduction with increasing bulk density ($p<0.01$ or 0.05).

Seedling height is typically reduced, but root length and penetration depth is the variable most consistently shown to be adversely affected by higher bulk densities (see Table 2). These studies also suggest that seedling response to compaction is species-dependent and that growth is especially influenced by compaction in finer textured soils.

Relative Change in or Absolute Bulk Density Observed	**Conifer Growth Parameter and Observed Change**	**Source**
Loam 1: 1.83 g/cm^3 Loam 2: 1.75 g/cm^3 Sandy Loam: 1.75 g/cm^3	Rooting depth restricted	Heilman 1981
(Clay loam)	Height growth :	Froehlich 1979
6 Tractor Passes	-8.5%	
10 Tractor Passes	-13.9%	
(Sandy loam)		
6 Tractor Passes	-11%	
10 Tractor Passes	-21%	
1.59 g/cm^3	Root growth restricted	Minore et al. 1969
1.02 g/cm^3	Root growth restricted	Pearse 1958

Table 2: Summary of changes in Douglas-fir (Pseudotsuga-menziesii) seedling growth associated with mineral soil compaction.

2.8.3 Tree Growth

One of the most significant reasons for concern about increases in soil bulk density is its affect on conifer growth. Compaction always reduces air filled porosity. Poor aeration is suspected of being the main cause of poor root growth in compacted soils (Froehlich and

McNabb 1983, Graecen and Sands 1980). The increased soil strength associated with compaction also retards tree root extension (Corns 1988). Recolonization of skid trails by tree roots has been known to take up to five years (Wasterlund 1989).

Wert and Thomas (1981) estimated the volume (m^3) of 14- to 18-year old Douglas-fir (Pseudotsuga menziesii) poles that had naturally regenerated in one of three identified zones: (1) skid roads, (2) transition zone - 3 m on either side of skid roads, and (3) undisturbed. Skid roads in these loamy soils produced 74% less total stand volume (includes top but not stump) than undisturbed areas and had 41% fewer trees. The transition zones grew 25% less volume and 17% fewer trees. Tree heights in skid trails were significantly less ($p<0.01$) than both transition zones and undisturbed areas. Overall, taking mortality and reduced growth into consideration, it was estimated that the yield (m^3) from this second rotation was reduced by 11.8% due to compaction.

Douglas-fir (Pseudotsuga menziesii) stands thinned in the previous 5 to 15 years were measured for basal area growth before and after thinning (Froehlich and Berglund 1979). Each tree was placed in a disturbance class as follows: (1) Light - <10% of the root zone affected by compaction, (2) moderate - 40% of the root zone affected by increased bulk density ranging from 0 to 10%, and (3) heavy - >40% of the root zone impacted by bulk densities increased by at least 10%. Though there was a net growth increase as a result of the thinning, the basal area growth of moderately disturbed trees was found to be reduced by 14%, and heavily disturbed trees by 30% as compared to the lightly disturbed trees.

On the Bureau of Land Management (BLM) Salem District, four case studies were undertaken to determine the affects of compaction on timber production and compare compaction levels between harvest methods (Powers 1974). In the first case study, stem volumes of 55-year-old Douglas-fir (Pseudotsuga menziesii) grown on loamy soils of an old railroad bed (0.85 to 1.00 g/cm^3) and landing (1.04 to 1.10 g/cm^3) were compared to adjacent undisturbed areas (0.70 g/cm^3). Extrapolating present growth rates over the next 80 years, it was estimated that the compacted areas will produce 40% less volume than the control area. The compacted, clayey surface soils of the second site were "nearly void of vegetation", and no volume comparisons were provided. Tree heights and diameters were substantially less on compacted silt loam surface soils than the control in the third case study. Tree growth data was not provided for the fourth study.

Forristall and Gessel (1955), studying the affects of inherent soil properties on conifer production in western Washington, found that "...a bulk density of about 1.80 [g/cm^3] permits the growth of western redcedar (Thuja plicata) on a wet site, while a density of approximately 1.50 stops the growth of red alder roots; but Douglas-fir (Pseudotsuga menziesii) and western hemlock (Tsuga heterophylla) appear to have root growth restricted when soil density approaches approximately 1.25 gm. per cubic centimeter." The tree species growth/bulk density interactions observed in this study differ from the seedling species growth/bulk density relationship found by Minore et al. (1969), where Douglas-fir (Pseudotsuga menziesii) was found to be more tolerant of higher bulk densities than western hemlock (Tsuga heterophylla).

Bulk density was measured at four points around 16-year-old ponderosa pines (Pinus ponderosa) in a California plantation in order to assign each tree to a compaction level group (Helms and Hipkin 1986). In comparing the five compaction groups (1.2, 1.1, 1.0, 0.9, and 0.8 g/cm^3), it was determined that tree heights of the highest four bulk densities decreased by 14, 13, 1, and 0% as compared to the 0.8 g/cm^3 level. The volume per acre was also found to decrease in a similar trend, with decreases of 69, 55, 13, and 13% as compared to the lowest bulk density.

Interestingly, a somewhat higher stocking level was noted in the 0.9 g/cm^3 group. The authors suspect that this may be due to an increase in the available water capacity of the site's coarse-grained loam soils in association with the small increase in bulk density.

Clayton et al. (1987) observed tree growth in three clearcuts with loamy soils in Idaho, most naturally regenerated to lodgepole pine (Pinus contorta) and one planted to ponderosa pine (Pinus ponderosa). Height, diameter at breast height (dbh), and radial growth of trees in the three disturbance classes were compared. Significant ($p<0.10$) reductions in the measured attributes with increased bulk density was observed in only one of the three stands (a Pinus contorta stand). Significant reductions in one or more attributes, however, was associated with increased penetration resistance and soil displacement in all stands.

In a study of pondersoa pine (Pinus ponderosa) thinned 15 years earlier in eastern Oregon, Froehlich (1979) placed each tree in one of three disturbance classes: (1) Light - <10% of root zone affected by disturbance (2) moderate - 11-40% of the root zone impacted by increased bulk densities of 10%, and (3) heavy - >40% of the root zone affected by a 10% increase in bulk density. Surface soils were sandy clay loams. Trees in the moderate and heavy soil impact classes were found to grow 9.9 and 9.3 square centimeters per year (1.5 and 1.4 in^2/yr) of basal area, respectively, reflecting growth rate reductions of 6 and 12%.

In another study that year, Froehlich (1979) observed the affects of compaction upon a 17-year-old ponderosa pine (Pinus ponderosa) stand in Medford, Oregon for the Eugene BLM. Trees were placed in disturbance classes like those mentioned in the previous study. Heavily used skid trails (1.24 g/cm^3) were found to result in a 29% reduction in height growth. Volume growth was even further reduced. Trees on the heavily used skid trails averaged only about a third of the volume of pines growing on undisturbed soil.

Volume production of loblloly pines (Pinus taeda) planted in clayey soils on old and "still used" skid roads in North Carolina were compared to trees planted on an undisturbed adjacent field (Perry 1964). Those trees on the old skid roads produced only 46% as much cubic-foot volume as those in the undisturbed soils.

Another loblloly pine (Pinus taeda) growth/compaction study was undertaken by Moehring and Rawls (1970) in silt loam soils in Arkansas. The 40-year-old trees were placed in one of four disturbance classes according to where the tree was passed by a loaded tractor: (1) 25% - traffic on one side of tree (2) 50% - 2 sides (3) 75% - 3 sides, and (4) 100% - four sides. Half of the trees were treated when the soil was wet, the other half when dry. Though tree growth was not affected by dry-soil traffic, when traffic passed by three or four sides of a tree during wet weather growth was significantly reduced for five years (0.05 level). Bulk densities of skid trails where on average 13% greater than undisturbed soil.

The growth of 6- to 14-year-old lodgepole pine (Pinus contorta) growing on skid trails at three different sites in British Columbia was measured by Thompson (1990). The preliminary results of this experiment found significant differences in total height growth (reduced by 12 to 25%) and three year height increment at only one of the tree sites. This particular site was also characterized by calcareous soils, confounding the causal factor of the growth reductions.

Like conifer seedlings, the degree to which compaction affects trees depends on the species and soil texture. In addition, the percentage of the root zone impacted by elevated bulk densities seems to determine the extent to which growth will be affected. Tables 3 and 4 summarize some growth impacts associated with increased bulk density for Douglas-fir (Pseudotsuga menziesii) and ponderosa pine (Pinus ponderosa).

Relative or Absolute Change in Bulk Density and Change in Douglas-fir (Pseudotsuga menziesii) Growth	Source
Trees in skid roads (loam texture) -74% volume. Est. stand volume at rotation age: -11.8%.	Wert and Thomas 1981
1) <10% Root zone affected: No significant effect 2) ≤40% Root zone affected by +0-10% bulk density: -14% basal area growth 3) ≥40% Root zone affected by at least +10% bulk density: -30% basal area growth	Froehlich and Berglund 1979
Restricted root growth at 1.25 g/cm^3	Forristall and Gessel 1955
(Loam texture) Est. -40% volume on railroad beds (0.85-1.00 g/cm^3) and landings (1.01-1.10 g/cm^3).	Power 1974

Table 3: Effects of compaction on Douglas-fir (Pseudotsuga menziesii) trees.

An important observation made by Froehlich and McNabb (1983) was that conifer growth response was highly variable with absolute bulk density, soil texture and tree species. When expressed as the relationship between the percent change in height growth and percent increase in bulk density, however, a fairly consistent general relationship exists between the two (see Figure 1).

Relative or Absolute Change in Bulk Density and Change in Pinus ponderosa Growth	Source
(Loam) 0.8 g/cm^3: Base level 0.9 g/cm^3: -0% Height growth, -13% vol/ac 1.0 g/cm^3: -1% Height growth, -13% vol/ac 1.1 g/cm^3: -13% Height growth, -55% vol/ac 1.2 g/cm^3: -14% Height growth, -69% vol/ac	Helms and Hipkin 1986
(Sandy clay loams) 1) ≤10% root zone affected . No growth affect. 2) 11-40% root zone affected by ≥+10% bulk density. -6% growth rate. 3) >40% root zone affected by ≥+10% bulk density. -12% growth rate.	Froehlich 1979
Height growth -29% (1.24 g/cm^3)	Froehlich 1979

Table 4: Compaction and Pinus ponderosa growth.

According to this figure, conifer height growth is reduced with increasing compaction with negative effects occurring at a 10% increase in bulk density. Why this relationship should hold consistently across soil types and tree species is unknown.

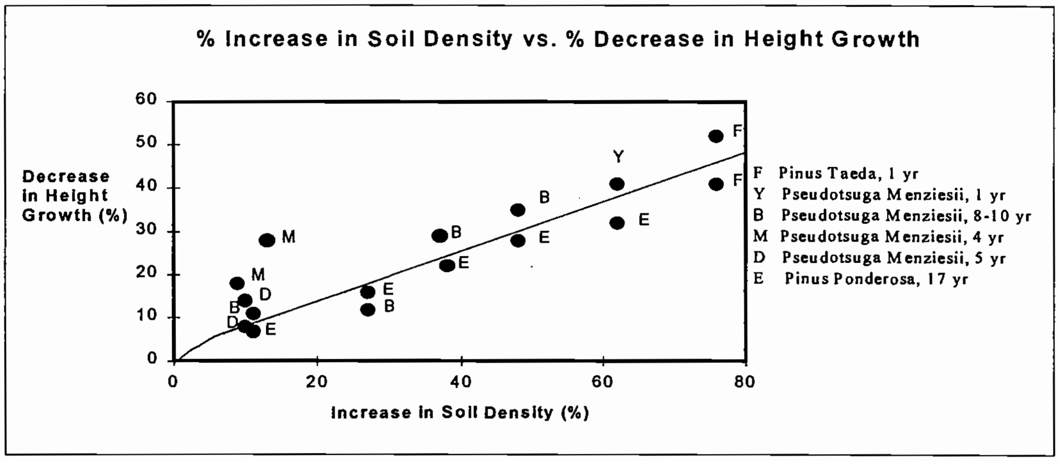

Figure 1: Relationship between the increase in bulk density and the decrease in seedling height growth. From F-Foil and Ralston (1967); Y-Youngberg (1959); B-Bureau of Land Management; and D,M,E-Froehlich 1979. Line is fitted visually. (Source: Froehlich and McNabb 1983)

2.9 Hydrologic Effects of Compaction

"The soil surface is a filter that determines the path by which rainwater reaches a stream channel" (Dunne and Leopold 1978). If water does not infiltrate the soil, it can pond on the surface or move as overland flow, changing the volume, timing, and peak rate of storm runoff as well as eroding topsoil and organic residues. Changes in the ability of water to move into, through, and be stored within the soil (as noted by alterations of infiltration, hydraulic conductivity (k_e), sorptivity (S_0), and porosity) can also affect streamflow properties and the availability of water to plants. Following is a discussion of those studies linking bulk density and compaction to water movement into and through the soil.

On agricultural soils, Meek et al. (1992) noted a 53% reduction in infiltration and 58% decline in hydraulic conductivity with an increase in bulk density from 1.6 to 1.8 Mg/m^3.

Walker and Chong (1986) reported that S_o and the void ratio (e) mirrored changes in bulk density. In a later study, sorptivity, the Boltzmann Constant and effective hydraulic conductivity of silty Illinois soils were measured to observe changes associated with different bulk densities (Gardner and Chong 1990). Bulk densities in the range of 1.15 to 1.629 Mg/m^3 were tested at moisture contents of 10, 15, and 20%. The results from the lab-created cores found that both S_o and k_e were log-linearly and inversely related to bulk density. To place this in context of runoff potential, the incipient ponding time (t_p) was estimated. This estimate was made from the 10-year, 1-hour storm and S_o values measured from soil cores collected from undisturbed and disturbed soils on a Shawnee National Forest logging site in Illinois. T_p values for undisturbed soils were calculated at 34.4 seconds, while the center and wheel rut of skid trails had values of 19.1 and 5.8 seconds, respectively. The authors concluded "...that logging activities did increase the runoff potential of the watershed."

Purser and Cundy (1992) measured saturated hydraulic conductivity (k_s) and bulk density in skid roads following high-lead cable yarding in the Cascade Mountains to attempt to quantify changes in soil hydrologic properties following logging. Bulk density increased significantly from a range of 0.10-0.95 g/cm^3 to 0.34-1.13 g/cm^3 ($p<0.025$). Accompanying that change was a reduction in pore space estimated to be 33%. Post-logging k_s values were also significantly lower ($p<0.025$) than before. When compared to the 1-hour, 100-year rainfall event, the reduction in saturated hydraulic conductivity was not expected to result in Hortonian overland flow, though raindrop splash and surface sealing of exposed cable roads may have increased the risk of overland flow occurring. Reduced porosity increased the risk of saturation overland flow.

Though skid road soil property changes were substantial, they represented only 5-7% of the unit. The cumulative effects of such an impact would be difficult to quantify.

Bulk density, infiltration rates, and macroporosities were measured on 29 different sites in fine sandy loams and silt loams in northern Montana and Idaho to ascertain the changes in soil properties after logging (Kuennen et al. 1979). Disturbed bulk densities were significantly higher than undisturbed ($p<0.05$), with most compaction occurring in the surface four inches. One- and five-minute infiltration rates were also found to be significantly lower on disturbed sites, with an estimated reduction in initial rates of 40%. Porosity was significantly lower on disturbed sites at depths of 2, 6, and 10 inches.

Other studies measuring infiltration rates after ground harvesting equipment have found similar results. Infiltration rates of secondary and primary skid trails and landings in soils of the Atlantic Coastal Plain were determined to be only 22, 11, and 10% of the rate observed on undisturbed soils (Hatchell et al. 1970). Permeability was reduced by 35% in cut-over areas and 92% on skid trails in tractor units in southwestern Washington (Steinbrenner and Gessel 1953).

Cafferata (1980) observed the affect of different logging equipment both on soil bulk density and several other soil properties at four sites in the Sierra Nevadas. Bulk density was significantly increased in skid trail ruts created by a crawler tractor, rubber-tired skidder and TSV in soils ranging in texture from a loam to a loamy sand. The tractor, however, decreased infiltration capacities by 78 percent as opposed to 67 percent for the other vehicles. Other soil properties were not found to differ with equipment type. Macroporosity in the surface 2.5 cm layer decreased by approximately 75 percent within six passes of any vehicle, while conductivity decreased by 80 percent.

Reductions in infiltration rates, like compaction, can be long lived. Twenty-six years after harvest, it took 18.5 minutes for a quart of water to infiltrate an old skid road in North Carolina as compared to 3.5 minutes in an adjacent control area (Perry 1964). Assuming that infiltration rates are associated with a linear decline in bulk density over time, the author projects that it will take approximately 40 years for the skid trails to return to normal infiltration rates.

A tractor-skidded shelterwood, high-lead cable-yarded clearcut, and a clearcut skidded and machine piled with tractors were compared for differences in infiltration rates in the Oregon Cascades (Johnson and Beschta 1980). Infiltration rates were found to be more affected by soil surface conditions, such as percent bare ground, vegetative cover, or presence of rock (r^2=0.65), than logging treatment. Only the unit skidded and windrowed with tractors then burned showed a tangible treatment effect. The mean infiltration capacities of skid trails and cable roads, however, were found to be significantly lower than treatment averages.

It is important to note that great care must be taken in measurement scale and interpretation of infiltration data. The importance of temporal variation in infiltration rates was demonstrated by an infiltrometer study conducted on logging sites in the Oregon Cascades (Johnson and Beschta 1981). Both undisturbed and disturbed soils were found to exhibit 50% higher infiltration rates in fall than in summer. Though the cause is unknown, the authors propose that summer soils may be non-wettable due to changes in soil organic matter which is reduced after the fall rains begin. The implications of this study are that “such seasonal changes may exceed affects due to applied treatments...”.

3. Methods

3.1 Objectives

Broad Objective: Characterize affects on soil physical properties by cut-to-length (CTL) and skyline operations at different thinning intensities in second-growth, Douglas-fir (Pseudotsuga menziesii) forests.

Specific Objectives:

1) Determine if significant changes in mineral soil bulk density occur in the following treatments and locations:
    - A) Cable Units
        - 1) In the center, edge, and halfway between cable roads.
    - B) CTL Harvest Units
        - 1) Undisturbed soils subjected to harvester or both harvester and forwarder traffic.
        - 2) Old skid trails from historical harvest entries subjected to harvester or both harvester and forwarder traffic.
2) Characterize and determine the areal extent of soil disturbance throughout the harvest units.
3) Determine if slash provides any protection against soil compaction.

3.2 Site Selection

This analysis was part of a larger project, the Willamette Young Stand Thinning and Diversity Study. This was a combined effort between Oregon State University and the Willamette National Forest. Concern about endangered species and the harvest of old growth have led to a reduced availability of large and old stands as a source of timber from public lands of the Pacific Northwest. In turn, attention is now being focused on young stands for timber production. The overall objective of the parent study was to understand the environmental and economic effects of thinning in young stands. On this premise, the stands in this study were non-randomly selected by the following criteria:

- Young conifer stands (30-50 years old)
- Uniform stand characteristics (trees per acre, tree size, volume)
- Stands must be large enough to provide sound information on wildlife, soil and vegetation responses, economics and logging systems that can be expected from thinning on an operational scale.

Though the larger study actually encompasses units within the Oakridge, Blue River, and McKenzie ranger districts on the Willamette National Forest, the two case studies presented here occur only on the Oakridge Ranger District (Sections 19 and 20, T 19 S, R 4 E). Two 30-50 year-old Douglas-fir (Pseudotsuga menziesii) stands were selected, located approximately 12 miles northeast of the town of Westfir (see Figure 2).

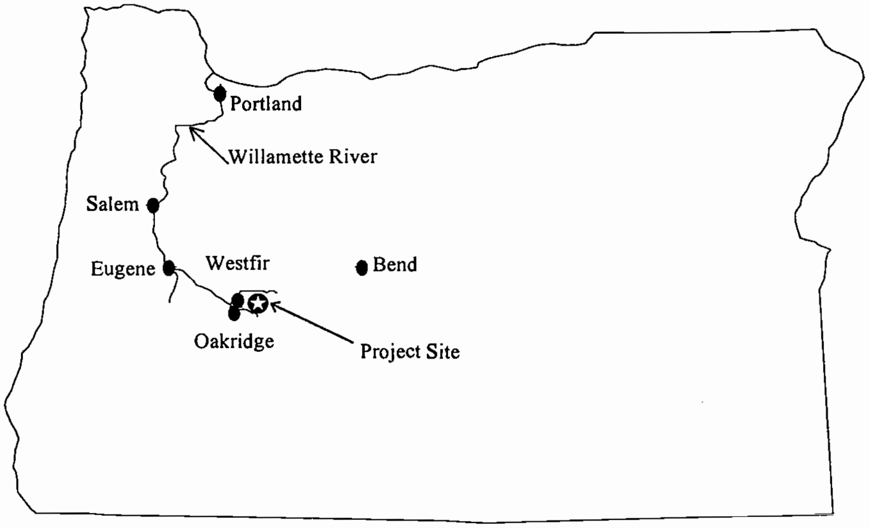

Figure 2: Project site location.

3.3 Site Description

3.3.1 Cable Units

The skyline harvest units were located in the Huckleberry Flats area (T 19 S, R 4 E, Sect. 32, see Figure 3), with slopes averaging 25% (maximum 60%) and a northeast aspect. The units were composed of 45-year-old Douglas-fir (Pseudotsuga menziesii) with an average diameter at breast height (DBH) of 10.4 inches. Stocking was estimated at 204 trees per acre. Understory species included western redcedar (Thuja plicata), western hemlock (Tsuga heterophylla), cherry(Prunus spp.), and bigleaf maple (Acer macrophylla). Ground vegetation included salal, vine maple, and Oregon grape.

In both case studies, the assignment of harvest method and silvicultural prescription was not random. Silvicultural prescriptions for each sampled unit were as follows:

- Units 86 and 89 (35 and 40 acres): Light thin with patches. Half-acre clearcuts at 330 foot spacing, rest of unit thinned to 100-110 trees per acre (11 and 10 MBF/Ac removed, respectively).
- Unit 88 (47 acres): Heavy thin. Thin to 50-55 trees per acre with an average spacing of 29 feet (7 MBF/Ac removed).

Soils in skyline units 86, 88, and 89 are best described by Mapping Unit 23 of the Willamette N.F. Soil Resource Inventory (SRI) (Legard et al. 1994). This landtype is a moderately deep to deep, slightly plastic to plastic landtype derived from colluvium and residuum. Surface soils are generally thin shotty loams. Subsoils are generally clay loams, silty clay loams, and clays. Depth to bedrock ranches from three to eight feet. This landtype is well to moderately well drained. Permeability is rapid in the surface soils and moderate to slow in the subsoils. Old skid trails from the original harvest entry 30 to 50 years ago are present in the units but account for only a small percentage of the area.

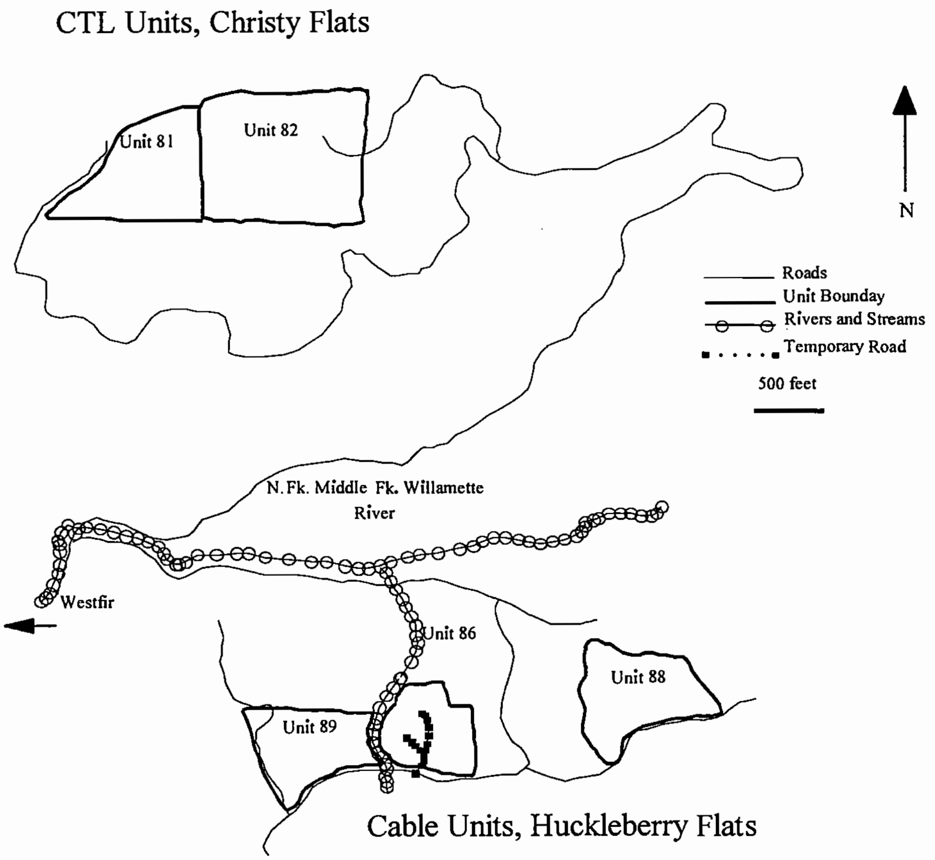

Figure 3: Project site map.

3.3.2 CTL Harvest Units

The CTL harvest units were located on Christy Flats, with slopes averaging 5% and a southern aspect (T 19 S, R 4 E, Sect. 19 & 20, see Figure 3). The units were composed of 50-year-old Douglas-fir (Pseudotsuga menziesii) with an average diameter at breast height (DBH) of 13 inches ranging up to 23 inches. Stocking was estimated at 277 trees per acre. Understory species included western redcedar (Thuja plicata), western hemlock (Tsuga heterophylla), cherry (Prunus spp.), and bigleaf maple (Acer macrophylla). Ground vegetation included salal, vine maple, and oregon grape. Of three units, the two heaviest thins were selected for sampling. It is important to note that when harvest activities were suspended due to high soil moisture conditions, only the northeast quarter of unit 82 was completed and available for post-harvest data collection (see Logging Systems and Timing of Harvest). The silvicultural prescriptions were described as follows:

- Unit 81(50 acres): Heavy thin. Thin to 50-55 trees per acre (16 MBF/Ac. removed) with an average spacing of 29 feet.
- Unit 82 (96 acres): Light thin plus patches. Half-acre clearcuts at 330 foot spacing, rest of unit thinned to 100-110 trees per acre (14 MBF/Ac. removed).

Soils are best characterized by SRI Mapping Unit 14. These soils are deep to very deep, slightly plastic to plastic and are derived from residual and colluvial materials. Surface soils are thin shotty loams and silt loams. Subsoils are thick silt loams, silty clay loams, and clay loams. The landtype is well drained. Permeability is rapid in the surface soils and moderate to slow in the subsoils. A substantial percentage of both units are in skid trails from the original harvest entry 30 to 50 years ago and had to be accounted for during data collection.

3.4 Logging Systems and Timing of Harvest

3.4.1 CTL Harvest Units

Harvest was undertaken by one harvester-forwarder pair. The harvester was a Timberjack[2] 2618 (tracked carrier) with a South Fork Squirt Boom and a Waterous 762b hydraulic harvesting head (estimated static ground pressure: 7.9 psi). The forwarder was an eight wheel drive Timberjack 1210 with bogie tracks on the rear tires. Front and rear ground pressures for this

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[2] Mention of trade names in this document is for information purposes only and does not constitute endorsement.

vehicle are estimated to be 7.0 and 3.8 psi unloaded increasing to 8.2 and 10.5 psi when loaded. It is estimated that this forwarder can carry up to a 30,864 lb (14,000 kg) load (equipment specifications sheet). A coincident production study at the site (Brown 1995) determined the average load to contain 82 pieces (543 ft^3, average DBH = 13 in).

Both the harvester and forwarder traveled on designated skid trails spaced approximately 60 feet apart. Trails were flagged in by the operator and approved by the Forest Service sale administrator. Delimbing and bucking took place on the skid trail in front of the harvester such that both the harvester and forwarder traveled over many tops and limbs.

Harvesting activities began in August 1995 and continued through November 1995. High soil moisture contents shut the operation down at this time, leaving only the northeast quarter of Unit 82 completed. Therefore, post-thinning data covers only this portion of the units. The sampling period covers a wide range of soil moisture contents at time of harvest.

The harvester is similar to a crawler tractor as far as performance over the soil surface, but differences in the function of the two machines may produce very different soil impacts. First, since the purpose of the harvester is to fall and process trees and accumulate logs as opposed to skidding, the number of passes over a trail is generally reduced. Second, most processing takes place on the skid trail directly in front of the harvester, thus travel occurs over a mat of slash.

The eight-wheel drive forwarder used in this study is designed with double bogies under the log bunk, which can be likened to two pairs of in-line dual tires. Based upon forest industry standards for determining footprint size, the bogies are comparable to one large tire 15 feet in diameter. Standard rubber-tired skidders have ground pressures in the range of 120-175 kPa (17-

25 psi), while estimated ground pressures for forwarders have substantially lower values (Wingate-Hill and Jakobsen 1982).

In addition to those mentioned above, there are other characteristics of the forwarder that help reduce the effects of skidding on soil. The forwarder can carry a much greater volume of wood to the landing than conventional skidding, reducing the necessary number of equipment passes. Also, the forwarder travels over the same slash mat created by the harvester, that may help to reduce soil disturbance and compaction by acting as a barrier against tire action and absorbing and distributing the weight of the machines over a larger area. Perhaps more importantly, logs are carried within the forwarder's bunks, which eliminates the rutting and disturbance associated with dragging partially suspended logs. Soil disturbance may be further reduced by the use of bogie tracks suited over the rear tires for improved traction and greater weight distribution. Bogie tracks are similar in design to the cleats of a tracked vehicle.

3.4.2 Cable Harvest Units

Manually felled and processed trees were yarded to landings with a Koller 501 trailer-mounted smallwood yarder with an Eagle Eaglette Slackpulling Skyline Carriage. Skyline roads were identified and marked prior to felling at a spacing of 100-150 feet. Tail trees and intermediate supports were used where needed to maintain at least partial log suspension over the ground. Skyline harvest activities began in November 1994 and continued through August 1995. Through this period, harvest occurred over dry to wet soils and over snow in some cases.

3.5 Data Collection

Soil bulk density and disturbance data were collected in both the skyline and CTL harvest units. The data collection methods were the same, though the spatial arrangement of sampling points differed. Soil bulk density and disturbance data were collected concurrently in both case studies, but additional information was collected in the skyline units by mapping soil disturbance. The following sections describe the data collection methods and sampling methodology in more detail.

3.5.1 Bulk Density Measurements

Bulk density sampling was conducted with a dual-probe Campbell Pacific nuclear densimeter. This device works on the principle that radiation absorbed by the soil is proportional to its mass (Klute 1986). Gamma radiation is emmited from the tip of the source probe, and a radiation detector in the tip of the second probe measures the amount of radiation received within a specified period of time. This provides a measure of the average wet soil bulk density between the tips of the two probes. Soil moisture samples were collected at each data collection point in order to calculate dry bulk density. Because an average bulk density is measured, buried roots, organic material, and rocks will affect measures. Bulk density measures were taken at the four and eight inch levels for this study. Manufacturer specifications state that the densimeter is accurate to 0.01 g/cm^3.

3.5.2 Areal Extent and Definitions of Soil Disturbance

Soil disturbance data gathered simultaneously with the bulk density data in the ground-based harvest units was used to ascertain an estimate of the areal extent of soil disturbance. To obtain an estimate in the cable units, the surface area and slope location of soil disturbance was mapped on skyline cable roads. Included in this sample were cable roads sampled for bulk density plus a random selection of enough roads to equal 25% of the total number within a unit. An equal number of transects located halfway between cable roads were surveyed as well in order to determine how much disturbance occurred in this zone. As previously discussed in the Soil Disturbance Associated with Forest Harvest section, disturbance is defined as "...any direct movement or compression of soil or surface litter during mechanized thinning and harvesting operations" (Wingate-Hill and Jakobsen 1982). Disturbance classes for both case studies are defined as follows:

Undisturbed: Litter still in place and no visual evidence of compaction.

<u>Skid Roads Only</u>:

Rut: Paired depressions where machine tracks/tires traveled.
Berm: Displaced soil piled at the edges of skid roads.
Center: Zone between wheel ruts.

<u>General Disturbance</u>:
Compacted: Visual evidence of skid road, landing or other vehicular traffic.
Mixing: Visible mixing of the mineral and organic soil horizons.
Exposed: Lack of litter cover.
Scalped: Removal of upper mineral and organic horizons to an unspecified depth.
Pile: Located beneath slash pile.
Rutting: A furrow in the soil surface from vehicle traffic or cable yarding.
Landing: Landing site.
Other: Disturbance not falling into the above categories.

3.5.3 Slash and Duff Measurements

Visual estimates of slash depth (nearest inch) and average diameter (nearest quarter inch) were recorded at each bulk density measure point in both cable and CTL harvest units. Duff depth (nearest half inch) was also estimated at these points. Estimates were made during both pre- and post-harvest surveys.

3.6 Spatial Location of Sample Points

3.6.1 Cable Units

Pre-harvest bulk density data was collected on flagged cable roads prior to felling from January through July 1995 as scheduling permitted. For the first 150 feet of the cable road (from landing), plot centers were spaced 50 feet apart in order to capture the expected more intensive changes in this zone (see Figure 4). The following plot centers were set at a 200 foot spacing.

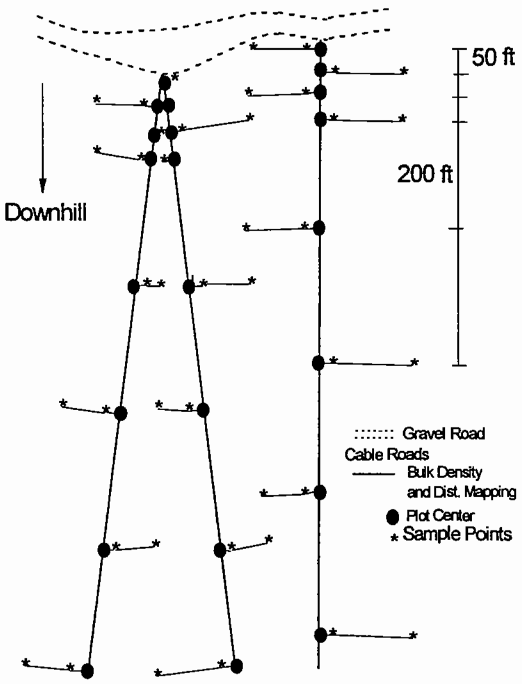

Figure 4: Example of cable unit sampling design.

One plot consists of three bulk density samples, depending on the proximity to the next cable road. The first sample was taken at the plot center in the middle of the flagged corridor, the second ten feet from the plot center at the edge of the road clearing, and the third halfway to the next cable road or a maximum of 100 feet. The second and third samples followed an azimuth perpendicular to that of the cable road. Where adjacent cable roads were less than forty feet apart, the third sample was excluded. When closer than twenty feet apart, only the center sample was be taken. The side to which samples were taken along the cable road alternated. Post-harvest bulk density sampling was conducted at the same sample plots as pre-harvest, although new holes for the nuclear gauge probes were created. Figure 5, Figure 6 and Figure 7 show unit maps and which cable roads were sampled.

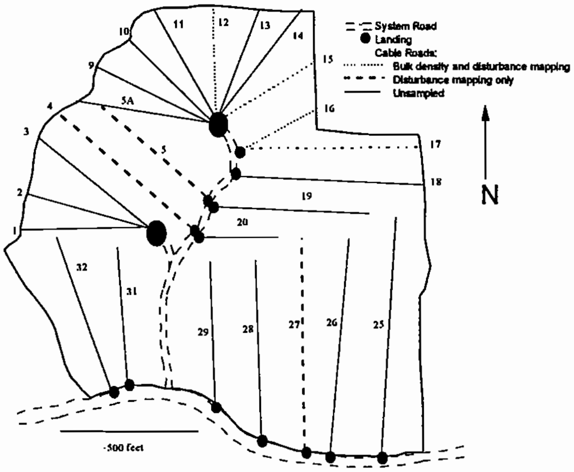

Figure 5: Unit 86 map of sampled cable roads.

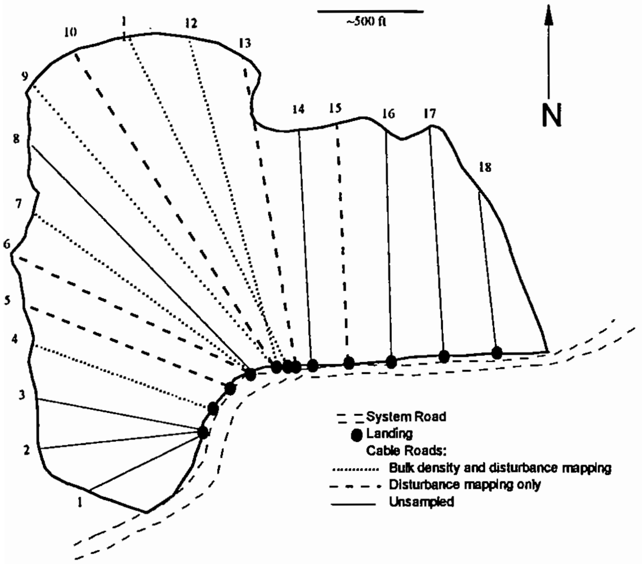

Figure 6: Unit 88 map of sampled cable roads.

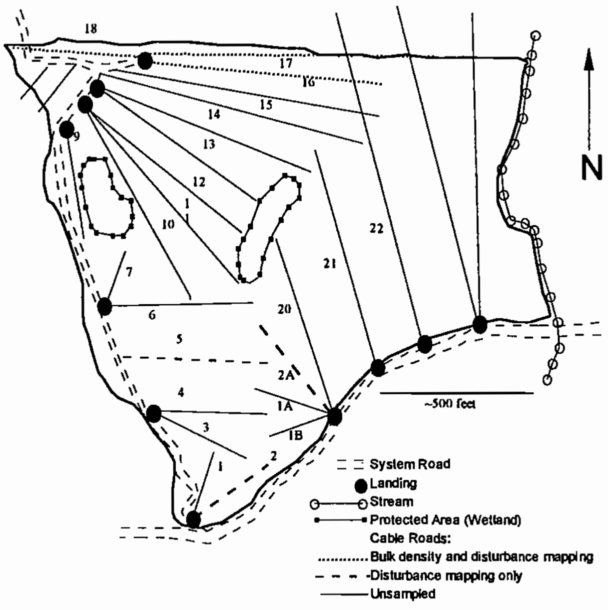

Figure 7: Unit 89 map of sampled cable roads.

3.6.2 CTL Harvest Units

Two plot types were utilized for the CTL units study. For the first type (Type 1), plot centers were located by first randomly selecting a subsample of points from a full grid covering each unit, then using a random azimuth and distance to offset from the selected grid points. A sampling density of approximately one plot per acre was utilized. Three bulk density measurements and soil disturbance classifications were taken in each Type 1 plot. These points were located on the end of 20 foot random azimuths 120 degrees apart which radiated from the plot center (see Figure 8). The second plot type (Type 2) consisted of a subsample of old skid

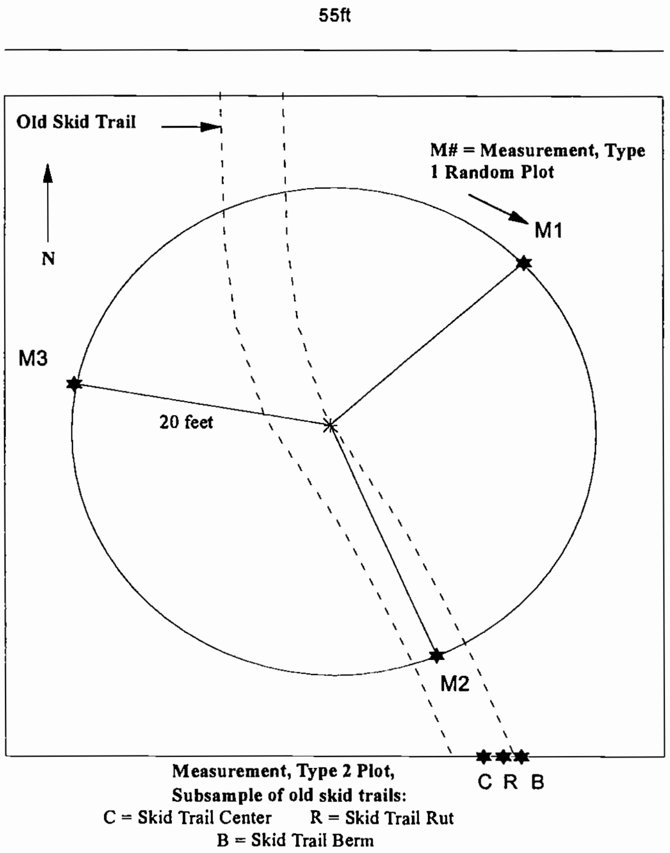

Figure 8: Mechanized harvest unit plot design.

trails. The center of Type 2 plots was located by walking in a standardized pattern around the perimeter of the Type 1 plot to determine if any old skid trails were present. The first old skid trail to be encountered became the location of the Type 2 measurements. These measures were located on the rut, berm, and center of the historic skid trail (see Figure 8). Thus, a given plot may have from three to six measurements depending on whether or not an old skid trail was present. Each Type 1 sample plot represents approximately a 3025 ft^2 block, with the smallest distance between Type 1 measurements being approximately 35 feet. The distribution of Type 1 and 2 sample points in the CTL units is mapped in Figure 9.

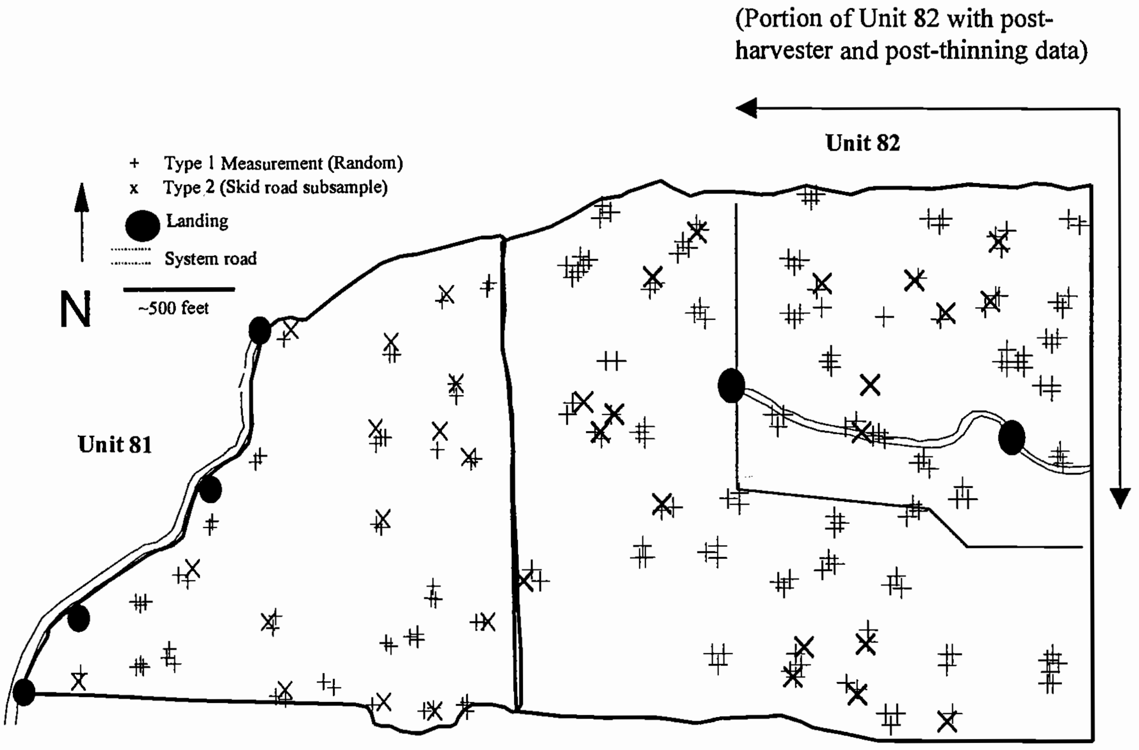

Figure 9: Location of Plot 1 measurements and Plot 2 skid road subsamples in Units 81 and 82.

4. Results and Discussion

4.1 Cut-to-Length Harvest Results

The data from the cut-to-length (CTL) harvest units consists of three groups: pre-thinning (P), post-harvester (PH), and post-thinning (PT, after harvester and forwarder). The pre-thinning group encompasses all of Units 81 and 82, but as described in section 3.4, Logging Systems and Timing of Harvest, only the northeast quarter of Unit 82 was harvested during the data collection period (approximately 25 acres). When the harvest entry began, a delay between when the harvester and forwarder each arrived presented the opportunity to assess the impacts of the harvester only. To minimize changes to the original study design, subunits that were excluded during the original random selection from the full grid were reincorporated into the sample set to increase the sample size in the harvested area. Some of these plots had already been treated by the harvester, making it is difficult to determine if old skid trails were present. These plots were thus classified as having no pre-thinning condition information.

During the data collection period, a total of 117 points were sampled in Unit 81 and 311 in Unit 82. At each point a measurement was taken at both the four and eight inch depth resulting in a total of 234 measurements in Unit 81 and 621 measurements in Unit 82. A summary of sample size by unit and sample category is provided in Table 5.

4.1.1 Areal Disturbance Results

Disturbance observations made at bulk density data collection points were used to estimate areal soil disturbance in the CTL harvest units before, during, and after harvest (See Figures 10-15). Only data collected in the randomly placed Plot 1 samples were used in these calculations. The unit-wide estimate of the percent area in old skid trails was used in both

Sample Category Plot 1 = Random sample Plot 2 = Non-random sub-sample of skid trails	Number of Measurements Unit 81 4 in	 8 in	 Unit 82 4 in	 8 in
Pre-Thinning (P)				
Plot 1				
Undisturbed	52	52	141	141
Disturbed (Old Skid Trails)	20	20	21	21
Plot 2	45	45	57	56
Post-Harvester (PH)				
Plot 1				
Undisturbed	--	--	15	15
Disturbed	--	--	12	12
Plot 2	--	--	9	9
Post-Thinning (PT)				
Plot 1				
Undisturbed	--	--	26	26
Disturbed	--	--	19	19
Plot 2	--	--	11	11

Table 5: Summary of CTL units data.

the post-harvester and post-thinning disturbance calculations. As the post data sets contained plots both with and without pre-thinning condition information, the percent of the area attributed to new disturbance alone was determined as the difference between the total area disturbed and the area in old skid trails. The "other" category includes disturbances such as windthrow and animal activity.

The results suggest that the combination of both old harvest entries and this thinning has disturbed a substantial portion of the unit, and that efforts to re-use old skid trails has met only moderate success. This is not surprising, as the skid trail pattern used in the original entry would be expected to differ from the designated trails and equipment-specific layout for the current harvester/forwarder pair. Discrepancies between the areas categorized as exposed or mixed between the post-harvester and post-thinning disturbance values could be attributed to a number

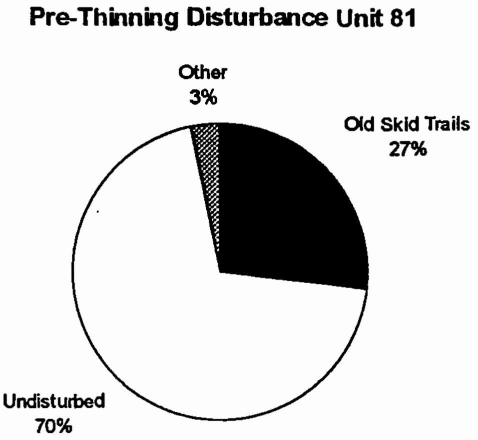

Figure 10: Pre-thinning disturbance in CTL Unit 81.

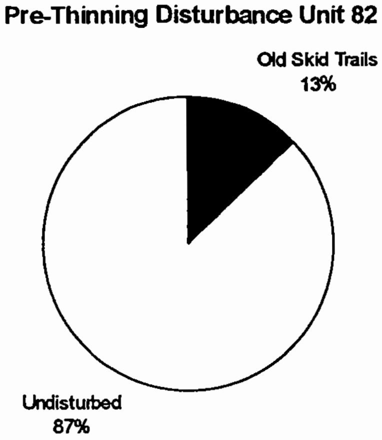

Figure 11: Pre-thinning disturbance in CTL Unit 82

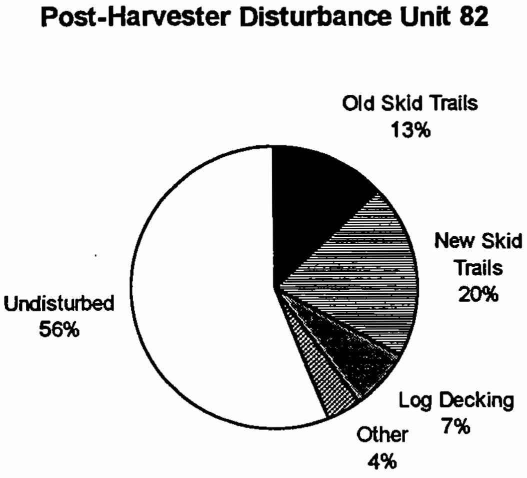

Figure 12: Post-harvester disturbance in CTL Unit 82

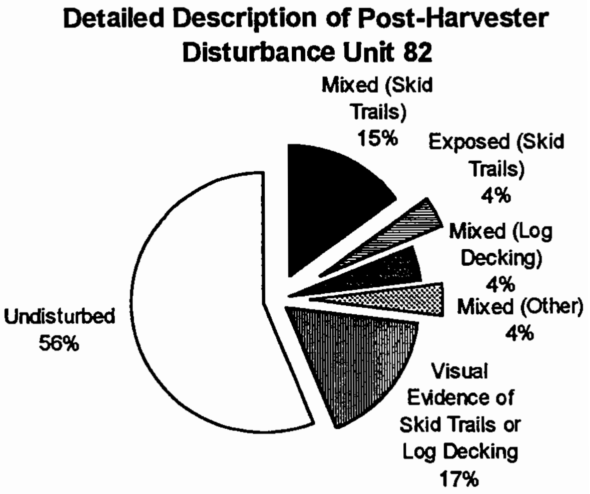

Figure 13: Post-harvester disturbance (detailed) in CTL Unit 82.

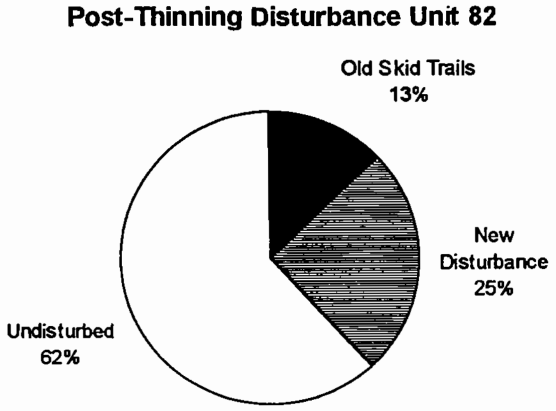

Figure 14: Post-thinning disturbance in CTL Unit 82.

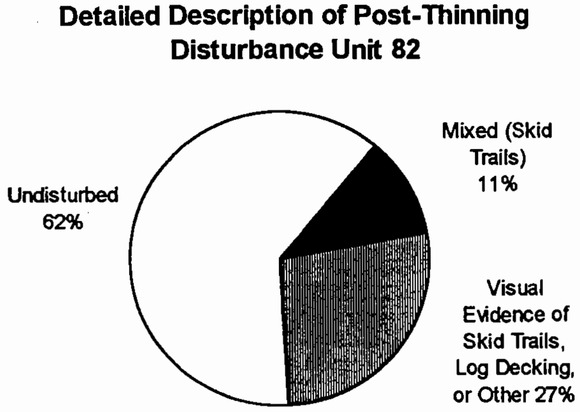

Figure 15: Post-thinning disturbance (detailed) in CTL Unit 82.

of factors including different data sets, a change of observers, modifications in slash distribution after the forwarder entry, or sampling error.

Overall, approximately 40 percent of the unit has been affected by the combination of current and past entries, with 0-4% of the unit in an exposed condition, 11 to 23% mixed, and ≤4% of the unit disturbed by other mechanisms such as windthrow. Very light disturbance, or areas where the duff was disturbed but remained intact, was estimated to cover 17-27% of the unit.

4.1.2 Pre-Thinning Bulk Density Results

Bulk density measurements taken at both the four and eight inch depth were placed in five disturbance classes including undisturbed soil, the rut, berm, or center of old skid trails, and an "other" category for perturbations such as windthrow or animal activity. No analysis was performed upon data in the "other" category.

A one-way analysis of variance and Tukey-Kramer multiple comparison test was performed to determine what differences existed between the disturbance classes within both units. This included both Type 1 and 2 data. The results of both tests are displayed in Table 6 and Table 7. Sensitivity analyses performed found no suspicious points to influence the conclusions of the multiple comparison tests. At the four inch depth, both units showed no detectable difference between undisturbed soil and berms of old skid trails at the 90% level. A significant difference was noted, however, between undisturbed soil and the center of old skid trails, where this disturbance class was 16% and 10% higher in bulk density for unit 81 and 82, respectively. Though the difference between the ruts of old skid trails and undisturbed soil was significant in Unit 82 (+8%), a difference was not detected in Unit 81. In both units, the rut and center of skid trails was more dense than the berm.

Disturbance Class	Count	Mean Bulk Density (g/cm^3)	s^2	90% CI (Tukey HSD) (g/cm^3)	Homogenous Groups (90% Tukey HSD)
4 Inch Depth					
Undisturbed	52	0.82	0.015	0.78 - 0.85	AB
Old Skid Trails:					
Rut	20	0.91	0.044	0.86 - 0.97	BC
Berm	26	0.80	0.029	0.74 - 0.85	A
Center	17	0.98	0.027	0.91 - 1.04	C
8 Inch Depth					
Undisturbed	52	0.91	0.012	0.88 - 0.94	A
Old Skid Trails:					
Rut	20	1.05	0.032	1.00 - 1.10	B
Berm	26	0.94	0.026	0.89 - 0.98	A
Center	17	1.07	0.026	1.02 - 1.13	B

Table 6: Unit 81 pre-thinning data summary and disturbance class multiple comparison test.

Disturbance Class	Count	Mean Bulk Density (g/cm^3)	s^2	90% CI (Tukey HSD) (g/cm^3)	Homogenous Groups (90% Tukey HSD)
4 Inch Depth					
Undisturbed	140	0.80	0.018	0.78 - 0.82	A
Old Skid Trails:					
Rut	28	0.87	0.025	0.82 - 0.92	B
Berm	33	0.78	0.021	0.74 - 0.82	A
Center	18	0.89	0.023	0.84 - 0.94	B
8 Inch Depth					
Undisturbed	140	0.90	0.022	0.88 - 0.93	A
Old Skid Trails:					
Rut	28	1.07	0.030	1.02 - 1.12	B
Berm	33	0.90	0.027	0.85 - 0.94	A
Center	17	1.00	0.022	0.94 - 1.06	AB

Table 7: Unit 82 pre-thinning data summary and disturbance class multiple comparison test.

At the eight inch depth, old skid trail berms were not significantly different from undisturbed soils in either unit. Ruts, in contrast to the four inch depth, were found to be 13 and

16% greater in mean bulk density when compared to the undisturbed soil in each unit. The center of old skid trails was significantly higher in Unit 81 (+15%), but a detectable difference between this disturbance class and undisturbed soil was not noted in Unit 82.

On the whole, it appears that the zones of old skid trails where equipment traveled and/or trees were dragged were at least 10% higher in bulk density than undisturbed soil. This increase is not consistent across the width of the skid trail, however, possibly due to local differences in bulk density, initial impact, or recovery over time. The edge of these skid trails (berms), probably consisting mostly of displaced soil, were indistinguishable from undisturbed soil.

4.1.2.1 Spatial Analysis of Pre-thinning Bulk Density Patterns

Density contour maps of the undisturbed soil were developed using ordinary kriging with the mapping program Surfer® (see Figure 16 and Figure 17) as a means of investigating the possibility that spatial patterns could influence conclusions about treatment effects. Kriging, a technique first developed by the mining industry, creates maps by estimating values of a given variable at unsampled locations (Rossi et al. 1992, Trangmar et al. 1985). Fortin et al. (1989) compared the adequacy of different sampling designs (systematic, random, and systematic-clustered) and intensities (0.41 and 0.52 plots/acre) against an intensive sample set (systematic, 1.6 plots/acre) for accurately reproducing kriged maps of vegetation patterns. Their results suggest that "sampling designs that contain varying sampling steps, like random and systematic-cluster designs, seem more capable of detecting spatial structures than a systematic design". The sampling design used in this study was a combination of the two, with clustered sampling from an offset-grid occurring at intensities of 0.56 to 0.63 plots/acre (Units 81 and 82, respectively). The use of an incomplete grid, however, may have resulted in poor spacing of plot locations (see

Figure 9) For this reason, these maps are considered only an approximation of bulk density patterns in the units. The maps suggest that patterns of bulk density throughout the units are random and not likely to affect results of statistical tests. Unit 81 does show a pocket of high density in the northwest corner at both sampling depths, but this may be due to the fact that only one measurement is available to extrapolate density values in that area. Also, this area does not fall into the post-thinning sampling data.

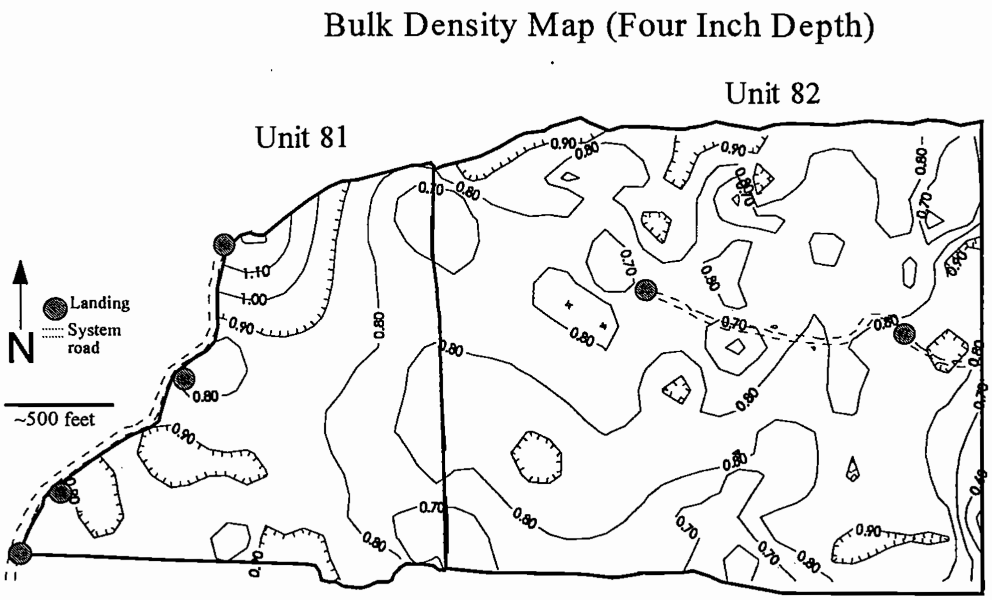

Figure 16: Four inch depth bulk density map for Units 81 and 82 using ordinary kriging.

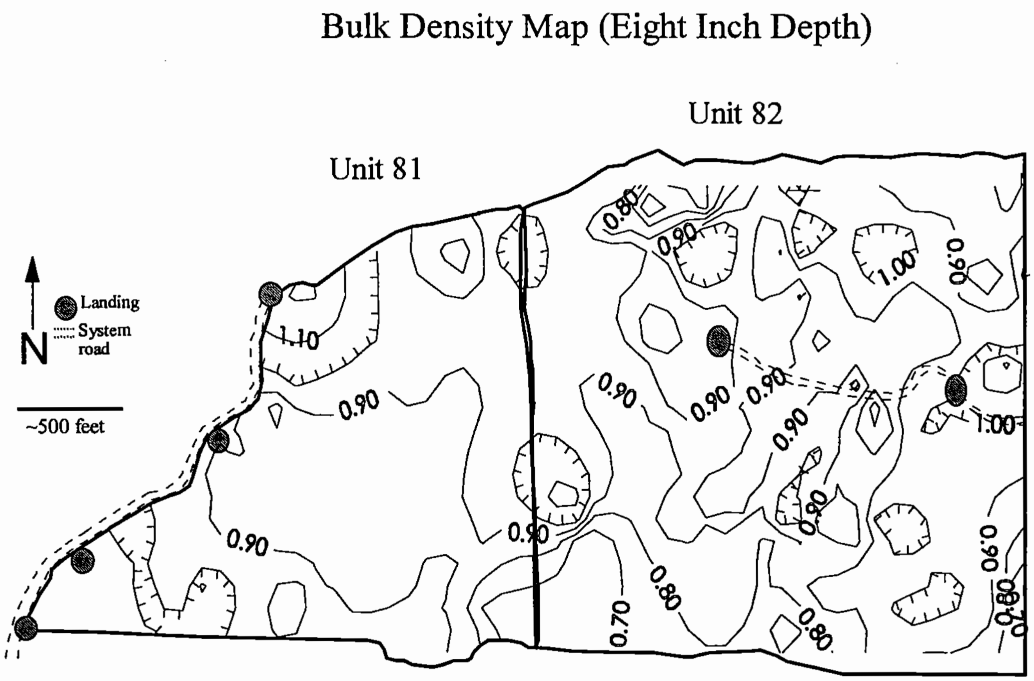

Figure 17: Eight inch depth bulk density map for Units 81 and 82 using ordinary kriging.

4.1.2.2 Areal Extent of Compaction Prior to Thinning

To determine the areal extent of compaction in Units 81 and 82 due to the original harvest entry, the percentage of the random sample points (Plot 1) falling into those categories found significantly greater in bulk density than undisturbed soil was calculated. According to the previous ANOVA results those categories found to be "compacted" included:

Unit	4" Sampling Depth	8 " Sampling Depth
81	Center of old skid trails	Rut and center of old skid trails
82	Rut and center of old skid trails	Ruts of old skid trails.

As a proportion of Plot 1 samples, the percentage of each unit in the above categories is summarized in Table 8.

	% of Unit Compacted Prior to Thinning	
	Unit 81	Unit 82
4 Inch Depth	4	10
8 Inch Depth	6	4

Table 8: Percentage of CTL units compacted prior to thinning entry.

4.1.3 **Thinning Treatment Bulk Density Results**

Essentially two groups of data are available for assessment of harvest impacts: data encompassing the effects of the harvester only and data collected after both harvester and forwarder traffic. Within these two groups are three other data classes, including data on previously undisturbed soils, newly disturbed old skid trails, and data with an unknown pre-thinning condition (undisturbed or old skid trail). The following questions will be addressed for both the post-harvester and post-thinning data sets:

1) Is there a change in bulk density on previously undisturbed soils after equipment traffic?

2) Is there a change in bulk density due to new equipment traffic on old skid trails?

3) Is the mean bulk density of soils with no pre-thinning condition information significantly different from previously undisturbed soils? If yes, is the mean significantly different from the rut, berm, or center of old skid trails?

4.1.3.1 Post-Harvester Results

Thirty-six data points at each depth were collected to characterize the impacts of the harvester. The five classes of this data are summarized in Table 9. Because the thinning operation deposited a layer of slash across most of the unit which could conceal old skid trails, the Undisturbed (no-pre) category was kept distinct from the Undisturbed data collected prior to thinning.

		4 Inch Depth		8 Inch Depth	
Disturbance Class	n	Mean Bulk Density (g/cm^3)	s^2	Mean Bulk Density (g/cm^3)	s^2
Newly disturbed old skid trails	6	0.92	0.012	1.06	0.011
Impact on previously undisturbed soils	2	0.74	0.045	0.93	0.012
Undisturbed	7	0.82	0.003	0.91	0.007
Disturbed by harvester (no-pre)	13	0.88	0.009	0.98	0.009
Undisturbed (no-pre)	8	0.81	0.034	0.95	0.009

Table 9: Post-harvester data summary by disturbance class.

4.1.3.1.1 Effect of Harvester Traffic on Previously Undisturbed Soil

A two-sample t-test was used to compare the bulk density of undisturbed soil to that of soils impacted only by harvester traffic. There was no evidence that harvester traffic on previously undisturbed soil increased bulk density at either sampling depth (p=0.44 and 0.23). This is not entirely suprising as the harvester generally does not make more than two passes over a given skid trail and duff typically remains intact.

4.1.3.1.2 Effect of Harvester Traffic on Old Skid Trails

The effect of harvesters on old skid trails was assessed through a series of multiple comparison tests between the newly-disturbed skid trail classes of rut, berm, or center, the average undisturbed bulk density, and the mean pre-thinning bulk density of the old skid trail classification. The results of these comparisons at each depth are provided in Table 10, Table 11 and Table 12. Tests were investigated at both the 90 and 95% level. Results are presented at the highest level at which differences were detectable.

Old Skid Trail Ruts (Model p-values = 0.0234 and 0.0000)					
Disturbance Class	n	4 Inch Depth		8 Inch Depth	
		Mean Bulk Density (g/cm^3)	Homogenous Groups (90% Tukey HSD)	Mean Bulk Density (g/cm^3)	Homogenous Groups (95% Tukey HSD)
Newly Disturbed Ruts	2	0.96	AB	1.13	AB
Pre-thinning Ruts	21	0.88	B	1.08	B
Undisturbed	141	0.80	A	0.90	A

Table 10: Post-harvester ANOVA of old skid trail ruts with model p-values and multiple comparison tests.

Old Skid Trail Center (Model p-values = 0.0092 and 0.0142)					
Disturbance Class	n	4 Inch Depth		8 Inch Depth	
		Mean Bulk Density (g/cm^3)	Homogenous Groups (90% Tukey HSD)	Mean Bulk Density (g/cm^3)	Homogenous Groups (90% Tukey HSD)
Newly Disturbed Center	2	0.97	AB	1.03	AB
Pre-thinning Center	17	0.89	B	1.01	B
Undisturbed	141	0.80	A	0.90	A

Table 11: Post-harvester ANOVA of old skid trail centers with model p-values and multiple comparison tests.

Old Skid Trail Berms (Model p-values = 0.8253 and 0.4462)					
Disturbance Class	n	4 Inch Depth		8 Inch Depth	
		Mean Bulk Density (g/cm^3)	Homogenous Groups (90% Tukey HSD)	Mean Bulk Density (g/cm^3)	Homogenous Groups (90% Tukey HSD)
Newly Disturbed Berms	2	0.82	A	1.03	A
Pre-thinning Berms	19	0.78	A	0.89	A
Undisturbed	141	0.80	A	0.90	A

Table 12: Post-harvester ANOVA of old skid trail berms with model p-values and multiple comparison tests .

In all cases, there is a trend of increased bulk density across the width of old skid trails. This increase, however, was not found to be significant perhaps due to the limited sample size. The rut and center of old skid trails was not significantly different from either undisturbed soil or the pre-thinning bulk density of the same disturbance class. The berms of old skid trails were not significantly different from undisturbed soil either before or after this current harvest entry.

4.1.3.1.3 Analysis of Post-Harvester Data Without Pre-Thinning Condition Information

Data without pre-thinning condition information was also compared against undisturbed soils. Test results are summarized in Table 13. Disturbed soil without pre-thinning condition information was not found to be significantly different from the mean pre-thinning undisturbed bulk density.

Data without pre-thinning condition information (Model p-values = 0.1781 and 0.1241)					
Disturbance Class	n	4 Inch Depth		8 Inch Depth	
		Mean Bulk Density (g/cm^3)	Homogenous Groups (90% Tukey HSD)	Mean Bulk Density (g/cm^3)	Homogenous Groups (90% Tukey HSD)
Undisturbed (Pre-thinning)	141	0.80	A	0.90	A
Disturbed (post-harvester)	8	0.82	A	0.94	A

Table 13: Post-harvester ANOVA of data without pre-thinning condition information.

4.1.3.2 Post-Thinning Results (Harvester and Forwarder Traffic)

Fifty-five data points (Plot 1 and Plot 2) at both sampling depths were collected to characterize the completely harvested portion of Unit 82. Ten different disturbance classes are represented in this group. A statistical summary of this data is provided in Table 14.

Disturbance Class (ND = No data, D = Disturbed, U = Undisturbed)				4 Inch Depth		8 Inch Depth	
P	PH	PT	n	Mean Bulk Density (g/cm^3)	s^2	Mean Bulk Density (g/cm^3)	s^2
D	ND	U	1	0.66	--	1.05	--
D	D	D	3	0.98	0.012	1.06	0.004
U	ND	D	6	0.92	0.013	1.02	0.007
U	ND	U	11	0.71	0.020	0.82	0.030
U	D	D	1	0.85	--	0.96	--
U	U	U	8	0.78	0.003	0.90	0.004
ND	D	D	15	0.91	0.007	1.03	0.015
ND	U	D	2	0.91	0.014	1.10	0.060
ND	U	U	6	0.87	0.001	1.00	0.013
ND	D	U	1	0.82	--	1.03	--
ND	ND	D	2	0.96	0.000	1.03	0.002

Table 14: Summary statistics of post-thinning data by data class. P = Pre-thinning, PH = Post-harvester and PT = Post-thinning.

Three questions were investigated with these data: was the bulk density of previously undisturbed soil raised by the traffic of this harvester/forwarder pair? Did the mean bulk density of old skid trails change? How did the mean density of soil with no pre-thinning condition information disturbed by the this entry compare to undisturbed soil and old skid trails? An analysis of each of these questions follows.

4.1.3.2.1 Effect of Harvester and Forwarder Traffic on Previously Undisturbed Soil

Previously undisturbed soil impacted by this entry was compared against the mean pre-thinning undisturbed bulk density in a two-sample t-test. Data with and without post-harvester information were combined for this test and disturbance was not broken into categories. The results are provided in Table 15. A significant difference in bulk density over the undisturbed level was observed at both the four and eight inch depths (p=0.04 and 0.05, respectively). An average increase of 12% was noted at four inches and 11% at eight inches. To assess changes specific to skid trail location, the mean bulk density of each category was compared to the mean and upper confidence interval of the undisturbed density (see Figures 18 and 19).

Category	n	4 Inch Depth (p-value = 0.04)		8 Inch Depth (p-value = 0.05)	
		Mean Bulk Density (g/cm^3)	s^2	Mean Bulk Density (g/cm^3)	s^2
Undisturbed	141	0.80	0.018	0.90	0.022
Newly Disturbed	7	0.91	0.012	1.01	0.006

Table 15: ANOVA of post-thinning impacts on previously undisturbed soil.

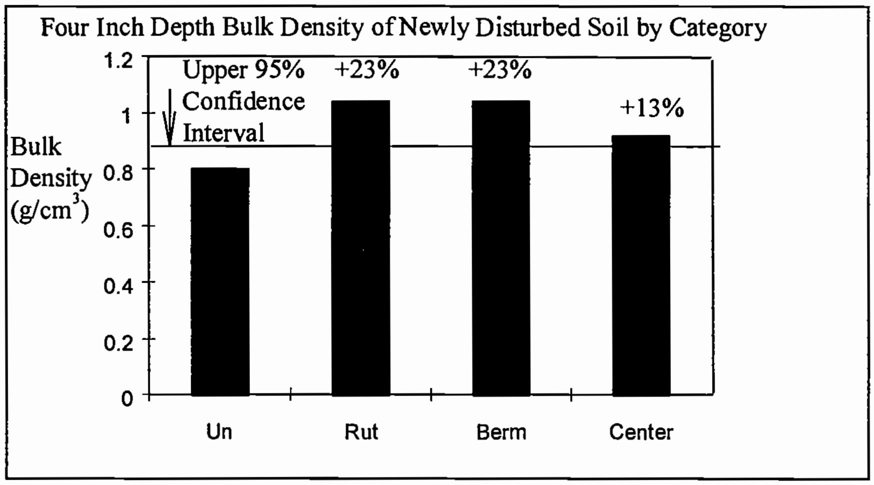

Figure 18: Four inch depth bulk density of newly disturbed soil by disturbance category, shown with upper 95% confidence interval for undisturbed soil.

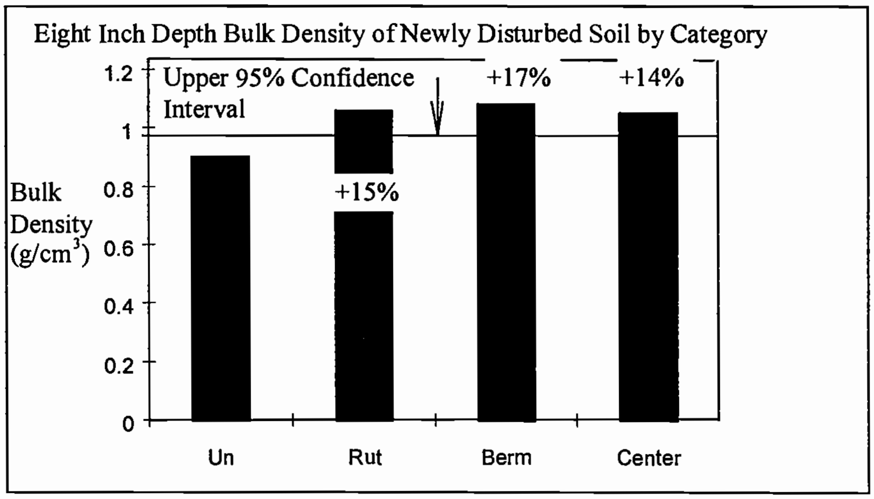

Figure 19: Eight inch depth bulk density of newly disturbed soil by disturbance category, shown with upper 95% confidence interval for undisturbed soil.

The results of both comparisons to the undisturbed state suggest that soil compaction has occurred on soils previously unaffected by the original harvest entry. When averaged across the skid trail, density has increased by an estimated 12% at the four inch depth and 11% at the eight inch depth. Looking at specific locations within the skid trail, increases of 23 and 15% were estimated for the ruts (4 and 8 inch depth), 23 and 17% in the center, and 13 to 14% in the berm or edge of skid trail.

The average density of newly disturbed soils was also compared against the bulk density of old skid trails with a Tukey HSD multiple comparison test. Results are provided in Table 16. Newly disturbed soil was not found to be significantly different from the bulk density of old skid trails at either sampling depth.

Disturbance Class	4 Inch Depth (p-value = 0.10)				8 Inch Depth (p-value = 0.004)			
	n	Mean Bulk Density (g/cm^3)	s^2	Groups (90% Tukey HSD)	n	Mean Bulk Density (g/cm^3)	s^2	Groups (90% Tukey HSD)
Newly Disturbed	7	0.91	0.012	A	7	1.01	0.006	AB
Old Rut	21	0.88	0.025	A	21	1.08	0.035	B
Old Berm	19	0.78	0.027	A	19	0.89	0.037	A
Old Center	17	0.89	0.024	A	16	1.01	0.040	AB

Table 16: Multiple comparison of newly disturbed soil and old skid trails.

4.1.3.2.2 Impact of Harvester and Forwarder Traffic on Old Skid Trails

To assess the impact of the current entry on existing skid trails, the rut, berm, and center data were combined in both the pre- and post-thinning data sets. Thus, the average bulk density across the width of the skid trails is being compared before and after this new entry. The test results are provided in Table 17. There is no evidence that this recent harvest entry increases the bulk density of old skid trails at either depth (p=0.56 and 0.52, respectively), although the low sample number may have contributed to this result.

	4 Inch Depth (p-value = 0.56)			8 Inch Depth (p-value = 0.52)		
Category	n	Mean Bulk Density (g/cm^3)	s^2	n	Mean Bulk Density (g/cm^3)	s^2
Old skid trails	57	0.85	0.027	56	1.00	0.035
Newly disturbed skid trails	4	0.90	0.032	4	1.07	0.002

Table 17: Post-thinning two-sample t-test of newly disturbed old skid trails.

4.1.3.2.3 Impact of Harvester and Forwarder Traffic on Plots Without Pre-thinning Information

For the data without pre-thinning condition information three data classes were compared as two-sample t-tests against the mean pre-thinning undisturbed bulk density: forwarder impact (F), harvester and forwarder impact (HF) and observed forwarder impact but harvester impact unknown (H?F). Where a significant difference was found, the data was compared against old skid trail data.

Disturbance Class	n	4 Inch Depth			8 Inch Depth		
		Mean Bulk Density (g/cm^3)	s^2	p-value	Mean Bulk Density (g/cm^3)	s^2	p-value
F	2	0.91	0.014	0.25	1.10	0.060	0.062
HF	15	0.91	0.007	0.001	1.03	0.015	0.001
H?F	2	0.96	0.000	0.097	1.03	0.002	0.23
Undisturbed	141	0.80	0.018	---	0.90	0.022	---

Table 18: Post-thinning t-tests comparing data without pre-thinning condition information to undisturbed soils.

At both four and eight inches, disturbance class HF was found to be significantly different from the bulk density of undisturbed soil (p=0.001). Disturbance class F was greater at eight but not four inches (+18%), while disturbance class H?F showed the opposite results with a 17% greater density at four inches. As the pre-thinning condition of these measure points is unknown, it cannot be said that a given data class having a greater bulk density than undisturbed soil is due to this entry as opposed to the original harvest event.

When those disturbance classes that were found to be significantly different from the undisturbed were compared against the rut, berm and center of old skid trails in a multiple comparison test the following results were found (see Table 19, Table 20 and Table 21).

As can be seen in the test results, these three disturbance classes may differ in bulk density from the berm of old skid trails, but in no cases was the bulk density any greater than that

4 Inch Depth (Model p-value = 0.1063)				
Disturbance Class	n	Mean Bulk Density (g/cm^3)	s^2	Groups (90% Tukey HSD)
H?F	2	0.96	0.000	A
Rut	21	0.88	0.025	A
Berm	19	0.78	0.027	A
Center	17	0.89	0.024	A

Table 19: Post-thinning multiple comparison of disturbance class H?F to old skid trails.

Disturbance Class	4 Inch Depth (p-value = 0.04)				8 Inch Depth (p-value = 0.0025)			
	n	Mean Bulk Density (g/cm^3)	s^2	Groups (90% Tukey HSD)	n	Mean Bulk Density (g/cm^3)	s^2	Groups (95% Tukey HSD)
HF	15	0.91	0.007	B	15	1.03	0.042	B
Rut	21	0.88	0.025	AB	21	1.08	0.035	B
Berm	19	0.78	0.027	A	19	0.89	0.037	A
Center	17	0.89	0.024	AB	16	1.01	0.040	AB

Table 20: Post-thinning multiple comparison of disturbance class HF to old skid trails.

8 Inch Depth (Model p-value = 0.0054)				
Disturbance Class	n	Mean Bulk Density (g/cm^3)	s^2	Groups (90% Tukey HSD)
F	2	1.10	0.060	AB
Rut	21	1.08	0.035	B
Berm	19	0.89	0.037	A
Center	17	1.01	0.040	AB

Table 21: Post-thinning multiple comparison of disturbance class F to old skid trails.

found in the rut or center of old skid trails. Again, since there was no pre-thinning condition information, the occurrence of a bulk density significantly greater than the undisturbed level can be attributed to either the original entry, the current entry, or a combination of both. The low sample sizes may also conceal and more definitive conclusions.

4.1.3.3 Slash Depth and CTL Effects on Soil Bulk Density

No analysis was performed with the slash depth data collected. Increasing the sample size in the harvested portion of Unit 82 still yielded smaller than desirable sample sizes after breaking the data into their prospective categories. Therefore, it was decided that further dividing the data by slash depth would not leave a sufficient sample size to address the questions of how the CTL system affects soil bulk density on old and new skid trails.

4.1.3.4 Areal Extent of Compaction After CTL System Thinning

Significant compaction on previously undisturbed soil was not observed as a result of harvester traffic alone (see 4.1.3.1.1). In contrast, this data set suggests that the combination of both harvester and forwarder traffic resulted in compaction across the width of the skid trail (see Figures 18 and 19). Thus, using the estimated percent of the unit newly disturbed (see Figure 14) it was predicted that an additional 25% of the harvested portion of Unit 82 was compacted (see Figures 20 and 21).

4.2 Cable Harvest Results

4.2.1 Areal Disturbance Results

Data collected during the cable road disturbance surveys were used to determine the type and extent of soil disturbance within cable roads and on a unit-wide basis. Since no disturbance was observed on any transects between cable roads, it was assumed that all disturbance was

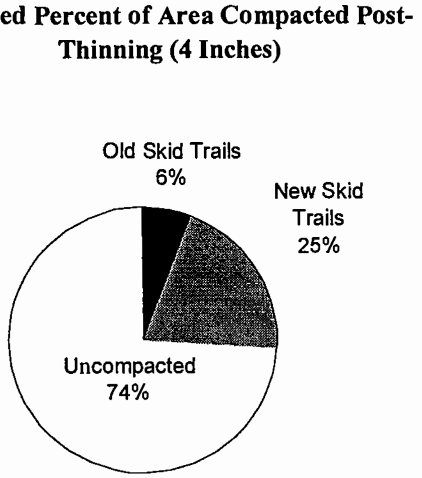

Figure 20: Unit 82 estimated post-thinning compaction.

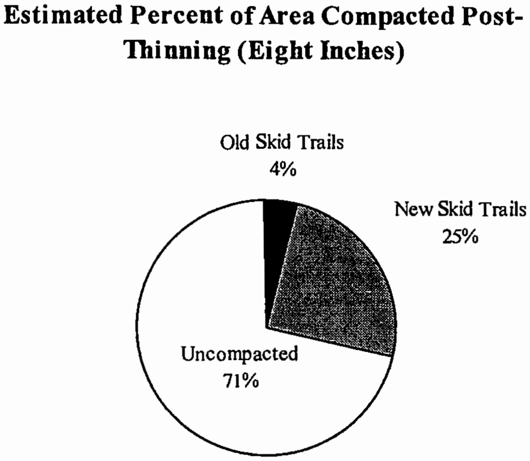

Figure 21: Unit 82 estimated post-thinning compaction.

isolated to the cable road corridors themselves. Results of this survey are provided in Table 22 below.

During disturbance surveys, the length and width of each disturbance category was estimated. The categories displayed in Table 22 are those disturbance types that actually occurred within the harvest units. An areal percentage by disturbance category was determined for each sampled cable road, and the average of these represented the mean disturbance per cable road in a unit (based on an average cable road width of twenty feet). The mean disturbance per cable road was then used to calculate disturbance on a unit-wide basis. Both the highest unit disturbance level (1.8%) and highest average disturbance by cable road occurred in Unit 88, the

				% Exposed		% Rutted		% Mixed	
Unit	Unit Area (Ac.)	% Area in Cable Roads	% Area Disturbed	Unit	CR	Unit	CR	Unit	CR
86	35	13	0.89	0.04	0.3	0.05	0.4	0.8	6.0
88	47	13	1.8	0.30	2.0	0.40	3	1.1	9.0
89	40	8	0.42	0.05	0.6	0.07	0.9	0.3	4.0

Table 22: Estimated percent soil disturbance by unit and cable road.

heavy thin. The disturbance category affecting the most area across all units was mixing of the mineral and organic horizons (0.3 - 1.1%). The percent of area exposed or rutted was similar and never reached 0.5% of a total unit area.

Actual disturbance per sampled cable road is shown in Table 23. A fourth category, Pile, is included in this table. This does not suggest that slash piles are considered as having a negative effect on soil conditions, but that a unique condition existed, which also precluded local determination of soil disturbance. Thus, it is important to note that the lower percentage of undisturbed area observed in Unit 89 is due in large part to the frequency of unsurveyable ground under slash piles.

Cable Road 11 in Unit 88 experienced the greatest degree of disturbance, followed by Cable Road 7 in the same unit. Both of these cable roads were approximately one thousand feet in length and were harvested during the winter months. Cable Road 18 in Unit 89 actually had the least area left undisturbed, but disturbance fell only into the mixed category with no exposure or rutting observed. The least disturbance was associated with sampled areas in Unit 86, which had summer-harvested cable roads that never exceeded 620 feet in length.

Several factors that may be linked to soil disturbance are noted in Table 23, including cable road length, silvicultural treatment, period of cable road use, and the estimated volume yarded per road where available. Figures 22 through 24 show disturbance plotted against cable road length, volume, and month of harvest.

A positive relationship between soil disturbance and cable road length is visually evident (see Figure 22). A similar trend is noted between soil disturbance and volume yarded in Figure 23. When related to season or month of use, the greatest disturbance would generally be expected occur during wet soil conditions and lowest when soils were dry or snow-covered. A peak in disturbance levels was indeed noted during the wet winter months (January, February and March), while less disturbance was observed during the other months (see Figure 24). Given the variation and limited data, however, the influence of season of use remains relatively unclear.

						Disturbance Class (% Area)				
Unit	Cable Road	Treat-ment	Length (ft)	Est. Vol. Yarded (ft^3)	Harvest Period	Exp	Rut	Mix	Pile	Un
86	4	LTP	537	--	July	0	0	4.4	0	95.6
86	5	LTP	423	--	July	0	1.4	7.7	0	90.9
86	12	LTP	354	4410	August	0.68	0.4	3.6	0	95.3
86	16	LTP	250	9114	August	0.68	0.4	3.6	0	95.3
86	27	LTP	613	--	Dec.	0.02	0.25	9	0	90.7
88	4	LTP	420	6000	Jan.	0	1.9	11	0	87.1
88	5	LTP	585	--	Jan.	0.9	1.1	0.74	1.7	95.6
88	6	LTP	863	--	Jan.	1.1	2.2	4.1	0	92.6
88	7	LTP	970	9100	Jan.	3.2	4.3	12.1	0	80.4
88	9	LTP	1158	14750	Feb.	1.9	1.8	8.3	0	88
88	10	LTP	1334	--	Feb.	1.7	3.6	7.7	2.7	84.3
88	11	LTP	1438	--	Feb.	4.4	5.6	14.3	0	75.7
88	13	LTP	1412	--	March	0.3	4.8	11.8	2.8	80.3
88	15	LTP	1135	--	March	0	1.9	13.3	0	84.8
89	2	HT	338	--	Oct.	0	0	1.4	18.9	79.7
89	2A	HT	470	--	Nov.	1.9	2.3	7	0	88.8
89	5	HT	771	--	April	0.6	1.7	6.5	3.7	87.5
89	16	HT	484	8085	April	0.4	0.5	5	8.7	85.4
89	17	HT	546	8085	April	0.7	1	3.8	5	89.5
89	18	HT	187	8085	April	0	0	34.5	14.4	51.1

Table 23: Summary data by cable road. LTP = Light thin with patches, HT = Heavy thin.

In all of these figures (22, 23 and 24), cable road 18 in Unit 89 lies outside of the rest of the data. This suggests a unique influence on soil disturbance at this location. Though a profile of this cable road is not available, it is known that the direction of yarding occurred almost cross-slope in comparison to the other roads and that achieving adequate deflection may have been difficult. The degree of deflection achieved above the cable road profile is a possible source of soil disturbance in this case. It was also close to the road system, and the upper was portion used as a landing and equipment parking area. Cable road profiles were available for three of the

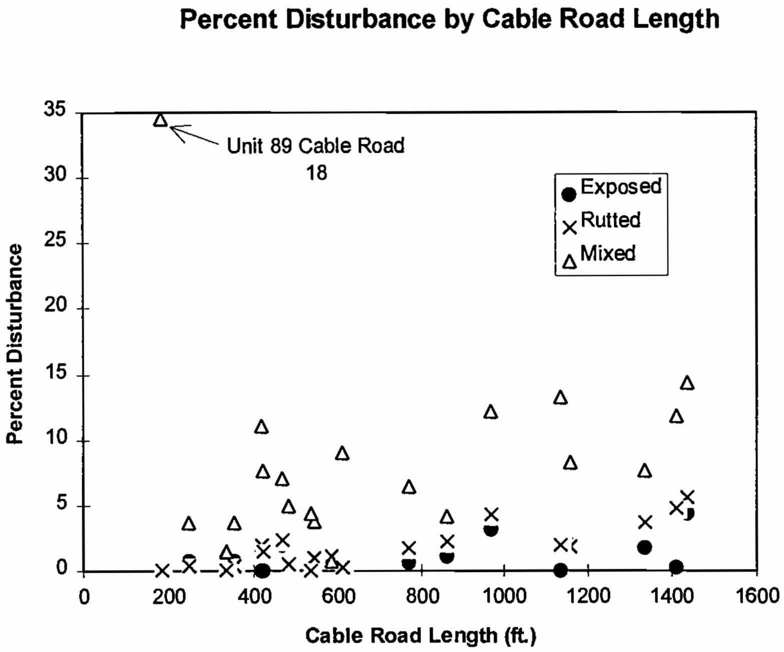

Figure 22: Percent soil disturbance by cable road length.

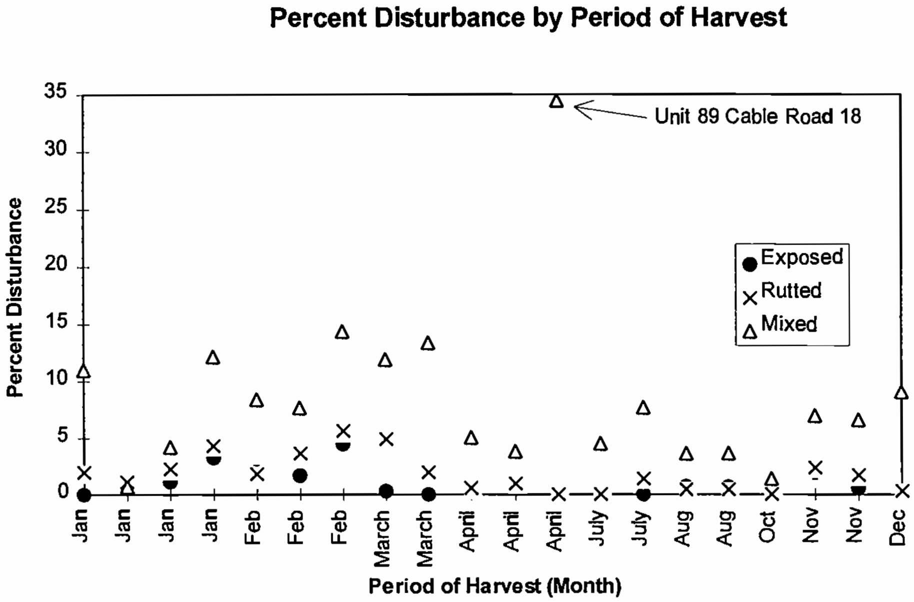

Figure 23: Percent soil disturbance by period of harvest.

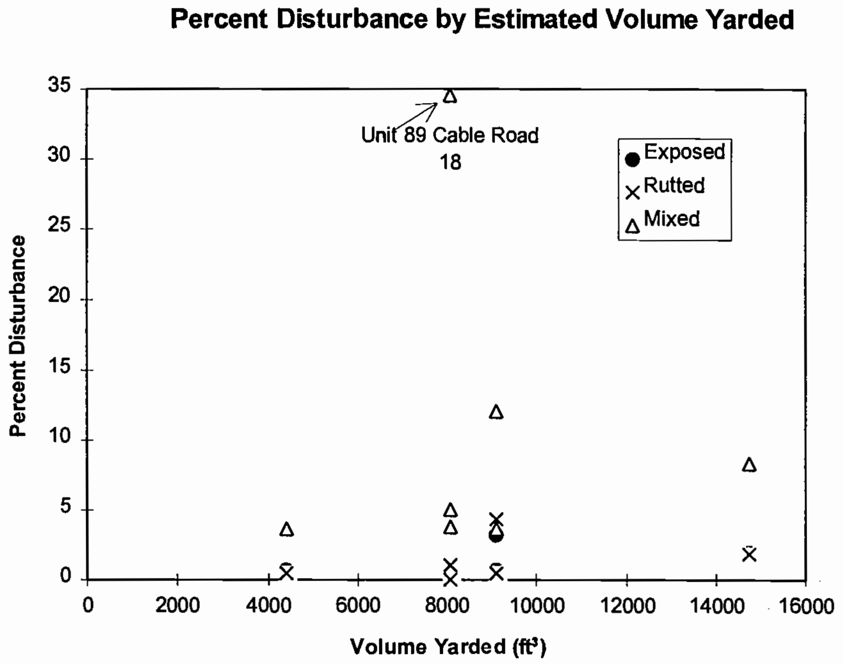

Figure 24: Percent soil disturbance vs. total volume yarded.

cable roads sampled in Unit 88 (see Figures 25 - 27). It was expected that either overall profile form and/or profile microtopography would correspond with potential deflection difficulties and thus disturbance, especially exposure and rutting.

Disturbance on cable roads 9 and 10 was similar, with slightly more rutting occurring on cable road 10. Overall disturbance was greater on cable road 11. On these three roads, most deep rutting (>6 inches) occurred within 500 feet (horizontal distance) of the landing except for cable road 11 where half-foot ruts were found as far as 1000 horizontal feet away. On all profiles, deep rutting occurred on the bench immediately below the landing, though an intermediate support was located at the bench end on all roads. While cable roads 9 and 10 have a rise in topography beginning at 1000-1200 feet (horizontal) from the landing, road 11 continued to decline. Even though overall slopes on cable road 11 were steeper, it is possible that the climb in elevation at the ends of roads 9 and 10 was enough to elevate the tailhold and increase deflection. It is apparent from these profiles that both the micro- and macro-topography of the skyline profiles had an affect on the degree of soil disturbance.

As the effects of soil disturbance are determined not only by their areal extent but spatial distribution, disturbance within cable roads was “mapped” by plotting a ratio of the distance from the landing where a disturbance occurred to the total cable road length versus the disturbance type. This produced a plot showing the continuity of a given disturbance on a scale corrected for total cable road length (see Figure 28). The cable roads have also been grouped within length categories to compare disturbance with total length.

Except for the mixing category, disturbance due to skyline thinning at these sites did not appear to form contiguous lengths of disturbed soil. A strong pattern of disturbance level or continuity with cable road length is not apparent, especially in Unit 86 where disturbance appears to decrease with the longest road. Overall, the charts suggest that the greatest amount and extent occurred on roads of intermediate and long lengths in Units 88 and 89. Charts of the remaining sampled cable roads are provided in Appendix A.

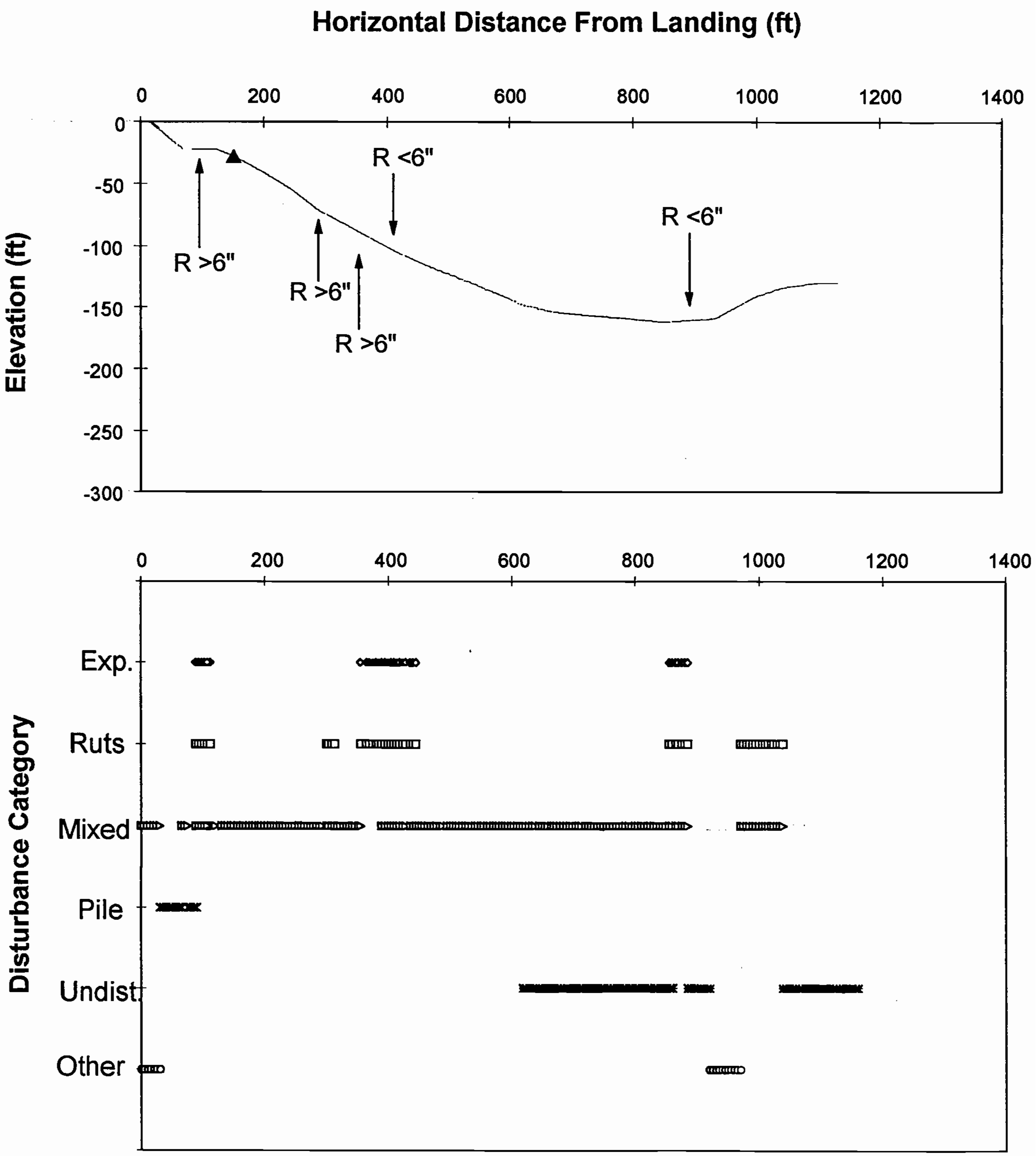

Figure 25: Unit 88 Cable road 9 profile and location of soil disturbance Filled triangles denote intermediate supports. R < or > 6" symbolizes rut depth.

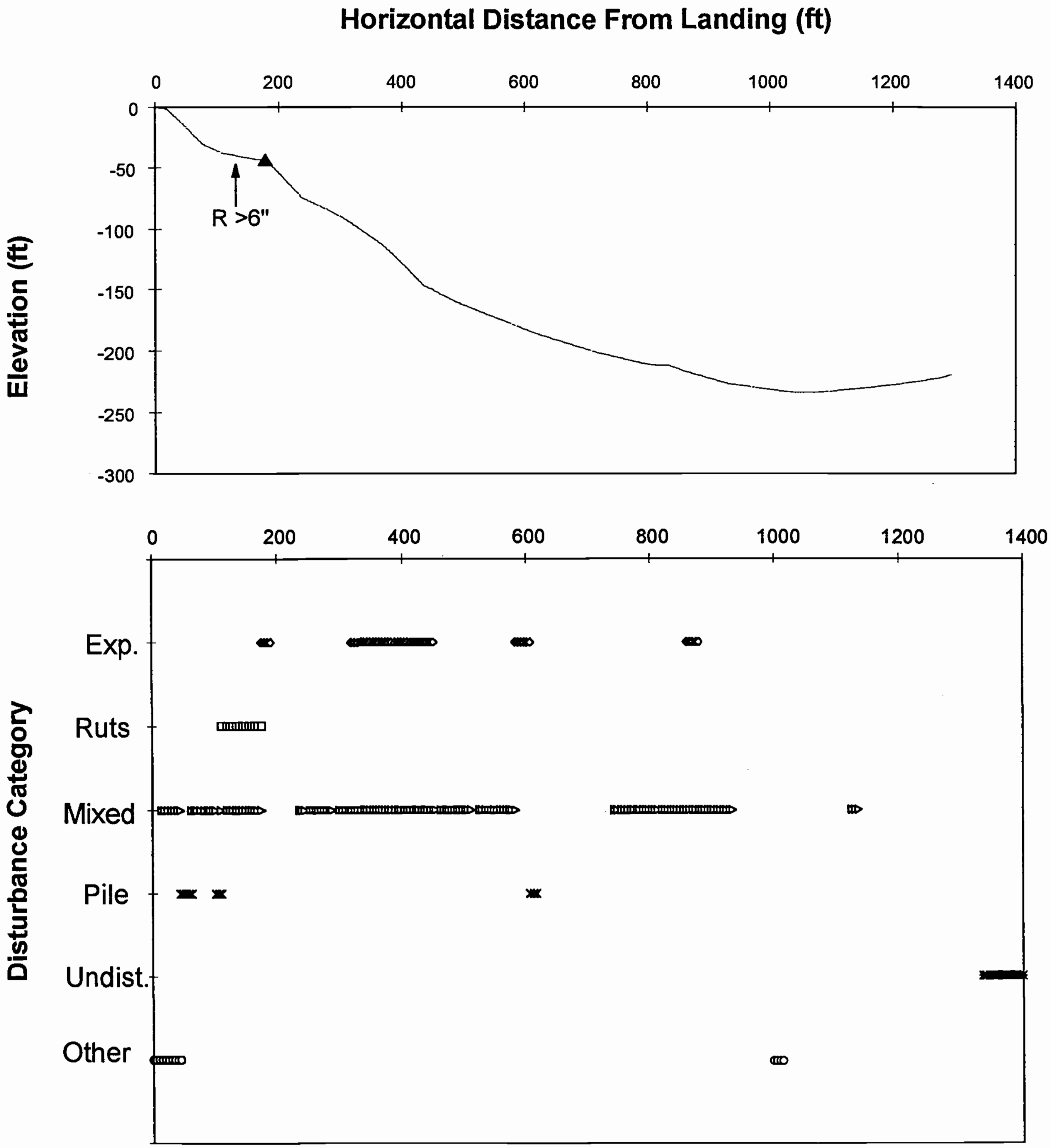

Figure 26: Unit 88 Cable road 10 profile and location of soil disturbance Filled triangles denote intermediate supports. R < or > 6" symbolizes rut depth.

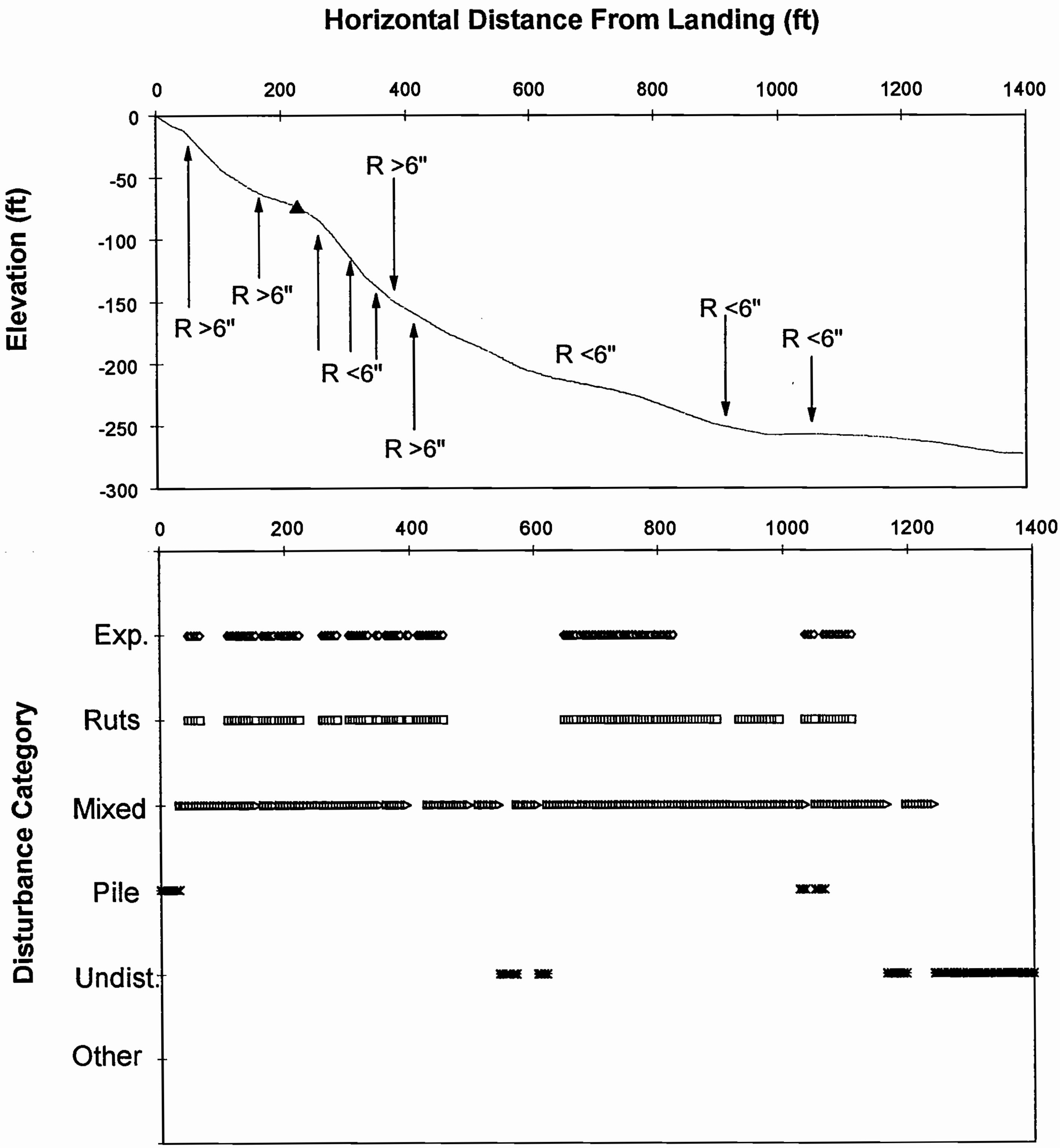

Figure 27: Unit 88 Cable road 11 profile and location of soil disturbance Filled triangles denote intermediate supports. R < or > 6" symbolizes rut depth.

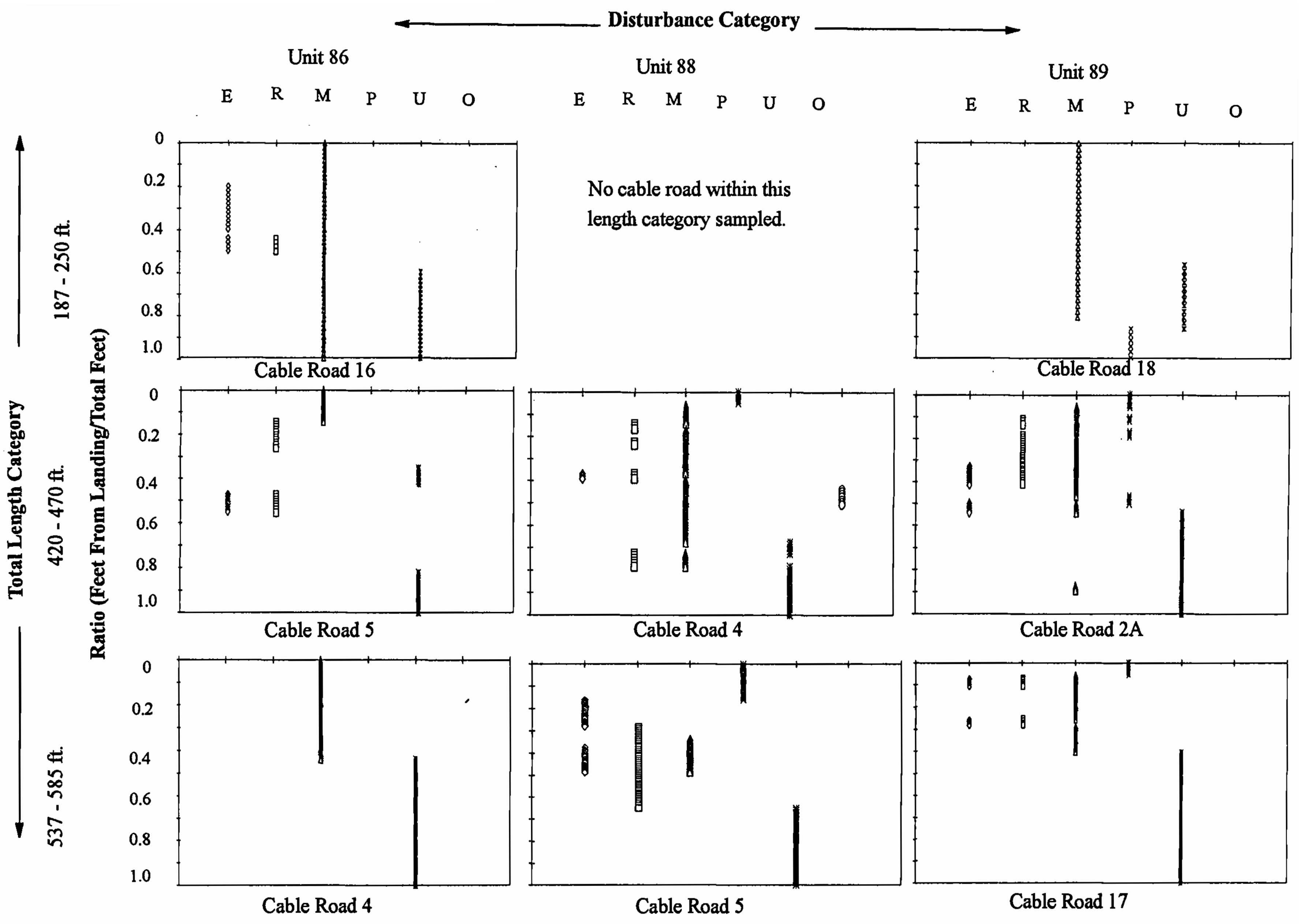

Figure 28: Soil disturbance on cable roads, normalized for length and grouped by total length category and unit. E=exposed, R=rutted, M=mixed, P=slash pile, U=undisturbed and O=other.

4.2.2 Skyline Bulk Density Analysis

4.2.2.1 Pre- and Post-Thinning Summary Statistics

As described in the Methods section, skyline bulk density data was collected both before and after thinning in the center, edge, and halfway between cable roads. Post-thinning data was collected in approximately the same location as pre-thinning. The sample size and summary statistics for both pre- and post-thinning data are summarized Table 24 and Table 25.

	n-size		Average (g/cm^3)		Variance		CV (%)	
Unit	4 Inch	8 Inch	4 Inch	8 Inch	4 Inch	8 Inch	4 Inch	8 Inch
86	38	38	0.86	0.95	0.009	0.008	11.2	9.3
88	40	35	0.86	0.93	0.017	0.021	15.2	15.5
89	33	30	0.94	0.95	0.009	0.019	9.9	14.6

Table 24: Summary statistics for pre-thinning cable unit data.

	n-size		Average (g/cm^3)		Variance		CV (%)	
Unit	4 Inch	8 Inch	4 Inch	8 Inch	4 Inch	8 Inch	4 Inch	8 Inch
86	31	31	0.89	0.97	0.007	0.005	9.4	7.1
88	36	36	0.91	0.97	0.033	0.051	19.8	23.3
89	27	27	0.91	0.95	0.022	0.019	16.2	14.6

Table 25: Summary statistics for post-thinning cable unit data.

4.2.2.2 Post-Thinning Bulk Density Results

Before analyzing the skyline data for possible harvest affects, the pre-thinning data was reviewed for possible spatial trends. A Tukey-Kramer multiple-comparison test between slope positions relative to the landing and between cable roads (cross-slope variation) within units was performed at the 95% level to test for any natural patterns in bulk density. Bulk density was not found to change with slope position ($p>0.05$, see Appendix B), but Cable Road 15 in Unit 86 was found to be significantly different from other roads within the same unit at both sampling depths and required further attention during the analysis. A combination of Tukey-Kramer multiple comparison tests and multiple linear regression were used to answer questions of interest about the possible affects of cable thinning on soil bulk density.

To determine if post-thinning bulk density in the center, edge or halfway between cable roads had changed significantly from pre-harvest (undisturbed) values, a multiple comparison test between the four categories for each unit was performed. The results of these tests are summarized in Table 26, Table 27 and Table 28. According to these results, there is no evidence

Disturbance Class	Count	Mean Bulk Density (g/cm^3)	s^2	CV (%)	Homogenous Groups (90% Tukey HSD)
4 Inch Depth					
Undisturbed	38	0.86	0.009	11.2	A
Cable Road:					
Center	11	0.91	0.003	6.2	A
Edge	10	0.86	0.013	13.4	A
Between roads	10	0.91	0.005	7.7	A
8 Inch Depth					
Undisturbed	38	0.95	0.008	9.3	A
Cable Road:					
Center	11	0.97	0.004	6.9	A
Edge	10	0.95	0.007	8.6	A
Between roads	10	0.99	0.003	6.0	A

Table 26: Unit 86 Tukey-Kramer multiple comparison test between pre- and post-thinning soil soil conditions.

Disturbance Class	Count	Mean Bulk Density (g/cm^3)	s^2	CV (%)	Homogenous Groups (90% Tukey HSD)
4 Inch Depth					
Undisturbed	40	0.86	0.017	15.2	A
Cable Road:					
Center	13	0.97	0.051	23.2	A
Edge	13	0.84	0.021	17.3	A
Between roads	10	0.93	0.019	14.7	A
8 Inch Depth					
Undisturbed	35	0.93	0.021	15.5	A
Cable Road:					
Center	13	0.98	0.091	30.9	A
Edge	13	0.89	0.031	19.8	A
Between roads	10	1.06	0.015	11.6	A

Table 27: Unit 88 Tukey-Kramer multiple comparison test between pre- and post-thinning soil soil conditions.

Disturbance Class	Count	Mean Bulk Density (g/cm^3)	s^2	CV (%)	Groups (90% Tukey HSD)
4 Inch Depth					
Undisturbed	33	0.94	0.009	9.9	A
Cable Road:					
Center	11	0.90	0.030	19.3	A
Edge	8	0.89	0.031	19.7	A
Between roads	8	0.95	0.005	7.7	A
8 Inch Depth					
Undisturbed	30	0.95	0.019	14.7	A
Cable Road:					
Center	11	0.95	0.024	16.4	A
Edge	8	0.91	0.027	18.0	A
Between roads	8	1.01	0.005	7.2	A

Table 28: Unit 89 Tukey-Kramer multiple comparison test between pre- and post-thinning soil conditions.

that cable thinning changed bulk density significantly from pre-thinning values in the center, edge or halfway between cable roads in any of the units sampled.

Multiple linear regression was used to determine what other factors had an association with variation in soil bulk density. Four factors were tested in relation to soil bulk density: estimated volume yarded over a sampling point, proximity to the landing, slash depth, and the visual disturbance class. The basic disturbance classes (mixed, rutted, exposed, etc.) were grouped in a qualitative ranking of disturbance severity from zero to ten (see Table 29) and were

Code	Description of Soil Disturbance
0	Pre-thinning condition
1	Undisturbed (post-thinning)
2	Evidence of disturbance, litter intact
3	Light Mixing (Surface 1-3 in.)
4	Heavy Mixing (>3 in.)
5	Exposed
6	Mixed, Ruts <6 in. deep
7	Mixed, Ruts >6 in. deep
8	Exposed, Ruts <6 in. deep
9	Exposed, Ruts >6 in. deep
10	Old Skid Road

Table 29: Soil disturbance severity codes for bulk density analysis.

included as indicator variables. Though all disturbance classes were observed in the disturbance mapping surveys, codes six and eight were not represented in the bulk density data. Slash depth, yarded volume, and proximity to the landing were also grouped and included as indicator variables (see Table 30). Indicator variables for unit and cable road 15 in unit 86 were included in order to account for bulk density differences at that level. Scatterplots of bulk density versus slash depth, yarded volume, and soil disturbance category are provided in Figures 29 - 34.

Variable	**Levels of Indicator Variables**	**Level**
Estimated Volume Yarded at a Point (ft^3)	0*	0
	1 - 4000	1
	4001 - 8000	2
	8001 - 16000	3
	>16000	4
Slash Depth (in.)	0*	0
	0.1 - 2	1
	2.1 - 3.9	2
	4 - 3.9	3
	4 - 5.9	4
	>6	5
Distance from Landing (ft.)	50*	0
	100	1
	150	2
	>150	3

*Table 30: Levels within skyline regression indicator variables. * Denotes reference level.*

For both sampling depths, the full regression model was as follows:

$$y = \beta_0 + \beta_{1\text{-}2}(\text{Unit}) + \beta_3(\text{Unit 86 Cable Road 16}) + \beta_{4\text{-}7}(\text{Volume}) + \beta_{8\text{-}14}(\text{Disturbance}) + \beta_{15\text{-}17}(\text{Distance}) + \beta_{18\text{-}21}(\text{Slash Depth})$$

where Unit 89 and the combination of disturbance codes zero and one were the reference levels for their prospective indicator classes (see Table 30 for other reference levels).

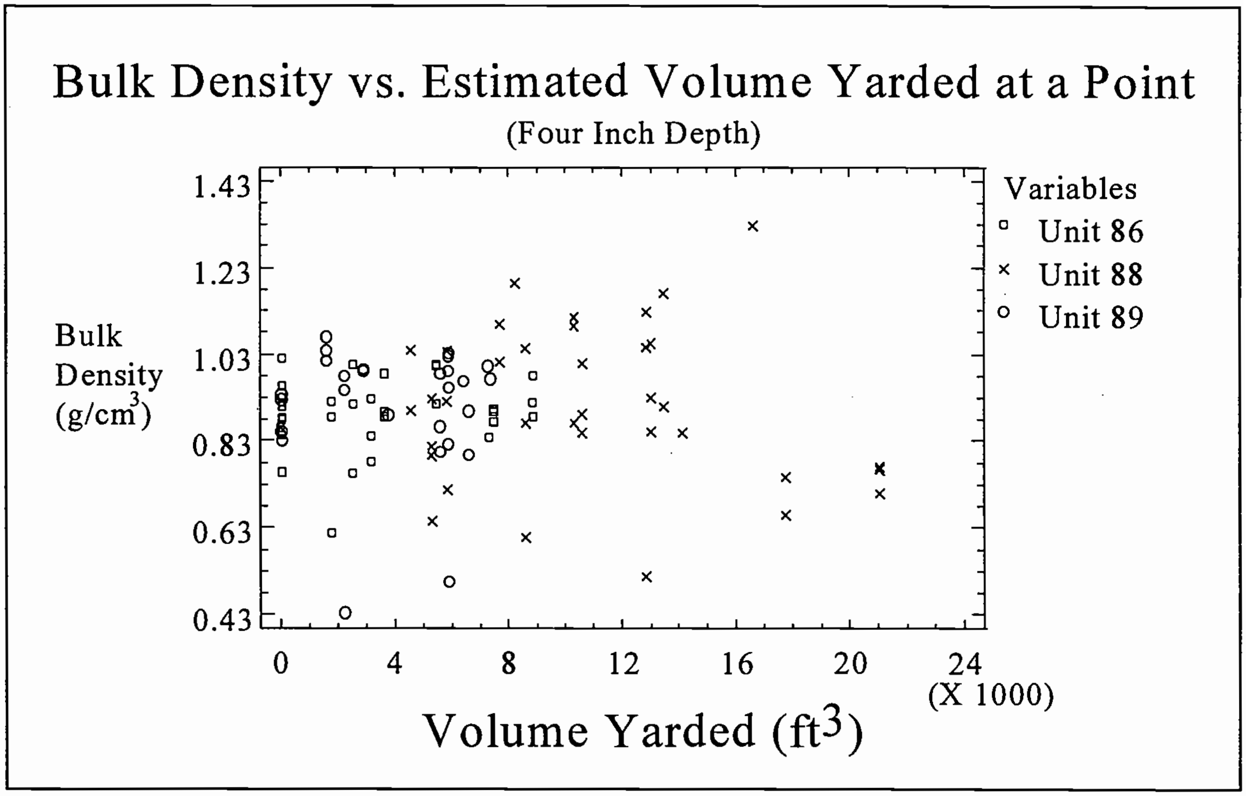

Figure 29: Four inch depth bulk density versus estimated volume yarded at a point.

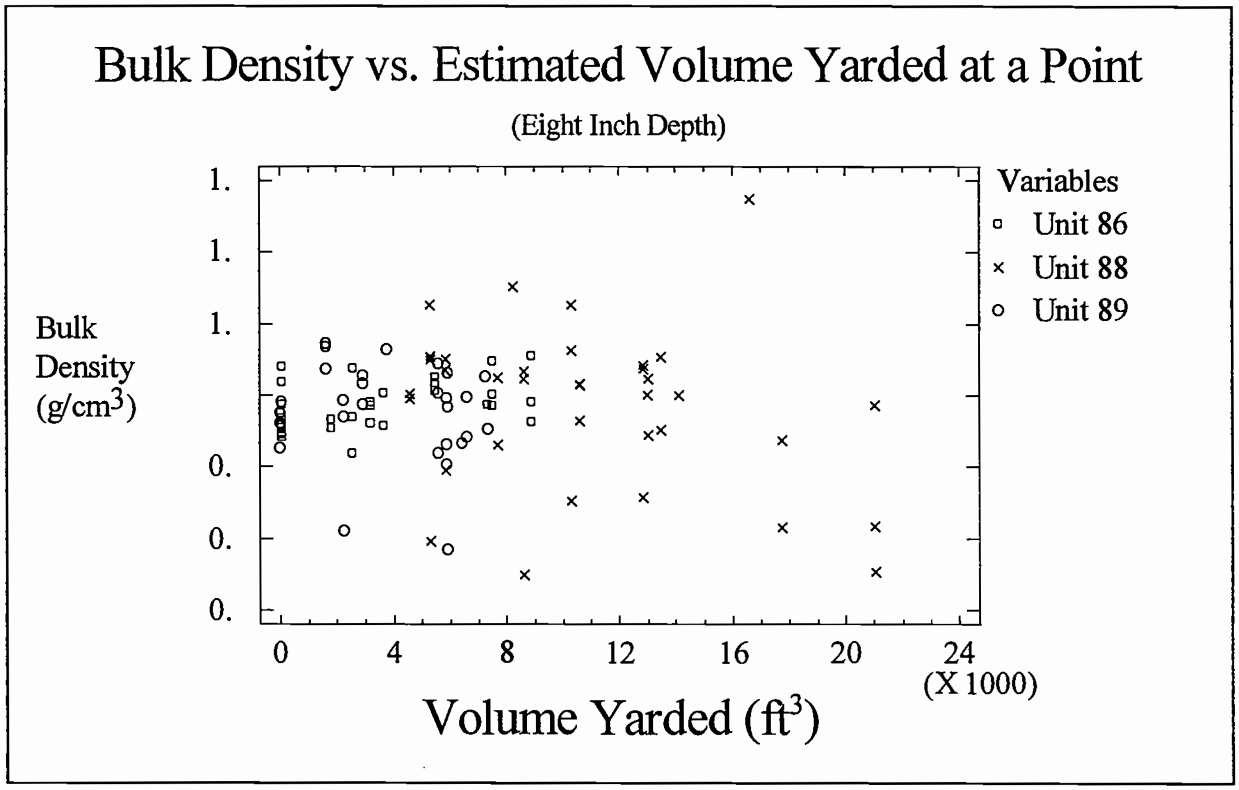

Figure 30: Eight inch depth bulk density versus estimated volume yarded at a point.

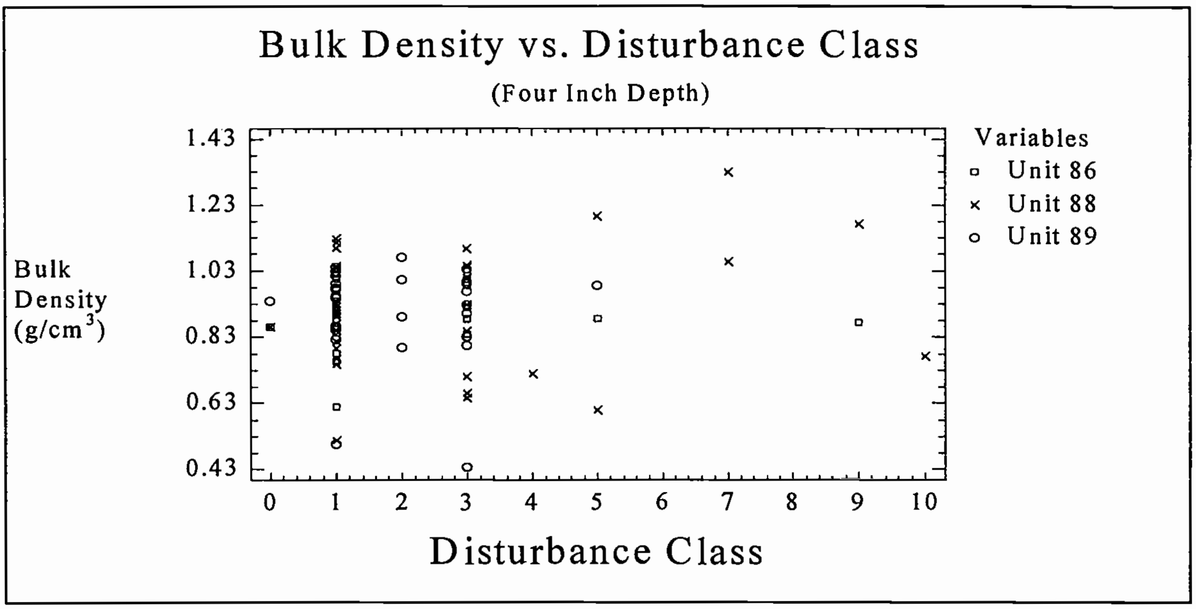

Figure 31: Four inch depth bulk density versus soil disturbance class (see Table 29 for explanation of codes).

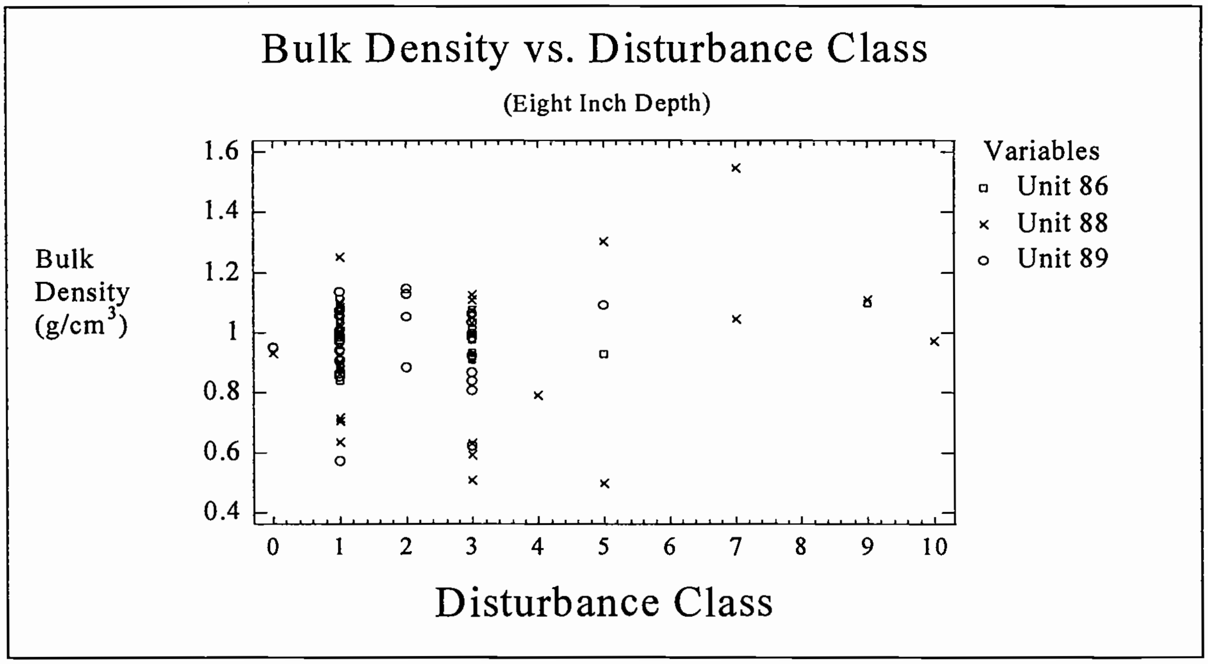

Figure 32: Eight inch depth bulk density versus soil disturbance class (see Table 29 for explanation of codes).

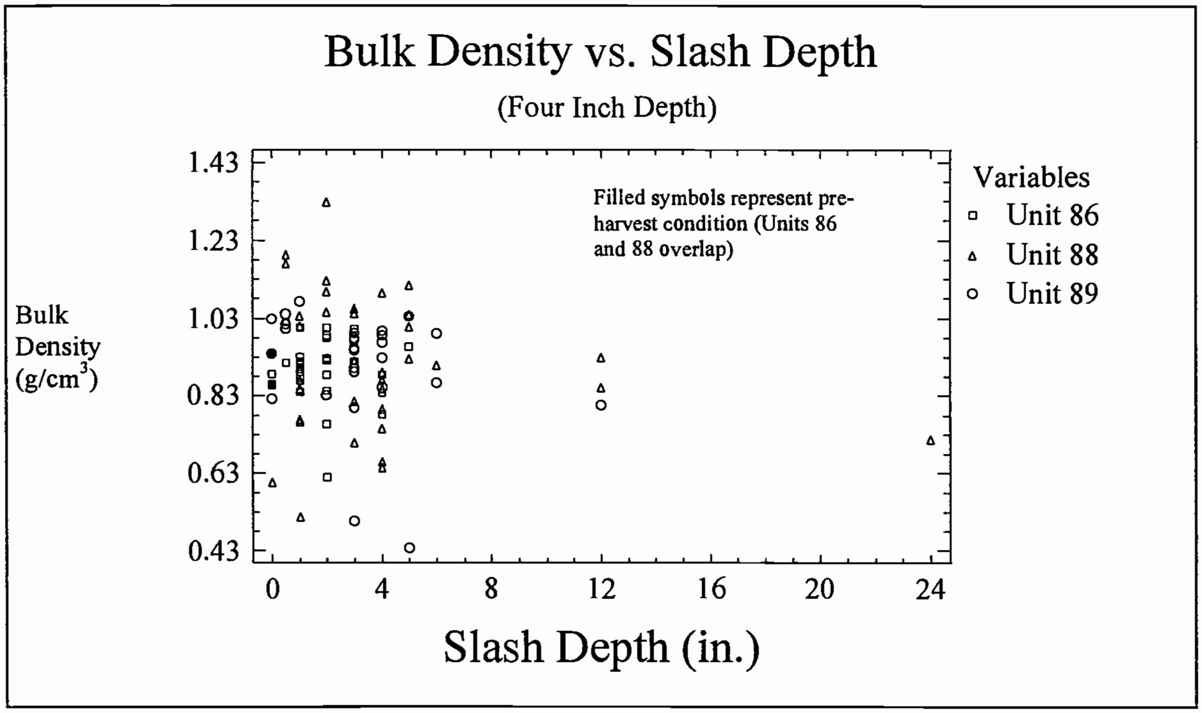

Figure 33: Four inch depth bulk density versus slash depth.

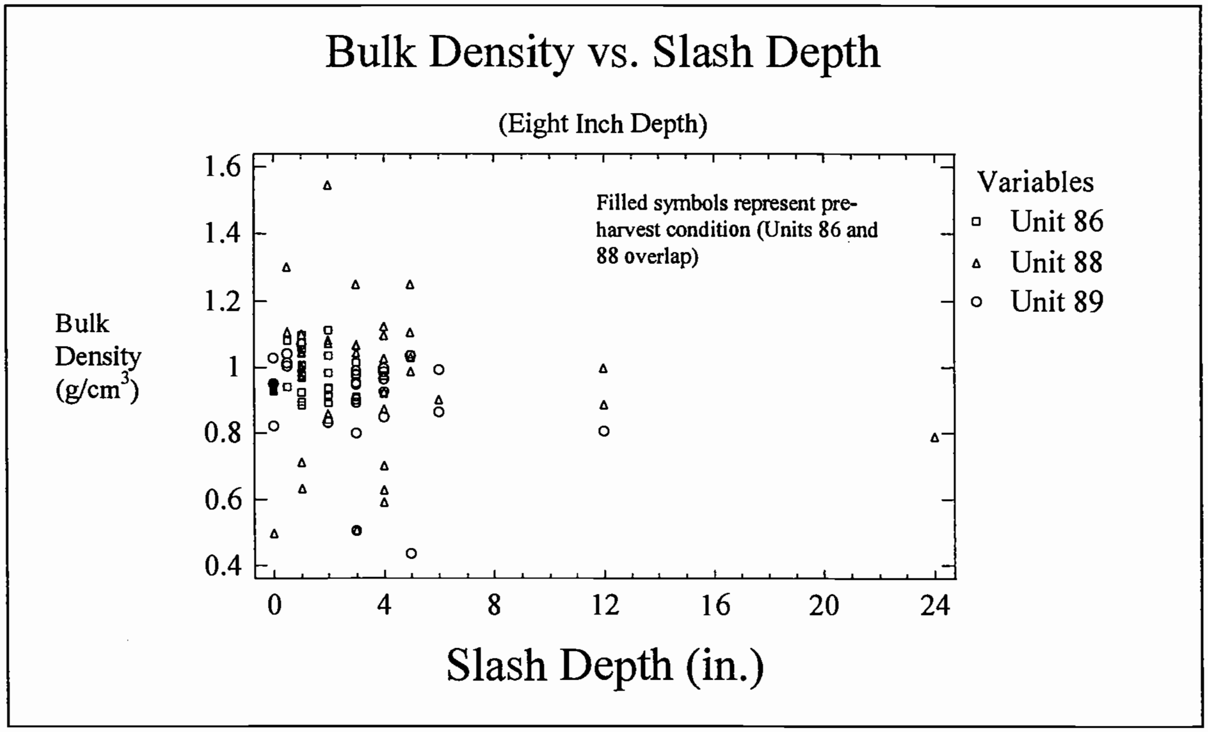

Figure 34: Eight inch depth bulk density versus slash depth.

Using backwards stepwise regression (F-stat = 2), the reduced model for both sampling depths retained only the coefficients for disturbance code seven and the yarded volume level greater than 16000 ft^3. The reduced model regression equations are provided in Table 31.

Model	P-values
Four Inch Depth ($r^2 = 12\%$)	
Post-thinning Bulk Density =	
0.907372	0.0000
+ 0.350918 (Disturbance Code 7)	0.0006
- 0.13643 (Yarded Volume > 16000 ft^3)	0.0216
Eight Inch Depth ($r^2 = 14\%$)	
Post-thinning Bulk Density =	
0.966033	0.0000
+ 0.417219 (Disturbance Code 7)	0.0002
- 0.174424 (Yarded Volume >16000 ft^3)	0.0081

Table 31: Multiple linear regression models for post-thinning soil bulk density in cable units.

The regression results provide some evidence that measurements taken within fifty feet of the landing had different densities than those farther away ($p>0.10$). In addition, the bulk densities of points with no slash after thinning were not significantly different from those points with slash at any observed depth ($p>0.10$).

There is some evidence, however, that the bulk density of mixed soil with ruts greater than six inches in depth is increased by 0.35 g/cm^3 at four inches and by 0.42 g/cm^3 at eight inches as compared to undisturbed soil. Also, a decrease in bulk density of 0.14 g/cm^3 at four inches and 0.17 g/cm^3 at eight inches is associated with points where over 16000 ft^3 of timber has been yarded as compared to points where no yarding had occurred. It is important to note that only data from Unit 88 was available in both of these regression terms and thus conclusions drawn may only apply to that unit.

Regardless, the higher density associated with Disturbance Code 7 would represent only a small fraction of the area since the general rutted condition was estimated to amount to less than one-half of a percent of a unit on average. Also, the reduction in bulk density observed with volumes over 16000 ft^3 was based only on data from the first 150 feet of two cable roads within Unit 88. For this reason, changes in soil density associated with this cable thinning are considered negligible.

5. Summary and Conclusions

5.1 General Observations

The small average diameter of second-growth stands and greater emphasis on thinning versus clearcut prescriptions presents the opportunity for increased mechanization of logging systems in the region. Mechanized harvest is said to offer many advantages over conventional logging systems including safer working conditions during felling operations, improved utilization of marketable timber, optimization of log lengths as required by the mill and the potential for reduced soil compaction and disturbance. A knowledge gap exists, however, about the effects of harvester-forwarder (CTL) and skyline thinning systems on soils in the Pacific Northwest. Severe soil compaction and disturbance have been linked to reduced conifer growth, erosion and altered soil hydrologic properties. Thus, assessing the degree of soil compaction and disturbance associated with these thinning systems is important to help determine if there will be any long-term affects on stand health and growth. The objective of the two case studies presented was to quantify the degree and extent of soil compaction and disturbance incurred during thinning operations with a CTL system and a small-wood cable yarder.

In the two CTL units (Units 81 and 82), it was necessary to account for the existing 50-year-old skid trail network to isolate effects specific to this new thinning entry. Sample points were randomly located prior to thinning using an offset grid sampling method and classified as undisturbed or already impacted by old skid trails. A sub-sample of old trails was also collected within the random plots where old trails were present. Sampling occurred as close as possible to these original points both post-harvester and post-thinning. However, thinning operations were completed only in the northeast corner of Unit 82 (approximately 25 acres) during the sampling period. Additional plots were placed in this portion of the unit to increase the post-thinning sample size, but not all points have pre-thinning data since thinning activities had already begun in that area. Post-thinning results apply only to the northeast portion of Unit 82 sampled.

The skyline roads of three units were sampled (86, 88 and 89) non-randomly both pre- and post-thinning for bulk density and disturbance. As in the CTL units, post-thinning sample points were located as close to pre-thinning points as possible. Areal disturbance estimates were made from transects both on top of and halfway between skyline roads where disturbance was mapped. Since no disturbance was observed between skyline roads, disturbance is assumed to occur only within skyline road corridors.

From the random sample in the CTL units it was estimated that approximately 27% of Unit 81 and 13% of Unit 82 were already in old skid trails. Exposed or mixed soil was not observed in either of the units but windthrow and animal burrowing were found to have disturbed three percent of Unit 81. The bulk density of these 50-year-old skid trails was statistically different from that of undisturbed soil, though the compaction was not consistent across the width of the trail. The longevity of soil compaction has been well documented in other research papers (Froehlich 1979, Froehlich and Berglund 1979, Geist et al. 1989, Vanderheyden 1980, Wert and Thomas 1981). The center of old skid trails was 10-16% more dense at the four inch depth in both units, but only ruts in Unit 81 were also greater in density (+8%) at the same depth. At the eight inch depth, skid trail ruts were consistently more dense (13-15%), as well as the center of trails in Unit 82 (+15%). In neither unit was the bulk density of skid trail berms statistically different from undisturbed soil. Based on the estimated area in old skid trails, the amount of area classified as rut or center and the classes determined to be statistically different from undisturbed soil, it is estimated that 4 and 10% of Unit 81 (4 and 8 inch depth) and 6 and 4% of Unit 82 were already compacted prior to this thinning entry. It is important to note, however, that the difference in bulk densities between old skid trails and undisturbed soil may not be due to compaction but to scalping of the surface soil. The heavy tracked equipment and skidding of large diameter trees typical of historical harvesting entries may well have removed a substantial portion of the soil surface. Since bulk density naturally increases with depth in the soil profile, measurements taken on scalped soils may well be greater in density. No attempt was made in this analysis to differentiate between these two possibilities.

As there was a delay between the arrival of the harvester and forwarder at the CTL units, sampling was conducted to isolate effects specific to the harvester. It is emphasized that logging activities during the data collection period were limited to the northeast corner of Unit 82 and that all post-activity data are associated with that area. The harvester disturbed 27% of the area outside of old skid trails, for a total of 40% of the area affected by the original harvest and/or this thinning entry. Four percent of soils in the harvested portion were exposed, and 9% experienced mixing of the mineral and organic horizons. Another four percent of the area fell into the "Other" category including windthrow or animal disturbance. A re-assessment of disturbance after the forwarder had completed yarding found 25% of the area newly disturbed for a total combined and new disturbance of 38%. Exposed or mixed soil was not observed. Discrepancies between the post-harvester and post-thinning disturbance values are attributed to sampling error, redistribution of slash during skidding activities, slightly different data sets and/or different surveyors.

The results are very similar to other studies of CTL systems in the Pacific Northwest. Total disturbance values of the other studies ranged from 16-26%, though one study which took place in the southeast United States had values as high as 38% (Armlovich 1995, Gingras 1994, Hogervorst and Adams 1995, Lanford and Stokes 1995).

Disturbance in the skyline units was substantially lower. The maximum area disturbed (1.8%) was associated with the heavy thinning in Unit 88. Units 86 and 89 (both light thinnings) did not experience even a 1% disturbance of the total area, though 13 and 8% of the units were within skyline corridors. Mixing of the mineral and organic horizons accounted for most of the disturbed area, with exposure and rutting never reaching one half of a percent on a unit-wide basis. Except for mixing, the areas of exposure and rutting were small, discontinuous and usually occurred within 150 feet of the landing. Disturbance was associated with both micro- and macro-topographic relief, but the macro relief (e.g., elevation of tailhold tree) appeared to contribute most to overall deflection and thus soil disturbance. McMahon (1995) also found disturbance with cable logging in New Zealand to be discontinuous, though the greatest disturbance was associated with mid-span ridges. As the slopes in the New Zealand study were described as convex, results may not be comparable to the mostly concave slopes associated of this study.

In comparison to other cable harvest soil disturbance surveys, my values appear to be very low (Baumgras et al. 1995, Dyrness 1965, McMahon 1995, Purser et al. 1992). This is likely due to the inclusion of landings and/or roads in the other disturbance assessments whereas my study did not. Though Baumgras et al. (1995) found no significant difference between disturbance in units with shelterwood, modified shelterwood and thinning prescriptions, the lower disturbance noted in my study may also be due to the relatively low amount of volume yarded. In addition, the relatively small diameter of the yarded trees may have diminished the opportunity for soil disturbance as compared to the harvest of large-diameter old-growth stands (Dyrness 1965, Purser et al. 1992).

Rutting was not observed in the CTL unit, and did not account for a large area in the skyline units. Though rutting has been associated with reduced conifer growth in the southern United States (Reisinger et al. 1992, Tiarks 1990), the small, discontinuous ruts observed in the skyline units are not expected to impact tree growth. The "exposed" disturbance category constituted up to 4% of the area harvested in the CTL unit before the forwarder entered, but this disturbance was also relegated only to small, discontinuous patches and is not expected to result in large-scale reduced infiltration, overland flow or erosion.

It is again emphasized that "disturbed" is not meant to indicate a negative impact, but merely that an observable change has occurred relative to the undisturbed state. It is also important to note that large discrepancies in visual classification of soil disturbance can occur due to different observers, different data sets, or a combination of both.

As for changes in bulk density, the harvester alone was not found to significantly compact undisturbed soil ($p>0.10$). The impact of both the harvester and forwarder combined did, however, significantly increase the bulk density of previously undisturbed soil by an average of 12 (4 inch depth) and 11% (8 inch depth, $p=0.04$ and 0.05). When compared to the density of old skid trails, the degree of compaction with the CTL thinning entry was not found to differ ($p>0.10$). Neither the harvester alone nor the combined traffic of harvester and forwarder affected the bulk density of old skid trails. It is likely that the initial harvest entry increased soil strength on old skid trails to the point where further compaction was not necessary in order to bear the weight of the harvester and forwarder.

It is estimated that this new entry contributed an additional 25% (4 and 8 inches) to the compacted area, for a total compacted area of 29-31%. This is based on the estimated area in new skid trails and the assumption that compaction is constant along the width (both ruts and center) and length of the trails regardless of the number of equipment passes and slash depth. Analysis of data collected on the same thinning unit for a different study suggested that compaction did not occur in the center of skid trails until very high traffic levels at the four inch depth and not at all at eight inches (Allen and Adams 1997). Again, these results apply only to the northeast 25 acres of Unit 82. This area is characterized by slopes less than 10 percent with estimated equipment traffic levels ranging from three passes at the ends of trails, to 30 passes on secondary trails and over 40 passes on primary skid trails. This is representative of most of Unit 82 except for areas near streams with steeper slopes.

The bulk density of the center, edge and zone between skyline roads after thinning was compared to pre-thinning values in order to determine if there was an overall change in density. A Tukey-Kramer multiple comparison test revealed no evidence that a significant difference existing among the four categories. In addition, multiple linear regression was used to determine if soil disturbance, the volume yarded over a given point, proximity to the landing or depth of slash was associated with changes in soil bulk density in the skyline units. There was some evidence that mixed soil with ruts greater than six inches deep was 0.35 and 0.42 g/cm^3 (4 and 8 inch depth) more dense than undisturbed soil (p=0.0006 and 0.0002). However, only two points from Unit 88 were associated with this coefficient, and both were from a skyline road known to have a higher average bulk density than the rest of the sampled roads. In addition, measurements were taken at the rut bottom suggesting that the increased bulk density may be more likely attributed to sampling at a lower depth in the soil profile. For these reasons, deep ruts with mixed soil are not considered to be associated with compaction on these sites.

The regression results also suggested that the soil bulk density of skyline roads where over 16000 ft^3 was yarded were significantly reduced by 0.14 and 0.17 g/cm^3 at four and eight inches in depth ($p=0.022$ and 0.008). A possible mechanism for this reduced bulk density is unknown though it may be associated with mixing of the organic and mineral horizons. Again, only two points from Unit 88 contributed to this coefficient and would represent only the top 150 feet of two skyline roads within this unit. Overall, the analysis suggests that thinning with this skyline system did not significantly affect soil bulk density or result in an unacceptable level of soil disturbance.

As noted in the literature review, many studies have associated increased density with a decline in one or more conifer growth parameters (Corns 1988, Foil and Ralston 1967, Froehlich and Berglund 1979, Halverson and Zisa 1982, Hatchell et al. 1970, Heilman 1981, Mitchell et al. 1982, Sands and Bowen 1978, Wert and Thomas 1981, Youngberg 1959). Other studies have found no apparent affect (Campbell et al. 1973, Miller et al. 1996). The absolute bulk density at which a given conifer growth parameter is negatively affected has been found to vary substantially with soil texture and species (Foil and Ralston 1967, Froehlich 1979, Heilman 1981, Minore et al. 1969, Zisa et al. 1980). Using the results of other compaction studies, Froehlich and McNabb (1983) observed a strong association between the percent decrease in height growth and the percent increase in bulk density (see Figure 1). This figure suggests that an approximate 10% reduction in height growth is observed at bulk density increases as low as 10%. The percent reduction in height growth continues to increase with further compaction.

Based on that conclusion, up to 10% of Unit 81 and 29% of Unit 82 (extrapolating results across entire unit) are compacted to a degree that could result in at least at 10% reduction in conifer height growth. A mechanism for such a strong linear association between increasing bulk density and conifer height growth regardless of tree species, soil texture, climate or other factors is unclear. Without a firm understanding of the spatial pattern of compaction, how many trees are affected and an estimate of stand's response to the thinning it would be difficult to accurately estimate if and how much of a growth loss would occur (Froehlich 1979, Froehlich and Berglund 1979, Helms and Hipkin 1986). Also, the rooting depth of the remaining conifers likely extends to much greater depths than those sampled in this study. With a large area of uncompacted soil potentially available below eight inches, the growth of trees on this site may not be altered by surface compaction.

Several studies of forest soils in the Pacific Northwest have associated altered hydrologic properties and water movement into and through soil with changes in bulk densities (Cafferata 1980, Johnson and Beschta 1980, Kuennan et al. 1979, Purser and Cundy 1992, Steinbrenner and Gessel 1953). The absolute and/or relative changes in bulk density observed in this study as a result of CTL harvesting are comparable to those studies above, suggesting that an alteration in soil hydrologic properties may have occurred at this site. However, it has also been suggested that the seasonal variation in infiltration rates may be greater in magnitude than changes due to forest management impacts alone (Johnson and Beschta 1981). In addition, both the moderate slopes and lack of exposed soil of these sites would mitigate any increased potential for overland flow and erosion. For these reasons, concerns about potential changes in soil hydrologic properties associated with compaction in the CTL units may not be warranted with regards to loss of site productivity or water quality due to erosion. However, further study of links between compaction and hydrologic processes important to plant and soil micro- and macro-fauna growth and species composition as well as delivery of water to streams through changes in subsurface flow, aeration and porosity may deserve attention.

5.2 Management Recommendations

Despite the use of designated skid trails, the combined entries into the CTL units disturbed and compacted a considerable amount of area. This is not surprising because of the different harvest systems used in each entry and the fact that all skid trails do not remain readily visible through time. To minimize soil disturbance and compaction associated with forest harvest, it is recommended that land managers effectively design, accurately map and commit major skid trails to the long term transportation network. Soil tillage is also a consideration after final harvest, in areas with old skid trails or locations where new compaction was unavoidable.

In the skyline units, most soil disturbance was associated both with micro- and macro-topographic features and the elevation of the tailhold. Specifically, mid-slope ridges and slopes with tailhold trees at relatively low elevations experienced the greatest disturbance. Using detailed skyline road profiles and deflection modeling to plan the optimal location of support trees and tailholds is expected to minimize soil disturbance due to skyline yarding.

5.3 Further Research

Additional research about the effects of mechanized harvest on forest soils is needed. The relationship between those effects and site and stand productivity and the management of significant impacts should also receive further investigation. A greater pool of information about soil disturbance and compaction will aid the land manager in decisions regarding the timing, method, and extent of forest harvest. Suggested areas of research include:

1) Further clarification of the factors associated with compaction which act to decrease tree growth.

2) Further clarification of the extent of the conifer rooting zone that must be impacted and the degree of density change needed before growth and vigor is significantly affected

3) Development of accurate and efficient methods of designing and committing skid trails to the long term transportation network

4) Assessing the need for and application of mechanical or other methods of alleviating soil compaction in thinned stands

5) Determining the effects of soil disturbance such as rutting, mixing, and exposure on long term soil and stand productivity

6) Clarifying the role of logging slash in protection against soil compaction and how any beneficial results of slash can be effectively managed on the ground

7) Further testing of the effectiveness of statistical designs in accounting for spatial patterns of soil bulk density

8) Clarification of the environmental processes linked to soil hydrologic properties and if changes in those properties associated with forest harvest and yarding equipment are discernible from natural spatial and temporal patterns of soil hydrologic properties.

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7. Appendix A

Charts of Soil Disturbance by Skyline Road Length

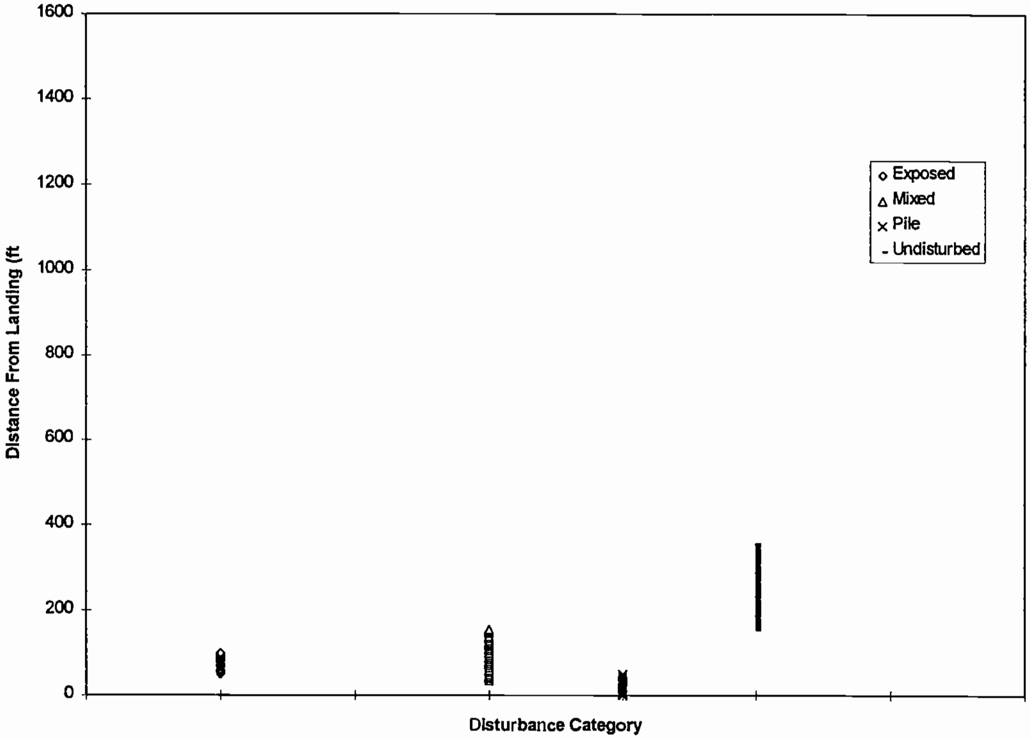

Figure 35: Unit 86 skyline road 12 soil disturbance by distance from landing.

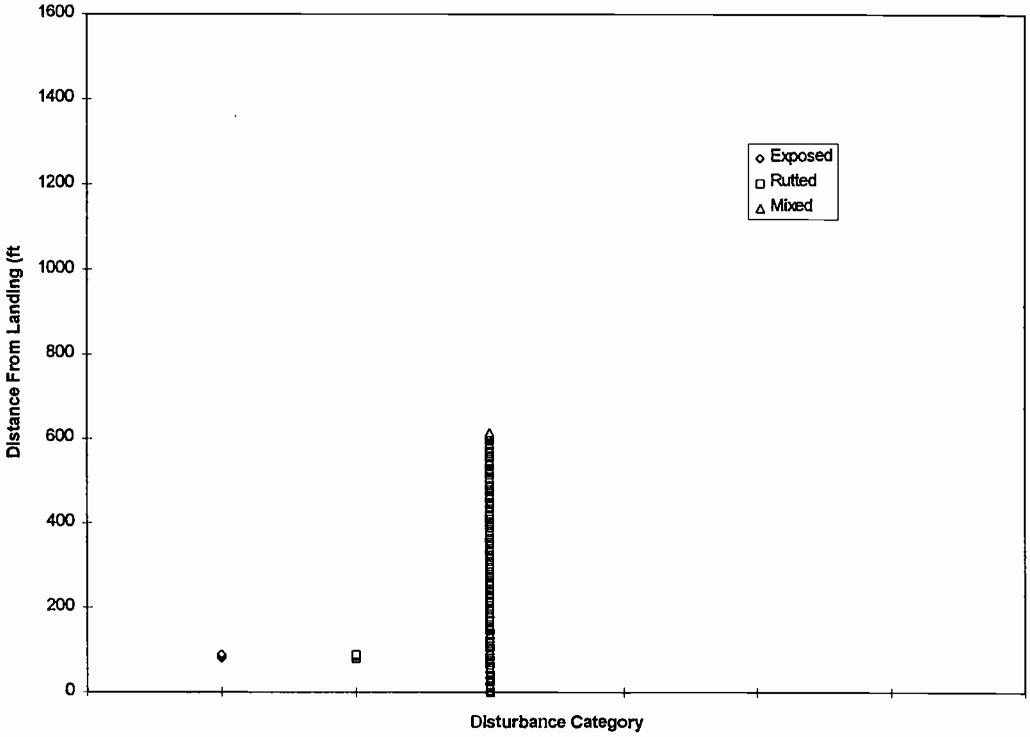

Figure 36: Unit 86 skyline road 27 soil disturbance by distance from landing.

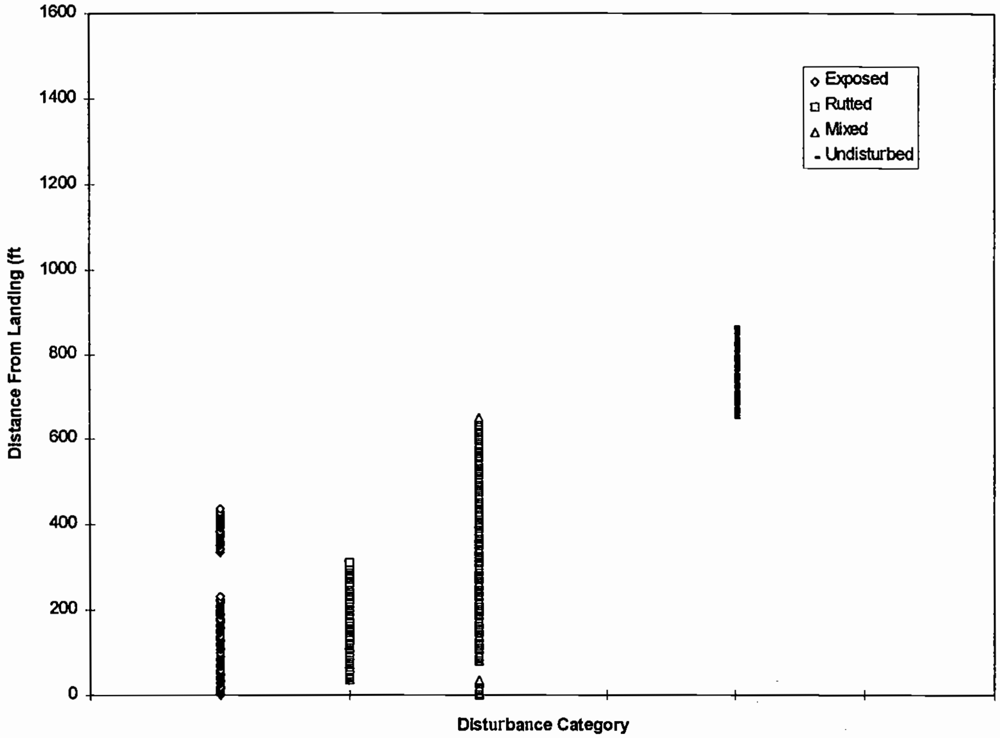

Figure 37: Unit 88 skyline road 6 soil disturbance by distance from landing.

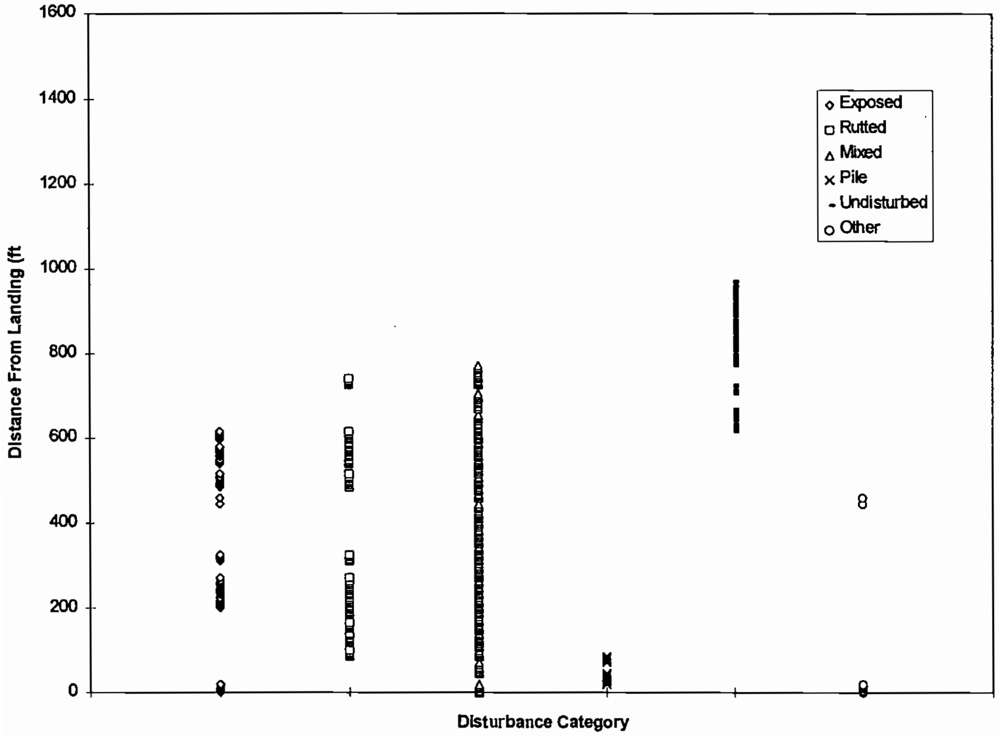

Figure 38: Unit 88 skyline road 7 soil disturbance by distance from landing.

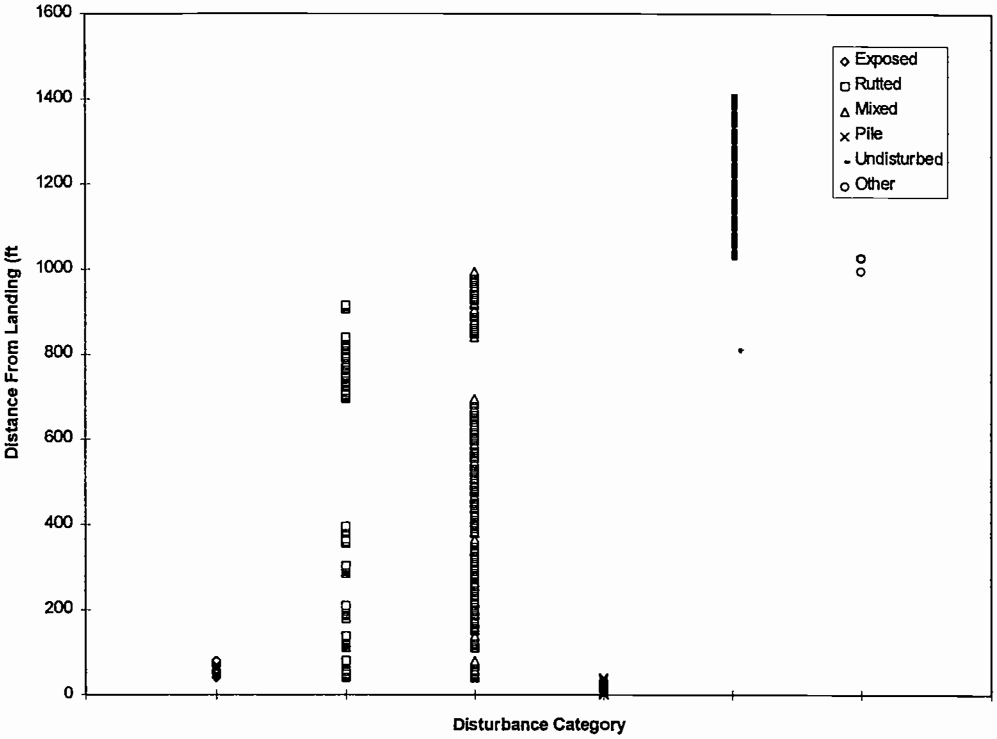

Figure 39: Unit 88 skyline road 13 soil disturbance by distance from landing.

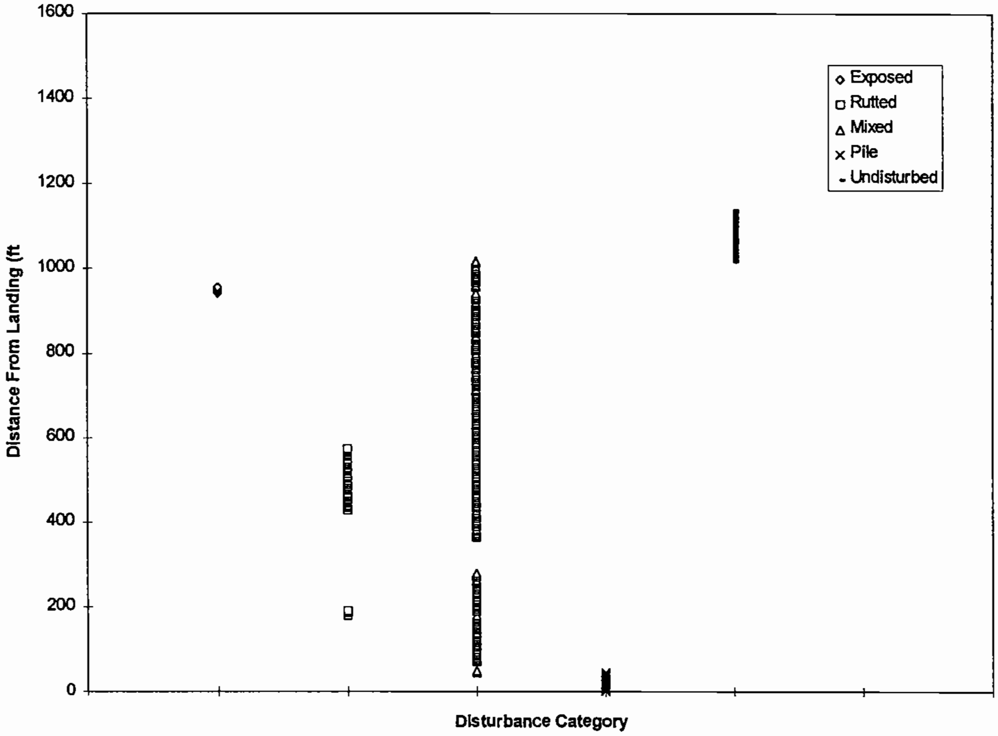

Figure 40: Unit 88 skyline road 15 soil disturbance by distance from landing.

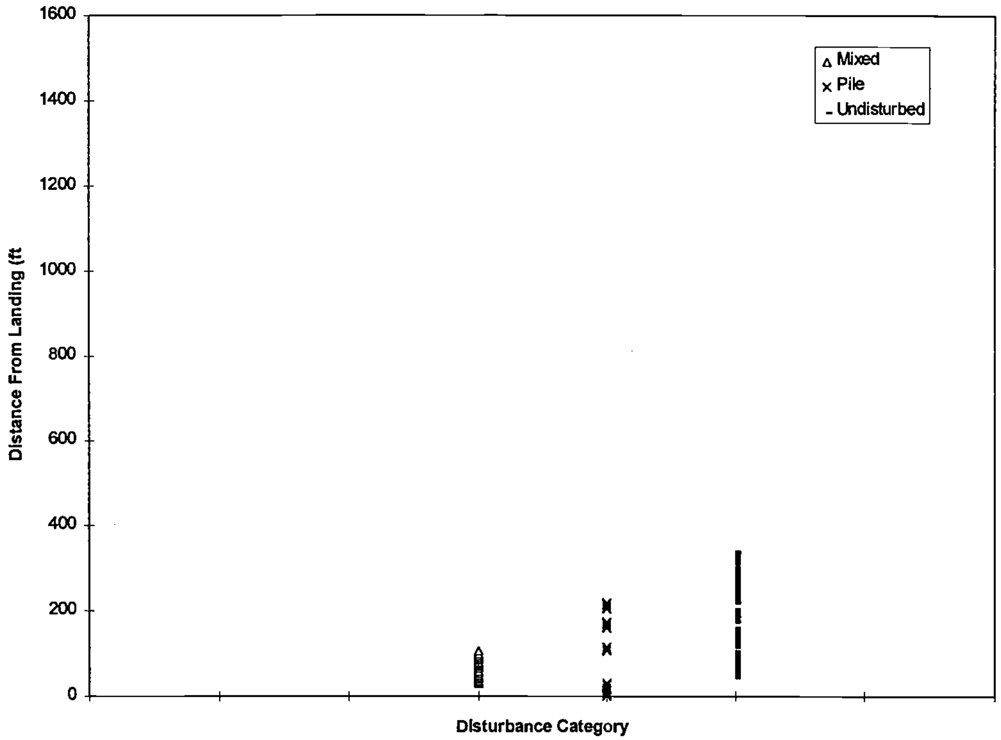

Figure 41: Unit 89 skyline road 2 soil disturbance by distance from landing.

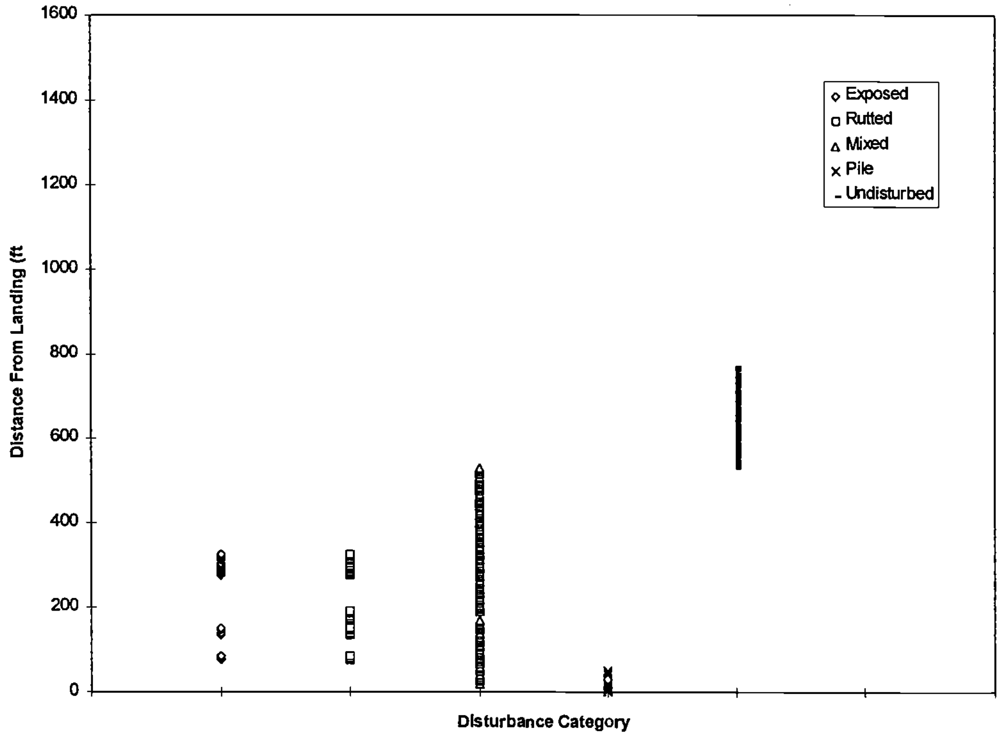

Figure 42: Unit 89 skyline road 5 soil disturbance by distance from landing.

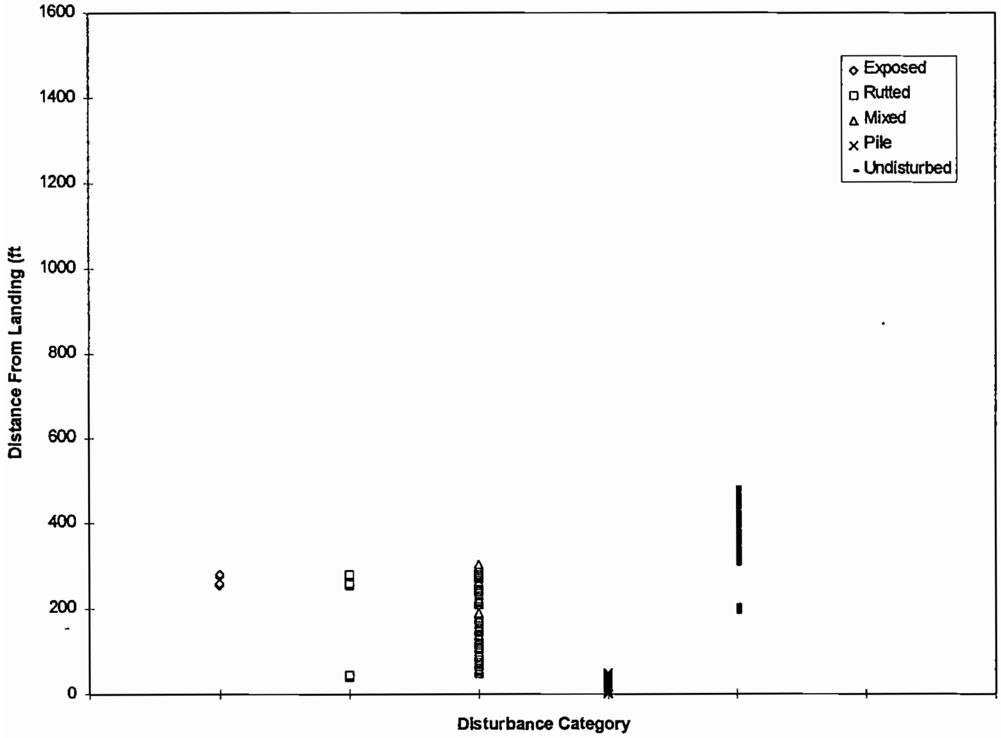

Figure 43: Unit 89 skyline road 16 soil disturbance by distance from landing.

8. Appendix B

Statistical Tests for Pre-thinning Spatial Bulk Density Patterns in the Skyline Units

1) Tukey-Kramer multiple comparison tests for significant differences between skyline road bulk density within units.

		4 Inch Depth		8 Inch Depth	
Skyline Road	n-size	Avg. (g/cm^3)	Groups	Avg. (g/cm^3)	Groups
12	9	0.81	A	0.92	A
15	12	0.94	B	1.03	B
16	14	0.85	AB	0.92	A
17	3	0.76	A	0.89	A

Table 32: Unit 86 Tukey-Kramer multiple comparison tests for pre-thinning bulk density differences between skyline roads (95% level).

	n-size		4 Inch Depth		8 Inch Depth	
Skyline Road	4”	8”	Avg. (g/cm^3)	Groups	Avg. (g/cm^3)	Groups
4	7	4	0.81	A	0.87	A
7	9	8	0.92	A	0.95	A
9	11	11	0.87	A	0.96	A
11	8	8	0.85	A	0.90	A
12	5	4	0.80	A	0.92	A

Table 33: Unit 88 Tukey-Kramer multiple comparison tests for pre-thinning bulk density differences between skyline roads (95% level).

	n-size		4 Inch Depth		8 Inch Depth	
Skyline Road	4”	8”	Avg. (g/cm^3)	Groups	Avg. (g/cm^3)	Groups
16	11	10	0.94	A	0.90	A
17	14	13	0.95	A	0.97	A
18	8	7	0.94	A	0.98	A

Table 34: Unit 88 Tukey-Kramer multiple comparison tests for pre-thinning bulk density differences between skyline roads (95% level).

2) Tukey-Kramer multiple comparison tests for significant differences between slope position bulk density within units.

		4 Inch Depth		8 Inch Depth	
Distance from Landing (ft)	n-size	Avg. (g/cm^3)	Groups	Avg. (g/cm^3)	Groups
0	5	0.91	A	1.02	A
50	9	0.87	A	0.94	A
100	9	0.84	A	0.94	A
150	12	0.85	A	0.96	A
350	3	0.87	A	0.86	A

Table 35: Unit 86 Tukey-Kramer multiple comparison tests for pre-thinning bulk density differences between slope position or distance from landing (95% level).

	n-size		4 Inch Depth		8 Inch Depth	
Distance from Landing (ft)	4"	8"	Avg. (g/cm^3)	Groups	Avg. (g/cm^3)	Groups
0	12	9	0.89	A	0.88	A
50	4	4	0.80	A	0.90	A
100	9	7	0.87	A	1.05	A
150	11	11	0.83	A	0.89	A
350	3	3	0.87	A	0.97	A
550	1	1	0.87	A	0.95	A

Table 36: Unit 88 Tukey-Kramer multiple comparison tests for pre-thinning bulk density differences between slope position or distance from landing (95% level).

	n-size		4 Inch Depth		8 Inch Depth	
Distance from Landing (ft)	4"	8"	Avg. (g/cm^3)	Groups	Avg. (g/cm^3)	Groups
0	9	9	0.94	A	0.98	A
50	4	4	0.96	A	0.94	A
100	9	8	0.94	A	0.92	A
150	7	7	0.94	A	0.96	A
350	4	2	0.94	A	0.88	A

Table 37: Unit 89 Tukey-Kramer multiple comparison tests for pre-thinning bulk density differences between slope position or distance from landing (95% level).