AN ABSTRACT OF THE THESIS OF

Robert T. Parker for the degree of Master of Science in Forest Resources presented on August 24, 2000. Title: Soil Compaction in Central Oregon Volcanic Ash Soils and the Subsequent Effects on Residual Ponderosa Pine Growth.

Abstract approved: ______________________________

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Although previous research in central Oregon has shown soil compaction can lead to a decline in site productivity, the subject is not understood well enough to predict the growth changes resulting from a given level of soil compaction. A study was initiated to relate the basal area, height and volume periodic annual increment (PAI) of residual, 70 to 80 year-old ponderosa pine (*Pinus ponderosa* Laws.) trees to compacted soil conditions, as measured by soil strength.

This study was superimposed on the USDA Forest Service Long Term Site Productivity Project research plots in Central Oregon and thus constrained by its design. Soil strength and tree growth were measured on six of these plots. Three plots had been thinned with a mechanical harvester and the stems removed with a grapple skidder from the plots (Complete Removal). Three other plots were thinned to similar stocking levels with the harvester, but the stems were left in place to minimize disturbance (No Removal). No true control existed for these installations as both the Complete Removal and No Removal plots were compacted by the harvester. A recording penetrometer was used to determine soil strength

along systematically spaced grid points, to a depth of 24 inches. Each tree within each plot was mapped and measured for total height, diameter at breast height, and radial growth increment at diameter breast high (DBH).

The soil conditions around each residual tree were evaluated using 15, 30-, and 45-foot radius plots. The penetrometer readings that fell within each of these plots were averaged to represent the overall soil conditions affecting each tree. The Complete Removal plots had significantly higher soil strength conditions than the No Removal plots ($p \leq 0.05$). The percent increases in average soil strength of the Complete Removal plots over the No Removal plots were 39, 42 and 44 percent for the 15-, 30- and 45-foot radius plots, respectively.

Potential associations between basal area, height and cubic volume PAI growth rates and replication, treatment, soil strength and other covariates were explored with general linear models. Soil strength was not a significant factor for basal area PAI or for volume PAI at the 30- and 45-foot radius. Total height and cubic volume PAI at the 15-foot radius declined significantly ($p \leq 0.05$) with increasing soil strength.

The volcanic ash soils did compact as a result of the low level of mechanical thinning activity conducted on the study sites. Tree growth was statistically associated with increased soil compaction. Lack of a true control prevents full evaluation of the mechanical harvesting-related compaction; however, skidding resulted in a measurable increase in soil compaction in the Complete Removal plots. Forest management practices that lead to frequent entries appear likely to compact these volcanic ash soils. Depending on logging patterns, large areas could be impacted without careful planning. It appears that compaction effects are long-lasting and cumulative, thus the risk of reducing long-term site productivity is a concern.

SOIL COMPACTION IN CENTRAL OREGON VOLCANIC ASH SOILS AND THE SUBSEQUENT EFFECTS ON RESIDUAL PONDEROSA PINE GROWTH

by

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Robert T. Parker, Author

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1.0 INTRODUCTION

The health of forest lands in the United States and their productivity for aesthetic, environmental and forest product values is coming under increasing attention from land managers and the public alike. The influence of soil conditions on long-term forest productivity is beginning to be recognized as a significant consideration and has led the USDA Forest Service, for example, to implement a long-term, nation-wide research program to study soil and forest interactions (Powers 1990). Timber harvesting practices have been shown to affect large areas of soil, particularly when ground-based harvesting equipment is used (Snider and Miller 1985). Increasing fiber values, an emphasis on stand density control, uneven-aged management and improving machine technology make it possible to economically enter stands at relatively young ages and increase the frequency of harvest entries over time. More frequent entries and widespread machine traffic can cause large-scale and significant alterations to soil conditions, such as decreased porosity, decreased aeration, displaced or diminished organic matter and increased soil strength. In extreme cases, ground-based commercial thinning operations have been shown to result in machines traveling over 50 percent or more of a harvest unit within a single entry (Zaborski 1989). Research has shown that the volcanic ash soils of Central Oregon are readily compacted by logging equipment and remain compacted for long periods of time, leading to reduced growth and survival of both seedlings and mature trees (Froehlich 1979, Froehich and McNabb 1984).

Powers (1990) noted, beyond conceptual models, we lack a specific understanding of what a given soil change means in terms of its long-term effect on productivity. Uncertainty and skepticism about the effects of management activities on forest soils and productivity will persist until we establish and maintain studies that will help us document and understand those effects (Miller and Hazard 1987).

The purpose of this study is to determine whether mechanical thinning operations lead to soil compaction and whether the basal area, height and volume periodic annual growth rates of ponderosa pine (*Pinus ponderosa* Laws) are influenced by compacted soil.

2.0 LITERATURE REVIEW

2.1 Central Oregon Volcanic Ash Soil Characteristics

In the Intermountain portion of the western United States, extensive areas of forestland occur on volcanic ash soils, including sites examined in this study (Geist et al. 1989). These ash-derived soils range from very fine-textured, fine-ash dominated material to coarse, well-graded pumice. Fine ash soils are noted for their very low natural bulk densities, averaging 43.6 lbs/ft^3 (Geist et al. 1989). The volcanic ash soils common throughout Central Oregon are also noted for their low bulk density, high porosity, low organic matter content, low shear strength, nonplasticity and well-graded surface horizons (Cullen et al. 1991). These soils are young (7,000 to 10,000 years old), have poorly developed horizons and are relatively infertile (Youngberg and Dyrness 1963). Tree growth on these soils shows positive responses to nitrogen, phosphorus and sulfur (Cochran 1972, 1978).

2.2 Susceptibility to Compaction

Due to the low bulk densities or low weight to volume ratio typical of northwest soils, they tend to be of relatively low strength and thus are susceptible to compaction under the influence of external loads (Froehlich and McNabb 1984, Geist and Cochran 1991). The very low bulk density of volcanic ash soils has often resulted in the soils being considered as among the least susceptible soils to compaction from logging and other disturbances (McNabb 1981). However, all soils, regardless of their initial densities, will compact and their soil strength will increase in order to support heavy, non-natural loads imposed on them. Theoretically, they should compress to the same strength if subjected to the same load, although the resulting bulk densities do not have to be the same (McNabb 1981). Soil strength, or resistance to compaction and other applied energy, is dependent on several factors, such as particle size distribution, particle size shape or roughness, percent organic matter and initial porosity (Bodman and Constantin 1965, Cruse et al. 1981, Froehlich 1980, Howard et al. 1981). In general, soils that have highly graded particle size distributions, coarse particle textures, low organic matter content and high initial porosities are most susceptible to compaction, which characterize central Oregon volcanic ash soils very well.

Determining the extent to which a particular soil will compact is not a simple process. It is dependent on a complex interaction of water potential, duration of the applied external load, kneading action (resulting from the actions of tire treads and tractor tracks over the ground), and vibration. Vibration can produce much more compaction in coarse-textured soils than an equivalent static load (Larson et al. 1980, Vomocil et al. 1958, Dexter and Tanner 1974, Soehne 1958, Chancellor 1977, Froehlich and McNabb 1984).

The application of an external load increases bulk density linearly with the logarithm of the force applied, although the slope of the line tends to be a unique property of a particular soil (Froehlich and McNabb 1984). Moisture effects susceptibility to compaction but its influence is not uniform among different soil types. In general, moisture acts as a lubricant between soil particles, resulting in reduced friction between particles so that a given force results in increased compaction (Raney et al. 1955). Thus, some soils are more susceptible to compaction at high moisture levels than when dry (Soehne 1958). The influence of soil moisture seems to be dependent on the distribution of particle size (Froehlich and McNabb 1984). Some soils, such as Central Oregon volcanic ash, compact readily at all moisture regimes (Raghaven et al. 1977, Froehlich et. al 1980).

2.3 Timber Harvesting and Compaction

Timber harvesting and related activities, including skidding logs, piling slash and mechanical site preparation with ground-based equipment have the capacity to introduce compactive external loads across harvest units. Selective logging in the Intermountain West has contributed to extensive compaction of the forest soils (Snider and Miller 1985). The frequency of skid trails in commercial thinnings can be quite high and has been found to account for 20 to 35 percent of the harvest unit surface area for a single entry (Adams 1991). Where repeated entries occur, skid trails can cover 80 percent of the surface area (Froehlich et al. 1981). Other authors have also noted the large extent to which ground-based equipment can influence soil characteristics through harvesting. Laing and Dashall,

(1983) noted 42 percent of an area surveyed in eastern Washington had been impacted by machinery. Murdough and Sones (1984) found 38 percent of an area in the Oregon Cascades had experienced machine impacts. Zaborski (1989) found 54 percent of a study area in Eastern Oregon had been disturbed and 25 percent of the area had been impacted to detrimental levels. Alterations to soil physical properties, particularly bulk density and soil strength, occur quite quickly as activities are conducted. For example it has been found that 90 percent of all the compaction that ultimately occurred in a skid trail was created from the first four machine passes (Sidle and Drilca 1981). Among the variables that can influence compaction, the number of passes is the most important variable (Sidle and Drilca 1981, Weaver and Jamison 1951).

2.3.1 Logging Method Comparisons

Compared to ground-based systems, other logging methods have the capability to remove harvest volumes with lower levels of ground disturbance. In general, cable logging has much less impact than ground-based vehicles (Auerlich et al. 1974, Krag et al. 1986, Allen et al. 1999). However, the disadvantage is that it costs significantly more than ground-based vehicles and is less practical on gentle ground (Powers 1974). Economically, it has been estimated that a 55 percent increase in logging costs over traditional ground-based logging costs is justifiable when the traditional logging produces maximum compaction levels (Stewart et al.

1988). However, since using cable systems on gentle ground can be twice as expensive as ground-based systems, using this approach may not be cost-effective (Stewart et al. 1988). In one survey of differing logging methods in Idaho, it was found that tractor logging disturbed on average 30 percent of the area, while ground cable systems averaged 23 percent, skyline cable systems 9 percent, and helicopter logging 4 percent (Megahan 1980). Horse logging was found to disturb only 11.8 percent of the area within the harvest unit (Garrison and Rumell 1951).

Combinations of different systems have been experimented with. In one study, a mechanical harvester and forwarder were compared to a harvester and skyline combination (Allen et al. 1999). The harvester and forwarder produced more soil compaction but the harvester and skyline system produced more soil disturbance. While mechanical harvesters and skyline systems still create site impacts, the degree of soil disturbance and compaction may not cause long-term environmental problems (McIver 1995), and may present a reasonable trade-off to traditional ground-based tractor systems. The main variables that influence compaction from logging are soil type, soil moisture, vehicle weight, depth of litter covering the soil and number of trips by the machines (Froehlich 1978). Other variables that should be considered when examining compaction are the compactive effects of the logs being skidded, the vehicle's center of gravity, ground slope and the influence of both the static and dynamic forces being created. Static ground pressure in itself is not a good predictor of compactive force (Froehlich 1980). Soil compaction is related to applied pressure, but ground pressure distribution under load is much different from static pressure, therefore the weight per contact area is not equal to the compactive force (Lysne and Burditt 1983). As an example, it has been shown that when comparing caterpillar-type tractors and rubber-tired skidders of equal static ground pressure, the tractors exerted as much as 50 percent greater dynamic pressure than the skidders (Froehlich and McNabb 1984, Clayton 1990). Even vehicles with comparatively low gross weights can cause significant compaction through the effects of vibration (Lull 1959).

2.3.2 Associated Logging Activities

Other harvest-related activities, such as piling slash and mechanical site preparation, can also introduce compactive forces to a site. Bulk density was found to increase after compaction that resulted from site preparation in northern Idaho, particularly if little logging slash was left on the soil surface (Page-Dumroese 1993). Also, as the intensity of site preparation increased, overall bulk density increased significantly, and to greater depths, in the soil profile. An additional negative impact from machine piling of slash is that large amounts of topsoil can be moved on the site and placed into the piles of slash (Glass 1976). Machine piling has been shown to result in large-scale losses and/or redistribution of organic matter (Minore and Weatherly 1988).

2.3.3 Timber Harvesting and Erosion

Soil compaction and displacement can have an impact on the erodibility of forest soils, although the results can be quite variable, depending on factors such as soil type, slope and other conditions. In some instances, the increased densification of a soil can make it more resistant to erosion since the soil particles are more resistant to movement (Greacen and Sands 1980). In other instances, soil compaction and disturbance can have the opposite effect and lead to increase in erosion due to the loss of organic matter and topsoil, decreased soil porosity and increased surface runoff (Dyrness 1965, Shetron et al. 1988). Skid trails and landings that have been compacted also frequently experience a considerable amount of soil displacement caused by the machinery. There may be some benefits to a minor amount of soil displacement and exposure of mineral soil, such as the preparation of a seedbed and reduction of competing vegetation. However, it may also lead to accelerated erosion (on steep ground), loss of productivity and disruption of the biological processes important to nutrient cycling (Clayton 1990). Finally, heavy equipment operations not only compact and displace the soil, but they also alter the soil surface through mixing and changing the thickness of the A horizon, possibly leading to increased erosion (Helms and Hipkins 1986).

2.4 Alterations to Soil Physical Properties from Compaction

Soil compaction is a general term that can be regarded as an overall description of the condition of the soil following various machine operations (Froehlich and McNabb 1984). Through compaction, many of the physical properties of a forest soil can be changed and, as a result of those changes, the growth dynamics of the forest can be altered substantially as well. Some of the significant properties that are altered through compaction are bulk density, soil strength, infiltration, aeration, macroporosity, hydraulic conductivity and cation exchange capacity.

Bulk density, or the weight to volume ratio of a soil, is a common measure of soil compaction and is readily increased as through logging activity. Forest soils typically have a low initial bulk density and therefore bulk density can increase substantially from ground-based harvest activities (Dickerson 1976, Hatchell et al. 1970, Froehlich 1978, Miles 1978). Bulk density increases proportionally with the square root of the number of machine passes and it has been noted that most of the damage occurs within the first four to six passes (Froehlich 1980, Resinger et al. 1988, Gent et al. 1984). Compaction forces the soil particles closer together and the fine particles fill in the larger pores, thus densifying the soil (Lull 1959). Soils have been shown to increase in bulk density, ranging from 16 to 40 percent (Allbrook 1986, Davis 1992, Miles 1976, Froehlich 1980, Lull 1959).

As ground-based harvesting activities increase, bulk density increases to greater depths in the soil profile (Page-Dumroese 1993).

Soil strength may be defined as the ability to support an externally imposed load or alternatively, as the ability to resist penetration, as in the case with tree roots. Soils will compress under external loads until the point that they develop sufficient strength to support the load and resist further compression, regardless of natural or compacted condition (Froehlich 1979, McNabb 1981). Increases in soil strength are associated with the reduction in the number of pore spaces greater than 10 um in size and in general, the larger the pores, the more readily they are diminished by compaction (Allbrook 1985).

Soil compaction can greatly reduce soil porosity (Dickerson 1976, Moehring and Rawls 1970) and similarly lowers hydraulic conductivity (Gent et al. 1984, Reinhard 1964). Infiltration rates have been shown to decline by 40 times when soil was compacted from 2.16 to 2.70 oz./in^3 (Chancellor 1977). Infiltration rates may be the soil characteristic which is most influenced by compaction. Tractor skid trails have been shown to have a 53 percent drop in macropores with a corresponding 92 percent drop in permeability requiring 619 times longer for water to enter the A horizon and 20 times longer to enter the B horizon (Lull 1959). Froehlich (1980) found that following 20 passes over a tractor skid trail, the soil macroporosity had dropped by 43 percent, while hydraulic conductivity and infiltration rates decreased 80 percent and 78 percent, respectively. As porosity and infiltration rates are reduced, the potential for increased runoff rises, leading to the possibility of less water penetrating the soil and being available for tree growth (Dickerson 1976, Froehlich 1980).

The overall effect of compaction on moisture retention is variable, depending on the specific soil involved. Moisture retention is often higher in compacted soils but it can increase or decrease depending on the particular soil (Warkentin 1971). It appears, however, that the absolute change is relatively small and unimportant compared to the other physical property changes (Froehlich and McNabb 1984). While total water storage capacity may remain unaffected or even increase, soil compaction increases the proportion of small pores. Since the movement of water from small pores to large pores acts as a barrier to soil water movement, compaction may reduce water availability (Eagleman 1962). Water availability may be reduced in compacted soil because a larger proportion of the water is held in micropore space and is held at too high of tension to be available for the plants (Chancellor 1977).

One of the difficulties with soil compaction is that it tends to be a long-term phenomenon. While the soil surface layer has been shown to return to pre-disturbance conditions in a relatively short period of time, at depth the soil can remain compacted for at least 40 years or more (Froehlich et al. 1985, Vora 1988). The duration of compaction depends on the degree of initial change, which in turn depends on soil texture, moisture, structure, the number of machine passes, total machine loading and operator skills (Froehlich et al. 1985, Geist and Cochran 1991).

2.5 Measuring Soil Compaction

In order to study the effects of compaction, the researcher must decide how to measure the compaction that has occurred. Preferable choices are dependent on the specific questions of interest the study focuses on, the resources available, the degree of variability in the soil parameter being studied, the physical difficulties encountered accessing and sampling a site, financial limitations and the desired sampling error (Terry et al. 1981). Some of the problems associated with measuring forest soils in the field can be the physical characteristics of a site, such as steep slopes, remote access, a high degree of spatial variability and rock content (Flint and Childs 1983). The degree of variation can be particularly challenging since the variation within an area can easily be as high as that found between different areas (Aljibury and Evans 1961). Sites with a high concentration of large stone fragments are difficult to obtain samples from and also tend to be prone to high sampling errors (Cunningham and Matelski 1968). The greatest challenge to measuring soil compaction is that soil physical properties tend to interact with one another. So the researcher must be careful when examining just one property as its behavior may vary with variation in other soil properties. Also, moving from one soil type to another soil type, those properties and their interactions may change greatly (Alexander et al. 1985).

Two common measurements of compaction are bulk density and soil strength. Bulk density, or the weight to volume ratio of a soil, is a frequently used measure of the effects of compaction and can be measured through a variety of means, such as: paraffin clod; irregular-hole; air permeability and radiation (Howard and Singer 1980).

One of the advantages of measuring bulk density is that if it is known, then it may be possible for other soil physical properties to be expressed on a volume basis (Drew 1973). However, bulk density can be difficult to measure, especially if deeper portions of the soil profile are examined. Also, if the question of interest relates to how tree roots develop, bulk density is not directly related to the effects of compaction on root growth but rather is an association (Froehlich and McNabb 1984). Finally, while bulk density is a useful indicator of soil compaction, just recording the absolute change in bulk density may not be an appropriate avenue for assessing whether significant damage has occurred. Rather, it is probably better to depict compaction as the relative change in bulk density (Clayton 1980, Froehlich 1980).

While the change to bulk density is often used to measure compaction, soil strength, the measure of compaction used in this study, tends to be ignored. Even though the volcanic ash soils in this study have lower bulk densities than other forest soil types, it still increases in strength at the same rate as other soils when compacted (Froehlich and McNabb 1984). Soil strength does have some disadvantages as it is a secondary rather than direct indicator of compaction and it is highly variable, both from point-to-point and among measuring instruments. It is influenced by more than just compaction, such as water content and soil texture

(Chancellor 1977). However, it is a direct measure of a specific soil property (strength) and it offers fast and easy measurements over extensive areas. Also, it is an indicator for soil resistance to compaction as well as a direct measure of a property affecting root growth and development (Chancellor 1977, Greacen and Sands 1980).

2.6 Effects of Compaction on Tree Growth

Soil compaction has been shown to depress tree growth and can have the effect of either temporarily or permanently reducing site productivity (Haupt 1958). The effects of compaction on tree growth are a complex interaction between soil strength, water and nutrient availability and aeration (Greacen and Sands 1980). This, combined with the inherent variability between soil types, soil conditions and vegetation in disturbed sites has led to inconsistent findings among researchers. Tree growth has been shown to respond positively following intermediate harvests in ponderosa pine (Agee and Biswell 1970). However, in tree seedlings, there can be a proportional relationship between increasing bulk density and decreasing height growth (Froehlich and McNabb 1984). Seedling growth on moderate to heavily compacted soils tended to lag progressively behind seedlings growing on less compacted soil (Froehlich 1979). Natural regeneration seedlings tend to have more difficulty getting established in heavily compacted soils and can experience as much as a fifty percent height reduction compared to adjacent, non-compacted sites (Steinbrenner and Gessel 1955).

Seedlings that were grown in compacted soil had markedly shorter roots and also had less secondary root branching than seedlings growing in non-compacted soil (Pearse 1958). However, there may be some variability in the effect of compaction on different tree species (Minore et al. 1969). Lodgepole pine had the highest ranking among several northwest conifers for the ability to penetrate compacted soil. Older trees may have reduced growth rates as well. A 64-year old ponderosa pine in southwest Oregon showed reduced height growth for 17 years after the soil had been compacted (Froehlich 1979). Ponderosa pine trees growing on compacted skid trails were approximately 20 percent shorter in height than similar trees growing in uncompacted soil (Helms et al. 1986). Fifteen to 25 year old stands of ponderosa pine had a mean volume loss of 40-50 percent (Clayton et al. 1987). A 60-year-old residual ponderosa pine stand in central Oregon experienced 12 percent slower basal area growth rates up to 16 years following harvest (Froehlich 1979).

In a 26-year old loblolly pine stand (*Pinus taeda*, Linneaus 1753), there was a 13 percent reduction in height growth but a 48 percent reduction in volume growth for trees growing in compacted soil (Perry 1964). Similarly, in a 32-year-old Douglas-fir stand, trees growing on compacted soil experienced a 30 percent average height growth reduction and a 55 percent reduction in volume growth compared to trees growing in uncompacted soil (Wert and Thomas 1981). In a

California study, Helms and Hipkin (1986) found that ponderosa pines growing in compacted soil had growth rates equivalent to one full site class less than trees growing in uncompacted soil, a reduction of approximately 10 – 12 percent. The Bureau of Land Management in western Oregon found that heavy compaction could result in stand-level future volume losses of 12 to 15 percent, which was considered to be unacceptable and avoidable (BLM 1983).

The reduction in growth rates seems to be a function of the percent of the root zone affected, the intensity of the compaction (total soil strength and extent through the soil column) and the extent of root damage. Damage on three sides of loblolly trees reduced basal area growth by 36 percent and on four sides the reduction was 43 percent (Moehring and Rawls 1970). Individual tree growth normally increases after thinning but in one example, 60 percent of the western hemlock (*Tsuga heterophylla*, Rafinesque) trees growing in heavily compacted areas actually had lower growth rates after thinning than before (Forehlich and Berglund 1976).

The decreases in growth may be partially the result of increasing soil strength causing decreased tree root growth due to the increased resistance to penetration (Sands et al. 1979). Soil strength tends to increase geometrically with increasing bulk density and tree root elongation has been shown to decrease geometrically with increasing soil strength (Sands et al. 1979, Greacen and Sands 1980). Also, mycorrhizal fungi penetration through the soil decreases significantly with increasing soil strength (Skinner and Bowen 1974). Fine roots can penetrate compacted soil up to 1015.3 pounds per square inch (PSI) and roots also tend to differentially select areas of lower soil strength and so can follow cracks and voids through otherwise impenetrable soil (Greacen and Sands 1980). However, tree root elongation essentially ceases at soil strength levels exceeding about 435.1 PSI (Sands et al. 1979), a level easily exceeded in well-compacted skid trails and landings.

Extensive site preparation and subsequent compaction has also been observed to reduce commercial tree growth (Amaranthus et al. 1996). A number of interrelated factors may influence the observed growth differences, such as compaction, root damage and loss of organic matter. Root penetration can be severely restricted in soils where compaction has increased soil strength to levels exceeding 435.1 PSI (Sands et al. 1979). Compaction reduces the pore space needed for root penetration, leading to a reduction in the production of feeder roots where mycorrhizae form. The ability of seedlings to rapidly form root tips and mycorrhizae is critical for establishment on harsh sites (Amaranthus et al. 1996). Microbial immobilization might be slowed down due to reductions in aeration following compaction as well (Miller and Sirois 1986).

2.7 Recovery From Compaction Through Natural Processes

Although compaction may lead to declines in productivity, these effects are reversible through natural processes, given enough time for recovery (Froehlich et al. 1985). The time involved may be fairly short as was seen in a Minnesota study where the soil recovered completely from compaction after just one winter, although the area had been harvested lightly and in dry soil conditions (Mace 1971). Other studies also show relatively fast recoveries, but frequently only the surface layers have been examined while the deeper soil recovers much more slowly (Thorud and Frissel 1976, Miles 1975). In the Oregon Coast Range, the soil bulk density at 7.9 and 11.8 inch depths was significantly higher than adjacent soil 32 years after logging, although the surface had apparently recovered (Wert and Thomas 1981). In North Carolina, skid trails were found to take at least 40 years to recover to pre-disturbance conditions and in Mississippi the recovery period was estimated to require at least 12 years in sandy soils (Perry 1964, Dickerson 1976). In another study, bulk density at 9.84 inches had not changed appreciably after 40 years time (Powers 1974). Reduced productivity losses from the displacement of soil are more difficult to quantify but may actually result in irreversible long-term impacts (Harvey et al. 1989).

The natural processes of freezing and thawing are thought to assist in the recovery of soils from compaction, but in many forested areas of central Oregon, deep snow cover early in the winter limits the amount of recovery. Also, the soils often have less than 20 percent clay content by weight, so very little shrink-swell action takes place (Page-Dumroese 1993). Sandy soils, in particular, may be less likely to recover from compaction because the processes of freezing and thawing are less effective (Greacen and Sands 1980). Freezing and thawing are thought to not have much influence because water only expands 9 percent so, depending on the exact soil moisture content, the soil itself may only expand around 3 percent (Froehlich and McNabb 1984). Frost heaving may not change bulk density as much as previously thought. The bulk density in a Minnesota cornfield had not changed after nine years time (Blake et al. 1976). Both flora and fauna can also loosen and mix soils but their effectiveness in compacted soil is probably much reduced, although biological processes for loosening soil probably increases substantially if the soil is left covered with litter to protect the roots and soil fauna (Froehlich and McNabb 1984).

2.8 Management Options for Avoiding or Reducing Compaction

Natural processes as a means of restoring soils to a pre-disturbance condition are generally not reliable or timely aids for the forest manager. However, there are a number of management options available through which soil compaction might be avoided or, if introduced, may at least be ameliorated to some degree (Sands, Greacen and Gerard, 1979, Chancellor 1977, Gilmour 1977, Rice and Datzman 1981, Page-Dumroese 1991, Jurgensen et al. 1991, Donnelly and Shane 1986, Geist et al. 1989, Froehlich 1979, Davis 1992).

The most reliable means of eliminating or reducing soil compaction is to be diligent that it does not occur in the first place, which may be accomplished in several ways. As noted above, when utilizing ground-based skidding machines on gentle ground, very high proportions of an area can be disturbed from machine travel within a single entry. And since a high percentage of the change to soil density occurs within the first few passes with a tractor, it becomes imperative that the flow of equipment over the ground be carefully controlled and the number of entries minimized (Kroger et al. 1983).

2.8.1 Designated Skid Trails to Minimize Compaction

Designated skid trails constrain traffic to just a few trails, which then receive a high impact, but the disturbance is restricted to a small percentage of the area (Bradshaw 1979, Garland 1993). Also, multiple harvest entries result in additive growth losses over time due to increases in the percentage of the area being impacted by skid trails (Froehlich 1979, Froehlich and McNabb 1984). All skid trails should be regarded as a permanent part of the total transportation system, requiring careful thought and planning to minimize costs as well as damage to the forest resource (Garland 1993). The benefits of using designated skid trails can be substantial. Designated skid trails, combined with line pulling, resulted in only four percent of an area being disturbed compared to twenty two percent for an area without designated skid trails (Bradshaw 1979). In another study, designated trails reduced the extent of skid trail impacts by 67 percent (Froehlich et al. 1981). The effect of designated trails on volume production and costs can be variable. One study found that designated skid trails reduced production by eleven percent and increased costs 29 percent (Bradshaw 1979). Another study (Olsen and Seifert 1984) found that the benefits of significantly reducing damage to advance regeneration and reducing the area compacted to less than 50 percent were adequate to recover the marginally increased costs.

In conjunction with designated skid trails, reducing machine travel can be greatly facilitated by falling trees in the direction of intended skid so that less movement is needed for removal (Garland 1993). In addition, the proportion of ground impacted by skidding machines can be further reduced if the skidder's winch line is pulled out to reach trees instead of driving it to each one (Bradshaw 1979).

2.8.2 Organic Matter Retention to Minimize Compaction

Another potentially effective means of reducing or minimizing compaction is to leave intact as much of the forest litter and soil organic matter as possible, including the smaller branches and tops created by the logging operations. In some harvesting systems, such as cut-to-length mechanical harvesters, the harvester strips the branches and tops the tree such that the debris forms a slash mat, which the harvester and forwarder then walk over. Keeping the machine from directly operating on the mineral soils has been shown to keep compaction to minor levels (Omberg 1969, King and Hines 1979, Shelton et al. 1988, Page-Dumroese 1993). Leaving woody residue also helps protect mineral soil from erosion (Gilmour 1977, Rice and Datzman 1981). The nutrient supply, soil microbe populations and nutrient cycling process are also facilitated by retention of the woody debris (Page-Dumroese et al. 1991, Jurgensen et al. 1991). Soil organic matter has a cushioning effect, which helps to minimize compaction (Lull 1959, Sands, Greacen and Girard 1979).

Soil compaction is considerably influenced by the level of moisture in the soil and thus needs to be considered beyond the nature of the impact itself (Sands et al. 1979). Many soils compact readily mid-way between field capacity and the wilt point, but each compaction pressure will have its' own optimum moisture content. Typically, heavy loads reach the highest increases in bulk density at low moisture content while light loads reach their highest increases in bulk density at higher moisture contents. Therefore, utilizing light equipment during dry soil conditions may be the best strategy for minimizing compaction on some soils (Lull 1959). However, some soils such as volcanic ash compact readily at all moisture regimes, so soil moisture guidelines will not be an effective management tool (McNabb 1981). In general, most forest soils will be compacted by logging equipment under both dry and wet conditions, which makes soil moisture management guidelines somewhat ineffective tools for controlling compaction (Adams undated).

Other options include using smaller, lighter equipment, operating on frozen ground or deep snow cover, soil tillage, and using either low ground pressure tires or wide tracks.

3.0 STUDY OBJECTIVES

Given the extensive body of literature indicating common management practices can lead to reduced site productivity, this study on soil compaction and residual tree growth seemed relevant. This study was undertaken to:

1. Develop a format for characterizing the soil strength conditions throughout a significant proportion of the rooting zone in stands of ponderosa pine.
2. Utilize that format to quantify the effects of mechanical harvesting equipment used during commercial thinning on the soil strength conditions of three ponderosa pine stands growing in the central Oregon volcanic ash region.
3. Compare those soil conditions to tree growth following harvesting, at both the individual tree and stand level.
4. Provide an archival record of the soil conditions within a subset of the Bend USDA Forest Service Long-term Site Productivity Plots for future tracking and analysis of potential soil and tree growth interactions.

4.0 STUDY SITE HISTORY

Early in this century, large areas of Central Oregon were heavily harvested with a variety of logging systems, such as railroad, tractor and horse logging. These activities resulted in extensive clearcut removal of the old-growth ponderosa pine stands, which led to the development of large-scale, homogeneous second-growth stands. By the 1980's, progressive stand development resulted in nearly 200,000 acres of ponderosa pine approaching the risk of significant loss from mountain pine beetle (Dendroctonus ponderosa) infestation due to stagnation and competition stress.

The Deschutes National Forest initiated a timber harvest program designed to reduce the basal area per acre stocking within these stands in order to improve the vigor of the residual trees and avoid the potential for catastrophic mortality from pathogens. The goal was to manage the stands on a selective harvest basis rather than clearcutting, which would follow the recent trend throughout the West towards producing forests with more diversified structures, frequently through the use of mechanical thinning operations. In addition, it was thought that selective harvests would provide a more even flow of timber, improve timber quality, and enhance recreational, scenic, and wildlife values.

The Deschutes National Forest and the Pacific Northwest Research station realized that unique research opportunities were possible through a long-term research program. Study plots were established to provide a basis for investigating the myriad questions of interest that could be investigated (Little et al. 1988). Following is a list of some of the research that has been undertaken on these plots to date:

1. Effect of Management Practices on Soil Biochemical Activities.
2. Effects of Prescribed Fire and Silvicultural Activities on Organic Mass and Nutrient Redistribution in Ponderosa pine Ecosystems of Central Oregon.
3. Nutrient Relations in Second-Growth Ponderosa Pine.
4. Soil Nitrogen Dynamics.
5. Comparison of Mechanized Systems for Thinning Ponderosa Pine and Mixed Conifer Stands.
6. Effects of Intensive Harvesting and Slash Treatment on Growth, Biomass and Product Potential of Second-Growth Ponderosa Pine.

The long-term site productivity (LTSP) series of research plots were established in 1991 and the study design utilized a randomized complete block of nineteen treatments repeated in three different locations or replications on the Deschutes National forest, as shown in Table 1.

Table 1. Schematic matrix of plot design for the Bend Long-term Site Productivity study.

	Remove Boles - Leave Tops & Limbs	Complete Removal Whole tree removed	No Felling	Fell, No Removal
Control	X1,1	X1,2 Treatment	X1,3	X1,4 No treatment
Broadcast Burn	X2,1	X2,2	X2,3	X2,4
Broadcast, Burn & Fertilize	X3,1	X3,2	X3,3	X3,4
Fertilize	X4,1	X4,2	X4,3	X4,4
Pile and Burn	X5,1			
Pile, Burn & Fertilize	X6,1			
Crush Slash	X7,1			

This study was superimposed on the existing Bend LTSP plots because they represented several advantages. For example, the Bend Silviculture Lab had already established the plots on the ground and the tree parameters were accurately measured in 1991 and 1996. Therefore, considerable time would be saved initiating the study and taking tree measurements. Also, five years had elapsed since the treatments, which allowed the possibility for growth trends to become evident. Finally, since the information from this study could be incorporated into the existing database of other research on these plots, it presented the opportunity for continued monitoring in the future, as well as adding to the extensive research into various aspects of forest ecology in second growth ponderosa stands. Even though the Bend Silviculture Lab has been closed, the Pacific Southwest Research Lab in Redding, California has taken over responsibility for the plots and so the potential for maintaining the integrity of these study plots is good.

All of the plots incorporate stands of second growth ponderosa pine that are relatively homogeneous in age (47 to 63 years breast height), development history, aspect, slope, soil type, site potential and stocking levels (competitive stress). Also, the plots are distributed among three well-separated areas within the central Oregon volcanic ash soil region to encompass more of the natural variation.

For this study, the Control - Complete Removal plots were used in conjunction with the Control - Fell, No Removal plots since they represent the extreme ends of potential soil disturbance during mechanical thinning and were not confounded with the site preparation and fertilization treatments. Some residual compaction from the logging in the 1920's and 30's may have been detectable, but no attempt was made to do so. Each of the three areas, or replications, encompasses approximately 49 total acres. Within each replication area, 19 treatments were applied to plots approximately 0.90 acre in size each. But to provide a buffer against edge effects, measurements were only taken on a 0.40 acre area within each plot. Each pair of Complete Removal and No Removal plots were thinned in 1991 to roughly similar stocking levels to somewhat homogenize the stocking and competition stress.

At the time the study was initiated, the goal was to continue thinning the plots at 10-year intervals, as that was considered to be the optimal prescription. Both the Complete Removal and No Removal plots were mechanically thinned with a small feller-buncher during the summer months of 1991. The Complete Removal plots were subsequently skidded with a rubber-tired grapple skidder. The Fell, No Removal plots were not skidded. No further harvesting activity has been conducted in the study areas since the initial treatment in 1991 and none is planned for 2001.

Prior to treatment, the stand age, trees per acre and basal area per acre stocking were estimated for all plots. Following treatment, the variables measured were:

1. Stems per acre.
2. Tree DBH.
3. Tree total height (Ht).
4. Length of crown.
5. Crown width.
6. Volume of woody residue.
7. Understory composition, by percent and basal area by species.

8. Surface soil bulk density and nutrient content (N,P,S, and C).

9. Tree foliar concentrations of N.

Following the treatments in 1991, the region experienced unusually droughty conditions through 1995. Then, in 1992, 1994 and 1996, the Pandora moth caterpillars (*Coloradia Pandora* Blake) heavily defoliated many areas in central Oregon, including the study areas. The defoliation did not appear to result in noticeable mortality on any of the study plots. It is likely these two agents resulted in lower than expected tree growth during the time between when the stands were treated and later remeasured in 1996. The treatments appeared to have created very little stem damage, thus it is not likely to have affected the growth results.

5.0 STUDY SITE DESCRIPTION

The study area is located east of the Oregon Cascade Mountains in what is known as the high desert region. Elevation of the plots range from 4500 ft. to 5200 ft. and the local climate is noted for a wide range of both annual (90-100 F. in summer to –20 to –30 F. in winter) and diurnal (90+ F. daytime to <20 degrees nighttime) temperatures. Precipitation is low, averaging as low as 17 inches annually, much of which is in the form of winter snow. The three areas are described in Table 2.

Table 2. Site description information for the Swede Ridge, Sugarcast and East Fort Rock study areas.

SITE INFORMATION	SWEDE RIDGE	SUGARCAST	E. FORT ROCK
DISTANCE (miles).*	9.5	14.8	14.3
BEARING (degrees) *	235	192	156
LATITUDE	43° 50' 56"	43° 50' 08"	43° 50' 16"
LONGITUDE	121° 20' 43"	121° 20' 07"	121° 10' 06"
ELEVATION (Feet)	4500 - 4800	4500 - 4700	4800 - 5200
PRECIPITATION	18-30"	20-30"	14-17"
SITE CLASS	5	4 to 5	5 to 6
SITE INDEX (Meyers)	65 to 85	70 to 90	50 to 70
AVG. PRE-TRTMNT B. AREA/AC. - CR&NR**	142 Sq. Feet	140 Sq. Feet	100 Sq. Feet
AVG. PRE-TRTMNT TREES/ACRE - CR&NR	316 Trees	286 Trees	195 Trees
AVG. PRE-TRTMNT DBH. - CR&NR	9.1 Inches	9.5 Inches	9.7 Inches
POST-TRTMNT BASAL AREA/ACRE - C.R.	116 Sq. Feet	70 Sq. Feet	65 Sq. Feet
POST-TRTMNT BASAL AREA/ACRE - N.R.	104 Sq. Feet	62 Sq. Feet	81 Sq. Feet
POST-TRTMNT TREES/ACRE - COMPLETE R.	123	69	79
POST-TRTMNT TREES/ACRE - NO REMOVAL	123	53	73
POST-TREATMENT SPACING - COMPLETE R.	19 X 19 Feet	25 X 25 Feet	23 X 23 Feet
POST-TREATMENT SPACING - NO REMOVAL	19 X 19 Feet	29 x 29 Feet	24 X 24 Feet
AVERAGE DBH - COMPLETE REMOVAL	12.1 Inches	12.5 Inches	11.3 Inches
AVERAGE DBH - NO REMOVAL	11.6 Inches	12.0 Inches	12.6 Inches
AVERAGE HEIGHT - COMP. REMOVAL	57.9 Feet	58.7 Feet	46.6 Feet
AVERAGE HEIGHT - NO REMOVAL	61.0 Feet	64.5 Feet	50.6 Feet
SURFACE SOIL	Cryandepts	Cryorthents	Cryorthents
SURFACE SOIL DEPTH	24 to 60"	24 to 50"	20 to 40"
BURIED SOIL	Cobbly sandy loam	Sandy loam	Sandy loam
VEGETATION			
Bitterbrush (Purshia tridentata)	X	X	X
Bottlebrush squirreltail (Sitanion hystrix)		X	
Cheatgrass (Bromus tectorum)			X
Idaho fescue (Festuca idahoensis)	X		X
Manzanita (Arctostaphylos patula)	X	X	
Rabbitbrush (Chrysothamnus viscidiflorus)	X		X
Ross sedge (Carex rosii)	X	X	
Snowbrush (Ceanothus velutinus)	X	X	
Western needlegrass (Stipa occidentalis)		X	

*Note: Distances and bearings are from the Deschutes National Forest Supervisors office in Bend, OR.

** CR - Complete Removal NR - No Removal

The soils for the three study areas are primarily composed of volcanic ash deposited as a result of Mt. Mazama eruptions approximately 7,000 to 10,000 years ago. Typical soils on the Swede Ridge site are well drained Cryandepts, derived from air-laid pumice/lava colluvium and tuft, with loamy coarse sand and coarse sandy loam textures (Volland 1985). The Sugar cast soils are well drained Cryorthents, derived from Mazama air-laid or flow pumice over lava or outwash, with loamy coarse sand and sandy loam textures (Volland 1985). The East Fort Rock soils are also well-drained Cryorthents, derived from Mazama air-laid/lava colluvium and cinders with a loamy coarse sand texture (Volland 1985). Slopes range from 0 percent to 25 percent but generally average less than 10 percent. The volcanic ash surface soils overlay a range of deeper material, from glacial till in the Swede Ridge area to bedrock composed of hard basalts, andesites or rhyolites in the Sugar Cast and East Fort Rock areas (Larson 1976).

Most of the physiographic site variables, biomass and nutrient capital distributions would be quantified well enough that analysis of covariance could be utilized to isolate site differences from other possible sources of variation. These factors could potentially strengthen comparisons made between the results of this study to other stands within the volcanic ash region.

The logging methodology used to reduce stocking generally did not create site impacts that were visually apparent. The total fiber volume removed was fairly low and it seems few passes were required by the harvesting and skidding equipment to remove the trees. The exact harvesting equipment used is not known, but was probably much smaller machines than the large mechanized harvesting equipment commonly used today, which can weigh in excess of 60,000 lbs. Although the harvesters used on these study plots were probably smaller, they probably had relatively smaller tracks, and thus the ground pressures may have been similar to larger equipment. But sites logged with the large machines tend to have very pronounced skid trails that are compacted to much higher levels than were found on the Long-Term Site Productivity Plots. When surveying the three complete removal study plots, it was frequently difficult to determine where the skid trails had been. Figure 1 visually contrasts the differences in site impacts resulting from the two harvesting intensities.

Figure 1. Typical whole-tree harvest skid trail after 3 years.

Figure 2. Skid trail on LTSP Complete Removal plots after 5 years.

Both of these units were thinned with mechanical harvesters, however the whole-tree harvest system likely utilized much larger equipment and removed substantially more volume from the site.

6.0 STUDY METHODS AND PROCEDURES

6.1 Study Design.

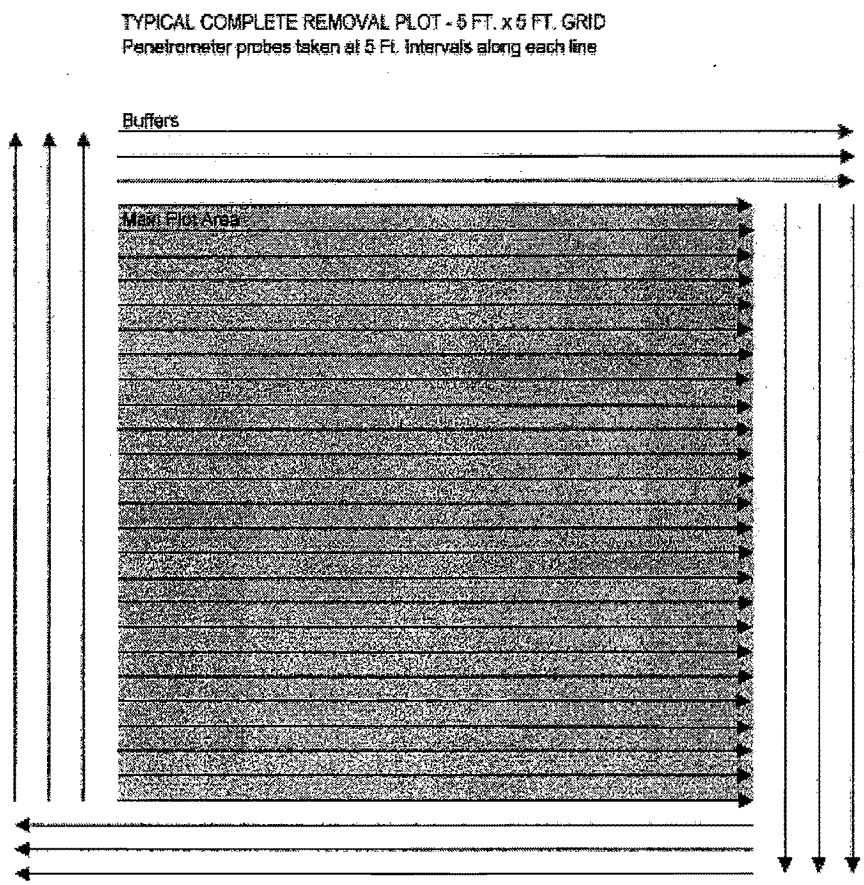
The Bend Long Term Site Productivity plots were not originally designed to study the relationships between soil strength conditions and tree growth. However, since the plots were already established, and growth data were available for the various treatments, a design examining soil conditions was superimposed on the existing design.

6.1.1 Soil Strength Measurements.

During the summer months of 1995 and 1996, each of the six plots chosen for the study was surveyed with a recording penetrometer to determine soil strength conditions. Variation in soil moisture may lead to variations in resistance to penetration, thus leading to variable penetrometer readings. However, since the soil strength measurements were taken from mid- to late summer, the moisture conditions did not vary substantially and probably did not introduce excessive variability in the results. Of the nineteen treatment options per replication, only two of the four control plots were utilized since they were not confounded with slash treatment or fertilization treatments. On the three plots that had been mechanically thinned and skidded with rubber-tired skidders (Complete Removal), five foot by five-foot grids were established across the units to sample soil strength. Ten-foot by ten-foot grids were used on the plots in which the trees had been felled with mechanical harvesters, but not removed (No Removal). A wider spacing was utilized on the No Removal plots since no skidding equipment had impacted the site and the variability in soil strength conditions appeared to be much less than on the Complete Removal plots. In addition, a fifteen-foot buffer around each plot was also surveyed in order to capture more complete rooting environment information for trees near the plot edges.

The grids were established by driving metal stakes into the ground on two opposite sides of the plots at five or ten-foot intervals, as appropriate for the treatment. Each stake was then numbered with flagging such that the stakes on both sides of the plot at the starting point were numbered '1' and the subsequent stakes followed in matching numerical order. A cloth measuring tape was then stretched between each pair of matching numbered stakes and a penetrometer reading was taken at each five or ten foot interval along the tape, depending on the plot type. All plot lines were started from the same side of the plot. Approximately 1,100 individual probes were required for each Complete Removal plot, while the No Removal plots required approximately 250. Figure 3 is a schematic of a typical plot layout.

Figure 3 – Sampling design for penetrometer measurements.



Before a penetrometer measurement was taken, all slash, litter and duff was lightly scraped aside so that the probe only measured the resistance in the ash soil. At each grid intersection point, the recording penetrometer measured soil strength down through the soil profile to a depth of 24 inches. Soil strength was recorded in kilopascals of resistance at 1inch intervals through the soil profile. Each penetration file was stored within the penetrometers' internal memory and identified by a unique number. These files were later downloaded into a personal computer for analysis. For the purposes of this study, each penetrometer reading was assumed to represent the soil conditions for the entire soil volume represented by that grid point. Each grid point represented 50 cubic feet of soil volume on the Complete Removal plots and 200 cubic feet on the No Removal plots. Therefore, the penetrometer results should only be regarded as an approximate indication of overall soil strength since the tip of the probe only represents a one-half- inch-wide measuring point and is therefore sampling a small percentage of the actual total soil volume. However, the observed variability in soil strength conditions was coarse enough that the grids appeared to adequately capture that variation.

6.1.2 Tree Measurements.

Initial condition tree data (post-treatment) was collected when the plots were set up in 1991 and the tree data information was remeasured during the summer of 1996. The data collected included tree identification number, DBH, total height, crown height, crown width, and percent defoliation by the pandora moth. DBH measurements were made with a steel diameter tape to the nearest 1/10th inch. Basal area was calculated for all trees using these measurements and the formula Basal Area = (DBH^2) (.005454154). The height of every tree was measured with an optical dendrometer. Percent defoliation was an ocular estimate of the defoliation that occurred on the top half and bottom half of the crowns in 1992, 1994 and 1996. The percentages for the three defoliation events were then averaged.

Volumes were determined from local volume tables created for the LTSP plots, which were calculated for each of the three replications using equations derived from 95 trees (five trees in each of the nineteen plots). For each tree used in the volume calculations, diameters were measured using an optical dendrometer at various intervals along the bole. Calipers were used to determine the diameters at stump height and at 4.5 feet to assess tree taper. Total volume (V) was determined from these measurements using Grosenbaugh's (1964) STX program, with a modification for determining bark thickness along the bole (Grosenbaugh 1964, Cochran 1976 and 1978). These volumes were then related to DBH and height using the formula: $\log V = a + b(\ln DBH) + c(\ln Ht)$ (Schumacher and Hall 1933).

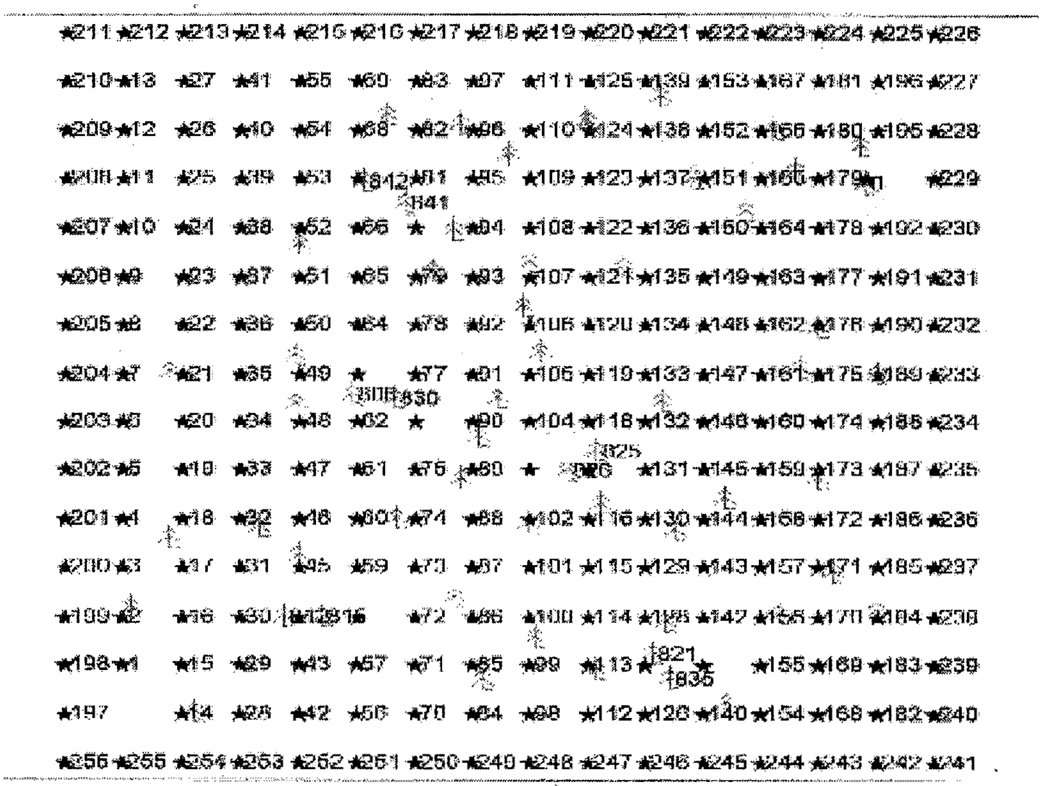
The five measure trees per plot used for volume calculations were chosen by first selecting the largest and the smallest trees per plot. The remaining trees were selected randomly from the remaining diameter classes. In this way, the full range of diameter classes was represented. All diameter and height measurements were made at the beginning of 1991 and in the fall of 1996. The measurements for estimating volume were made in the late summers of 1992 and 1996. The periodic annual increments were determined by dividing the total growth for the period by the number of intervening years.

6.1.3 Tree and Soil Data Spatial Analysis.

In order to relate each tree to the soil conditions surrounding it, all the trees in each plot were mapped during the penetrometer data collection process. When the transects were laid out with the cloth tapes, the location of a tree was identified by its distance down the transect line closest to that tree and the starting point and also the distance to the right of and perpendicular to the transect line. In this way, each penetrometer point and each tree could be mapped in a spatial analysis program for future analysis.

Figure 4 is a typical plot map showing the numbered penetrometer points, which are indicated by the 'star' map symbols. Tree locations are indicated by the ‘tree’ symbols.

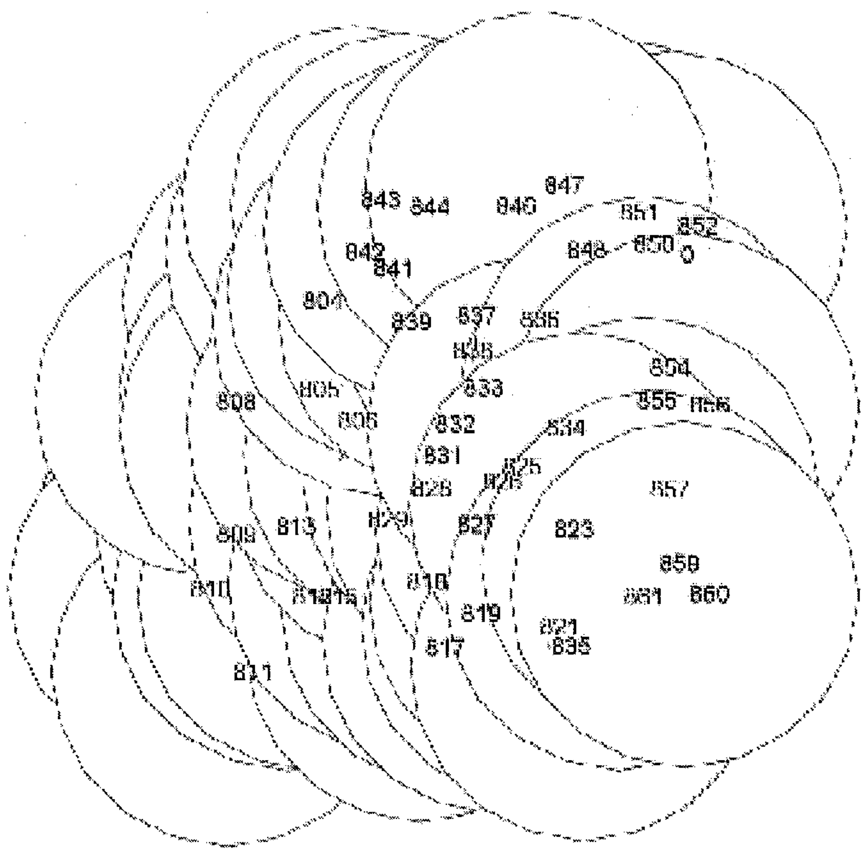
Figure 4. Schematic diagram of penetrometer points and tree locations.



In order to relate the growth rate of each tree to the average soil strength conditions around it, spatial analysis software was utilized. The grid for a plot was drawn and each intersection point was assigned the unique file number for the penetrometer probe that had been taken at that point. The map grid points were then linked to a spreadsheet file that contained the penetrometer soil strength data. Each individual probe file contained 24 soil strength measurements taken as the probe was pushed through the soil to a maximum depth of 24 inches (Appendix A - Table 1). The average of those 24 readings was used to represent the soil strength value for a particular grid point. In some instances, sub-surface rock or tree roots prevented the penetrometer from penetrating the full 24 inches. In those cases, the probe was moved six inches in a random direction until either a full probe could be made or it was determined too much interference existed at that point and a partial probe was accepted. For probes that did not achieve full depth, the penetrometer assigned values of zero for the uncompleted portion of the probe. These files were later edited in the spreadsheet so the average soil strength values only considered the depths actually achieved.

Once the penetrometer point data was set in a map, the tree locations were drawn and numbered appropriately. Then each tree was linked to an outside spreadsheet data file containing its basal area, height and volume periodic annual growth information. The spatial analysis program was then utilized to draw a 15-foot radius circle around each tree. The software identified the penetrometer files within each circle and a unique soil strength file was created for each tree that represented their average (Appendix A - Table 2). The same process was reiterated using 30- and 45-foot-radius circles around each tree. Fifteen, 30-and 45-foot-radii were used as an attempt to determine if increasing the volume of soil sampled would better detect alterations to the rooting environment. Since ponderosa pine roots can extend up to five times the width of the crown, the 45-foot radius should encompass most of the rooting zone (USDA Handbook 654 1990) Figure 5 illustrates a plot in which 45-foot radius plots have been established around each tree.

Figure 5. Schematic diagram of individual tree plots within a study plot.



The soil strength values for all the probes within a given radius were averaged to perform the statistical analysis. As a result, some of the inherent soil strength variability was lost or masked. Tables 1, 2, and 3 in Appendix A are provided to show that variability. Table 1 shows the raw penetrometer data that was collected with the recording penetrometer for the East Fort Rock - Complete

Removal plot. Table 2 shows how the averaged individual penetrometer probes were then combined to provide average soil strength readings for each tree. Finally, Appendix A - Table 3 shows the plot-level and individual tree average soil strength values for the 15, 30- and 45-foot radius tree plots.

6.2 Statistical Analysis

This study was designed to test two null hypotheses:

1. No significant differences in soil strength existed between the complete removal and fell, no removal plots.
2. Soil strength conditions had no influence on basal area, height or volume periodic annual increment (PAI) growth.

An additional goal of the study was to provide a basis for predicting ponderosa pine periodic annual increment growth rates for a given average soil strength value in volcanic ash pumice soil types.

It was determined that the first hypothesis could be tested with a t-test that would combine the soil strength data from all three Complete Removal plots and compare that to the No Removal plots soil strength data.

General linear models, or GLMs were used to test the second hypothesis. The analysis was multivariate, i.e., it looked at the effects of soil compaction on three separate growth response variables: basal area, height and volume periodic annual increment. Therefore, separate GLM analyses were performed for each.

The models were a function of treatment and the average soil strength conditions around each tree and the covariate variables, which were: initial tree size, initial tree size squared, and percent defoliation from the pandora moth. The initial tree size parameters for the basal area PAI, height PAI and volume PAI models were basal area, height and volume, respectively. To take into account the possibility that growth might be curvilinear with increasing tree size, the initial tree size squared variables were included in the model. The average soil strength conditions were defined as the total volume of soil around each tree to a depth of 24 inches and to a radius of 15, 30 or 45 feet. For each of the basal area, height and volume PAI analyses, separate models were performed for the three radii to determine if increasing the volume of soil examined would increase the sensitivity for detecting soil compaction. Also, GLMs were utilized because they provide Type III, or Yates' weighted sum of squares. With Type III, the variation associated with each variable in the analysis is adjusted for and independent of all other variables, so the model indicates the importance of each variable relative to all other variables. Multiple linear regression provides Type II sum of squares where each variable is not independent, but instead is influenced by the other variables in the model. Therefore, GLMs were more appropriate for determining the significance of the main variables of interest, soil strength and treatment.

Multiple linear regression models were developed to predict the basal area, height and volume PAIs for each tree. The differences between the actual and predicted PAIs of paired trees were compared through a Pearson Correlation analysis. The correlation analysis was required because when the study was initiated, it was necessary to assume that the growth response of each tree was independent of all other trees. There was no alternative but to utilize the Complete Removal and No Removal plots within the LTSP study and the limited number of trees within them. The limited scope of the six plots did not allow for only measuring widely separated individual trees, independent of adjacent trees. Therefore, the study design and analysis was conducted as if the trees were independent, but with the understanding that if they ultimately were not, the analysis might be compromised. The models would have too many degrees of freedom and the error sum of squares would be too small, possibly leading to inappropriately rejecting the null hypothesis when, in fact, there was no significant difference.

Multiple linear regression analyses were also required to develop the desired predictive capabilities which could be used to create graphs that would help to interpret the results of the GLMs, and possibly provide the basis for a management monitoring tool as well.

7.0 RESULTS

This study found that mechanical commercial thinning operations significantly altered the soil physical properties of the volcanic ash soils, as measured by increases in soil strength. And, those increases in average soil strength conditions were associated with significant height PAI growth reductions at the 15, 30-, and 45-foot radius, as well as volume growth changes at the 15-foot radius ($p \leq 0.05$). Possible basal area PAI and other volume PAI growth differences were suggested, but were not statistically significant (Table 3). Because the models predict PAIs for individual trees, the per acre estimates were derived by multiplying the average annual increment per tree times the number of trees on a plot, and then scaling the result up to a per acre growth rate.

Table 3. Predicted growth results per treatment and replication, contrasting the differences between the lowest and highest soil strength conditions found per plot.

			Soil Strength	Predicted Basal Area PAI		
BASAL AREA PAI	**Soil Strength/Tree**		**% Increase**	**Square Ft. Per Acre Basis**		**Growth**
Complete Removal	**Lowest PSI**	**Highest PSI**	**Low to High**	**Low Strgth**	**High Strgth**	**%Difference**
East Fort Rock	200.96	279.52	39%	1.88	0.74	-61%
Sugarcast	184.45	244.15	32%	1.73	1.78	3%
Swede Ridge	220.97	328.03	48%	2.03	1.08	-47%
No Removal						
East Fort Rock	146.42	179.04	22%	0.62	0.64	3%
Sugarcast	164.29	184.13	12%	0.93	0.26	-72%
Swede Ridge	149.57	211.65	42%	1.67	0.80	-52%

			Soil Strength	Predicted Height PAI		
HEIGHT PAI	**Soil Strength/Tree**		**% Increase**	**In Feet per Tree**		**Growth**
Complete Removal	**Lowest PSI**	**Highest PSI**	**Low to High**	**Low Strgth**	**High Strgth**	**%Difference**
East Fort Rock	200.96	279.52	39%	0.684	0.218	-68% *
Sugarcast	184.45	244.15	32%	0.664	0.496	-25% *
Swede Ridge	220.97	328.03	48%	0.700	0.654	-7% *
No Removal						
East Fort Rock	146.42	174.04	19%	0.494	0.242	-51% *
Sugarcast	164.29	184.13	12%	0.746	-0.137	-102% *
Swede Ridge	149.57	211.65	42%	1.14	0.931	-18% *

			Soil Strength	Predicted Volume PAI		
VOLUME PAI	**Soil Strength/Tree**		**% Increase**	**Cubic Feet Per Acre Basis**		**Growth**
Complete Removal	**Lowest PSI**	**Highest PSI**	**Low to High**	**Low Strgth**	**High Strgth**	**%Difference**
East Fort Rock	200.95	279.52	39%	42.48	20.83	-51% **
Sugarcast	184.45	244.15	32%	54.12	49.16	-9% **
Swede Ridge	220.97	328.03	48%	59.66	55.10	-8% **
No Removal						
East Fort Rock	146.42	179.04	22%	22.46	15.11	-33% **
Sugarcast	164.29	184.13	12%	19.80	11.82	-40% **
Swede Ridge	149.57	211.65	42%	67.59	61.20	-9% **

* - Soil Strength was a significant model variable at the 0.05 probability level.
** - Soil Strength was a significant model variable at the 0.10 probability level.

7.1 Soil Strength by Treatment T-Test Analysis

The first question of interest was whether a significant difference in soil strength existed between the Complete Removal and No Removal plots. Two-sample t-tests were performed, comparing the soil strength means of the three Complete Removal plots to the soil strength means of the three No Removal plots. The Complete Removal plots were significantly different ($p \leq 0.05$) from the No Removal plots for the 15, 30- and 45-foot radius tree plot sizes (Table 4).

Table 4 . Two-sample T-Tests for Soil Strength by Treatment.

	15 Ft. Radius			30 Ft. Radius			45 Ft. Radius		
	Complete Removal	Pooled Variance	No Removal	Complete Removal	Pooled Variance	No Removal	Complete Removal	Pooled Variance	No Removal
Mean Soil Strength (PSI)	247.0		177.5	248.2		175.1	249.5		173.8
Variance	1628.6	854.2	47.7	1245.2	691.0	136.8	1162.1	634.0	105.9
Observations	3.0		3.0	3.0		3.0	3.0		3.0
df	4.0			4.0			4.0		
t Statistic	2.9			3.4			3.7		
P(T<=t) one-tail	0.022			0.014			0.011		
t Critical one-tail	2.13			2.13			2.13		
Percent difference	39%			42%			44%		

For the fifteen foot, thirty foot and forty-five foot radius plots, the percent increase in average soil strength for the Complete Removal plots over the No Removal plots was 39, 42 and 44 percent, respectively.

7.2 Growth Effects Analysis

The second null hypothesis was that there was no correlation between soil strength and tree growth. This was tested with General Linear Models analysis of covariance (SAS Institute, 1988). For each tree, the soil strength conditions were first estimated for a volume of soil defined by a 15-foot radius around that tree. This data was correlated with the basal area PAI, height PAI and volume PAI growth for that tree. The analysis was then repeated for soil volumes defined by the 30- and 45-foot radii. The three soil volumes were analyzed as a sensitivity analysis to determine whether examining an increasing proportion of the total rooting environment would more accurately detect alterations to soil conditions. Analysis of covariance showed that the covariates (basal area, height and volume), covariates squared and percent defoliation by the pandora moth were statistically significant in all cases at a $p \leq 0.05$ level. The main variables of interest, soil strength and treatment, were significant for height PAI at the 15, 30- and 45-foot radii ($p \leq 0.05$). Soil strength was also significant for volume PAI at the 15-foot radius, but was not significant for the 30- and 45-foot radius. Soil strength was not significant for basal area PAI. Replication, or area, was also significant only for height PAI. Similarly, the interaction terms are also only significant for height PAI (Table 5).

Table 5. Probability of higher F-values from the analysis of covariance for PAIs of Basal Area, Height and Volume for individual trees.

		Basal Area			Height			Vjolume	
VARIABLE	15 Ft.	30 Ft.	45 Ft.	15 Ft.	30 Ft.	45 Ft.	15 Ft.	30 Ft.	45 Ft.
Covariate	0.0001	0.0001	0.0001	0.0356	0.0076	0.0010	0.0001	0.0001	0.0001
Covariate Squared	0.0014	0.0015	0.0012	0.0495	0.0115	0.0019	0.0001	0.0001	0.0001
Percent Defoliation	0.0001	0.0001	0.0001	0.0002	0.0003	0.0012	0.0001	0.0001	0.0001
Soil Strength	0.2533	0.0691	0.1534	0.0001	0.0001	0.0001	0.0135	0.0589	0.0510
Treatment	0.6139	0.9053	0.8891	0.0371	0.0014	0.0027	0.4344	0.8358	0.8295
Repetition	0.2426	0.1995	0.4359	0.0261	0.0020	0.0031	0.1149	0.2915	0.1836
Soil Strength*Rep	0.6810	0.5649	0.8069	0.0033	0.0004	0.0010	0.1874	0.3979	0.2809
Repetition*Treatment	0.5529	0.2153	0.3603	0.0886	0.0014	0.0135	0.2736	0.3151	0.6578
Soil Strength*Treatment	0.4845	0.4462	0.6357	0.0138	0.0003	0.0008	0.0685	0.3544	0.4343
S. Strength*Rep*Trtmt	0.2593	0.1679	0.4421	0.0213	0.0007	0.0075	0.0530	0.2806	0.7061
Model Degrees of Freedom	14	14	14	14	14	14	14	14	14
Error Degrees of Freedom	233	233	233	233	233	233	233	233	233
Corrected total Deg. Of F.	247	247	247	247	247	247	247	247	247
R-Squared	0.620329	0.616912	0.612928	0.561702	0.577247	0.57321	0.670454	0.665064	0.666176
C.V.	41.91831	42.10651	42.32487	47.2013	46.35669	46.5776	39.53984	39.86185	39.79566
Root MSE	0.0046674	0.0046884	0.004713	0.227404	0.223335	0.2244	0.143622	0.144792	0.144551
PAI Mean-FtSq./Feet/CuFt	0.0111345	0.0011135	0.011345	0.481774	0.481774	0.48177	0.363234	0.363234	0.363234

Note: Significant variables are highlighted. $P \leq 0.05$

7.3 Predicting Growth Effects

Because the dependent variable height PAI exhibited significant and quantitative associations to changing soil strength values, multiple linear regression models were used to describe those responses and to obtain predicted growth rates used in the Pearson correlation coefficient analysis. The regression models were also utilized to graphically describe the height growth and soil strength relationships. Although not significant, basal area PAIs and 30- and 45-foot radius volume PAIs appeared to differ with changing soil strength and were also graphed to indicate potential effects. These models individually analyzed the PAI responses of basal area, height and volume to increasing soil strength, the main variable of interest, as well as the covariates (tree size, tree size squared and percent defoliation), treatment, repetition and interaction terms that were combinations of treatment, repetition and soil strength. There was a wide range of soil strength values on both the treated plots as well as the control plots, and all trees in the study were used to develop the regressions, with each tree forming a tree growth and soil strength relationship. Since the No Removal plots had been thinned with mechanical harvesters but not skidded, some compaction occurred on these plots as well. Thus, they did not represent a true control for the study.

As shown in Table 6, the r-squared values indicate the models reasonably account for the variability. Other research has shown that r-squared values for tree growth prediction models typically fall between .4 and .6, so the models for this study seem to predict tree growth well (Hann and Larson 1990). However, the main variable of interest, soil strength, is significant ($p \leq 0.05$) only for height PAI and volume PAI at the 15-foot radius. Therefore, interpretations based on soil strength are limited.

Table 6. Adjusted r-squared values from the multiple linear regression models.

Basal Area PAI			Height PAI			Volume PAI		
15 ft.	30 ft.	45 ft.	15 ft.	30 ft.	45 ft.	15 ft.	30 ft.	45 ft.
0.5975	0.6169	0.5897	0.5354	0.5518	0.5476	0.6507	0.6449	0.6461

7.4 Tests for Independence

The study was initiated under the assumption that the growth response of each tree to the soil condition environment was independent of all other trees and the statistical analyses were made under that assumption. Pearson correlation analysis tests (SAS Institute, 1988) were utilized to assess the validity of the assumption of independence, using the 30-foot radius soil strength data. It was assumed that if no significant relationship existed at the 30-foot radius, then none would exist for the 15-foot radius data, which was essentially a subset of the 30-foot data. A separate correlation analysis was not performed using the 45-foot soil data. However, it may be more likely for a correlation to exist at the 45–foot radius due an increasing potential for root overlap. For this analysis, each tree was first paired with its closest adjacent tree. Then the differences between the actual and predicted PAIs of one tree were compared to the differences between the actual and predicted PAIs of its paired tree to determine whether the differences were significantly correlated. The results of the paired tree comparisons are shown in Table 7.

Table 7. Pearson Correlation Analysis for the 30-Foot Radius.

	Prob $\geq$ 0.05	R value	R squared
Basal Area PAI	0.1116	0.14850	0.0021
Height PAI	0.3868	0.08109	0.0066
Volume PAI	0.0135	0.22880	0.0524

The analysis shows that the error in predicted and actual basal area and height growth of paired trees was not significantly correlated at the 30-foot radius, assuming a $p \leq 0.05$ significance level. However, volume is shown as significant and suggests a correlation exists. Since basal area was the most accurately and precisely measured variable used in the study, a high degree of confidence exists for the indication of no correlation. Tree heights were probably not quite as accurately and precisely measured. Since each tree, however, was measured with an optical dendrometer, it is reasonable to have a high level of confidence in the accuracy of both the tree heights and the indication of no correlation. Tree volume was likely the least precise variable since it was calculated, rather than measured, using Grosenbaugh's (1964) STX program with a modification for determining bark thickness along the bole (Grosenbaugh 1964, Cochran 1976 and 1978). Therefore, less confidence is placed in the correlation analysis for volume. So the independence assumption was assumed as valid in interpreting the results from the GLM analysis.

7.5 Graphical Representation of Predicted PAI Growth as a Function of Soil Strength

To help interpret the results of the GLMs, the regression models were utilized to predict height PAI using the 15-, 30- and 45-footradii and volume PAI for the 15-foot radius, which were significantly correlated with soil strength. Although basal area PAI and volume PAI for the 30- and 45- foot radii were not significantly correlated with soil strength, the same procedure was utilized to look at the potential growth trends associated with increasing soil strength. In this procedure, the PAIs per plot were predicted, first assuming all trees were growing at the lowest average soil strength conditions that had been found, and then at the highest average soil strength values. The predicted PAIs for the lowest and highest soil strength conditions were used as anchor points and a line connecting the two points was then graphed. When the regression models were used to determine those endpoints, the average covariate values per plot were used.

The relationship between basal area PAI and increasing soil strength appeared to differ with treatment and area (Figures 6, 7, and 8).

Figure 6. The relationship between Basal Area PAI and soil strength at a radius of 15 feet.

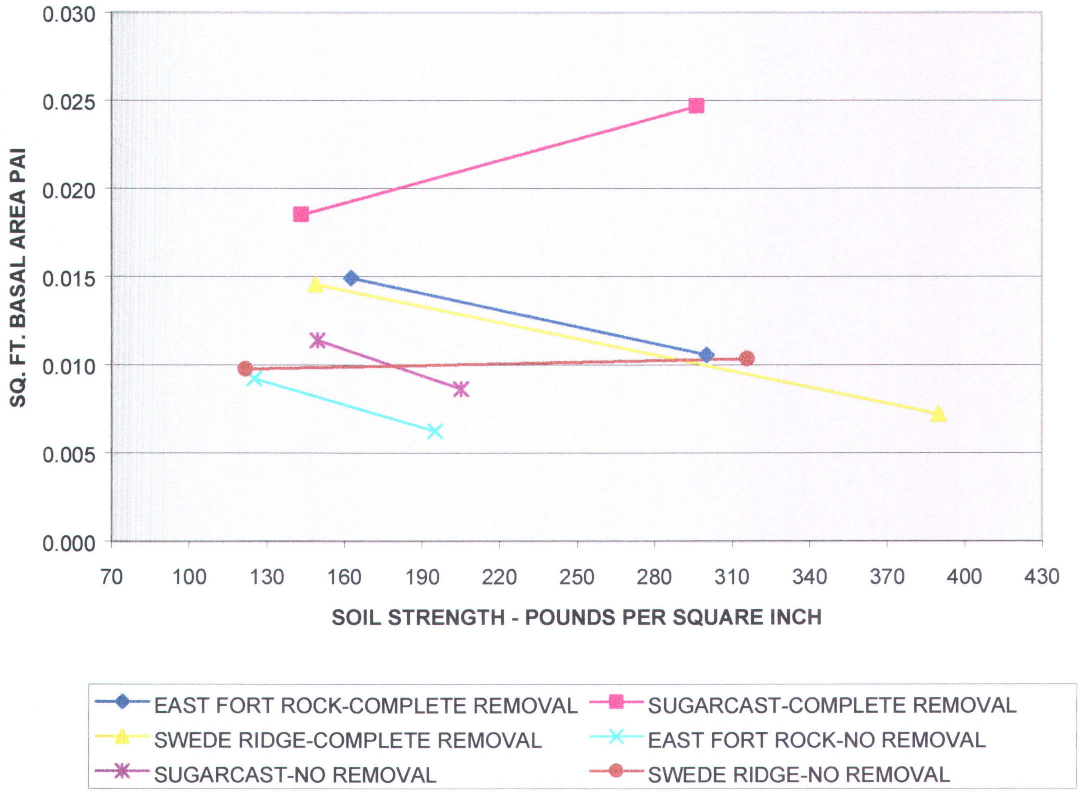


Figure 7. The relationship between Basal Area PAI and soil strength at a radius of 30 feet.

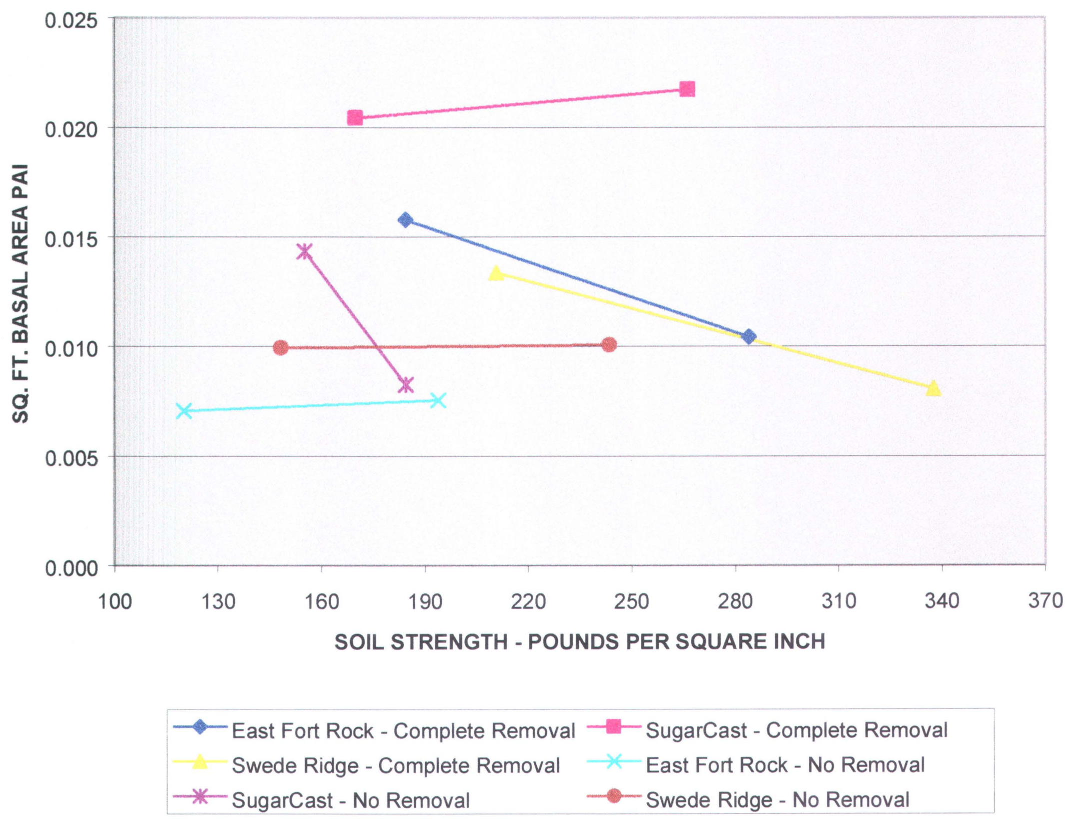
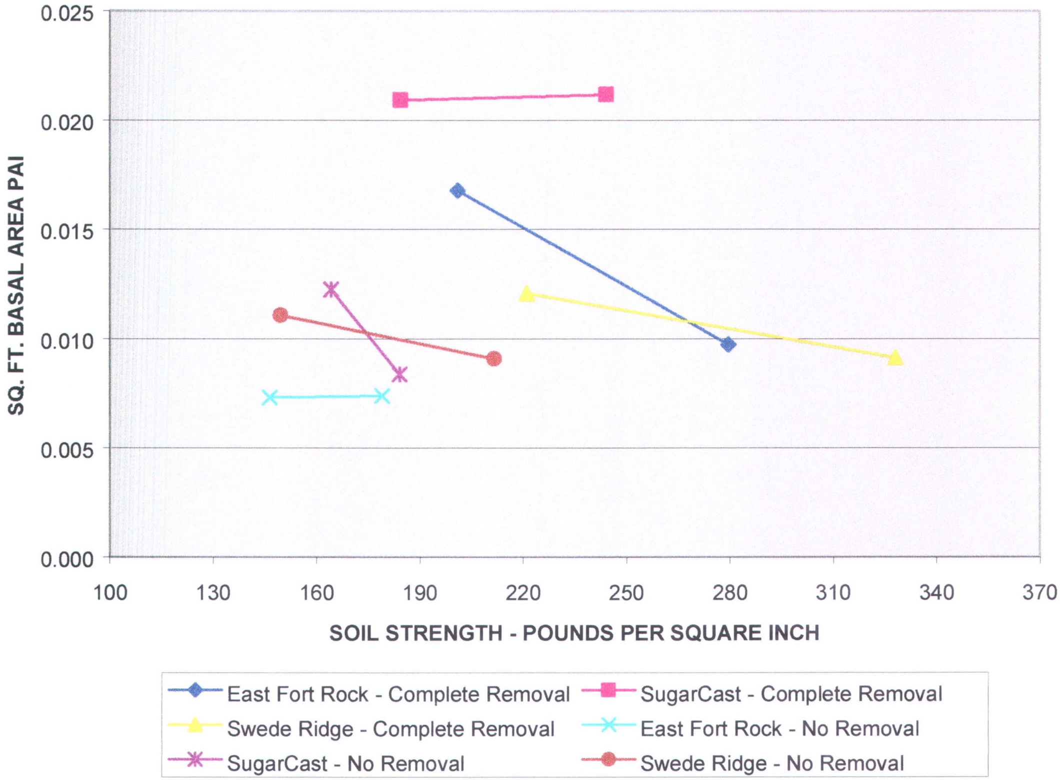


Figure 8. The relationship between Basal Area PAI and soil strength at a radius of 45 feet.



The soil strength variable was not statistically significant ($p \leq 0.05$) for basal area in the GLM models so the graphs for basal area PAI may only be considered as potential indications of growth effects from compaction. Basal area PAI seemed to show a somewhat inconsistent relationship with soil strength. For example, the East Fort Rock - Complete Removal is negative for all three radii while the East Fort Rock - No Removal is negative at the 15-foot radius and approximately neutral for the 30- and 45-foot radii. The Sugar Cast - Complete Removal graph shows a positive trend for all three radii, but becomes more neutral as the radius increases. The Sugar Cast - No Removal is distinctly negative throughout. The Swede Ridge - Complete Removal is negative for all three radii but the Swede Ridge - No Removal plot is slightly positive at 15 and 30 feet, but negative at 45 feet. So, as the radius increases from 15 to 45 feet, basal area PAIs generally trend towards a negative or neutral association with increasing soil strength.

Soil strength was significant for height growth and height PAI appears to have the most consistent relationship among the three response variables and increasing soil strength (Figures 9,10 and 11).

Figure 9. The relationship between Height PAI and soil strength at a radius of 15 feet.

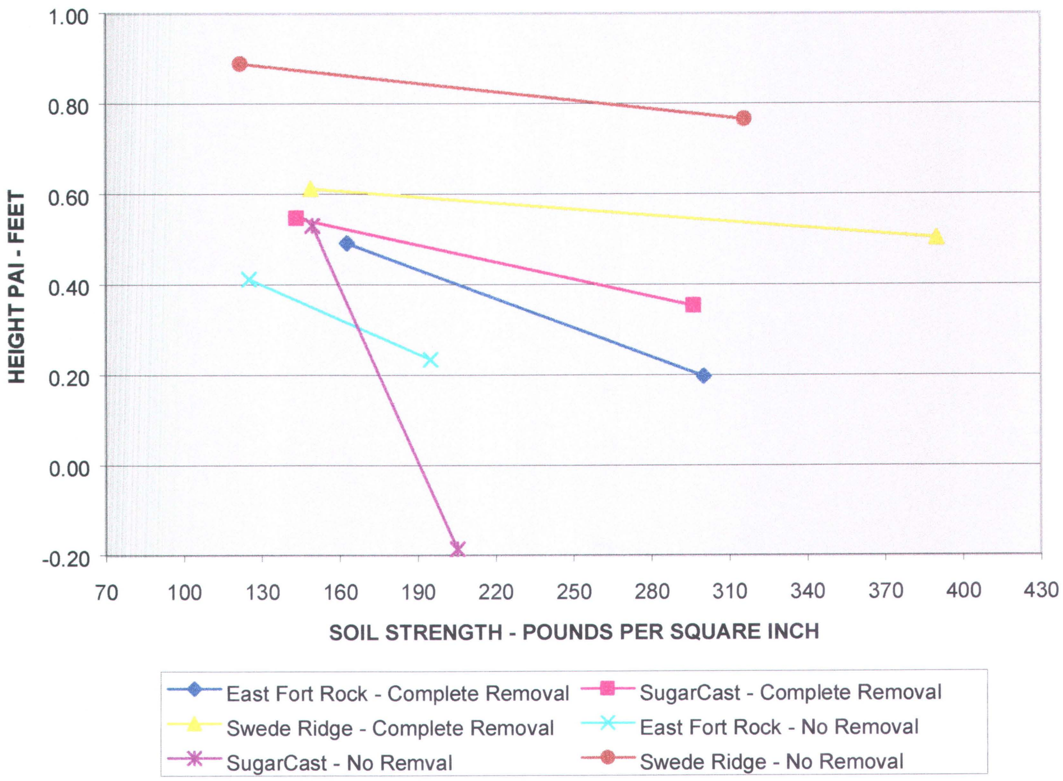


Figure 10. The relationship between Height PAI and soil strength at a radius of 30 Feet.

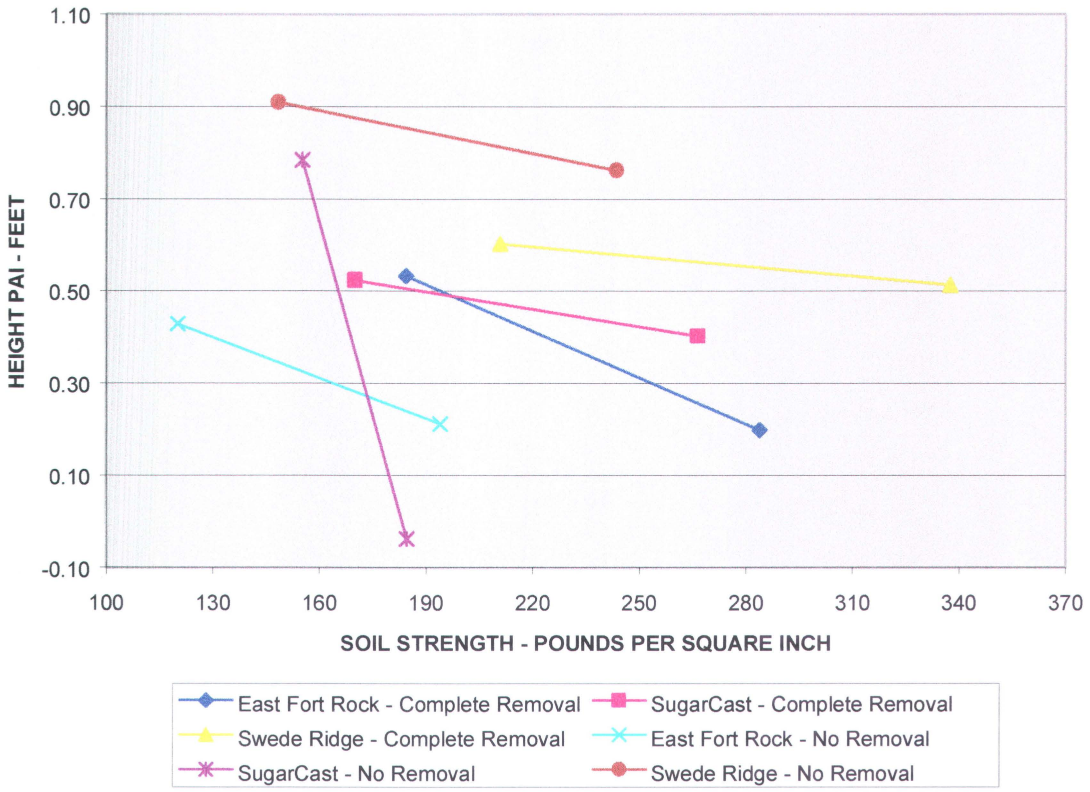
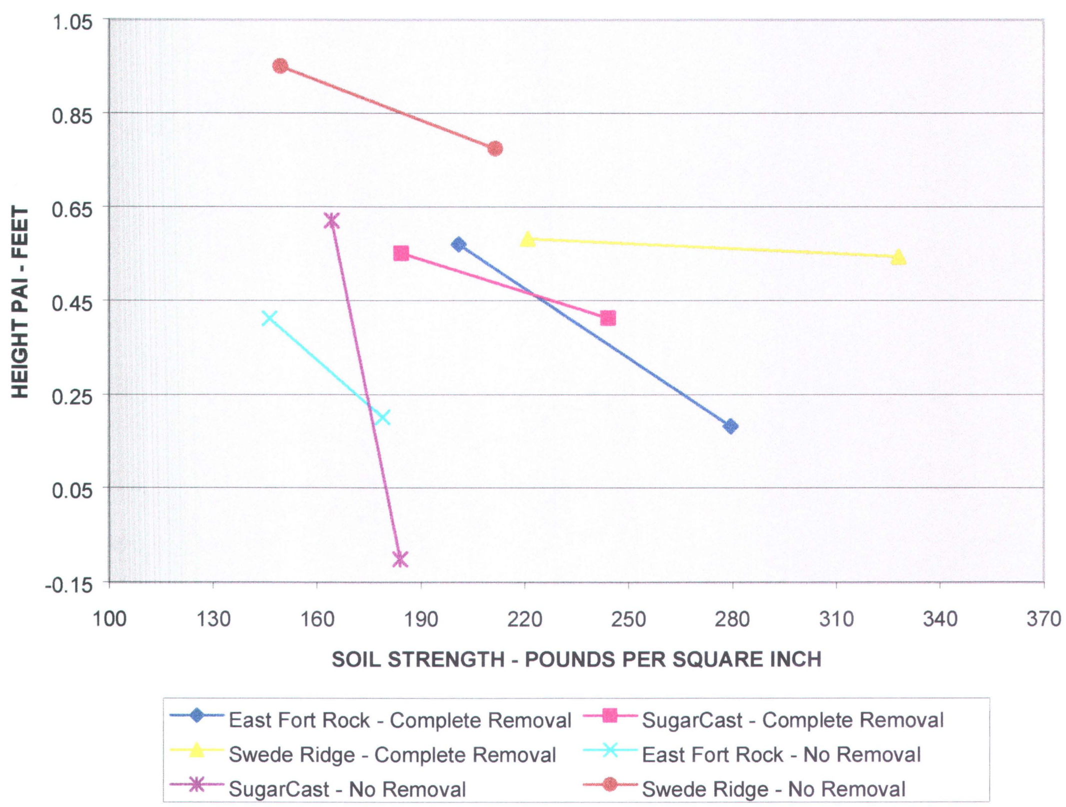


Figure 11. The relationship between Height PAI and soil strength at a radius of 45 feet.



All plots indicate a negative correlation between height PAI and increasing soil strength and the Sugar Cast - No Removal plots actually indicates a negative growth rate at the higher soil strength values. However, the actual plot data does not agree with the predicted growth rate, but instead shows a slightly positive rate of height growth, approximately .165 feet per year. Although positive, it is still considerably lower than the other five plots, which range from .245 to .839 feet per considerably lower than the other five plots, which range from .245 to .839 feet per year growth. It appears that the growth rates decline over fairly short ranges in soil strength conditions. It should be emphasized that the soil strength values are averages, which tends to obscure the inherent variability within the penetrometer data.

Figures 12, 13, and 14 depict the predicted change in cubic volume PAI for each of the six study plots at the 15, 30- and 45-foot plot radii.

Figure 12. The relationship between Volume PAI and soil strength at a radius of 15 Feet.

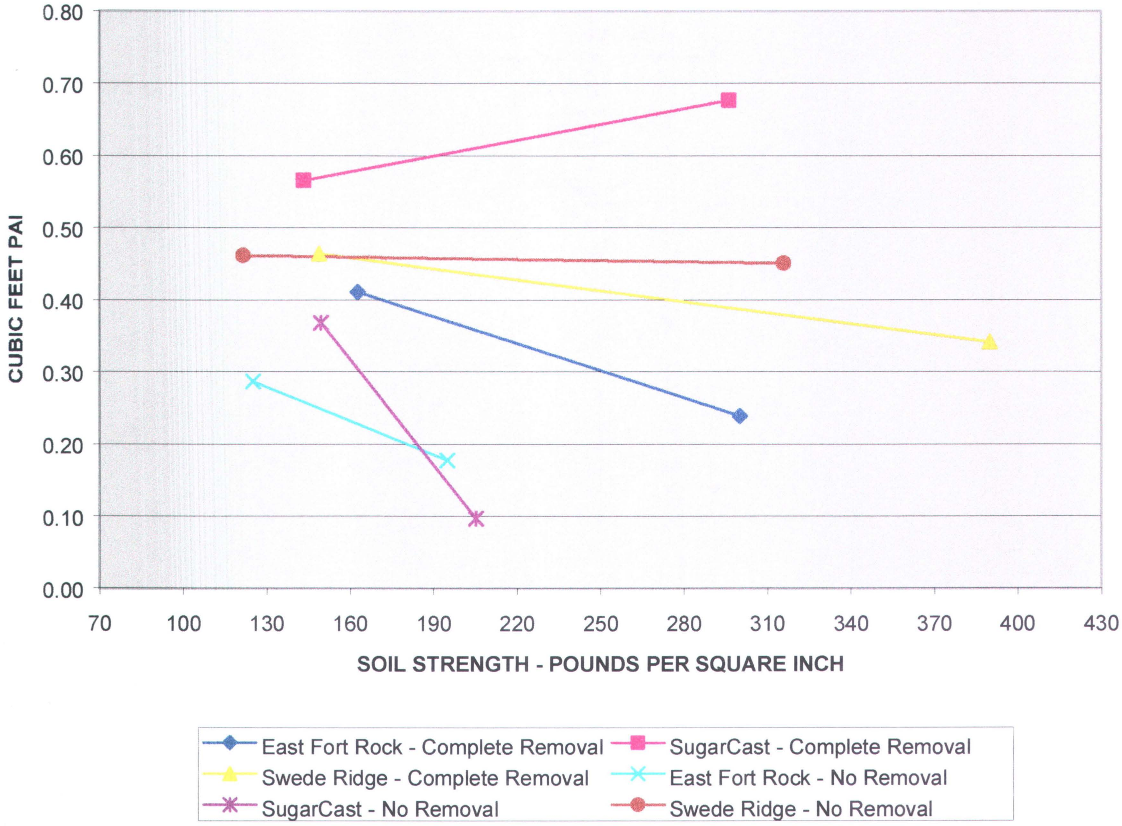


Figure 13. The relationship between Volume PAI and soil strength at a radius of 30 Feet.

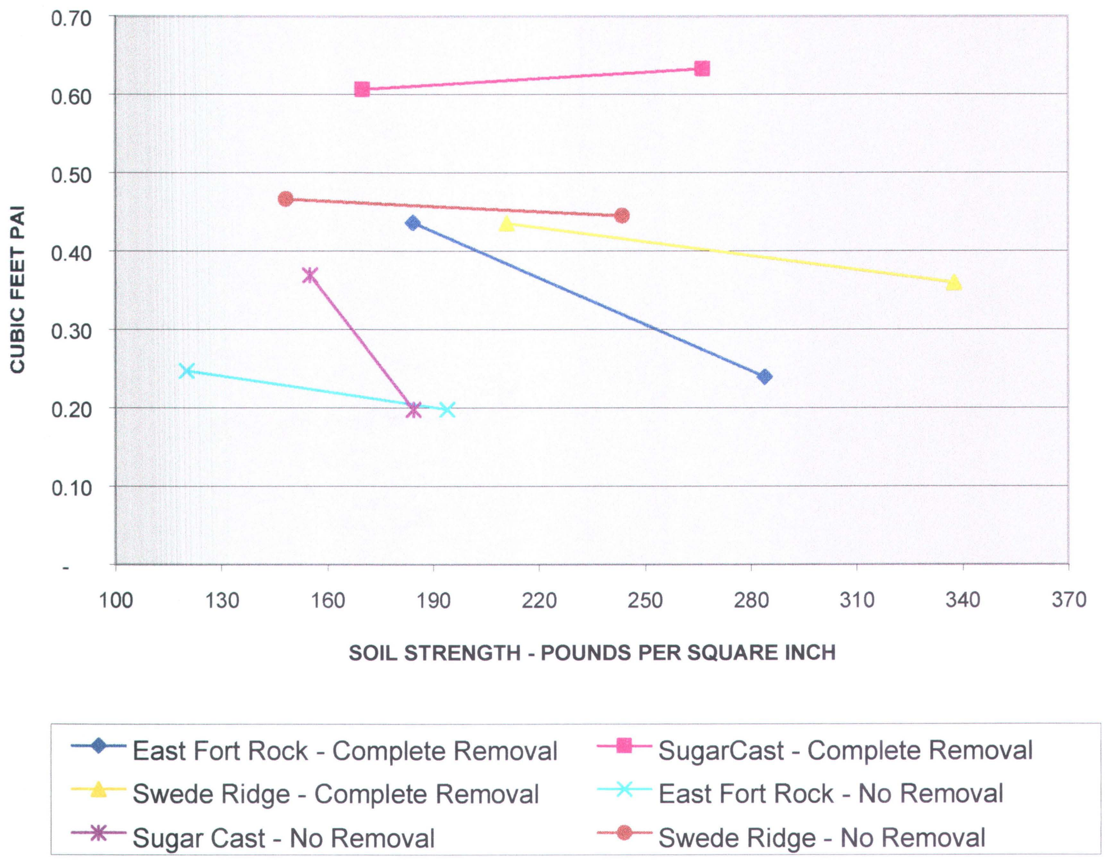
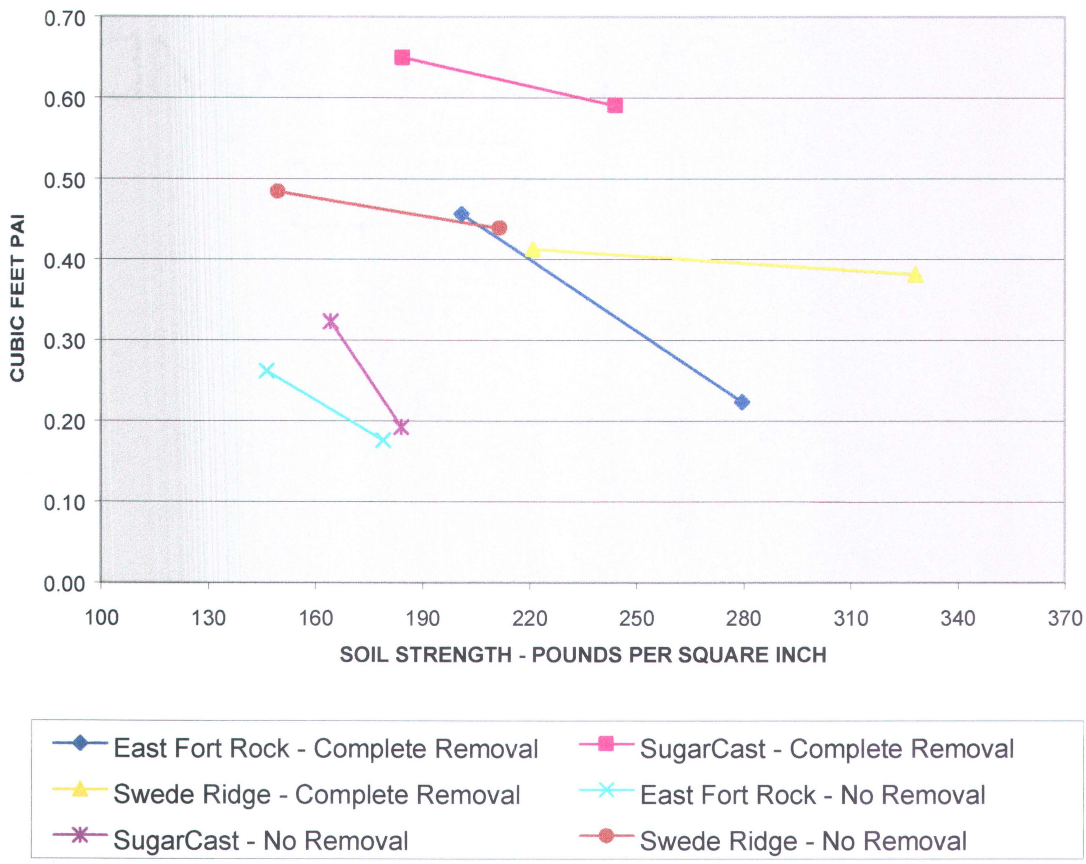


Figure 14. The relationship between Volume PAI and soil strength at a radius of 45 Feet.



The soil strength variable was only significant ($p \leq 0.05$) for volume PAI at the 15-foot radius, so the graphs for the 30- and 45-foot radii should only be considered as potential outcomes. Soil strength would have been significant at the $p \leq 0.10$ level for the 30- and 45-foot radii. At the 45-foot radius, volume PAI appears to decrease with increasing soil strength for all six plots. In the case of the East Fort Rock – Complete Removal plot, the decline in volume PAI is apparently over 40 percent (.46 to .22 cubic feet/year). With the exception of the Sugar Cast - Complete Removal plot, volume growth appears to decrease with increasing soil strength at the 15- and 30-foot radii as well. A possible explanation for the Sugar Cast exceptions is that in the regression model, the relative strength of the soil strength variable increases as the plot radius increases, which possibly results from a more complete examination of the total rooting environment in the larger radii. The graphs indicate that the No Removal control plots have lower soil strength values than the Complete Removal plots overall, and the range between the lowest and highest values are lower as well. However, the apparent level of growth differences appears to be generally similar for each of the Complete Removal and No Removal pairs.

8.0 DISCUSSION

These results seem to support other research, which indicates central Oregon volcanic ash soils compact readily (Froehlich 1979). In some studies, this was associated with measurable height and volume growth losses in ponderosa pine forests (Froehlich 1979, Helms et al. 1986, Clayton et a. 1987). In this study, only height PAI and volume PAI at the 15-foot radius were significantly related to soil strength. Basal area PAI and volume PAI at the 30- and 45-foot radius were not significantly related to soil strength. Although the graphs from the results of the regression analyses generally indicated reduced growth rates, the results were inconsistent. This also reflects previous research, which has shown inconsistent results between studies (Agee and Biswell 1970). One explanation for the inconsistencies may be that other variables effecting growth, such as initial tree size and pandora moth defoliation, had a much greater influence than did soil strength. Other growth variables not accounted for in this study, such as canopy position, crown ratio and competitive stress, likely had much greater importance to the growth trends than did soil strength.

Another possible explanation may be that while soil strength was the measure of compaction used in the study, compaction actually implies a complex interaction of alterations to the soil. For example, in addition to increasing soil strength, there may be a reduction in water supply, nutrients and aeration, as well as mechanical damage to the roots (Greacen and Sands 1980). The changes to each of these factors and how they impact tree growth may well be highly variable from site to site. Unfortunately, it was beyond the scope of this study to try to separate those influences.

There were some advantages to superimposing this study on the existing LTSP plots. However, there were disadvantages as well. Most importantly, there was no true control group for the study. Ideally, the No Removal plots would have had no machine activity occur in the thinning process, so that theoretically, there would have been no compaction created when the LTSP study was initiated. But the No Removal plots were also thinned mechanically, thus the only difference between the No Removal and Complete Removal plots was that the felled trees on the No Removal plots were not removed with skidders. Secondly, there were an insufficient number of plots to have the duplication necessary to incorporate a plot-level competitive stress index into the GLM analyses. When such an index was attempted in the analysis, there was only one treatment per replication, thus the degrees of freedom for the competitive stress index was zero. Therefore, an important growth variable could not be utilized. If time had allowed, it may have been preferable to estimate a competitive stress index for each individual tree.

The results of the study were somewhat unexpected in that, during the process of measuring soil strength, the Complete Removal plots did not visually appear or physically feel more compacted than the No Removal plots. However, the penetrometer results showed the soil conditions between the two treatments were distinctly different. This observation may have some implications for the reliability of casual methods of assessing compaction.

The stands in this study could be considered predisposed to soil disturbance related site productivity declines due to the wide spread and shallow lateral rooting systems exhibited by ponderosa pine. It has been noted that, in some soils, 435.1 PSI tends to be an upper limit threshold beyond which fine roots are unable to penetrate the soil. (Graecen and Sands 1980). Other research has noted that fine root volume declines precipitously as soil strength increases even marginally above undisturbed levels (Sands 1981). A significant loss of fine root volume at average soil strength conditions less than the hypothesized 435.1 PSI threshold may explain the growth differences suggested by this study. Whether these differences are due to restrictions on root growth, reduced moisture availability, mechanical damage to the roots, a loss of soil organic matter, a combination of these, or other mechanisms, is difficult to determine. However, an association between increasing soil disturbance from mechanical thinning and reduced tree height growth seems to be indicated.

One of the study goals was to design a process for measuring soil strength conditions for a majority of the rooting environment over an extensive area, which for these plots was approximately one-half acre each. The process used for the study seemed to work well. Fortunately, access to all six of the plots was good and the terrain and soil conditions were favorable for using the recording penetrometer. The soils tended to be quite uniform in texture, with few large stone fragments.

Only rarely did large subsurface stones or other obstructions interfere with taking soil measurements. Measuring soil strength with the penetrometer seemed preferable to using only bulk density measurements, either with a core sampler or nuclear probe, given the time and personnel constraints of the study. Using a core sampler would have been much too slow and cumbersome for covering large areas intensively. A core sampler seemed particularly inadequate for attempting to sample continuously down through the soil profile to a depth of at least 24 inches.

Many older bulk density studies are restricted to just the upper few inches of the soil profile. This was unacceptable for two reasons. For one, the first two to four inches of volcanic ash soil seem to reverse compaction effects in a short period of time, probably through frost heaving. This would misrepresent the bulk of the soil profile, which is known to remain compacted for long periods of time (Wert and Thomas 1981). The other was the desire to look at a large percentage of the rooting environment. Bulk density measurements would have required extensive excavation to reach the lower soil layers. Also, the nuclear probe was judged to be inadequate not only due to a lack of availability and training as well as licensing issues, but was too slow to intensively measure the extensive plot areas involved. However, a nuclear probe measures a large soil volume per measurement, thus the variability from point to point might be less.

The Complete Removal plots required approximately 1000 individual probes with the recording penetrometer. This took about two to three days to accomplish, but provided an electronic record that reasonably represented the soil conditions over a total volume of nearly 1900 cubic yards. This seemed be an accurate representation because the soil strength variability in undisturbed soil was very low; so as long as the grid was tight enough to detect those areas disturbed by logging activities, the site was described adequately. An extensive survey of this magnitude would have been impractical with other methodologies. An additional benefit of the recording penetrometer was that all the soil probe files could be transferred to a personal computer and brought together in a spatial analysis program, along with the tree data. As a result, it was a relatively simple process to perform the analysis required by this study.

As noted previously, ponderosa pine trees tend to have shallow, wide-spreading, lateral root systems. As a result ponderosa pines are potentially exposed to substantial mechanical damage from logging operations, as well as degradation of the rooting environment. Fortunately, these risks can be ameliorated through silvicultural prescriptions, careful harvest planning and layout, and selection of logging processes and equipment. When designing a management prescription, emphasis can be placed on minimizing the number of entries over time since each entry will likely increase both the extent of soil disturbance across the site as well as the intensity of disturbance on areas previously impacted (Adams 1991, Froehlich 1980, Zaborski 1989).

Equipment choices and harvest planning can play a crucial role by defining the operational standards required of the operators. For example, harvesters with extension booms can minimize machine travel and thus site impacts compared to feller-buncher machines that must travel up to each tree. Also, management plans can require a desired minimum spacing between skid trails, restrict machine travel to only designated skid trails and specify appropriate size and spacing limits for landings. The success of these plans can be assured by identifying in the field where the skid trails and landings should be located as well as providing adequate supervision to enforce the provisions of the contract.

Equipment selection and harvesting methods can strongly influence site impacts. Another study parallel to this one was initiated to examine the alterations to soil conditions created by current mechanical harvesting practices. The results are summarized in Table 8, which contrasts whole-tree mechanical thinning systems to a cut-to-length system. Table 8 examines the changes in soil strength resulting from the estimated number of passes by both harvesters and skidders. As each penetrometer probe was taken, the amount of machine activity at that point was estimated and the probe classified into one of four categories: no disturbance; one to two passes; three to five passes or main skid trails. The soil probe data were further summarized at four soil depth categories in order to describe how soil strength changed with depth. These were: 0-6 inches; 6.1 to 12 inches; 12.1 to 18 inches and 18.1 to 24 inches [1].

[1]Unpublished data, available on file with the author.

Table 8. Increases in soil strength with number of passes and depth.

UNIT NAME AND ACTIVITY LEVEL	Soil Depth Categories in Inches				Percent Undist.	Percent in Trails
	0-6.0	6.1-12	12.1-18	18.1-24		
North Canal, Timco	Soil Strength in Lbs. Per Square Inch				61%	39%
Undisturbed soil	79	176	237	266		
1-2 Passes	168	365	398	418		
3-5 Passes	263	455	459	454		
Main Trails	389	672	644	605		
Section 33, Timco					37%	63%
Undisturbed soil	47	119	161	189		
1-2 Passes	79	243	314	338		
3-5 Passes	112	407	455	451		
Main Trails	252	571	581	544		
West Haner, John Deere					32%	68%
Undisturbed soil	67	146	202	229		
1-2 Passes	105	272	321	322		
3-5 Passes	133	420	473	450		
Main Trails	180	492	573	495		
East Haner, John Deere						
Undisturbed soil	46	133	173	202	29%	71%
1-2 Passes	62	200	256	292		
3-5 Passes	90	342	392	428		
Main Trails	156	531	514	494		
InBetween, Hydro-Axe					36%	64%
Undisturbed soil	60	139	188	231		
1-2 Passes	139	313	350	364		
3-5 Passes	223	507	513	494		
Main Trails	281	529	576	528		
Sisters, TimberJack					88%	12%
Undisturbed soil	126	176	204	262		
Skid Trail	179	327	286	283		

Timco & John Deere systems. Track-mounted harvesters with either bar-saw or hot-saw
Hydro-axe system. Four rubber-tired harvester with hot-saw cutting head.
TimberJack system. Six-wheel harvester with cut-to-length processor head.

The first five harvest units listed were all mechanically, whole-tree harvested between 1994 and 1997. The operations utilized large Timco, John Deere and TimberJack boom-type harvesters and either grapple skidders or caterpillar tractors. These units had large percentages of the ground disturbed by harvesting, ranging from 39 to 71 percent of the unit surface area impacted by machine travel. Designated skid trails were not enforced and machine travel off of the main skid trails was extensive. Soil strength increased markedly with only 1 to 2 passes and continued to increase rapidly with additional disturbance. Additionally, nearly all litter and soil organic matter in the soil A horizon was removed from the main skid trails, thus making the soil more susceptible to compaction as well as reducing nutrient availability.

The table does not address the landings, but the whole-tree style of logging requires large landings in which to limb, top, sort, deck, and load the logs. In contrast, the Sisters unit, which was logged in 1997 with cut-to-length equipment, had significantly less area in skid trails and the level of compaction in the trails was much less as well. Cut-to-length systems limb and top the trees in the woods, depositing much of the material in front of the machine, which creates a slash mat for it to walk over, thus elevating it off the ground and reducing compaction. Also, not only were the natural litter and organic layers protected, the residual logging slash left on site helped assure nutrient retention. Table 8 clearly shows a dramatic reduction in the percent of the area impacted as well as much reduced soil strength compared to the whole-tree systems. Also, cut-to-length systems usually require significantly fewer and smaller landings since space is not required for the delimbing and topping operations, which create large slash piles.

The statistical analysis for this study utilized the average soil strength information as an indicator of the overall rooting environment quality. The soil strength readings for each individual penetrometer probe were averaged to create an average soil strength value for that point. Similarly, all of the individual probes within either a 15, 30- or 45-foot radius soil study area were averaged to create an average soil strength value to represent the rooting environment around a tree. Using these average values tended to mask the full range of variability found in the soil strength conditions. Tables 1, 2 and 3 in Appendix A are provided to highlight that variability. The averaged information may explain some of the apparent anomalies in the data analysis, such as rapid PAI growth decreases over apparently minor increases in soil strength.

As explained previously, each penetrometer probe represented a volume of soil 2 feet deep and either five-foot or ten-foot square, depending on the treatment type. When the spatial analysis software was used to identify which penetrometer probes fell within either the 15, 30- or 45-foot radius soil analysis plots for individual trees, each probe that fell within the plot was assumed to represent the full 5 X 5 or 10 X 10 foot area. However, probes that lay towards the edge of the plot and were intersected by the plot circumference would actually represent only that portion of the soil volume within the plot circumference. A means to estimate the true soil volume for these probes was determined to be beyond the capabilities of the software and therefore, the analysis was forced to accept that compromise.

An examination of all the various graphs (Figures 6 through 14) does not seem to reveal an obvious treatment effect. A possible explanation for this is that although the Complete Removal and No Removal plots were treated differently, the treatments were not completely unique. Both treatments had a large range of soil strength values that tended to overlap. The No Removal plots had trees with high soil strength environments and the Complete Removals had trees with low soil strength environments. However, the mean soil strength for the Complete Removal plots was considerably higher than that of the No Removal plots, so on average, they would be expected to experience greater overall declines in height growth rates.

If the significant differences in height growth are determined to be sufficient reason to minimize soil compaction, the question then becomes what would be an appropriate management response to prevent or ameliorate the potential changes to site productivity. Reversing compaction through treatments such as subsoiling are expensive and, when attempted in areas with residual trees left in place, present a substantial risk of extensive mechanical damage to the roots, as well as the risk of facilitating the initiation and spread of root diseases. Determining whether or not subsoiling is appropriate should depend on a careful environmental as well as financial analysis. The uncertain growth benefits may not justify either the substantial financial investment or the risk of other damage. Forest managers should instead focus on prevention, since it has been shown that compaction can be reduced to acceptable levels for reasonable costs through thoughtful, well-planned stewardship practices.

Future study should include a continuing survey of the six study plots through time to determine if the apparent growth reductions increase, decrease, or stay the same. Similarly, it would be interesting to monitor the soil strength conditions to find whether natural processes will ameliorate compaction in soils that are not strongly affected by freezing and thawing. It would also be interesting to attempt to differentiate the effects of mechanical damage to the roots, resistance to root penetration and the loss of organic matter. Other questions of interest are how soil disturbance influences other components and functions of the ecosystem, such as soil biota, understory vegetation, moisture, and nutrient cycling. Finally, an attempt could be made to correlate the growth response to soil strength conditions found in this study to the other tree variables that influence growth response to density management, such as canopy position, crown ratio and competitive stress as individually measured for each tree.

9.0 CONCLUSION

Mechanical thinning operations with feller-bunchers and rubber-tired skidders created significant levels of soil compaction, as measured by soil strength. A significant reduction in height growth was correlated with increasing soil strength. Volume growth at the 15-foot radius was also significantly correlated with increasing soil strength. Basal area growth differences were suggestive, but not significant. This study seems to support previous research that had also indicated soil compaction may lead to a decline in ponderosa pine growth. However, it must be noted that because tree growth response to compaction is highly variable, depending on the specific tree species and soil type involved, the results of this study should only be applied to ponderosa pines growing in the central Oregon volcanic ash soils. And, given the degree of variability found in this study, caution may be advised even when applying the results to other sites in Central Oregon. It should also be noted that a decline in site productivity is not the only potential result of soil disturbance. For example, exposing mineral soil may facilitate the establishment of natural ponderosa pine regeneration. Other forest management objectives may also be a reasonable trade-off for limited site impacts, such as increased protection from losses due to insect and disease infestations, or wildfire. Nevertheless, management practices may lead to frequent entries that compact the soil both extensively and intensively. Because these effects are long lasting and cumulative, the risk of reducing long-term site productivity remains a concern.

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APPENDIX

Appendix A. Sample Penetrometer Data.

Tables 1, 2 and 3 are presented to clarify how the averaged soil strength values per tree were derived for the statistical analysis and to also show how some of the inherent variability in the data was lost or masked as a result of averaging. All of the soil strength values are in pounds per square inch (PSI).

Table 1 presents a small sample of the raw data collected by the recording penetrometer. The penetrometer recorded the soil strength at one-inch intervals to a total depth of 24 inches. Each row of data represents a single probe by the penetrometer.

Table 2 shows how all the averaged penetrometer files were combined to create an overall average soil strength value for each individual tree in the East Fort Rock – Complete Removal study area.

Finally, Table 3 shows the final average soil strength values used in the analysis for the East Fort Rock – Complete Removal study area, for the 15-, 30- and 45-foot radius plots around each tree.

Table 1. East Fort Rock – Complete Removal sample penetrometer data. Soil strength in pounds per square inch.

	Depth in Inches				Soil Strength Resistance in Pounds per Square Inch																				Avg.
File #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	PSI
1	52	94	92	122	172	167	192	208	213	239	248	230	238	263	284	284	280	289	300	296	299	306	303	326	229
2	8	33	57	95	134	155	157	178	184	201	207	190	187	183	184	187	216	230	192	202	204	213	240	270	171
3	0	0	18	30	62	73	101	98	133	161	184	191	184	179	188	175	171	171	167	202	223	241	228	230	142
4	17	44	73	73	36	42	42	45	100	192	113	102	124	160	190	190	181	180	188	177	174	184	205	340	132
5	7	11	7	33	113	178	193	192	212	215	221	234	248	259	239	245	265	269	246	227	244	294	337	357	202
6	22	33	17	0	40	100	132	134	143	151	158	162	164	180	202	164	101	79	92	97	178	294	267	155	128
7	5	18	37	89	124	122	133	102	104	101	137	167	164	223	284	288	312	336	365	377	363	357	328	299	201
8	49	36	47	89	189	257	317	351	306	281	346	358	366	384	359	349	342	338	376	393	414	470	502	520	310
9	7	13	46	98	119	104	116	133	160	193	235	232	187	193	190	192	204	211	228	248	261	256	276	350	177
10	28	31	44	68	85	104	102	71	69	69	80	121	129	141	171	219	287	381	557	403	97	104	107	11	145
11	14	42	63	92	125	162	199	227	228	241	242	267	342	438	288	206	229	320	344	379	433	489	605	688	278
12	0	5	7	16	6	6	5	12	17	18	29	223	411	568	219	86	86	88	89	89	89	89	89	89	97
13	25	27	8	9	71	190	251	282	464	214	411	471	513	543	568	513	350	253	169	201	305	409	412	95	281
14	46	89	81	97	88	86	121	214	317	361	347	335	354	333	321	362	566	675	500	278	217	272	261	295	276
15	19	40	119	239	265	258	261	299	333	339	347	329	351	376	435	412	439	499	613	644	530	631	279	60	338
16	25	34	49	96	163	201	256	337	351	289	305	366	524	611	572	587	85	622	569	612	339	73	71	69	300
17	13	22	77	125	189	239	253	288	296	225	214	259	317	382	493	561	510	496	398	400	388	299	361	361	298
18	15	20	51	143	207	215	225	253	346	414	268	403	450	483	466	387	324	394	620	133	90	92	94	95	258
19	25	33	78	157	184	189	139	113	130	166	313	82	84	83	84	86	86	86	85	85	86	86	86	85	110
20	12	8	0	0	39	143	226	213	172	203	362	187	90	94	93	94	94	97	98	101	102	103	103	10	110
21	6	15	27	67	90	101	107	155	212	208	194	210	246	315	385	391	347	342	315	367	456	482	580	321	247
22	5	0	22	62	133	210	287	418	411	340	433	505	531	592	367	620	324	103	106	114	116	117	116	117	252
23	6	29	18	29	40	95	161	289	260	163	115	210	352	288	204	317	462	421	78	80	81	81	82	80	164
24	0	25	50	84	98	103	136	163	188	140	118	303	373	417	393	389	97	101	101	101	102	98	98	96	157
25	38	88	139	166	51	168	171	253	421	323	308	326	81	86	86	86	88	88	88	88	88	88	88	89	146
26	42	78	80	97	116	116	96	107	119	139	153	180	201	137	147	229	136	161	157	225	105	105	107	106	131
27	8	22	50	71	90	92	75	133	56	187	175	188	234	317	149	279	302	302	297	398	307	111	112	115	170
28	6	26	33	58	95	94	117	141	155	162	187	212	214	188	184	216	226	240	287	320	348	389	400	379	195
29	6	11	41	169	293	269	249	263	311	332	349	325	312	281	228	211	198	247	290	291	284	300	285	114	236
30	5	42	57	35	50	56	75	78	67	66	66	122	132	135	248	107	216	213	206	199	219	258	269	25	123
31	22	60	90	78	63	42	35	23	19	28	83	175	127	122	147	188	213	242	240	192	194	233	303	342	136
32	16	59	29	37	27	98	219	284	314	308	266	213	146	127	185	308	388	421	431	435	420	376	350	403	244
33	12	47	80	69	90	133	170	202	202	216	213	218	193	205	222	233	242	253	253	246	219	190	193	201	179
34	31	38	78	122	113	64	59	66	68	67	52	50	36	36	30	19	19	35	62	129	180	210	205	200	82
35	15	18	29	47	66	136	183	184	185	145	134	147	168	190	235	246	258	248	242	210	213	272	261	136	165
36	12	18	18	33	56	33	34	33	42	56	38	29	30	33	39	67	93	77	69	70	66	147	97	97	54
37	0	15	9	64	143	182	189	203	201	157	115	146	155	172	250	490	217	371	362	423	501	623	636	682	263
38	9	30	70	147	173	170	169	181	188	215	169	202	160	382	414	81	85	86	86	88	88	89	90	91	144
39	37	84	183	283	334	367	374	367	384	410	0	0	0	0	0	0	0	0	0	0	0	0	0	0	282
40	42	113	164	203	180	184	212	103	233	263	261	279	328	470	216	355	403	447	482	502	335	289	308	342	280
41	16	28	54	118	182	174	158	130	153	223	178	259	288	335	304	233	429	648	302	75	74	77	77	8	188
42	29	63	96	159	184	213	249	278	250	213	221	282	311	349	370	357	445	489	513	657	687	625	297	78	309
43	33	195	477	421	677	387	384	115	441	434	500	630	635	502	627	265	86	89	88	86	86	89	89	90	309
44	8	12	17	48	77	89	163	227	285	384	211	155	137	173	129	182	393	494	558	565	534	547	604	550	273
45	9	11	39	66	49	26	17	13	20	39	27	39	75	153	177	105	97	168	293	273	381	105	98	104	99
46	0	13	22	68	102	94	89	73	56	59	134	297	548	556	311	372	358	301	468	536	648	688	643	676	296
47	27	40	57	49	50	57	75	77	56	45	59	78	96	441	240	48	39	59	68	121	173	195	199	167	105
48	8	51	119	167	182	175	148	145	141	127	141	161	213	293	352	317	293	324	405	501	564	498	300	261	245
49	14	17	0	13	50	116	157	187	213	234	253	293	426	475	533	0	0	0	0	0	0	0	0	0	199
50	38	98	101	95	92	117	141	236	259	157	153	160	191	230	296	344	457	637	539	416	199	69	69	68	215
51	14	33	57	83	97	52	208	245	280	324	362	273	255	306	0	0	0	0	0	0	0	0	0	0	185
52	5	18	85	187	194	204	212	237	201	240	466	475	355	339	377	373	475	326	68	92	94	96	97	96	221
53	18	48	115	169	180	180	192	228	172	119	202	331	0	0	0	0	0	0	0	0	0	0	0	0	163
54	6	35	45	51	82	95	86	75	81	94	124	343	0	0	0	0	0	0	0	0	0	0	0	0	93
55	23	66	183	290	329	326	318	317	321	321	318	324	329	311	327	365	438	465	487	410	92	97	101	97	277
56	15	47	89	103	100	80	60	45	34	44	62	84	90	68	91	173	370	557	233	241	69	192	292	347	145
57	41	106	152	195	180	157	172	189	173	167	196	214	321	337	210	269	248	217	230	294	335	339	361	374	228
58	16	12	25	50	101	139	124	113	125	126	125	133	146	260	263	304	0	0	0	0	0	0	0	0	129
59	17	54	77	90	169	225	207	202	212	226	193	199	217	211	188	195	216	241	282	255	294	312	337	343	207
60	6	14	77	196	260	308	331	361	358	365	379	384	361	370	350	359	363	337	304	295	321	320	344	305	295

Table 2. East Fort Rock – Complete Removal. Soil strength calculations for each tree, averaging all penetrometer files within the 45-foot radius.

TREE#	PENT#	PSI	TREE#	PENT#	PSI	TREE#	PENT#	PSI
160	25	146	173	142	185	186	399	342
160	51	185	173	169	234	186	456	275
160	78	166	173	196	336	186	400	331
160	106	104	173	223	136	186	427	251
160	79	225	173	250	242	186	454	220
160	52	221	173	277	215	186	481	289
160	133	191	173	278	349	186	508	273
160	756	108	173	251	294	186	509	223
160	26	131	173	224	183	186	482	223
160	53	163	173	197	253	186	455	305
160	80	229	173	170	350	186	428	278
160	107	137	173	171	224	186	401	337
160	108	170	173	198	261	186	374	398
160	81	112	173	225	299	186	402	397
160	54	93	173	252	319	186	429	274
160	27	170	173	279	262	186	483	229
160	757	159	173	248	310	186	510	217
160	821	232	173	167	248	186	484	258
160	822	140	173	194	313	186	457	341
160	823	119	173	221	229	186	430	273
160	824	106	173	275	221	186	425	382
160	855	161	173	276	376	186	452	218
160	854	200	173	249	201	186	479	222
160	853	164	173	222	208	186	507	168
160	852	215	173	195	257	186	480	250
160	134	146	173	168	306	186	453	200
160	825	204	173	141	174	186	426	173
AVG		163	AVG		259	AVG		272
161	133	191	174	306	220	187	454	220
161	107	137	174	277	215	187	481	289
161	108	170	174	278	349	187	508	273
161	824	106	174	305	295	187	535	203
161	134	146	174	332	298	187	562	302
161	825	204	174	333	257	187	563	263
161	856	137	174	275	221	187	536	222
161	858	296	174	276	376	187	509	223
161	161	97	174	301	243	187	482	223
161	188	221	174	302	231	187	455	305
161	215	172	174	303	114	187	510	217
161	242	330	174	330	123	187	537	317

161	243	149
161	216	143
161	189	275
161	162	154
161	826	330
161	827	221
161	828	198
161	829	238
161	859	260
161	857	200
161	214	185
161	187	230
161	160	162
AVG.		197
162	182	205
162	209	387
162	236	257
162	263	457
162	208	309
162	289	227
162	262	376
162	235	317
162	291	180
162	264	311
162	237	266
162	210	177
162	183	161
162	184	171
162	211	261
162	238	311
162	265	170
162	292	134
162	293	296
162	266	243
162	239	165
162	212	165
162	319	294
162	290	238
162	317	408
162	318	276
AVG.		258
163	129	220
163	100	293
163	101	170
163	125	200

174	357	130
174	384	258
174	329	164
174	355	190
174	328	248
174	356	213
174	383	195
174	385	195
174	358	309
174	331	217
174	304	389
174	359	301
174	386	308
174	360	334
AVG.		246
175	332	298
175	301	243
175	302	231
175	303	114
175	330	123
175	357	130
175	384	258
175	411	313
175	438	255
175	329	164
175	327	261
175	354	371
175	381	195
175	408	224
175	409	187
175	382	240
175	355	190
175	328	248
175	356	213
175	383	195
175	410	211
175	437	303
175	412	380
175	385	195
175	358	309
175	331	217
175	304	389
175	359	301
175	386	308
AVG.		242

187	533	224
187	559	229
187	532	426
187	505	265
187	478	202
187	452	218
187	479	222
187	506	198
187	560	436
187	561	272
187	534	387
187	507	168
187	480	250
187	453	200
187	588	364
AVG.		264
188	485	249
188	512	319
188	539	227
188	566	269
188	567	205
188	540	213
188	513	231
188	486	338
188	508	273
188	535	203
188	562	302
188	563	263
188	536	222
188	509	223
188	482	223
188	483	229
188	510	217
188	537	317
188	564	261
188	565	353
188	538	287
188	511	179
188	484	258
188	457	341
188	593	273
188	592	253
188	591	326
188	590	413
AVG.		267

163	126	138
163	127	177
163	128	118
163	155	173
163	182	205
163	209	387
163	236	257
163	208	309
163	206	314
163	179	210
163	152	153
163	153	229
163	180	165
163	207	322
163	234	272
163	235	317
163	181	181
163	154	193
163	237	266
163	210	177
163	183	161
163	156	184
163	157	268
163	184	171
163	211	261
AVG.		222
164	48	245
164	102	154
164	75	194
164	49	199
164	76	275
164	103	234
164	104	172
164	77	197
164	50	215
164	129	220
164	130	199
164	131	76
164	99	262
164	100	293
164	73	146
164	46	296
164	47	105
164	74	284
164	101	170

176	352	275
176	379	185
176	406	227
176	433	267
176	434	229
176	407	165
176	380	360
176	353	238
176	326	267
176	327	261
176	354	371
176	381	195
176	408	224
176	435	225
176	462	316
176	463	184
176	436	312
176	409	187
176	382	240
176	355	190
176	356	213
176	383	195
176	410	211
176	437	303
176	1015	147
176	1016	231
176	460	326
176	461	164
AVG.		238
177	438	255
177	489	168
177	544	370
177	517	296
177	490	284
177	463	184
177	436	312
177	437	303
177	464	369
177	491	234
177	518	208
177	546	283
177	519	351
177	492	233
177	465	240
177	520	218

189	566	269
189	567	205
189	564	261
189	565	353
189	594	293
189	593	273
189	620	110
189	647	253
189	674	297
189	675	272
189	648	293
189	621	278
189	592	253
189	591	326
189	618	169
189	645	295
189	372	347
189	673	223
189	646	172
189	619	226
189	590	413
189	644	267
189	617	232
189	842	275
189	843	188
189	844	112
AVG.		256
190	559	229
190	560	436
190	561	272
190	585	233
190	586	247
190	587	296
190	588	364
190	589	391
190	616	468
190	643	228
190	670	259
190	613	274
190	614	188
190	641	307
190	668	340
190	695	301
190	696	322
190	669	230

164	127	177
164	128	118
164	155	173
164	154	193
164	156	184
164	157	268
164	158	114
AVG.		199
165	69	322
165	42	309
165	15	338
165	16	300
165	746	282
165	43	309
165	70	190
165	97	383
165	98	259
165	71	216
165	44	273
165	17	298
165	747	459
165	748	312
165	18	258
165	45	99
165	72	182
165	99	262
165	100	293
165	73	146
165	46	296
165	19	110
165	749	333
165	20	110
165	47	105
165	74	284
AVG.		257
166	123	186
166	231	267
166	204	190
166	177	166
166	150	215
166	124	241
166	125	200
166	126	138
166	127	177
166	182	205
177	493	230
177	466	256
177	439	143
177	440	334
177	467	191
177	494	330
177	521	306
177	548	253
177	545	275
177	547	363
AVG.		268
178	387	291
178	306	220
178	332	298
178	333	257
178	334	189
178	335	179
178	384	258
178	439	143
178	412	380
178	385	195
178	358	309
178	331	217
178	390	366
178	416	241
178	361	244
178	388	224
178	415	296
178	442	338
178	443	203
178	389	297
178	362	182
178	359	301
178	386	308
178	413	331
178	440	334
178	468	210
178	441	287
178	414	231
178	387	291
178	360	334
178	387	291
AVG.		266
179	446	300
179	417	344
190	642	257
190	615	249
190	612	288
190	639	335
190	666	340
190	694	389
190	667	225
190	640	315
AVG.		298
191	535	203
191	562	302
191	533	224
191	557	319
191	530	257
191	504	324
191	531	305
191	558	336
191	559	229
191	532	426
191	505	265
191	506	198
191	560	436
191	561	272
191	534	387
191	507	168
191	584	264
191	585	233
191	586	247
191	587	296
191	588	364
191	589	391
191	611	390
191	613	274
191	614	188
191	641	307
191	615	249
191	612	288
191	640	315
AVG.		294
192	641	307
192	668	340
192	695	301
192	722	250
192	921	171
192	920	183

166	208	309
166	151	131
166	178	212
166	205	188
166	232	231
166	233	206
166	206	314
166	179	210
166	152	153
166	153	229
166	180	165
166	207	322
166	234	272
166	235	317
166	181	181
166	154	193
AVG.		218
167	283	335
167	256	310
167	229	378
167	202	232
167	203	343
167	230	245
167	257	320
167	284	308
167	285	201
167	258	148
167	231	267
167	204	190
167	310	286
167	311	349
167	312	195
167	205	188
167	232	231
167	259	179
167	286	182
167	287	201
167	260	291
167	233	206
167	206	314
167	234	272
167	261	202
167	313	358
167	314	206
AVG.		257

179	444	308
179	471	323
179	498	328
179	525	225
179	526	256
179	499	293
179	472	213
179	445	330
179	418	173
179	391	406
179	392	311
179	419	156
179	473	115
179	500	276
179	527	211
179	528	258
179	501	260
179	474	184
179	447	331
179	420	254
179	393	359
179	470	218
179	443	203
179	421	367
179	448	167
179	475	398
179	502	349
AVG.		269
180	446	300
180	471	323
180	498	328
180	525	225
180	553	377
180	526	256
180	499	293
180	472	213
180	445	330
180	473	115
180	500	276
180	527	211
180	554	271
180	555	321
180	528	258
180	501	260
180	474	184

192	723	213
192	696	322
192	669	230
192	639	335
192	666	340
192	693	201
192	720	80
192	923	172
192	953	253
192	952	267
192	922	239
192	721	272
192	694	389
192	667	225
192	640	315
192	692	217
192	664	255
192	691	241
192	718	218
192	924	203
192	719	233
192	665	225
192	638	384
AVG.		249
193	635	273
193	662	228
193	689	239
193	716	320
193	717	315
193	690	337
193	663	131
193	636	267
193	609	215
193	611	390
193	610	291
193	612	288
193	639	335
193	666	340
193	693	201
193	720	80
193	694	389
193	667	225
193	640	315
193	692	217
193	637	400

168	228	200
168	255	115
168	282	221
168	283	335
168	256	310
168	229	378
168	309	183
168	336	335
168	337	353
168	310	286
168	306	220
168	226	193
168	278	349
168	225	299
168	252	319
168	279	262
168	280	242
168	253	211
168	227	239
168	254	266
168	281	230
168	333	257
168	307	170
168	334	189
168	335	179
168	308	266
AVG.		254
169	123	186
169	93	324
169	94	315
169	95	124
169	96	364
169	120	306
169	121	223
169	122	211
169	119	306
169	147	299
169	174	244
169	201	307
169	229	378
169	202	232
169	175	277
169	148	267
169	149	250
169	176	342
180	447	331
180	476	189
180	448	167
180	475	398
180	502	349
180	529	408
180	556	374
180	530	257
180	503	403
AVG.		285
181	420	254
181	393	359
181	366	309
181	340	143
181	367	254
181	394	265
181	395	246
181	368	161
181	341	227
181	342	336
181	369	250
181	396	283
181	397	372
181	370	310
181	343	249
181	371	536
181	398	263
181	421	367
181	448	167
181	449	464
181	422	292
181	423	103
181	450	242
181	451	241
181	424	256
181	425	382
AVG.		282
183	263	457
183	288	131
183	289	227
183	262	376
183	291	180
183	264	311
183	265	170
183	292	134
193	664	255
193	691	241
193	718	218
193	925	166
193	924	203
193	719	233
193	665	225
193	638	384
AVG.		267
194	604	284
194	631	246
194	658	300
194	685	397
194	713	305
194	686	254
194	659	215
194	632	255
194	605	271
194	578	349
194	581	301
194	608	215
194	635	273
194	662	228
194	689	239
194	663	131
194	636	267
194	580	267
194	579	332
194	606	228
194	633	149
194	660	314
194	687	301
194	714	115
194	715	208
194	688	278
194	661	307
194	634	97
194	607	257
AVG.		254
195	960	267
195	930	257
195	713	305
195	686	254
195	662	228
195	689	239

169	203	343	183	293	296	195	716	320
169	204	190	183	319	294	195	927	238
169	177	166	183	346	227	195	957	116
169	150	215	183	347	279	195	987	170
169	146	249	183	320	283	195	956	166
169	173	255	183	290	238	195	926	246
169	200	105	183	315	254	195	717	315
169	151	131	183	342	336	195	690	337
AVG.		254	183	370	310	195	660	314
170	86	98	183	343	249	195	687	301
170	60	295	183	316	342	195	714	115
170	87	227	183	317	408	195	929	271
170	88	261	183	344	273	195	959	372
170	61	296	183	371	536	195	989	259
170	34	82	183	372	347	195	988	223
170	35	165	183	345	151	195	958	252
170	62	191	183	318	276	195	928	128
170	89	244	183	373	351	195	715	208
170	90	318	AVG.		286	195	688	278
170	63	308	184	236	257	195	661	307
170	64	297	184	263	457	AVG.		250
170	91	220	184	289	227	196	577	125
170	115	207	184	291	180	196	604	284
170	116	130	184	264	311	196	631	246
170	117	221	184	237	266	196	658	300
170	118	238	184	238	311	196	685	397
170	142	185	184	265	170	196	659	215
170	169	234	184	292	134	196	632	255
170	170	350	184	293	296	196	605	271
170	143	246	184	266	243	196	578	349
170	144	232	184	239	165	196	548	253
170	171	224	184	267	143	196	549	269
170	145	317	184	294	260	196	575	257
170	113	184	184	319	294	196	602	271
170	168	306	184	346	227	196	629	281
170	141	174	184	347	279	196	656	254
170	114	308	184	320	283	196	683	275
AVG.		239	184	321	251	196	684	193
171	770	218	184	348	249	196	657	236
171	769	162	184	290	238	196	630	199
171	768	331	184	316	342	196	603	226
171	767	323	184	317	408	196	576	317
171	6	128	184	344	273	196	600	372
171	65	137	184	372	347	196	627	318
171	11	278	184	345	151	196	682	158

171	10	145
171	736	259
171	33	179
171	61	296
171	34	82
171	7	201
171	737	310
171	738	186
171	8	310
171	35	165
171	62	191
171	89	244
171	90	318
171	63	308
171	36	54
171	9	177
171	739	223
171	740	151
171	37	263
171	64	297
171	38	144
171	741	240
AVG.		220
172	85	220
172	732	181
172	2	171
172	29	236
172	56	145
172	83	283
172	84	127
172	57	228
172	30	123
172	3	142
172	733	244
172	734	245
172	4	132
172	31	136
172	58	129
172	86	98
172	59	207
172	32	244
172	5	202
172	735	144
172	6	128
172	60	295

184	318	276
184	373	351
184	374	398
AVG.		262
185	319	294
185	346	227
185	347	279
185	320	283
185	321	251
185	348	249
185	344	273
185	371	536
185	398	263
185	399	342
185	372	347
185	345	151
185	318	276
185	373	351
185	400	331
185	427	251
185	454	220
185	455	305
185	428	278
185	401	337
185	374	398
185	375	293
185	402	397
185	429	274
185	403	365
185	376	300
185	425	382
185	453	200
185	426	173
AVG.		300

196	655	317
196	628	280
196	601	134
196	574	194
AVG.		264
197	546	283
197	604	284
197	548	253
197	549	269
197	575	257
197	602	271
197	629	281
197	656	254
197	683	275
197	657	236
197	630	199
197	603	226
197	576	317
197	547	363
197	653	423
197	626	317
197	599	307
197	572	388
197	573	146
197	600	372
197	627	318
197	654	382
197	682	158
197	655	317
197	628	280
197	601	134
197	574	194
AVG.		278
198	1006	289
198	1007	340
198	1008	292
198	1009	229
198	677	402
198	568	264
198	595	358
198	622	334
198	649	211
198	676	353
198	650	345
198	623	274

172	55	277
172	28	195
172	33	179
172	87	227
172	111	207
172	112	246
AVG.		191
		-
		-
		-
		-
		-
		-
		-
		-
		-

198	596	113
198	569	175
198	542	300
198	678	277
198	651	300
198	624	241
198	597	133
198	570	278
198	571	415
198	598	390
198	625	288
198	652	282
198	679	159
198	626	317
198	599	307
AVG.		284

Table 3. East Fort Rock – Complete Removal. Average soil strength per tree and per plot in pounds per square inch for the 15-, 30- and 45-foot radius.

15 FT. RADIUS TREE#	PSI	30 FT. RADIUS TREE#	PSI	45 FT. RADIUS TREE#	PSI
160	163	160	184	160	201
161	197	161	200	161	216
162	258	162	248	162	249
163	222	163	221	163	238
164	199	164	217	164	217
165	257	165	232	165	227
166	218	166	239	166	240
167	257	167	253	167	254
168	254	168	257	168	259
169	254	169	244	169	247
170	239	170	237	170	243
171	220	171	233	171	236
172	191	172	210	172	221
173	259	173	248	173	249
174	246	174	255	174	260
175	242	175	254	175	269
176	238	176	263	176	266
177	268	177	275	177	280
178	266	178	261	178	272
179	269	179	279	179	273
180	285	180	281	180	271
181	282	181	277	181	270
183	286	183	261	183	256
184	262	184	257	184	253
185	300	185	267	185	270
186	272	186	277	186	268
187	264	187	284	187	273
188	267	188	263	188	259
189	256	189	244	189	237
190	298	190	274	190	252
191	294	191	284	191	265
192	249	192	252	192	251
193	267	193	255	193	256
194	254	194	262	194	264
195	250	195	249	195	257
196	264	196	266	196	264
197	278	197	277	197	265
198	284	198	283	198	270
AVG.	253		253		253