Tillage of Compacted Soil in a Thinned Douglas-fir Stand in Western Oregon: Soil density and residual tree growth seven years after treatment

by

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Abstract

A set of 119 study trees was identified in a 65 year-old Douglas-fir stand after a thinning operation conducted seven years ago using pre-planned skid trails and ground-based machinery. Some of the trails were tilled using a winged subsoiler after this operation in order to alleviate the effect of compaction caused by the heavy machinery used during logging.

The primary objective of this study was to determine whether tilling compacted forest soils after a harvesting operation serves to alleviate the compaction over time, and if tillage has any discernable positive or negative effect on the growth of the residual trees adjacent to tilled skid trails. To clarify growth relationships, soil bulk density measurements were taken around study trees adjacent to undisturbed areas, tilled trails, and untilled trails. In addition, different tree growth parameters and competition indexes were evaluated to help distinguish thinning and other effects.

The results showed that although mean soil bulk densities were generally higher around trees adjacent to untilled skid trails, there was no statistical difference between the densities in untilled and tilled zones (95% confidence level). This may help explain the observation that seven years after the thinning and tillage, there was no apparent benefit or damage to the growth response of trees adjacent to tilled trails.

Regression analysis of several important stand and site variables showed that just two were meaningful in predicting growth, diameter at the time of thinning and Competition Stress Index after thinning (95% confidence level).

This suggests that limiting the area of compacted or tilled soil by the use of planned skid trails may have effectively restricted the treatment growth response to the influence of basic tree and stand characteristics after thinning.

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1. Introduction and Justification of the study.

As part of the sustainability concept in natural resource management, maintenance of soil productivity is of primary importance. Not only is the soil an essential foundation for other resources, in some respects it can be considered non-renewable at the human life-span. In Oregon, interest in protecting soil productivity has grown at the same time forest harvest operations have become increasingly mechanized to boost logging productivity and to reduce labor costs. Favorable timber characteristics and expanding capabilities of harvesting equipment now result in a very large amount of logging using ground-based systems.

Unfortunately, increased traffic by logging vehicles has the potential to negatively impact soils and forest site productivity. Many studies have shown that the growth of newly established plantations in clearcut areas as well as residual stands after ground-based thinning operations can be significantly affected by soil compaction. Ground pressure and vibration from heavy logging vehicles can consolidate soil particles and aggregates, resulting in soil conditions that can impede drainage, aeration, and root growth.

In recent years, thinning of young-growth conifer stands in Oregon has increased because of changes in both silvicultural standards and log prices and logging systems that make these operations more cost-effective. Although a basic understanding of compaction effects on residual stand growth currently exists, many questions remain about specific management practices and prescriptions to prevent or alleviate compaction problems.

One such practice is tillage of compacted skid trails, which is now prescribed after thinning by some resource managers. Research has shown clearly that tillage can help alleviate compacted conditions and improve the growth of seedlings planted in tilled soil, but there has been almost no investigation of the effects of tillage on residual tree growth in thinned stands. This case study was designed and conducted to help address this important information gap.

2. Objectives

This observational case study was initiated eight years ago by the Forest Engineering Department in cooperation with the USDI Bureau of Land Management. The initial phase of the study (Hogervorst, 1994) focused on the immediate effects of thinning and tillage on soil bulk density in a 58-year old Douglas-fir stand near Noti in western Oregon. The primary objectives of the current study were to:

a) Quantify soil bulk density levels for the different treatments seven years after the original operations.
b) Evaluate the growth of residual Douglas-fir trees before and after thinning and tillage.
c) Investigate potential relationships between residual tree growth and soil bulk density and tillage, including key local variables.

3. Literature review.

3.1 General effects of compaction on soils and plants.

Soil compaction is most often defined and identified by an increase in soil bulk density, which in turn is defined as the ratio of the mass of solids to the total soil volume. For western Oregon forest soils, bulk density values range from about 0.5 to

0.9 g/cm^3 (McGreer, 1979), which contributes to their reputation as low strength soils that are quite susceptible to compaction by heavy machinery during forest operations.

The main factors influencing the degree of compaction in forest soils are: 1) amount and type of energy applied; 2) soil texture and structure; 3) depth and nature of the surface litter; 4) soil moisture content (Adams and Froehlich, 1981).

Engineering analysis has shown that the level of compaction can vary significantly with soil moisture content, for any given soil and applied compactive energy. For many soils there is an optimum moisture level at which the highest compaction is reached. However, the low initial strength of most undisturbed forest soils often renders them susceptible to significant compaction over a wide range of moisture levels.

Coarse textured soils, and soils with a wide range of particle sizes often have the highest undisturbed densities, and thus attain the highest densities following compaction. However, fine textured forest soils suffer a larger increase in density on a percentage basis (McGreer, 1979). Froehlich and McNabb (1983) stated that soils with the highest compacted bulk density often are judged most susceptible to compaction, and such soils generally have a relatively broad distribution of particle sizes. Fine-textured soils may not be compacted to high densities because they have proportionally more micropore space, which retains more water than coarser-textured soils, and is resistant to densification because this moisture is not readily displaced.

Soil bulk density is a parameter that can be strongly associated with effects on root growth (Fisher and Binkley, 2000), with the range of bulk density tied to limits to root growth or tree species generally spanning from 1.1 g/cm^3 for silty clay soils to about 2 in clay loam. They also say that, in general, tree roots grow well in soils with bulk densities of up to 1.4 and it starts to cease around 1.7.

Some researchers have proposed that there is a threshold bulk density above which plant root growth is essentially stopped, and this value varies for the different species, soil moisture content and soil texture. Daddow and Warrington (1983) referred to this threshold as "growth-limiting" bulk density (GLBD), and their regression analysis suggested that soil texture is the most important soil property determining its value, although this relationship has some limitations for practical applications.

Changes in soil strength from compaction are likely to exert a very direct influence on root penetration. However, definition of limiting levels remains challenging, because although the force that roots can exert is in the range of 50 to 150 Mpa, some species can penetrate soil strength up to 300 MPa (Fisher and Binkley, 2000). Changes in soil aeration due to compaction also can influence rooting with the limit in oxygen concentration necessary for respiration ranging from 10 and 20%, and varying with species. Moreover, soil moisture is considered to be the parameter with greater influence on root development and distribution than other soil factors (Fisher and Binkley, 2000).

As far as the direct effects on roots, first it must be said that for most of the species the majority of the fine roots (< 2 mm) lie in the upper 20 cm of the soil (Fisher and Binkley, 2000). Unfortunately there are limited studies reporting detailed characteristics of roots for different species. For Douglas-fir, Strand (1964) found the following root distribution in dry weight of roots (g/l of soil): 0-8" 2.24 (accumulated percentage 38.2%), 8-16" 1.90 (70.6%), 16-24" 0.65 (81.7%) and 24-32" 1.07 (100%). Although such data are helpful, root distribution in terms of diameter classes is more useful, since fine roots play the main role in water and nutrient uptake.

When compaction takes place there is a reduction in the pore space in the soil, with potential and impacts on air and water available for plants. Cambell and others

(1973) studied effects of rubber tired skidder compaction on sandy loams to clay loams in Georgia, found that after 10-15 trips, the volume of large voids decreased, and the amount of plant available water was decreased by 15%.

Using undisturbed areas as a reference, Steinbrenner and Gessel (1955a) reported some results from another study (Steinbrenner and Gessel,1955b), determined that air permeability was reduced in 35% on cutover areas, and 92% on skid roads; macroscopic pore space showed a loss of 11% on the cut-over, and 53% on skid roads. Bulk density did not show a large change on the cut-over areas but increased almost 35% on the skid roads.

The effects of soil compaction on plant function is highly complex due to the numerous variables that can play a role. Whitaker (1983) states that it is misleading to discuss the effects of compaction in terms of threshold values of one soil physical concept such as bulk density (e.g., GLBD), since plant stresses created by compacted soil are additive and highly interdependent. For example, because soil moisture has a greater influence on root development and distribution than other soil factors (Fisher and Binkley 2000), compaction effects on porosity, drainage, and moisture retention all may be important.

3.2 Effects of compaction on seedling and tree growth.

To accurately interpret the effects of compaction on tree growth, it is useful to know in detail several parameters such as, species, age of the stand, silvicultural operations carried out on the stand, type of machinery used, as well as a detailed description of the site and stand conditions before and after treatment. Without such information the findings may be of limited use, particularly any conclusions that might be drawn for forest managers. Unfortunately, compaction studies vary widely in their quality and interpretation of the effects on growth.

Another complication is how authors define and separate different effects in a so-called "compacted area". Where harvesting operations have taken place we can find a wide variety of soil disturbances as: mixing, exposure, rutting, puddling, displacement, and scalping (Allen, 1997), and compaction (defined as an increase in soil bulk density), but not all these disturbances have been considered in tree growth studies. Several authors have found growth effects attributed to these other types of soil disturbance (Sirois et al., 1985; Zabowski et al., 1994).

Power (1974) isolated the effects of soil removal from those of actual compaction, and found that for a clay loam, height growth on areas compacted, on areas with topsoil removed, and on areas that were both compacted and with topsoil removed, was 35, 32 and 75% lower respectively, than on adjacent control areas. These results suggest that significant caution is needed when comparing and interpreting growth effects among studies that do not explicitly distinguish and evaluate types of disturbance other than compaction. And they also may help explain the wide variability in the results obtained from different studies.

Studies have shown that compaction can affect the growth of trees, be they older residual trees in thinned stands or newly-established seedlings in open areas like clearcuts.

There are numerous studies showing the effects of soil compaction on seedling growth (Foil and Ralston, 1967; Heilman, 1981; Minore et al., 1969; Sands and Bowen, 1978; Steinbrenner and Gessel, 1955; Younberg, 1959; Zisa et al., 1980;). Youngberg (1959), reports differences of up to 40% in 2-0 Douglas-fir seedling height growth associated with compaction. Froehlich (1979) found height growth differences of up to

16% for 1-0 Douglas-fir seedlings. Perry (1964) found height growth differences of 55% for planted loblolly pine after 26 years. Power (1974) found differences after 8 years in Douglas-fir seedlings of 9 times in height, and 3 times in diameter. In most of these studies it also was observed that soil compaction during harvesting operations affected the growth of seedlings established either by natural regeneration or planting.

The effects on seedling establishment appear not as harmful, as most observers report a reduction in the number of established seedlings only in the most heavily compacted areas. An exception is Steinbrenner and Gessel (1955), who reported that soil disturbance on skid roads reduced the stocking by nearly 50%, and the number of established seedlings by two-thirds when compared to the adjacent cut-over area.

Regarding thinning effects, Froehlich and Berglund (1976) state that the soil related factors assumed to be the most important in influencing the ability of a tree to respond to thinning when compaction occurs were, 1) the percent of the root zone compacted, 2) the percent increase in soil density above undisturbed levels and 3) the distance from the stem to the major compaction impact.

Moehring and Rawls, (1970) reported an interesting study, conducted on silt loams. Soils were compacted with 6 passes of a tractor on 1, 2, 3, and 4 sides of individual loblolly pines trees. They reported that effects were not significant on dry soils, but when wet, the basal area growth over a 5 year study period decreased by 0, 13.7, 36.3 and 43.4% for compaction on 1, 2, 3 and 4 sides, respectively. Moehring and Rawls (1970) also found for the two most heavily compacted areas, reductions in cubic stem volumes of around 36 and 43 percent, and Power (1974), reported reductions around 40% in volume growth on heavily compacted sites in thinned stands.

Froehlich and Berglund (1976) defined three compaction impact classes for individual trees, based on the aforementioned factors (root zone compacted, density increase, distance to compacted area). After stratifying residual trees by these categories they reported that 60% of the trees in heavily compacted areas, 14% of the trees in the moderate class and just 4% in the lightly disturbed class had a lower growth rate than those in undisturbed areas.

When comparing results between the Pacific Northwest and southeast U.S. Froehlich (1979c) mentions that given the shallow rooting pattern of western hemlock (Tsuga heterophylla), it is possible that this species would be more sensitive to soil impacts than loblolly pine (Pinus taeda Law.). This observation reminds us that the unique physiological characteristic of each species should be considered and that species-specific studies are most useful.

Froehlich and Berglund (1976) found that compaction from thinning reduced growth of residual trees in Douglas-fir stands over a wide range of age, i.e., 34 through 80 year-old stands. However, the response in thinned stands is complex because several factors related to the stand conditions can influence the net growth response, including variables such as diameter and level of release (Froehlich, 1979d). For example, for trees with good release the post to pre-thinning growth ratios with and without compaction were 1.21 and 1.42 respectively, whereas those with poorer release were 1.15 and 0.93 respectively. Good release was defined as having thinning release on at least two sides.

Froehlich and Berglund (1976) found that the tree diameter at time of thinning was the factor most strongly correlated with the basal area thinning response ratio (i.e., the ratio of basal area growth after to before thinning, for equal time periods). On the other hand, they found crown volume and crown length, which normally are important growth prediction parameters, had a limited range for the selected trees and consequently were of limited value in predicting growth responses. The smaller diameter stems typically increased in basal area at a higher relative rate than larger stems.

Wert and Thomas (1980) found that compacted skid trails had significant effects on the growth of natural regeneration in a Douglas-fir stand where no site preparation was carried out to facilitate early development of the new stand. Though this finding seems obvious, this work was unique in that it has been quantified the volume losses caused by the compaction on a stand basis since natural establishment, which showed 11.8% less volume, 30 years after the original clearcut.

3.3 Change in bulk density and area affected.

The interaction of so many soil, site, and operational factors has produced a wide range of compaction results, both within and between studies (Armlovich, 1995). This complexity makes interpretation and extrapolation of results very challenging. Depending on how the harvesting operations have been conducted, the percentage of area affected by compaction will vary. However, compacted area for traditional ground-based "loggers choice" (i.e., unplanned vehicle traffic) harvesting generally ranges from 20 to 35% for a single entry and up to 80% for multiple entries (Adams, 1991). It is important to keep in mind when considering these numbers that, while they represent a significant area covered by skid trails, the whole area under consideration has not suffered the same effects, and the degree of compaction and other disturbance usually varies considerably. For example, Allen and Adams (1997) found that compaction did not occur in the center of the skid trails until very high traffic levels.

Allen (1997) found in a ground-based thinning operation using harvester and forwarder that the impact of both vehicles combined was of a density increase 12% at 4 inches depth, and 11% at 8 inches depth. The total compacted area reached 29-31%, assuming that the compaction is constant along the width and length of the trails regardless of the number of equipment passes.

Froehlich (1979b), on a clay loam soil with an initial density of 0.92 g/cm^3 found no increase in soil bulk density at 3 trips, and 10% at 6 to 10 trips. But for a sandy loam soil with initial density of 0.87, he found a 7% increase, and a total of 15% at 10 trips. This and most other research literature generally indicates that most compaction can be expected in the first few vehicle trips.

Lenhard (1978) found that logging with a Clark 666 rubber-tired skidder on a dry volcanic ash soil resulted in the highest relative increase in density after four passes, from 0.75 to 0.88 g/cm^3; and density at 32 passes was slightly higher than at 4, yet macropore space had decreased 87%.

Power (1974) states that if wet soils are heavily traveled, damage by rubber-tired skidders will be similar to that caused by tractors. Studies of compaction from cable logging systems in the Pacific Northwest show no significant effects, (Dyrness,1965; Aulerich, 1974; Packer,1974), including a recent investigation of a young-stand thinning using a small wood yarding system (Allen et al., 1999)

Guo and Karr (1989) highlight the influence of soil moisture on the effects of compaction. Under dry conditions, one pass with the skidder increased density 16%, however, under moist conditions generally more than 50% of the total compaction occurred after one pass, and 90% of more after three passes. Moisture is likely to enhance compaction in soils with significant clay content, whereas loose-grained, sandy soils may compact readily even when dry.

There is wide variability in the reported figures for percentage of area affected and level of compaction. Steinbrenner and Gessel(1955), found an average 35% soil density increase (from 0.86 to 1.11 g/cm^3) on skid trails, which occupied 26% of the units. Hatchell et al.(1970), found between 12 and 20% of the logged areas in skid trails, with average increases in bulk density from 0.75 to 1.08 and 0.92 g/cm^3 (44% and 23% increases respectively). Armlovich (1995) found a maximum increment in bulk density of 28% for 0-4 inches depth after +30 passes and a minimum of 9% for 0-12 inches depth.

Froehlich (1978) studied compaction on a logging operation using a low ground pressure torsion suspension vehicle (TSV) whose design was expected to reduce soil impacts. He found less than a 3% increase in density at any depth with up to 20 trips, for a sandy clay loam with an initial bulk density of 1.06 g/cm^3 at 0-2" depth, 29% moisture content, and a thick litter layer (5-9"). In contrast, on a sandy loam, with initial bulk density of 0.65 at 0-2" depth, and litter layer of 2 to 8", soil density increased 58% within 3 trips; on another sandy loam, with initial density of 1.09, moisture content 13% and no litter layer, there was an increase of 11% for the 0-2" depth after 1 to 3 trips. It was noteworthy that the TSV minimally disturbed the litter layer, which apparently helped limit the degree and depth of compaction.

McNeel and Ballard (1992) found that for a total of 19.7% of area compacted in a mechanized operation, only 6.7% of the area was in heavily traveled trails, the rest was in lightly traveled trails. This further highlights the importance of examining not just the total percentage of area compacted but also the specific levels of compaction within the affected area. Likewise, Kairiuskstis and Sakunas (1989) reported that from numerous studies the impacts were greatest on wet soils, where 45% of the logging area was affected by heavy compaction (>15% bulk density increase), in contrast with dry soils where the percentage of such compaction was around 25% of the area.

Armlovich (1995) found a total of 23.2% of a harvest area affected by compaction after logging with a harvester-forwarder system in a second-growth stand in the lower Cascades of western Oregon. However, the affected area did not have the same level of compaction, and only 4.5% of the area had an increase higher than 15% when considering the 0-12 inch soil layer. This study used a single probe nuclear densimeter, which limits the detailed evaluation of effects on discrete soil layers.

It is generally accepted that the first few vehicle passes are the ones that increase the bulk density most rapidly (Adams and Froehlich 1981), after which density increases level off as the soil gains sufficient strength to support the vehicle. And because the maximum dynamic surface pressures are similarly high for a variety of conditions and vehicles (Lysne and Burditt 1983), it is not surprising that generally no major differences have been found between different types of logging equipment after a high number of machine passes (Armlovich, 1995).

3.4 Recovery of compacted soil conditions.

For western Oregon forest soils, the recovery of soils that have suffered compaction due to harvesting operations through the use of heavy ground-based harvesting machinery is quite slow generally. The normal recovery period may be as high as 30 to 50 years (Vanderheyden 1980) depending on the soil conditions, the site and its features and the kind of operation undertaken on them. Froehlich and Berglund (1976) state that soil texture can be an important influence on the amount of initial compaction and the rate of recovery.

Rain-dominated Pacific Northwest soils are less likely to show a high soil recovery rate, because the conditions that facilitate this are less common, including freeze-thaw cycles and coarse soil textures. Even in an area with freezing and thawing (central Oregon), Froehlich (1979 a) found that for a compaction study in a young ponderosa pine stand, the soil density after 16 years barely had changed from the values obtained at the time of thinning. In other regions, researchers have reported shorter recovery times. For example, McGreer (1979), and Hatchell et al.(1970) indicated that about 18 year period is necessary, and Dickerson (1976) indicated a 12 year recovery period.

Clearly, the long recovery time observed in many Pacific Northwest forest soils reinforces concerns about long term site productivity and other impacts of soil compaction. Thus, methods to reduce or alleviate soil compaction from forest operations are important to consider.

3.5. Methods to reduce or alleviate compaction effects

There are four major approaches to reduce or alleviate the degree and extent of soil compaction from forest operations:1) utilize cable systems with at least partial log suspension; 2) reduce the degree of compaction by vehicle, track, or tire design; 3) reduce the extent of compaction by restricting traffic to planned skid trails, 4) ameliorate compacted conditions and effects by conducting tillage operations with effective implements. This discussion will briefly review the latter two approaches, which were used in this case study.

For soil tillage, each set of climatic and soil conditions will dictate the ideal timing (i.e., moisture content) at which the operation is to take place, the depth to which the soil should be tilled, and the quality of the final product. Differences in implements and differences in soil conditions result in vastly different qualities of tillage (Whitaker,1983).

An important benchmark study was carried out by Andrus and Froehlich (1983), which compared different types of implements commonly used to loosen compacted soil. They tested brush blades, rock rippers, disk harrows and a modified winged subsoiler designed specifically for this task. They concluded that the winged-subsoiler produced the best results, with the highest amount of compacted soil tilled. The design of the winged subsoiler appears to promote significant soil lifting and fracturing, and also allows treatment of relatively deep compacted soil layers (Froehlich and Miles, 1984).

After a subsoiling or tilling operation some soil settling is expected, which will depend on the local climatic conditions as well as on the soil characteristics. Luce (1997) reported a settling effect after subsoiling, which was observed under both mulched and unmulched conditions. He observed a decrease in hydraulic conductivity following an initial increase, and even found surface sealing effects that subsequently affected the hydraulic properties of the soil.

Although tillage can be expected to be generally beneficial for compacted soils, its effects on seedling growth are variable, and in the case of residual trees in thinned stands, relatively unknown. Craig et al. (1977) reported an improvement in height of only 4% over the control trees, while Ritchie (1965) found a 69% improvement. These examples parallel the observation that different implements, in different conditions, can turn out in completely different soil treatment results. Kuipers (1963) highlights the importance of monitoring changes in properties such as moisture, temperature, aeration, and strength, if we want to extract cause-effect relationships between tillage and seedling and tree growth.

Whitaker (1983), comparing growth of germinating seedling of Douglas-fir and White fir in soil cores taken from tilled and nontilled compacted soils found that all the growth variables studied (shoot height, shoot weight, root weight and leaf area) resulted at higher values for the seedlings grown in the tilled soil cores than in the nontilled soil cores. She also found that root biomass production was the most effective indicator of soil conditions, and that in the top 20 cm this indicator benefited from soil loosening. This author advises that measurement of different soil physical, chemical and microbiological properties would aid in the interpretation of growth response.

An interesting study is being carried out at the Forest Service Southwestern Research Station in the Milford District, Plumas National Forest (Kliejunas and Otrosina 1997). This investigation has the objective of studying the effects of tilling operations on compaction and tree roots and its corresponding effects on a Jeffrey pine stand. Although this research is still ongoing, there are some initial findings that relate to the focus of this case study.

These researchers defined GLBD levels for two different types of soils, one with a loam surface layer overlaying a clay loam subsoil, and another one with a loamy sand surface over a coarse loam or coarse loamy sand subsoil layer. Such densities were generally reached or slightly exceeded at both the 10 cm and 30 cm depth in skid trails on both soils. They also found that tilling generally produced a positive effect in alleviating soil compaction, with bulk densities reduced to levels comparable to undisturbed areas, except for the loamy soil at 30 cm depth, which did not exhibit a significant change.

4. First stage of this study

The first part of this study began eight years ago, with the results of this work reported in 1994 as a Forest Engineering Department MF paper, "Soil Compaction from ground-based thinning and effects of subsequent skid trail tillage in a Douglas-fir stand" by Johan B. Hogervorst. This section will review the main features of this earlier study, including the original site and stand conditions, the operational treatments, and the initial findings and conclusions.

4.1 Objectives.

The main objectives of the initial study were:

a) Observe both logging and tillage and document those general factors that could affect soil physical properties and residual trees adjacent to designated skid trails.
b) Measure soil density around trees adjacent to untilled and tilled skid trails, and compare these to undisturbed soil densities.

In addition, a set of residual trees in three treatment categories (undisturbed, adjacent to untilled skid trails, adjacent to tilled trails) were identified for a long-term growth monitoring.

4.2 Site Description.

Most of the information in this chapter is more fully discussed in Hogervorst´s MF paper (Hogervorst, 1994), so what follows is intended to be a brief overview and general orientation for those unfamiliar with the initial study.

Location.

The study area is part of USDI Bureau of Land Management Eugene District lands, and is located 25 km west of Eugene in the Oregon Coast Range. The legal description of the location is: Lat. 44 1´12", Long. 123 29´00", NE 1 / 4 , NE 1 / 4, Sec. 11, T18S, R7W, Lane County, Oregon.

Site Description.

The slopes on the study area go from 1% up to around 30%, most averaging between 10 and 15%. From previous soil profile and map analysis performed by Hogervorst, the soils were described as primarily Jory series, with Bellpine series on a small part at the top of the unit. These soils are both clay loams, increasing in clay content deeper in the profile.

The vegetation is composed by salal (Gaultheria shallon Pursh) as the main understory species, dwarf Oregon grape (Berberis nervosa Pursh), California hazel (Corylus cornuta var. Californica [A.D.C.] Sharp), little wood rose (Rosa gymnocarpa Nutt), cascara buckthorn (Rhamnus purshiana DC.), red huckleberry (Vaccinium parvifolium Smith) and ocean spray (Hoodiscus discolor [Pursh] Maxim.). The overstory is nearly all Doulglas-fir, with a few hemlock and Pacific yew (Taxus brevifolia).

The understory vegetation is more dense in the lower parts of the slopes than in the upper parts, perhaps due to better soil conditions. However, this difference was not considered significant enough to be taken into account in the study, and the study area is otherwise quite homogenous in its characteristics.

Stand Description.

The forest stand currently is about 65 year-old Douglas-fir (Pseudostuga menziesii [Mirb] Franco), which was thinned in 1992 at about age 58. The current density is 172 trees/ha (the Appendix includes detailed data on the distribution in diameters and heights of the study trees). The stand generally appears in good condition, with no obvious signs of any disease or insects problems.

There is some visible forest regeneration, i.e., small seedlings two-years old or less, apparently encouraged by the opening of the canopy through the 1992 thinning.

4.3 Study Methods

Treatments

The thinning harvest took place in late July 1992 through the third week of August, and reduced stand densities from about 500 to about 170 trees per hectare. A set of parallel designated skid trails were laid out 46 m apart on the 7.5 ha study area, seven skid trails in total. The machinery used was composed of two small crawler tractors and a rubber-tired skidder. The log volume removed averaged about 31 thousand board feet (mbf) per hectare, with log sizes averaging 25 cm in diameter.

The crawler tractors were used just to skid the trees located on the trails, afterwards all logging was performed by the skidder. The trees were felled to lead by chainsaw, and decked on the landings by the other crawler tractor. Hot skidding was used at this harvesting operation, and the number of skidder passes was recorded to evaluate relationships with compaction levels (Hogervorst 1994).

In early September, 1992, four out of the seven skid trails were designated for tillage treatments (Figure 4.1). For this a winged subsoiler (Froehlich and Miles 1984) attached to a large tracked crawler tractor was used.

A total of 119 trees were chosen for long-term monitoring (Figure 4.1). These trees were not randomly selected, but were considered generally representative of the major strata, which were:

Undisturbed area trees or control trees: trees located in areas that did not experience any soil disturbance from the logging.

Untilled trail trees: these trees were located next to the skid trails that were compacted by the logging vehicles, and were not tilled.

Tilled trail trees: this group of trees were those located adjacent to the trails that were tilled after the harvesting process.

Using a double-probe nuclear densimeter (MC-1 Stratagage, Campbell Pacific Nuclear, Martinez, CA), six soil density measurements were taken around the tilled and untilled-trail study trees at three different depths, 10.2, 20.3 and 30.5 cm, and three around the control trees. Several measurements were taken of the trees themselves: diameter at breast height, total height, crown class, crown length, crown area index, as well as a competitive stress index (CSI) before and after the thinning (Arney, 1973) in order to characterize the competition caused by adjacent trees before and after harvest. Statistical tests included a multivariate repeated measures Analysis of Variance of treatment differences, as well as a stepwise multiple regression to evaluate relationships between bulk density and site and operating variables (Hogervorst 1994).

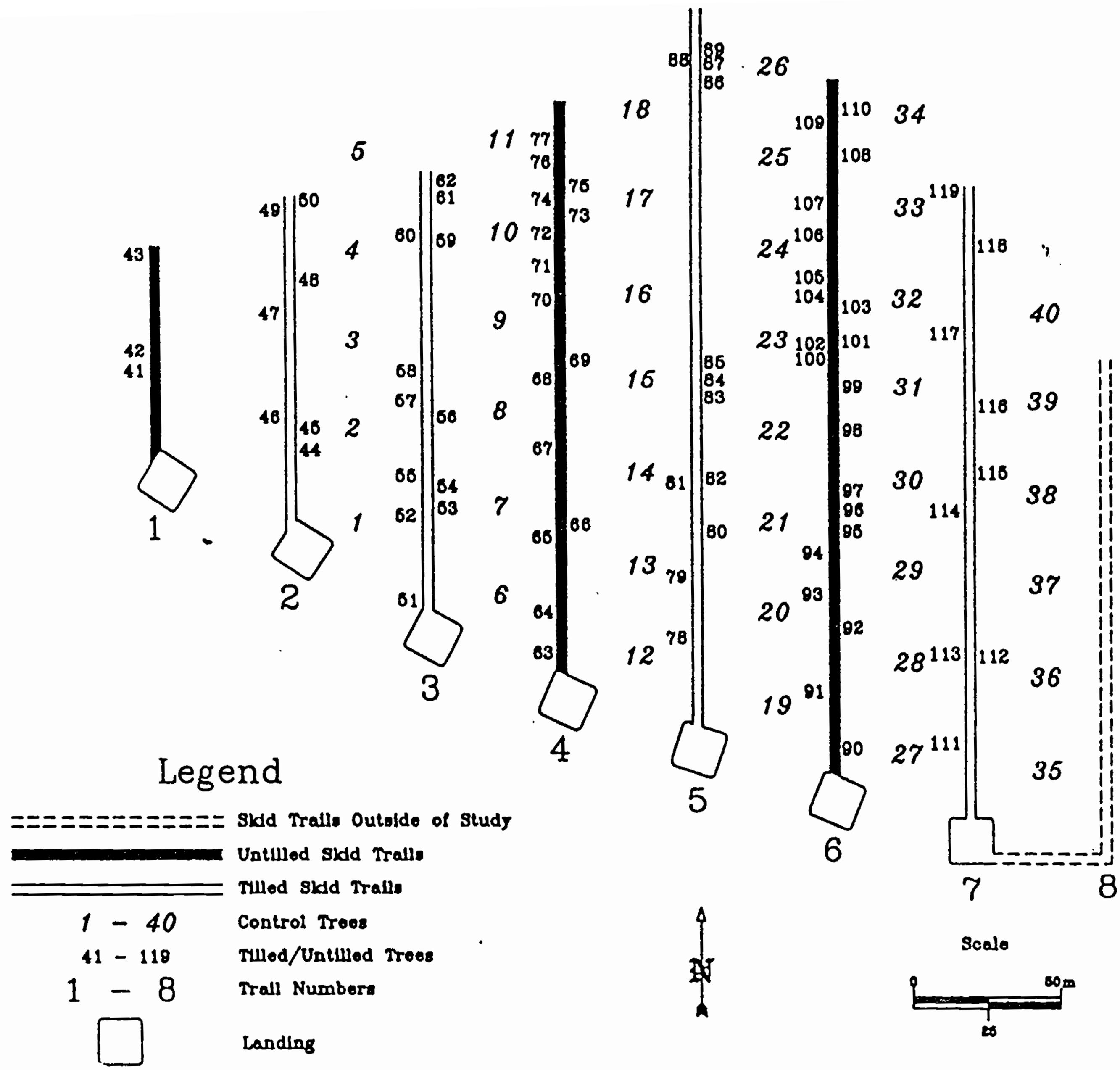

Fig. 4.1. Trees and trails locations (from Hogervorst, 1994)

4.4 Initial Results.

Hogervorst (1994) found that at two depths, 10.3 cm and 20.4 cm, the untilled trail population immediately after harvest showed a higher soil bulk density than the undisturbed soil, 17.8% and 11.2% respectively, but only the difference at the 10.3 cm depth was statistically significant (t-test, $p<0.001$, 0.05 alpha). At the third depth, 30.5 cm, soil densities were similar between untilled and undisturbed soils.

The tilled trail population showed the desired result: densities at 20.4 and 30.5 cm were similar to undisturbed soils, and at 10.3 cm the density increase was relatively small (6.1 %) and statistically insignificant.

Damage to the root systems of some of the trees adjacent to tilled trails was observed during and after the tillage. This occured primarily as severing of larger roots by the subsoiler shanks and such instances were noted to help interpret growth effects.

5. Current Study Methods

5.1. Field methods

5.1.1 Soil density measurements.

A single probe, nuclear densimeter (Model MC-3 Portaprobe, Boart Longyear Company) was used to measure soil bulk density seven years after the initial treatments. The double-probe densimeter used in the first part of this study was no longer functional due to its age. The density was sampled at 25.4 cm (10 inches), which provides an average of soil density over the 0-25.4 cm of soil depth. Although less than ideal for comparisons with the initial study results, this depth was judged very suitable for evaluating general trends in compaction and possible relationships with growth effects.

Soil density was measured during the last two weeks of August, 1999 when the soil moisture was low and consistent. The number and distribution of samples was the same as seven years before. Three samples were taken around the control trees and six samples around the treatment trees, three on trail side and three on off-trail side (Figure 5.1). All of the samples were taken within 0.9-1.1 times the crown diameter of the subject tree. These values were taken from root distribution studies for Douglas-fir in British Columbia (McMinn, 1963; Smith 1964). To help ensure measurement consistency and reliability, each soil measurement was taken twice, turning the probe 90 degrees.

5.1.2. Tree Measurements.

Growth responses of the treatments were evaluated primarily using the approach of Froehlich (1979c) and Froehlich and Berglund (1976). This method calculates a ratio of basal area growth for the post-thinning to pre-thinning periods of equal length, with the objective of reducing the variability due to individual tree elements such as genetic differences, micro-site differences, and other growth affecting factors.

For each study tree, the diameters at breast height were measured using a diameter tape, as well as the thickness of the bark using a bark gauge, in order to compute the basal area increments for the two seven-years periods. The raw data appear in Appendix 2.

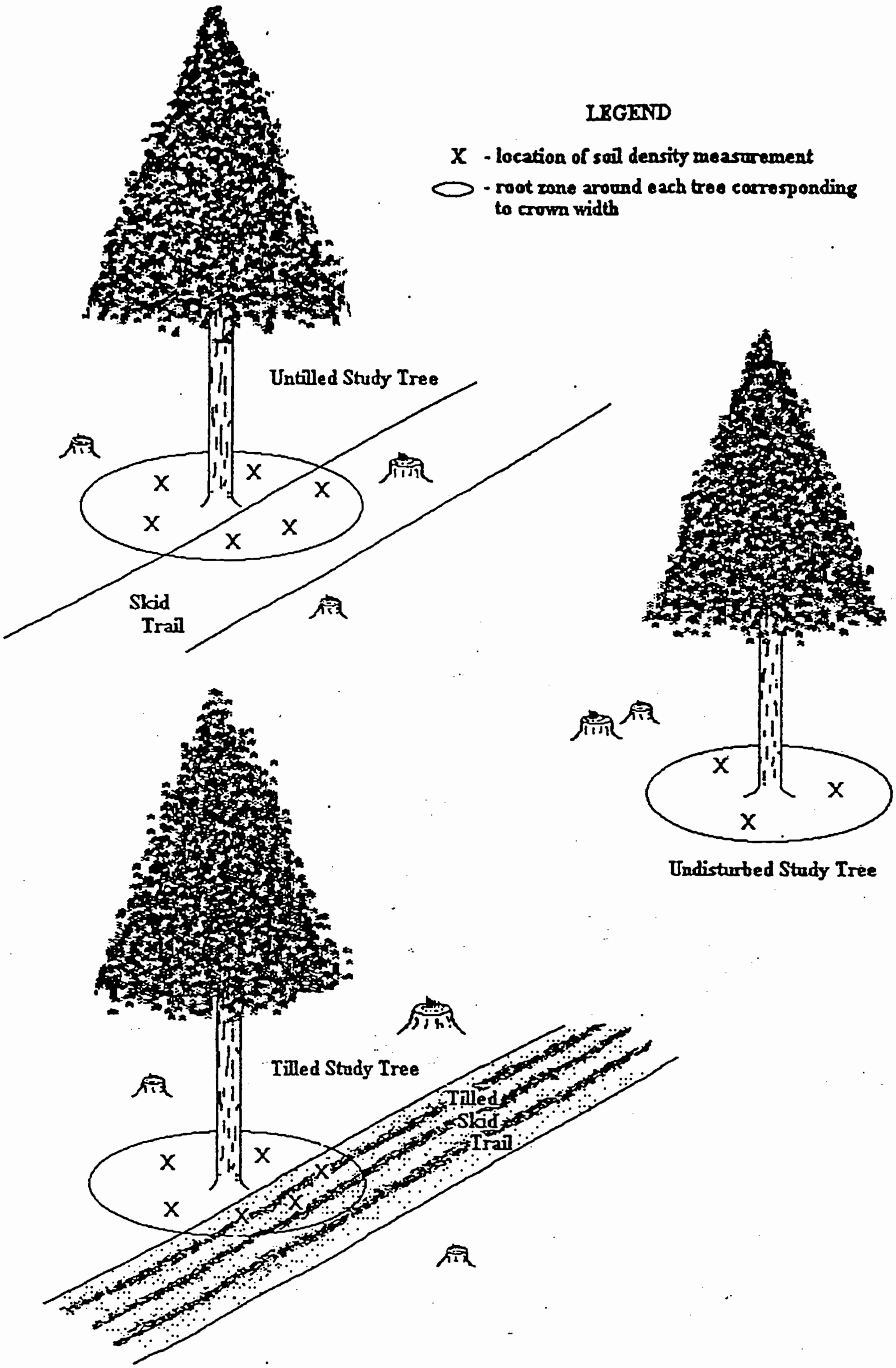

Fig. 5.1. Sampling of soil density around control, tilled and untilled trees (from Hogervorst, 1994)

To compute stem volumes, first the total heights of the trees were measured using a clinometer. However, the measurement error for these values is likely to be high with only six years of post-treatment growth (Arney, 1973). The data obtained are shown in Appendix 3.

To compute the volumes from heights and diameter, two volume equations for Douglas-fir were used, one from Weyerhaeuser Co., and the second one from Bruce and DeMars for second-growth Douglas-fir (both cited in Marshall, 1981). The results using both equations and the average of both are shown in Appendix 4.

5.1.3. Competition Stress Index.

To evaluate the effects of compaction and tillage on tree growth after thinning we first must account for the thinning effects, since a thinning response is expected following release of the stand. One approach to quantify the intertree competition is through the use of competition indices. One of the most widely used of these indices in the Pacific Northwest is Arney´s Competition Stress Index (CSI) (Arney, 1973):

$$CSI_j = 100\frac{(\sum AO_{ij} + A_j)}{A_j}$$

where

CSI_j = competitive stress index of the jth subject tree.

AO_{ij}= area of overlap of the ith competitor's growing space with that of the jth subject tree.

A_j = growing-space area of the jth tree.

The lower the value of this index the less competition has the subject tree.

This index has already been used in some studies to try to predict the periodic diameter growth after thinning in Douglas-fir. For example, Smith and Bell (1983) found that CSI before and after thinning can be used to estimate such growth responses quite reliably.

Hogervorst (1994) computed the Competition Stress Index values (Arney, 1973) for the study trees based on conditions at the time of thinning to facilitate interpretation of post-treatment growth responses. Three different variables were computed using this index, the index before the thinning, after the thinning and the difference between these two index values. They were considered for this study because they provide a quantitative expression of the following key factors before and after thinning:

- The response of the trees to the thinning is influenced by the spatial structure of the stand before the silvicultural treatment, which conditions the initial response of each tree to the release of the stand.
- Similarly, the growth of the trees after the thinning is directly affected by the new distribution of the trees in the stand.

The calculated indexes appear in Appendix 2.

5.2 Objectives, Hypotheses and Statistical Methods.

Following are the objectives and related hypotheses for this study and the statistical methods selected to test the hypotheses.

1) To identify potential differences in soil density among control sites and tilled and untilled skid trails.

- The hypothesis is that after seven years, some significant differences in bulk density levels should still exist between measurements taken around control trees and trees next to untilled trails. Smaller or no significant differences are expected between density levels around control trees and those next to tilled trails. (Note: For simplicity, the trees and soil measurements for the major treatment strata will be referred to hereafter as "untilled trees" and "tilled trees".)

2) To quantify and interpret post-treatment growth of residual trees.

- The hypothesis is that observed differences in soil density around study trees will help explain observed variations in post-thinning growth response.
- Another related hypothesis is that trees that suffered significant root damage seven years ago during the tilling operations will be evaluated as a separate class, with the expectation that this damage can reduce or preclude a positive thinning response.

The key variables that will be used for statistical summaries and tests are: growth ratio (basal area growth after thinning to basal area growth before thinning for an equal period of time), stem volume increment, crown length, crown class, diameter of the tree at time of thinning, Competitive Stress Index, and soil bulk density.

Froehlich and Berglund (1976) found that for a similar study with Douglas-fir, the variables involving crown, considered generally good predictor parameters for growth, did not turn out to be good predictor variables. They also found that the diameter at time of thinning has been a good predictor variable of the basal area ratio values after thinning.

Statistical Procedures.

Following are the steps that have been followed in order to analyze the collection of available data.

The specific variables used for this study are:

- Basal Area Ratio (BAR).The ratio of the basal area increment in the last seven years since the thinning to the basal area increment the seven years before the thinning.
- Volume Increment (cubic feet). Computed from the total height of the tree and the diameter at breast height (DBH), using the average of two volume equations for Douglas-fir, the Weyerhaeuser Douglas-fir cubic volume equation (Brackett, 1977) and the Bruce-DeMars second growth Douglas-fir volume equation (Bruce and DeMars, 1974), both cited by Marshall (1981). Both equations produce volumes in cubic feet, and because neither approach was clearly superior, the average of both increments using the two equations was used as the final variable.
- Soil Bulk Density (BD) (grams per cubic centimeter). This variable was transformed as follows: for each control tree the average of the three measurements was computed and that was the bulk density "assigned" to that tree; for the trail trees, which had two sets of measurements (3 on trail and 3 off trail), the average of the three densities in the trail was assigned as the bulk density for that tree.

- Competition Stress Index (CSI). This variable was calculated at the time of thinning by Hogervorst (1994), following Arney (1973). It was assessed in three different ways: Pre-thinning CSI, Post-thinning CSI and Change in CSI (difference between pre and post-values).
- Diameter at breast height (DBH).
- Crown Class (CC). This variable was also collected at the first stage of this project by Hogervorst (1994).

The raw data sets or these variables were then used to identify specific statistical applications, tests, and conclusions:

- First, the data for each treatment were scanned for outliers (i.e. those values beyond 1.5 the Inter-Quartile Range from the quartiles) and to characterize the data distributions.
- Second, using the above information and the test hypotheses, suitable statistical expressions and tests were identified.
- Finally, defensible conclusions about the initial hypotheses were extracted from the statistical outputs.

The initial screening of the data sets indicated that two types of statistical tests would be appropriate: ANOVA t-test analysis to compare means when the model assumptions are fulfilled, and in case that the variables do not comply with these, non-parametric ANOVA procedures.

Ideal conditions for applying the parametric model (standard ANOVA) are (Ramsey and Schaffer, 1997):

- The two populations have normal distributions.
- The populations standard deviations are all the same.
- Observations within each sample are independent of each other.
- Observations in any one sample are independent of observations in other samples.

However, some departures from model assumptions are allowed by the robustness of t-tests, F-tests, and confidence intervals. Key considerations for such departures include:

- Normality is not critical. Extremely long-tailed distributions or skewed distribution coupled with different sample sizes present the only serious distributional problems, particularly if sample sizes are small.
- The assumptions of independence within and across groups are critical.
- The assumption of equal standard deviations in the populations is crucial.
- The tools are not resistant to severely outlying observations.

A repeated measures design ANOVA was conducted to check whether there are differences between treatments. The resulting design is a 2x2 table and a 1x3 table:

	Control	Tilled	Untilled
In-trail		X	X
Off-trail	X	X	X

A one-way ANOVA also was used to check for differences in undisturbed bulk density among treatments, in order to provide a better understanding of the soil bulk density data and the variability. A General Linear Model (GLM) procedure available in SAS software was also used to conduct a second Analysis of Variance analysis.

For the cases where the presence of either outliers or long-tailed distributions can jeopardize the assumptions to undertake these tests, the Kruskal-Wallis non-parametric rank sum test and the two-sample Wilcoxon rank-sum test were conducted.

Finally, a multiple regression analysis was conducted using the growth variable BAR (Basal Area Ratio) as response variable and several other soil and site variables as independent variables. The regression was conducted using the Stepwise Procedure, with a level of confidence of 0.05.

6. Results and Discussion.

6.1 Soil Bulk Density.

Several different approaches were followed to determine whether a significant compaction effect exists. The first considered one soil bulk density value per tree, in order to more generally characterize soil conditions affecting each tree. This means that for the control trees, with three soil bulk density sampling points taken around the tree, the average was computed. For the other two study tree groups (tilled and untilled), one average for the three measurements off the trails and another one for the three in the trail were computed. The major limitation with this approach is that some information about data variability is masked by the averaging.

The second approach was to not average the individual measurements, thus consider each soil density measurement as one point sample. With this approach we have "control areas", two "off-trail undisturbed areas" for each of the two groups, tilled and untilled, as well as "in-trail tilled areas" and "in-trail untilled areas" (See Figure 5.1).

Following are the summary statistics for each approach (Tables 6.1 and 6.2) as well as the associated box plots (Figures 6.1 and 6.2):

	Averaged			Not averaged		
Treatment	Control	Tilled	Untilled	Control	Tilled	Untilled
Min	0.872	0.808	0.875	0.769	0.618	0.804
1st Quartile	0.942	0.929	0.922	0.917	0.922	0.910
Mean	0.970	0.962	0.947	0.970	0.962	0.948
Median	0.965	0.959	0.946	0.966	0.963	0.941
3rd Quartile	0.996	1.002	0.976	1.017	1.022	0.986
Max	1.096	1.117	1.066	1.169	1.179	1.114
Total n	40	40	39	120	120	117
Variance	0.00268	0.070	0.041	0.0048	0.0087	0.0039

Table 6.1. Summary statistics for soil bulk density (g/cm^3) off-trail measurements, averaged and not averaged point measurements.

Treatment	Averaged			Not averaged		
	Control	Tilled	Untilled	Control	Tilled	Untilled
Min		0.865	0.875		0.619	0.581
1st Quartile		0.945	0.990		0.942	0.962
Mean		0.984	1.018		0.984	1.018
Median		0.992	1.020		0.991	1.029
3rd Quartile		1.023	1.056		1.039	1.077
Max		1.130	1.172		1.238	1.261
Total n		40	39		120	117
Variance		0.0039	0.0038		0.009	0.0097

Table 6.2. Summary statistics for in-trail soil bulk densities (g/cm^3) measurements, averaged and not averaged point measurements.

These data show that soil bulk density has a wide range of values in a small area, as indicated by the difference between the minimum and the maximum, especially in the not-averaged approach. However, the data variability as expressed by the variance is quite small, which suggests that despite the wide range of observed values, there exists a significantly narrower interval that encompasses the main tendency in soil density values. This expectation is borne out by the box plots of the data (Figures 6.1-6.4)

Although not employed in this study, a geostatistical approach may be useful when studying soil parameters where spatial distribution is a important consideration. Allen (1997), for example, used a kriging approach to confirm that the background bulk density values varied spatially in a relatively random manner, which facilitated statistical analysis of treatment effects.

Comparison of the means in bulk densities for the three treatments was initially performed using graphical tools, including box plots, histograms and QQ plots for the two approaches (i.e., averaged and not averaged data). Following are the box plots for both approaches. The box plots show the median P_{50} for each population as a line within the shaded box; the box is defined by the first P_{25} (low end) and third quartiles P_{75}(upper end), thus embracing 50% of the data; the whiskers (or brackets) are located 1.5 times the IQR (Inter Quartile Range), which is the difference $P_{75} - P_{25}$, from the quartiles; finally, the isolated lines represent outliers defined as all those data points farther than 1.5 the IQR.

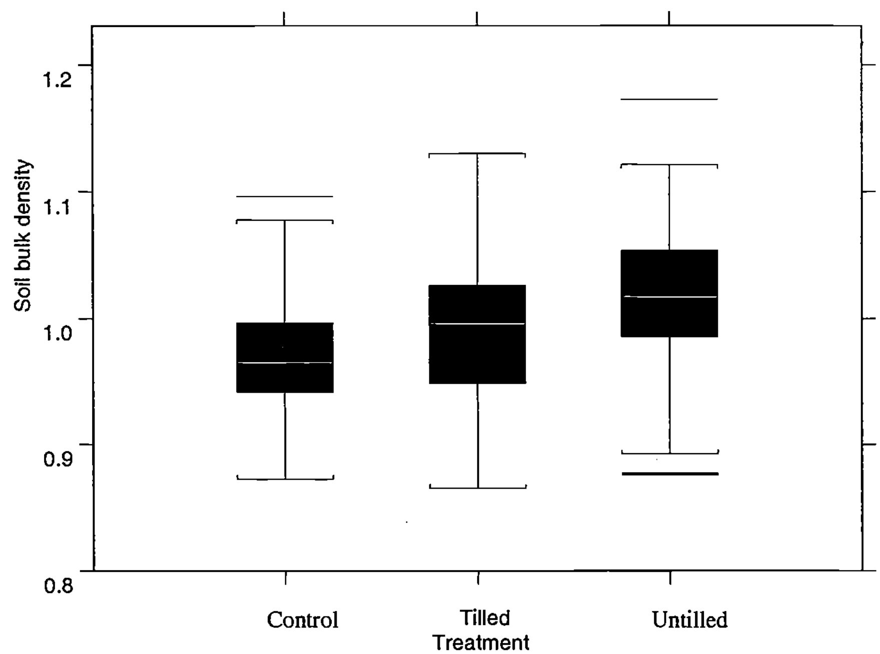

Fig. 6.1- Off-trail soil bulk density (g/cm^3) Box Plots, data averaged.

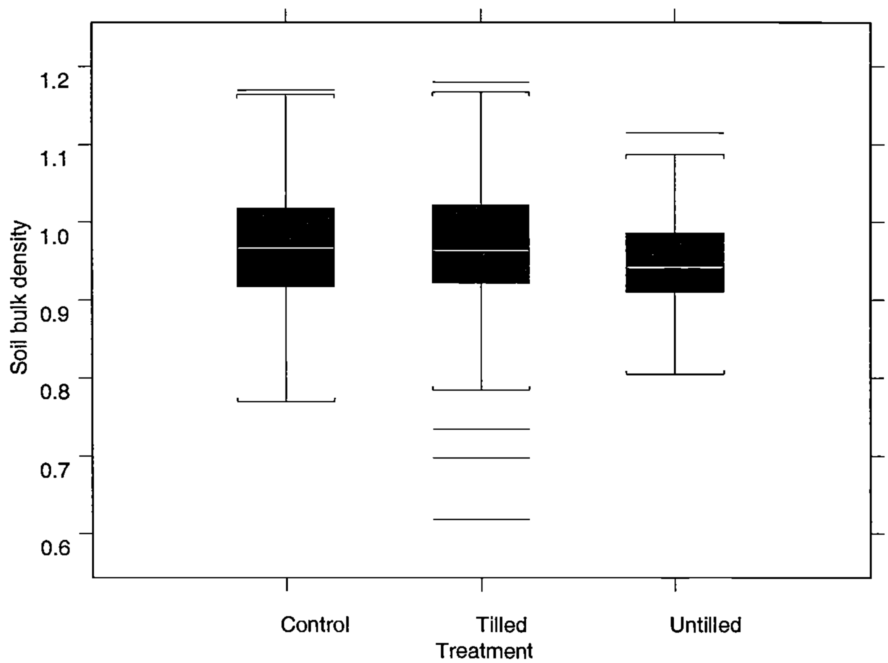

Fig.6.2 - Off-trail soil bulk density (g/cm^3) Box Plots, data not-averaged.

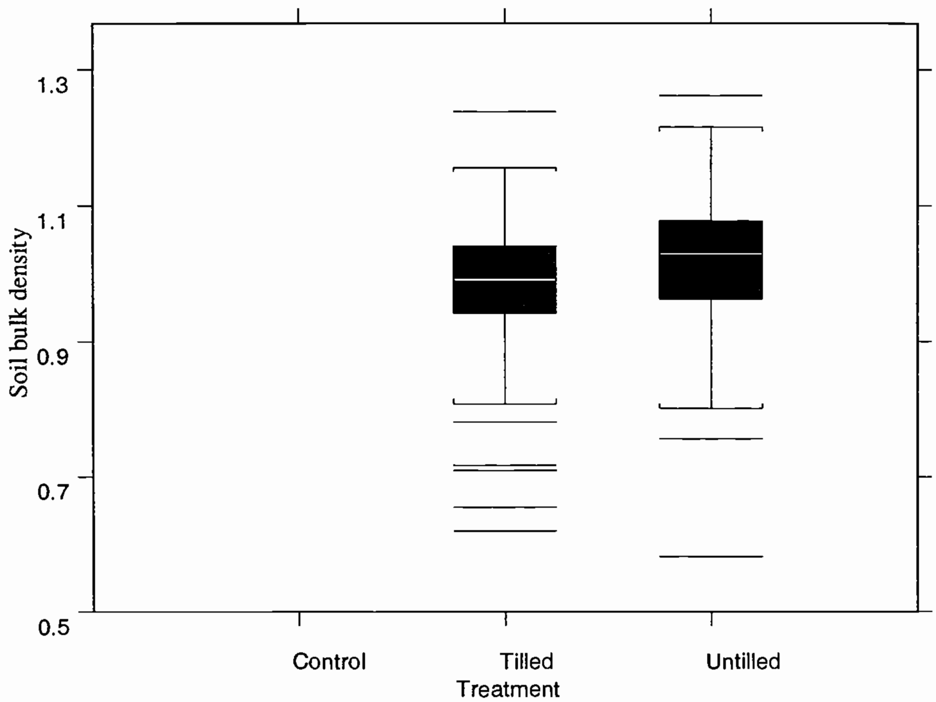

Fig 6.3. In-trail soil bulk density (g/cm^3), data not-averaged

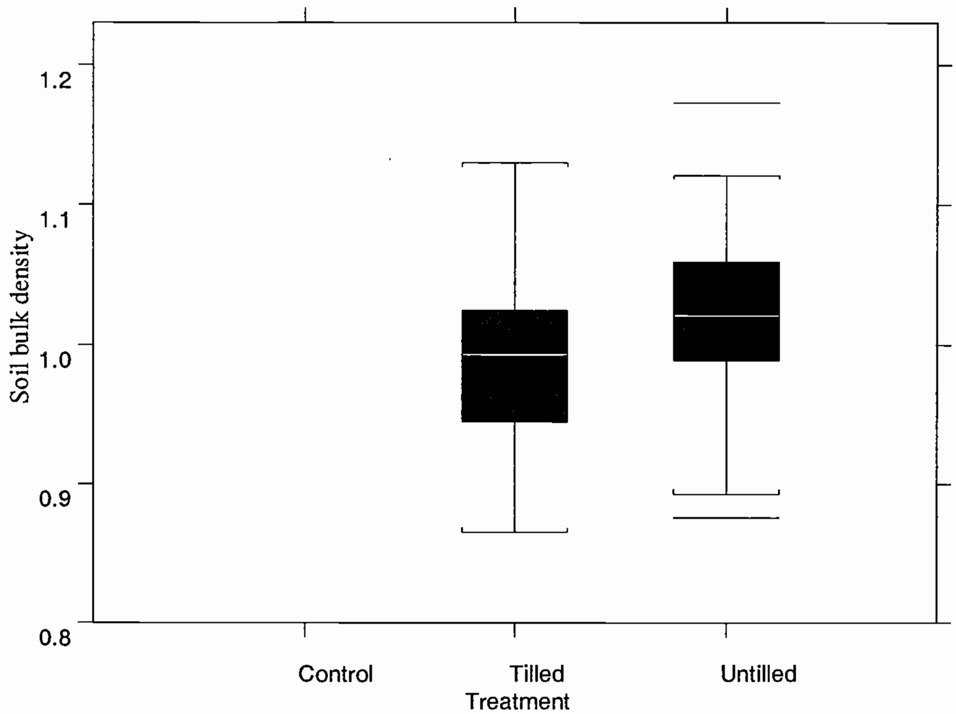

Fig 6.4. In-trail soil bulk density (g/cm^3), data averaged.

There were no major differences between the two approaches (data averaged vs. data not averaged) in terms of the main body of the data distribution. However, because different outliers and variability between both approaches can produce different final results in statistical comparisons, both approaches were used to compare the treatments means.

An initial question in evaluating treatment effects was whether soil density around control trees and in the undisturbed sides of the tilled and untilled trees could be considered from a similar population (see Tables 6.1 and 6.2). To check this an ANOVA F-test was conducted, which showed that not averaged data showed significant differences between populations (p-value = 0.025). However, there was no such difference when averaging the soils data, for a 95% significance level (p-value = 0.079). Because the mean values for each treatment were essentially identical for both the averaged and not averaged data (0.97, 0.96, 0.95 for control, tilled, and untilled respectively), these results show how sampling design and data handling can affect statistical results and interpretations.

Looking at the in-trail measurements, there was a significant difference in soil densities between tilled and untilled trails. Without averaging the measurements the two-sided p-value for a two sample t-test is 0.0072 (see Appendix 5), with a 95% confidence interval (0.984, 1.018). Averaging the data also showed a significant difference (p-value = 0.017), with a 95% confidence interval (0.984, 1.018).

Although there is a significant difference in the average soil density between tilled and untilled trails that follows the expected pattern (the tilled trails are lower that the untilled trails), the magnitude of the observed difference is only 0.034 g/cm^3 or 3.5% higher in the untilled trails. This difference is unlikely to have much practical significance, thus after seven years of treatment, tillage had only a minor effect on soil density.

The third approach, referred to at the beginning of this section, may be the most reliable since it not only uses the non-averaged data, but also considers a richer model to conduct the ANOVA analysis. The previous approach uses a simple means comparison one-way ANOVA, whereas this approach uses a Generalized Linear Model (GLM) to conduct the ANOVA test, making a better use of the information provided by the collected data (MathSoft's Data Analysis Products Division, 1998).

The model was used to determine whether the three groups of data (the control trees measurements, the off-trail measurements in tilled trees and off-trail measurements in untilled trees) came from different populations. The model used to conduct the ANOVA test is

$$BD = Trt + Tree\ (Trt)$$

Where

BD is soil bulk density surrounding each tree.

Trt is treatment (Control, Tilled or Untilled, categorical variables)

Tree(Trt) is the tree number nested by treatment category, so this term accounts for the variability due to each individual tree within each different treatment. This is a nested, mixed model, where the nested term is the random term.

The Least Squares Means for the undisturbed or off-trail measurements obtained from the model for the three different treatments are:

Treatment	Mean
Control	0.970
Tilled	0.962
Untilled	0.947

The results showed no significant differences between the three groups of undisturbed or off-trail measurements at a 95% level of confidence (F-value = 1.60, p-value = 0.2072). This similarity among means is consistent with Hogervorst´s (1994) findings when he compared, for three different depths, the off-trail and the control tree (undisturbed) data. The results allowed further statistical analysis of the bulk density data for the tilled and untilled trees, using the following nested model:

$$BD = Trt + Tree(Trt) + Side + Side \times Trt + Side \times Tree(Trt) + error$$

Where

BD is soil bulk density for the side of the tree being considered

Trt is treatment (Control, Tilled and Untilled, categorical variables)

Tree(Trt) is the tree number nested by treatment category, which considers the variability introduced by each individual tree nested by treatment

Side is a categorical variable considering whether the measurement was in the trail or off the trail

As described earlier, the terms Tilled and Untilled represent both in-trail and off-trail measurements taken for each of the two groups of study trees, so these means show the overall soil density levels around individual trees between the two treatments. Off-trail and In-trail groups represent the two sets of measurements taken around each tree when the tilled and untilled trees are pooled together, consequently these means show potential differences between the soil bulk density in the off-trail side and the in-trail side of all the treatment study trees. Graphical expressions and the least square means using the nested, Generalized Linear Model are as follows:

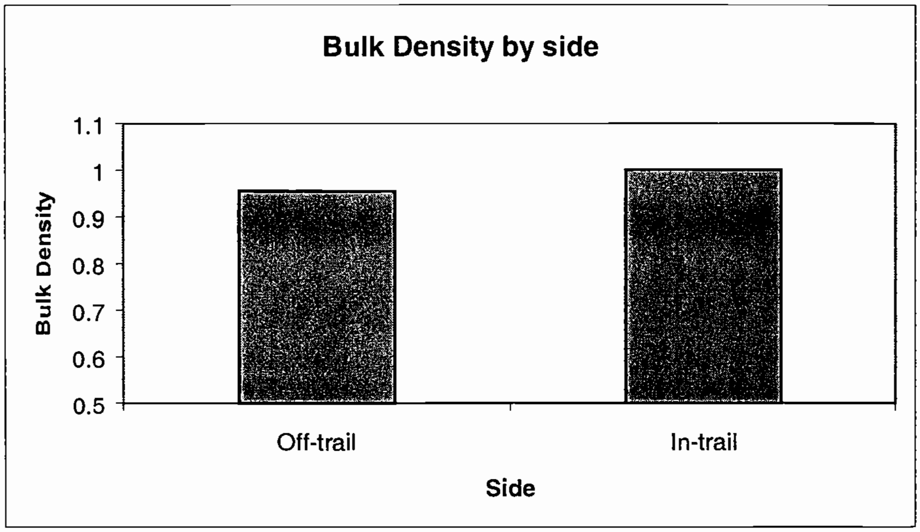

Fig. 6.5. Least Square Means for Off-trail and In-Trail bulk densities (tilled and untilled populations combined) obtained using the Generalized Linear Model: BD = Trt + Tree(Trt) + Side + Side x Trt + Side x Tree(Trt) + error.

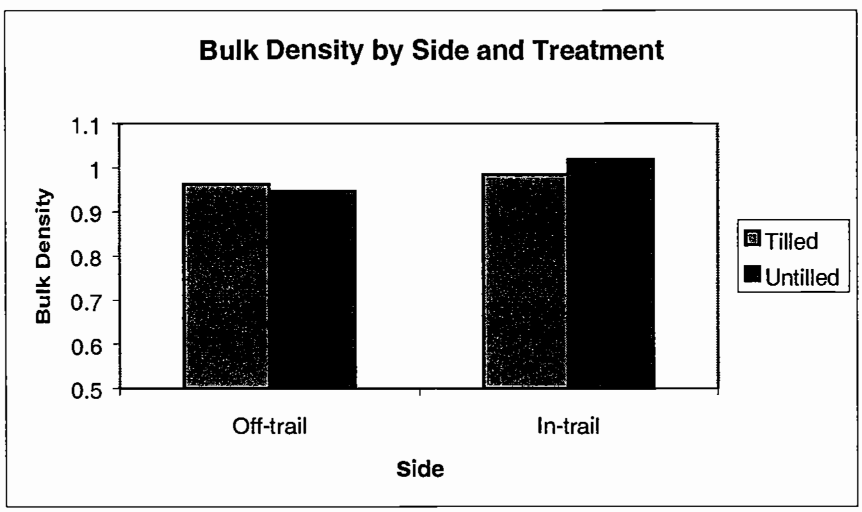

Fig. 6.6. Least Square Means for Off-trail, In-Trail, Tilled and Untilled populations obtained using the Generalized Linear Model: BD= Trt + Tree(Trt) + Side + Side x Trt + Side x Tree(Trt) + error.

The least square means of the bulk density populations obtained through the Generalized Linear Model procedure are as follows:

Treatment	Mean
Tilled	0.973
Untilled	0.983

Treatment	Mean
Off-trail	0.955
In-trail	1.001

Treatment	Side	Mean
Tilled	Off-trail	0.962
Tilled	In-trail	0.984
Untilled	Off-trail	0.947
Untilled	In-trail	1.018

Testing the hypothesis that differences exist in the bulk density values between the tilled and untilled populations, the results showed no significant difference (95% confidence) between the treatments (F-value = 0.91, p-value 0.3440). This model and related test also showed that, as expected, the difference between in-trail and off-trail populations is highly significant (F-value = 29.52, p-value = <0.0001), and that the interaction term between the side and the treatment is also very significant (F-value = 7.89, p-value = 0.0063).

The results obtained using this more complex GLM model, although different from the previous approaches statistically, were consistent in showing significant differences between the two treatments. However, they are also consistent in suggesting that mean differences in soil density are relatively small and of questionable practical significance, even when confined to in-trail areas; in this approach 0.022 to 0.071 g/cm^3 or about 2.3 to 7.5% higher in trails.

6.2 Tree Growth Response.

The second major goal of this project was to determine whether there is actually a difference between treatments in terms of stand growth, expressed as Basal Area Ratio (BAR) and stem volume. As explained earlier, BAR is the ratio of basal area growth from the last seven years after the thinning to basal area growth from the seven years before thinning. Such a value helps account for the effects inherent to individual tree and site characteristics. In contrast, the stem volume variable provides no such accounting and also is limited by the accuracy of the height measurements. Although the results for the volume data are likely to be of significant interest, these limitations suggest that the most robust conclusions will be drawn from the results using the BAR values.

Graphic expressions (box plots) of the BAR data by treatment are as follows:

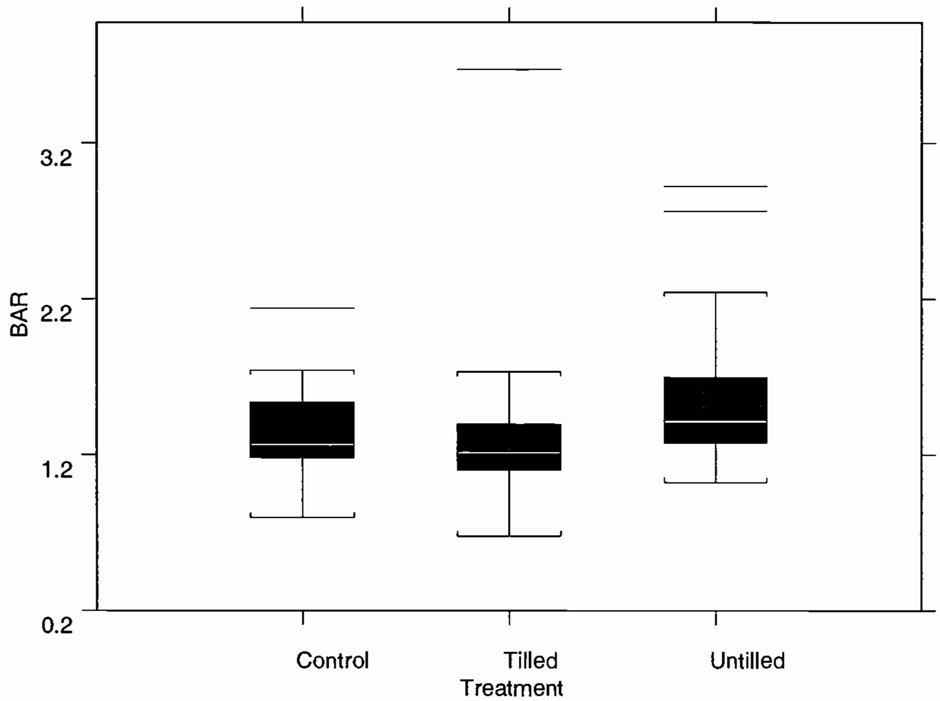

Fig 6.7. Box plots for BAR by treatment.

Visually, there appear to be only minor differences among the treatments. The plots also suggest:

- We have several outliers in the three populations, but there is one very unusual outlier in the tilled group.
- The standard deviations are quite close one each other.

The box plot suggests that the untilled tree population may have slightly higher growth than the tilled population, possibly due to root damage in some of the trees caused by the tillage. Although visual inspection in 2000 did not show any obvious effects (e.g., stem decay) of the trees originally noted with such damage by Hogervorst (1994), a plot of the BAR values for the tilled tree population was used to observe any obvious differences between damaged and undamaged tree growth responses:

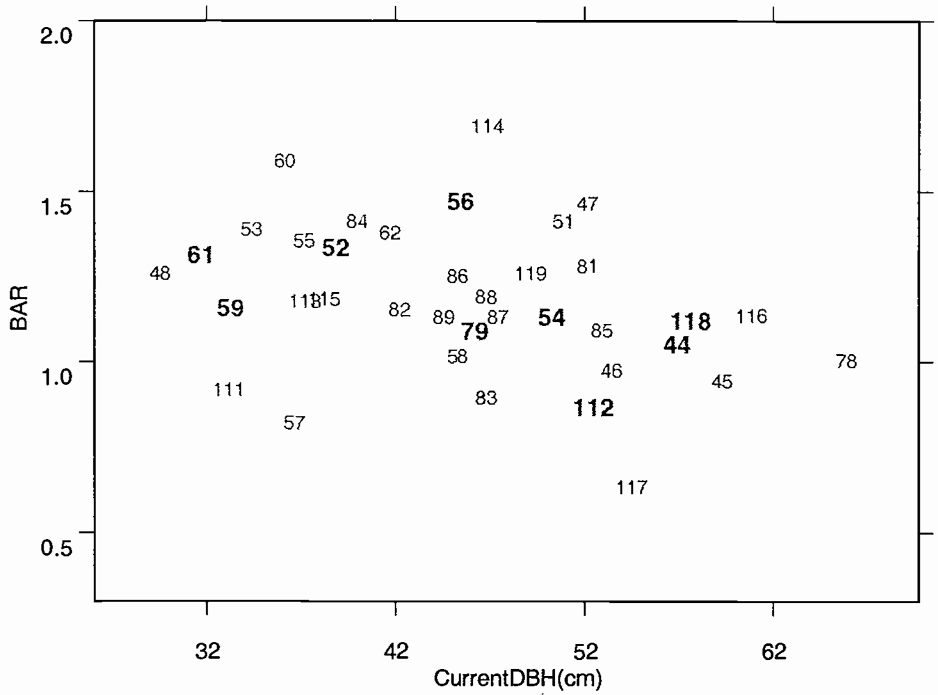

Fig 6.8. Plot of BAR by Current DBH (cm) for trees in the tilled group. Damaged trees: 44, 52, 54, 56, 59, 61, 79, 112, 118 (shown in bold type).

The plot suggests there is no appreciable difference between the BAR for the trees that were damaged compared to the rest of the trees for a similar diameter class. Although a statistical comparison of damaged and undamaged trees would provide stronger inferences, the small sample population of damaged trees (9) greatly limits a robust comparison.

Because of the outliers observed in the BAR populations, non-parametric statistical methods were considered. A Kruskal-Wallis ANOVA, which does not require population normality, was thus used to compare the treatment populations. The results of the test are given in Appendix 5, and provide strong evidence (two-sided p-value = 0.01 for a chi-square distribution with 2 degrees of freedom, significance level of 0.05) that the populations are statistically different.

A two-sample non-parametric test (Wilcoxon Rank Sum) also was used to compare the BAR populations. The results of this comparison suggest a difference between the untilled population and the other two groups:

Two-sample Wilcoxon Rank Sum test for Control vs.Tilled: p-value 0.210

Two-sample Wilcoxon Rank Sum test for Control vs.Untilled: p-value 0.048

Two-sample Wilcoxon Rank Sum test for Tilled vs.Untilled: p-value 0.003

A one-way Analysis of Variance also was conducted to test for significant differences among treatments, using the following model in order to capture the maximum information embedded in the collected data :

BAR = Trt+ Tree(Trt)

Where

<u>BAR</u> is the Basal Area Ratio

<u>Tree(Trt)</u> is the tree nested by treatment (Control, Tilled, and Untilled, categorical variables), so this term accounts for the variability due to each individual tree within each different treatment.

The results agreed with the previous non-parametric tests, i.e.,it was found that there is a significant difference among treatments (F-value = 3.87, p-value = 0.023). The least squares means for the BAR values with this approach were as follows:

Treatment	Least Square Means
Control	1.338
Tilled	1.309
Untilled	1.538

The consistency in results among the various statistical tests suggests that the differences in basal area growth among the treatments are significant and real. And because the tilled trees showed the lowest BAR, the tillage may have had a small negative effect on the thinning response, even though the trees with visually obvious root damage showed no obvious growth impact. It is important to note, however, that even the tilled trees showed a positive thinning response (i.e., BAR values > 1.0).

Equally noteworthy is the fact that the trees next to untilled trails did not show a lower growth level than tilled trees, and instead showed a higher mean BAR than both the tilled and the control trees. These results seem inconsistent with other studies that found reduced thinning responses due to compaction(e.g., Froehlich and Berglund, 1976). However, they may be explained by the relatively small area of the root zones affected by compaction, as well as the relatively small differences in the bulk density observed after seven years among treatments.

Stem volume growth responses among treatments were evaluated next, using the average of the volume increments since thinning calculated using the two volume equations mentioned earlier. Box plots for these data for the three treatments are as follows:

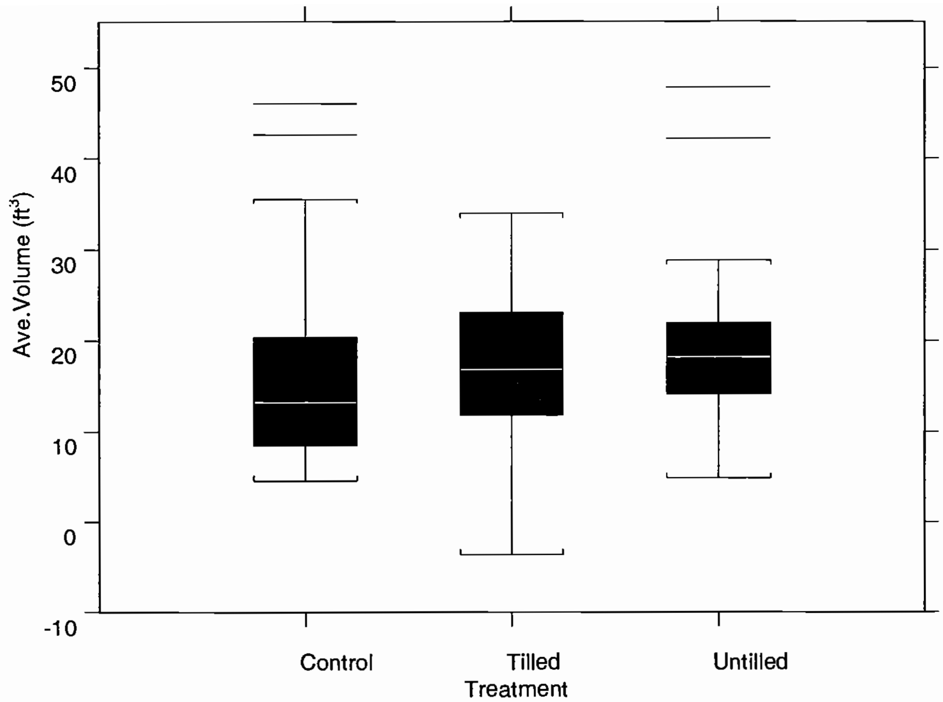

Fig 6.9. Box plots for the average of individual tree volume increments computed using the Weyerhaeuser and the Bruce-DeMars equations (cubic feet) by treatment.

Clearly, the distributions have some outliers as well as are quite long-tailed, so a non-parametric mean comparison method (Kruskal-Wallis rank-sum test) was used. The outputs from this analysis appear in Appendix 5, and show no significant differences between the three treatments (p-value = 0.1283). However, as suggested earlier, the volume variable is less robust than the BAR because it does not account for the different growth influences among individual trees before thinning. Such influences probably help explain the high data variability shown in Figure 6.9, and also tend to mask any treatment effects.

6.3 Multiple Regression Analysis.

Multiple Regression Analysis was conducted to help identify specific variables that could explain the observed growth responses, as measured by the BAR values. It is expected that the thinning could have a positive effect on residual tree growth. On the other hand, in the first years after thinning there may be a delay in this growth response, due to the effects of opening the stand and the initial need for trees to allocate energy and nutrients to develop sufficient canopy to exploit the newly available space.

Also, the spatial arrangement of individual trees before and after thinning can be complex and can change over time, providing another dynamic growth influence. Thus, the Competition Stress Index (CSI) (Arney , 1973) was used to generate three different variables for the regression analysis: <u>Pre-thinning CSI (PreThCSI)</u>; <u>Post-thinning CSI (PostThCSI)</u> and <u>the difference between them (ChThCSI)</u>.

Another variable that has shown significant correlations with growth response after thinning is the diameter of the tree. It is reasonable to expect such relationships, as diameter provides an index of several factors inherent to the tree, such as genetic qualities and hierarchical class in the stand. Some studies have found diameter at the beginning of thinning as a meaningful explanatory variable observed growth responses, better than diameter years after thinning. Both diameter variables were evaluated in the regression analysis.

Of particular interest in this study were soil physical conditions that could affect the growth of the trees after thinning. Trees in highly compacted soils are expected to have a lower growth response, after accounting for other site and stand variables, as long as the compaction levels or associated conditions (e.g., moisture, aeration) are sufficient to restrict roots systems and the area compacted is big enough to restrict a significant proportion of the root system.

In contrast, tillage is expected to improve conditions that restrict roots and related stem growth, although in thinned stands tillage could temporarily reduce tree growth by cutting and damaging roots. Either outcome can be revealed by the regression analysis by whether the sign associated with the tillage treatment variable is positive or negative.

Regression analysis began with matrix scatter plots of the different variables to be tested: Basal Area Ratio, Current DBH, DBH before thinning, Competition Stress Index before and after thinning and Change in Competition Stress Index before and after thinning. However, the plots did not suggest any obvious relationships between the variables, even after using different transformations of the data.

Consequently, a Stepwise Regression procedure was conducted to identify the variables that were significant in explaining the observed variation in growth responses, as expressed by the BAR values for all treatments. The following variables were found to be important through this procedure:

- For a 0.05 level of significance, Post-Thinning CSI (Partial R-square 0.1093) and DBH at the beginning of the thinning (Partial R-square = 0.1621), the model R-square is 0.2714.

  The model:

  BAR= 2.4898-(0.0033 x PostThCSI)-(0.0469 x DBH)

  (0.1764) (0.0007) (0.0099)

Where

PostThCSI is the Post-thinning Competition Stress Index

DBH is the diameter at breast height at the time of thinning

The numbers in brackets are standard errors of the coefficients.

- For a 0.1 level of significance, there is one additional variable, although it does not contribute much to the improvement of the model. This variable is the Average Crown Radius (Partial R-squared = 0.0217), the model R-squared is 0.2931.

  The model:

  BAR= 0.3865-(0.0028 x PostThCSI)-(0.2124 x DBH)+(0.1792 x AvCrRad)

  (0.1820) (0.0008) (0.0886) (0.0953)

  Where

  PostThCSI is the Post-thinning Competition Stress Index

  DBH is the diameter at breast height at the time of thinning

  AvCrRad is the average crown radius

  The numbers in brackets are standard errors of the coefficients.

As other studies have shown, the diameter before thinning seems to be a useful variable to predict the growth of the trees after thinning. The results also confirm the value of the CSI as an indicator of local stand conditions that affect thinning response in individual trees. The addition of the third variable, Average Crown Radius, also is not surprising because like the other two significant variables, it reflects a biologically important characteristic that can have a direct impact on individual tree growth (e.g., dominance, competition, and photosynthesis capacity).

Although there were some expectation that the soil related treatments (tilled and untilled) would show some relationship with the post-thinning growth responses, none of the these variables assumed significance using the stepwise regression procedure. However, given the observed small differences in bulk density levels seven years after treatment and the limited area of individual trees affected by compaction, the result is not surprising. The fact that BAR values were significantly higher for the untilled trees further reinforces the idea that soil compaction did not play a major role in the observed post-thinning growth responses.

7. Conclusions.

The importance of soil sampling and data analysis methods was shown in the comparison of averaged and not-averaged bulk density data. Clearly, the point-to-point variability in bulk density in soils like those studied here is sufficient enough to reveal or mask statistically significant differences, depending on the sampling design and data handling. Because of this variability, it is preferable to not average individual bulk density measurements prior to making statistical comparisons. If there is some advantage to data averaging, then more intensive sampling designs would be desirable to better characterize data variability.

Likewise, careful use of models for statistical comparisons is important for accurate interpretations, as shown by the difference in results with a simple ANOVA versus a more complex, nested model. These two procedures showed significant and insignificant differences respectively, between bulk densities for the tilled and the untilled treatments. Generally, we would give greater weight to the results using the more complex and complete model, which makes better use of the information in the available data.

The analysis of post-thinning basal area growth showed that there is a significant difference between the untilled trees and the other two groups, after analyzing the data with two different approaches. Although some differences were anticipated, the fact that growth was higher next to untilled trails was quite unexpected, since previous studies had suggested that growth impacts were much more likely. The reason for this may be either the limited period of post-thinning analysis or that other variables were more important in influencing growth. The results of the regression analysis clearly support the latter conclusion, and also supports the conclusion that the tillage did not cause any notable damage or benefit to tree growth seven years after thinning and tillage. Although not tested statistically, the trees whose roots were damaged by the subsoiler also did not appear to show either lower growth or any obvious disease symptoms.

Relatively simple stand data collected in the study provided the basis for a statistically significant regression model for describing post-thinning growth response. However, the fact that none of the significant variables (diameter at thinning, CSI, crown radius) were related to soil conditions suggests that compaction and tillage had little or no effect on growth seven years after treatment.

Finally, the fact that compaction did not cause an obvious decrease in growth of the stand suggests that limiting the compacted area by the use of designated skid trails may be an effective management strategy. Conversely, because tilled trees showed no obvious growth benefit, this management tool may have been unnecessary.

8. Future Research Needs.

Because of the limited period of post treatment study, it could be useful to continue the soils and growth monitoring for a longer period in order to come to more conclusive results. Concerns about long-term site productivity generally are framed over periods like decades, rotations, or centuries, and seven years of data provide only a preliminary indication of long-term effects.

It would also be helpful to further clarify the specific roles played by the different tree, stand and site parameters in the observed growth responses, in order to better prescribe and implement such management practices. Studies of the effects of similar practices for different tree species, stand conditions, and soil types would help clarify whether relationships are consistent or variable among different locations and stands.

Finally, wider economical appraisals of costs and benefits of the key practices used to mitigate soil impacts (i.e., designated skid trails, cable harvest systems, tillage) would help identify the most cost-effective management strategies.

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Appendix 1.

Soil Bulk Density Data

Columns

Tree-ID#: tree identification number
Test1-WD: wet density, test number one
Test1-WC: water content, test number one
Test1-DD: dry density, test number one
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Soil Bulk Density Data

Tree-ID#	Test1-WD	Test1-WC	Test1-DD	Test2-WD	Test2-WC	Test2-DD	Test3-WD	Test3-WC	Test3-DD	Test4-WD	Test4-WC	Test4-DD	Test5-WD	Test5-WC	Test5-DD	Test6-WD	Test6-WC	Test6-DD
1	1.115	0.166	0.949	1.030	0.154	0.875	1.208	0.242	0.965	1.248	0.221	1.026	1.226	0.220	1.006	1.187	0.227	0.959
2	1.088	0.194	0.893	1.123	0.200	0.923	1.134	0.206	0.928	1.025	0.229	0.796	1.177	0.224	0.952	1.117	0.234	0.882
3	1.349	0.242	1.107	1.272	0.240	1.032	1.182	0.205	0.977	1.162	0.194	0.968	1.336	0.216	1.119	1.450	0.241	1.209
4	1.316	0.250	1.066	1.207	0.288	0.918	1.105	0.262	0.843	1.240	0.253	0.987	1.250	0.249	1.001	1.238	0.273	0.965
5	1.254	0.221	1.033	1.159	0.232	0.927	1.277	0.199	1.078	1.221	0.214	1.007	1.088	0.226	0.861	1.116	0.246	0.870
6	1.126	0.220	0.905	1.197	0.264	0.932	1.202	0.222	0.979	0.997	0.219	0.778	1.161	0.258	0.902	1.179	0.322	0.857
7	1.135	0.207	0.927	1.122	0.232	0.890	1.261	0.248	1.012	1.192	0.235	0.956	1.302	0.216	1.086	1.172	0.219	0.953
8	0.977	0.209	0.769	0.980	0.211	0.770	1.178	0.243	0.935	1.190	0.255	0.935	1.200	0.218	0.981	1.070	0.223	0.846
9	1.142	0.239	0.952	1.141	0.220	0.921	1.078	0.192	0.886	1.127	0.224	0.902	1.073	0.213	0.859	1.038	0.178	0.860
10	1.102	0.240	0.861	1.252	0.263	0.988	1.248	0.250	0.998	1.274	0.230	1.045	1.097	0.246	0.851	1.238	0.254	0.984
11	1.219	0.262	0.956	1.240	0.203	1.037	1.230	0.259	0.971	1.247	0.215	1.032	1.212	0.221	0.990	1.255	0.239	1.016
12	1.186	0.212	0.973	1.099	0.244	0.855	1.188	0.201	0.986	1.198	0.213	0.976	1.309	0.221	1.088	1.242	0.212	1.030
13	1.205	0.255	0.950	1.234	0.237	0.986	1.076	0.211	0.865	1.079	0.182	0.897	1.162	0.179	0.983	1.191	0.182	1.009
14	1.129	0.185	0.944	1.144	0.199	0.945	1.161	0.211	0.949	1.108	0.161	0.946	1.201	0.199	1.003	1.091	0.221	0.869
15	1.309	0.250	1.058	1.243	0.242	1.002	1.119	0.219	0.900	1.168	0.233	0.934	1.276	0.296	1.030	1.221	0.208	1.013
16	1.312	0.225	1.087	1.109	0.207	0.932	1.192	0.207	0.983	1.209	0.218	0.990	1.313	0.187	1.126	1.208	0.185	1.024
17	1.305	0.199	1.106	1.457	0.226	1.232	1.158	0.224	0.933	1.380	0.203	1.178	1.308	0.194	1.114	1.240	0.225	1.015
18	1.164	0.207	0.957	1.180	0.206	0.973	1.282	0.216	1.066	1.286	0.203	1.083	1.155	0.186	0.968	1.082	0.155	0.926
19	1.134	0.255	0.879	1.140	0.270	0.869	1.128	0.233	0.895	1.183	0.259	0.924	1.148	0.245	0.902	1.122	0.284	0.838
20	1.212	0.245	0.966	1.254	0.259	0.994	0.908	0.236	0.672	1.143	0.245	0.897	1.379	0.286	1.093	1.244	0.288	0.955
21	1.159	0.239	0.919	1.193	0.237	0.946	1.161	0.220	0.940	1.160	0.213	0.947	1.131	0.227	0.904	1.171	0.246	0.925
22	1.277	0.221	1.055	1.193	0.255	0.938	1.171	0.218	0.952	1.208	0.255	0.952	1.288	0.234	1.054	1.208	0.246	0.961
23	1.215	0.229	0.986	1.124	0.241	0.883	1.126	0.237	0.889	1.125	0.238	0.887	1.132	0.231	0.900	1.173	0.227	0.945
24	1.273	0.271	1.001	1.333	0.274	1.060	1.349	0.297	1.052	1.309	0.262	1.047	1.176	0.250	0.926	1.158	0.232	0.925
25	1.214	0.216	0.998	1.232	0.221	1.010	1.291	0.262	1.029	1.350	0.269	1.080	1.356	0.253	1.103	1.403	0.259	1.144
26	1.276	0.220	1.056	1.248	0.210	1.039	1.181	0.186	0.994	1.228	0.185	1.043	1.187	0.239	0.947	1.077	0.225	0.852
27	1.314	0.230	1.084	1.257	0.258	0.998	1.289	0.249	1.039	1.369	0.257	1.113	1.163	0.220	0.942	1.219	0.206	1.013
28	1.067	0.204	0.862	1.117	0.198	0.917	1.136	0.236	0.899	1.161	0.230	0.931	1.168	0.226	0.942	1.196	0.241	0.954
29	1.216	0.224	0.991	1.120	0.196	0.924	1.291	0.286	1.005	1.333	0.270	1.063	1.206	0.231	0.974	1.223	0.235	0.987
30	1.227	0.214	1.013	1.295	0.206	1.089	1.135	0.205	0.929	1.192	0.212	0.979	1.189	0.235	0.953	1.258	0.236	1.022
31	1.130	0.213	0.916	1.145	0.209	0.936	1.241	0.197	1.044	1.193	0.174	1.019	1.149	0.232	0.917	1.107	0.195	0.912
32	1.299	0.209	1.090	1.393	0.225	1.168	1.098	0.185	0.912	1.200	0.177	1.023	1.396	0.248	1.130	1.343	0.200	1.143
33	1.122	0.208	0.914	1.139	0.191	0.947	1.213	0.228	0.984	1.158	0.211	0.947	1.237	0.204	1.032	1.242	0.221	1.021
34	1.246	0.246	0.998	1.210	0.251	0.959	1.241	0.232	1.010	1.205	0.231	0.974	1.167	0.240	0.926	1.251	0.219	1.032
35	1.161	0.187	0.974	1.213	0.167	1.046	1.279	0.209	1.069	1.210	0.189	1.021	1.197	0.254	0.943	1.135	0.196	0.939
36	1.170	0.175	0.994	1.104	0.182	0.922	1.263	0.269	0.993	1.283	0.268	1.015	1.130	0.207	0.922	1.104	0.205	0.899
37	1.148	0.192	0.955	1.144	0.194	0.950	1.086	0.167	0.918	1.098	0.196	0.902	1.155	0.18	0.974	1.132	0.188	0.944
38	1.186	0.199	0.986	1.132	0.213	0.919	1.095	0.196	0.898	1.098	0.213	0.884	1.269	0.241	1.027	1.229	0.222	1.007
39	1.269	0.250	1.020	1.268	0.242	1.026	1.127	0.245	0.881	1.179	0.224	0.954	1.115	0.260	0.854	1.298	0.231	1.067
40	1.121	0.182	0.939	1.074	0.196	0.877	1.167	0.188	0.979	1.149	0.187	0.961	1.183	0.214	0.968	1.148	0.210	0.938
41	1.162	0.184	0.978	1.089	0.186	0.903	1.055	0.194	0.861	1.069	0.173	0.891	1.018	0.166	0.851	1.071	0.186	0.890
42	0.917	0.135	0.782	0.966	0.141	0.826	1.046	0.168	0.877	1.068	0.183	0.885	1.172	0.201	0.971	1.034	0.223	0.911
43	1.071	0.149	0.922	1.074	0.167	0.907	1.164	0.186	0.978	1.134	0.173	0.960	1.104	0.188	0.916	1.048	0.171	0.876
44	1.177	0.208	0.969	1.125	0.202	0.922	1.200	0.199	1.001	1.169	0.245	0.924	1.181	0.221	0.959	1.206	0.196	1.010
45	1.210	0.167	1.043	1.199	0.178	1.022	0.926	0.186	0.739	1.021	0.167	0.853	0.909	0.185	0.723	0.976	0.230	0.745
46	1.119	0.187	0.931	1.185	0.147	0.988	1.157	0.198	0.959	1.080	0.194	0.895	1.260	0.243	1.017	1.147	0.275	0.871
47	1.125	0.218	0.906	1.148	0.207	0.940	0.863	0.225	0.638	0.851	0.252	0.599	1.116	0.211	0.904	1.034	0.170	0.864
48	1.178	0.271	0.907	1.190	0.227	0.963	1.237	0.231	1.006	1.288	0.243	1.045	1.402	0.236	1.166	1.274	0.255	1.020
49	1.254	0.252	1.002	1.317	0.252	1.065	1.097	0.228	0.968	1.122	0.196	0.925	1.162	0.212	0.949	1.130	0.238	0.892
50	1.127	0.244	0.983	1.207	0.24	0.967	1.032	0.184	0.849	0.919	0.199	0.721	1.256	0.255	1.001	1.327	0.241	1.086
51	1.156	0.212	0.944	1.118	0.214	0.904	0.980	0.191	0.789	0.965	0.188	0.779	0.964	0.175	0.789	0.959	0.168	0.792
52	1.128	0.276	0.851	1.104	0.237	0.867	1.203	0.241	0.961	1.171	0.219	0.951	1.239	0.215	1.024	1.217	0.238	0.979
53	1.132	0.233	0.898	1.163	0.245	0.918	1.239	0.237	1.002	1.135	0.260	0.974	1.064	0.211	0.852	1.023	0.199	0.824
54	1.060	0.258	0.801	1.051	0.220	0.830	1.077	0.191	0.885	1.092	0.188	0.963	1.278	0.279	0.999	1.210	0.242	0.968
55	1.242	0.258	0.983	1.242	0.249	0.992	1.435	0.308	1.126	1.516	0.308	1.208	1.356	0.275	1.081	1.432	0.286	1.146
56	1.103	0.315	0.788	1.101	0.210	0.890	1.149	0.221	0.928	1.076	0.243	0.833	1.073	0.218	0.854	1.112	0.219	0.893
57	1.133	0.205	0.928	1.124	0.193	0.931	1.036	0.205	0.830	1.028	0.221	0.807	1.083	0.215	0.867	1.036	0.200	0.835
58	1.104	0.196	0.907	1.113	0.189	0.923	1.127	0.187	0.939	1.106	0.170	0.936	1.177	0.222	0.954	1.150	0.221	0.920
59	1.136	0.209	0.927	1.196	0.251	0.944	1.290	0.260	1.030	1.299	0.233	1.065	1.209	0.221	0.988	1.288	0.232	1.057

Soil Bulk Density Data

Tree-ID#	Test1-WD	Test1-WC	Test1-DD	Test2-WD	Test2-WC	Test2-DD	Test3-WD	Test3-WC	Test3-DD	Test4-WD	Test4-WC	Test4-DD	Test5-WD	Test5-WC	Test5-DD	Test6-WD	Test6-WC	Test6-DD
60	1.186	0.230	0.955	1.282	0.232	1.049	1.231	0.252	0.979	1.249	0.242	1.007	1.193	0.228	1.068	1.296	0.228	1.068
61	1.401	0.262	1.139	1.389	0.263	1.126	1.285	0.275	1.010	1.323	0.254	1.069	1.285	0.247	1.038	1.222	0.235	0.987
62	1.276	0.246	1.030	1.220	0.236	0.983	1.061	0.204	0.856	0.967	0.184	0.783	1.178	0.254	0.924	1.307	0.281	1.026
63	1.173	0.283	0.890	1.223	0.300	0.922	1.231		0.974	1.262	0.249	1.013	1.214	0.292	0.922	1.189	0.239	0.949
64	1.230	0.265	0.965	1.283	0.276	1.007	1.228	0.276	0.951	1.132	0.261	0.870	1.231	0.344	0.886	1.251	0.317	0.934
65	1.162	0.205	0.975	1.228	0.243	0.984	1.226	0.333	0.893	1.225	0.303	0.921	1.199	0.268	0.930	1.176	0.276	0.899
66	1.153	0.208	0.944	1.115	0.203	0.912	1.204	0.236	0.967	1.192	0.212	0.980	1.247	0.234	1.013	1.245	0.212	1.033
67	1.188	0.268	0.919	1.202	0.268	0.934	1.186	0.259	0.926	1.072	0.234	0.837	1.234	0.251	0.982	1.219	0.242	0.976
68	1.104	0.244	0.859	1.110	0.197	0.912	1.074	0.249	0.824	1.139	0.289	0.849	1.193	0.225	0.966	1.242	0.256	0.986
69	1.127	0.243	0.883	1.201	0.247	0.953	1.366	0.257	1.110	1.256	0.231	1.026	1.262	0.231	1.031	1.264	0.202	1.061
70	1.208	0.223	0.985	1.107	0.184	0.922	1.167	0.208	0.959	1.156	0.236	0.919	1.249	0.227	1.021	1.114	0.243	0.871
71	1.217	0.250	0.967	1.247	0.230	1.017	1.041	0.210	0.831	1.356	0.286	1.070	1.213	0.233	0.980	1.226	0.219	1.007
72	1.186	0.288	0.897	1.283	0.272	0.931	1.209	0.278	0.930	1.212	0.260	0.951	1.182	0.260	0.921	1.227	0.260	0.957
73	1.208	0.262	0.946	1.198	0.249	0.948	1.106	0.237	0.868	1.180	0.228	0.931	1.120	0.233	0.886	1.098	0.207	0.890
74	1.262	0.284	0.977	1.297	0.245	1.052	1.202	0.237	0.965	1.275	0.258	1.017	1.300	0.300	0.999	1.332	0.272	1.061
75	1.169	0.224	0.945	1.108	0.235	0.872	1.152	0.251	0.900	1.181	0.218	0.962	1.204	0.270	0.933	1.218	0.252	0.965
76	1.197	0.226	0.970	1.102	0.231	0.961	1.339	0.296	1.043	1.284	0.292	0.992	1.115	0.266	0.849	1.201	0.247	0.954
77	1.274	0.250	1.023	1.290	0.224	1.066	1.285	0.214	1.071	1.325	0.223	1.103	1.347	0.268	1.079	1.295	0.240	1.054
78	1.156	0.213	0.941	1.110	0.192	0.917	1.072	0.213	0.858	1.152	0.220	0.932	1.153	0.214	0.939	1.190	0.222	0.968
79	1.194	0.196	0.999	1.159	0.199	0.60	0.852	0.182	0.671	0.872	0.149	0.723	1.213	0.208	1.004	1.258	0.203	1.055
80	1.057	0.175	0.881	1.218	0.170	1.047	1.140	0.192	0.948	1.176	0.200	0.976	1.127	0.194	0.932	1.186	0.241	0.945
81	1.079	0.211	0.868	1.064	0.226	0.838	1.255	0.233	1.022	1.284	0.245	1.038	1.242	0.195	1.047	1.269	0.195	1.074
82	1.087	0.166	0.921	1.244	0.211	1.033	1.205	0.234	0.971	1.178	0.216	0.961	1.116	0.203	0.912	1.097	0.226	0.870
83	1.273	0.189	1.084	1.209	0.204	1.004	1.184	0.197	0.986	1.133	0.224	0.908	1.326	0.213	1.113	1.168	0.224	0.943
84	1.308	0.214	1.093	1.185	0.194	0.991	1.277	0.207	1.070	1.223	0.220	1.003	1.173	0.230	0.943	1.161	0.221	0.939
85	1.238	0.229	1.009	1.255	0.221	1.033	1.156	0.238	0.918	1.197	0.219	0.977	1.218	0.216	1.002	1.251	0.209	1.042
86	1.365	0.197	1.168	1.286	0.213	1.074	1.224	0.193	1.032	1.352	0.204	1.147	1.135	0.199	0.936	1.130	0.211	0.919
87	1.287	0.193	1.094	1.327	0.198	1.129	1.276	0.178	1.097	1.360	0.187	1.174	1.249	0.176	1.073	1.316	0.175	1.140
88	1.238	0.201	1.037	0.984	0.177	0.816	1.071	0.213	0.857	1.135	0.189	0.946	1.147	0.166	0.981	1.174	0.168	1.007
89	1.192	0.181	1.011	1.257	0.195	1.062	1.232	0.196	1.036	1.250	0.191	1.059	1.367	0.200	1.167	1.402	0.209	1.192
90	1.293	0.285	1.008	1.207	0.256	0.951	1.071	0.216	0.854	1.010	0.209	0.801	1.122	0.216	0.905	1.115	0.228	0.886
91	1.167	0.196	0.970	1.157	0.260	0.876	1.241	0.283	0.957	1.159	0.248	0.910	1.092	0.199	0.893	1.146	0.255	0.890
92	1.093	0.223	0.869	1.164	0.236	0.928	1.122	0.210	0.912	1.067	0.207	0.860	1.079	0.215	0.863	1.094	0.220	0.873
93	1.148	0.201	0.947	1.148	0.211	0.937	1.046	0.264	0.782	1.118	0.280	0.838	1.337	0.254	1.083	1.200	0.244	0.955
94	1.069	0.208	0.860	0.998	0.207	0.791	1.172	0.232	0.940	1.137	0.219	0.917	1.071	0.188	0.882	1.151	0.218	0.933
95	1.370	0.282	1.089	1.304	0.265	1.039	1.268	0.276	0.992	1.219	0.316	0.903	1.195	0.273	0.921			
96	1.166	0.216	0.949	1.087	0.215	0.872	1.218	0.234	0.983	1.263	0.207	1.055	1.226	0.250	0.976	1.252	0.241	1.011
97	1.172	0.262	0.909	1.232	0.253	0.978	1.209	0.222	0.987	1.238	0.264	0.974	0.918	0.199	0.719	1.142	0.185	0.956
98	1.186	0.212	0.973	1.235	0.215	1.019	1.153	0.239	0.914	1.203	0.227	0.976	1.265	0.234	1.031	1.240	0.261	0.979
99	1.157	0.272	0.889	1.271	0.291	0.979	1.216	0.296	0.963	1.214	0.249	0.965	1.347	0.276	1.070	1.374	0.282	1.092
100	1.178	0.226	0.951	1.173	0.232	0.940	1.156	0.219	0.936	1.131	0.209	0.921	1.054	0.241	0.812	1.049	0.240	0.809
101	1.093	0.254	0.838	1.044	0.243	0.800	1.353	0.246	1.107	1.250	0.237	1.012	1.108	0.229	0.878	1.146	0.229	0.917
102	1.271	0.239	1.031	1.167	0.245	0.921	1.162	0.226	0.936	1.120	0.219	0.899	1.163	0.229	0.934	1.182	0.212	0.969
103	1.134	0.210	0.924	1.114	0.177	0.936	1.235	0.237	0.998	1.225	0.218	1.007	1.173	0.192	0.980	1.145	0.227	0.917
104	1.293	0.258	1.035	1.337	0.279	1.058	1.138	0.209	0.929	1.161	0.216	0.945	1.186	0.239	0.947	1.179	0.252	0.926
105	1.182	0.236	0.946	1.243	0.242	1.001	1.227	0.276	0.951	1.247	0.247	1.000	1.271	0.268	1.002	1.154	0.253	0.901
106	1.236	0.256	0.979	1.254	0.259	0.995	1.112	0.245	0.867	1.155	0.225	0.930	1.250	0.224	1.025	1.229	0.248	0.981
107	1.192	0.236	0.955	1.219	0.228	0.991	1.301	0.256	1.045	1.346	0.270	1.076	1.114	0.251	0.862	1.249	0.239	1.010
108	1.147	0.245	0.902	1.179	0.196	0.983	1.250	0.259	0.990	1.267	0.241	1.025	1.149	0.232	0.917	1.124	0.227	0.896
109	1.170	0.238	0.932	1.193	0.253	0.939	1.400	0.320	1.080	1.444	0.294	1.149	1.092	0.159	0.933	1.117	0.167	0.950
110	1.127	0.257	0.870	1.216	0.240	0.975	1.248	0.239	1.008	1.190	0.245	0.945	1.291	0.263	1.027	1.293	0.244	1.048
111	1.231	0.252	0.979	1.274	0.251	1.023	1.145	0.234	0.911	1.099	0.184	0.914	1.159	0.168	0.991	1.169	0.173	0.995
112	1.143	0.209	0.933	1.253	0.221	1.031	1.127	0.178	0.948	1.173	0.226	0.947	1.250	0.204	1.045	1.265	0.184	1.081
113	1.196	0.204	0.992	1.252	0.215	1.036	1.224	0.236	0.988	1.228	0.225	1.003	1.143	0.223	0.919	1.200	0.198	1.001
114	1.174	0.201	0.973	1.218	0.214	1.005	1.214	0.219	0.995	1.210	0.218	0.991	1.247	0.175	1.072	1.138	0.186	0.952
115	1.221	0.225	0.995	1.173	0.216	0.957	1.172	0.230	0.941	1.126	0.233	0.892	1.118	0.190	0.928	1.084	0.219	0.884
116	1.166	0.227	0.937	1.101	0.222	0.879	1.206	0.223	0.982	1.179	0.221	0.957	1.136	0.226	0.909	1.169	0.232	0.936
117	1.228	0.211	1.016	1.097	0.202	0.895	1.155	0.218	0.936	1.280	0.210	1.070	1.334	0.237	1.097	1.368	0.231	1.137
118	1.184	0.219	0.963	1.158	0.227	0.931	1.223	0.216	1.007	1.184	0.192	0.972	1.209	0.265	0.944	1.133	0.247	0.886
119	1.088	0.184	0.903	1.172	0.177	0.995	1.212	0.178	1.034	1.279	0.213	1.065	1.149	0.183	0.965	1.202	0.187	1.015

Soil Bulk Density Data

Tree-ID#	Test7-WD	Test7-WC	Test7-DD	Test8-WD	Test8-WC	Test8-DD	Test9-WD	Test9-WC	Test9-DD	Test10-WD	Test10-WC	Test10-DD	Test11-WD	Test11-WC	Test11-DD	Test12-WD	Test12-WC	Test12-DD
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41	1.275	0.218	1.056	1.266	0.233	1.033	1.342	0.251	1.091	1.315	0.260	1.055	1.276	0.229	1.037	1.263	0.252	1.011
42	1.218	0.206	1.013	1.204	0.206	0.998	1.258	0.235	1.023	1.294	0.236	1.058	1.013	0.205	0.807	1.039	0.749	0.794
43	1.122	0.234	0.886	1.016	0.190	0.826	1.251	0.230	1.013	1.274	0.258	1.016	1.123	0.242	0.881	1.185	0.303	0.881
44	1.282	0.293	0.988	1.332	0.275	1.056	1.421	0.247	1.174	1.352	0.267	1.085	1.505	0.246	1.259	1.463	0.245	1.218
45	1.190	0.208	0.981	1.093	0.223	0.869	1.288	0.257	1.031	1.327	0.256	1.071	1.075	0.191	0.383	1.077	0.221	0.856
46	1.222	0.203	1.019	1.131	0.206	0.924	1.169	0.195	0.973	1.152	0.174	0.978	1.137	0.247	0.888	1.144	0.236	0.908
47	0.879	0.172	0.703	0.895	0.169	0.731	1.260	0.215	1.036	1.272	0.241	1.031	1.146	0.219	0.926	1.218	0.224	0.993
48	1.226	0.275	0.951	1.232	0.267	0.964	1.313	0.330	0.982	1.289	0.336	0.952	1.257	0.277	0.980	1.233	0.292	0.941
49	1.116	0.175	0.941	1.005	0.178	0.826	1.038	0.185	0.853	1.106	0.208	0.898	1.120	0.209	0.910	1.031	0.195	0.835
50	1.218	0.253	0.964	1.142	0.23	0.912	1.06	0.29	0.769	1.101	0.309	0.792	1.282	0.263	1.019	1.289	0.31	0.979
51	1.184	0.248	0.935	1.179	0.238	0.940	1.366	0.259	1.107	1.342	0.229	1.114	1.197	0.230	0.967	1.080	0.218	0.862
52	1.237	0.282	0.954	1.301	0.242	1.060	1.303	0.289	1.014	1.236	0.271	0.965	1.168	0.228	0.939	1.106	0.222	0.884
53	1.341	0.251	1.090	1.390	0.289	1.101	1.251	0.303	0.947	1.266	0.241	1.025	1.287	0.295	0.991	1.266	0.291	0.974
54	1.209	0.235	0.973	1.225	0.289	0.936	1.337	0.305	1.032	1.253	0.262	0.990	1.223	0.266	0.957	1.104	0.237	0.867
55	0.870	0.158	0.712	0.877	0.171	0.706	1.285	0.296	0.989	1.290	0.270	1.020	1.248	0.272	0.976	1.175	0.272	0.902
56	1.016	0.186	0.830	1.141	0.249	0.891	1.192	0.243	0.949	1.202	0.235	0.966	1.118	0.239	0.878	1.258	0.270	0.988
57	1.201	0.218	0.982	1.195	0.210	0.985	1.072	0.231	0.840	1.130	0.216	0.913	1.191	0.238	0.952	1.228	0.241	0.987
58	1.243	0.264	0.979	1.321	0.231	1.090	0.996	0.218	0.777	1.141	0.301	0.839	1.127	0.208	0.918	1.087	0.237	0.850
59	1.226	0.298	0.927	1.133	0.257	0.876	1.352	0.264	1.088	1.363	0.282	1.080	1.287	0.237	1.050	1.269	0.253	1.016

Soil Bulk Density Data

Tree-ID#	Test7-WD	Test7-WC	Test7-DD	Test8-WD	Test8-WC	Test8-DD	Test9-WD	Test9-WC	Test9-DD	Test10-WD	Test10-WC	Test10-DD	Test11-WD	Test11-WC	Test11-DD	Test12-WD	Test12-WC	Test12-DD
60	1.217	0.269	0.954	1.232	0.266	0.966	1.431	0.316	1.115	1.245	0.313	0.932	1.132	0.287	0.845	1.149	0.287	0.862
61	1.223	0.296	0.927	1.308	0.317	0.990	1.251	0.321	0.929	1.325	0.282	1.043	1.378	0.302	1.076	1.328	0.283	1.044
62	1.331	0.287	1.044	1.243	0.273	0.969	1.407	0.303	1.103	1.252	0.273	0.979	1.099	0.270	0.829	1.293	0.305	0.987
63	1.262	0.298	0.963	1.310	0.277	1.033	1.310	0.282	1.028	1.268	0.280	0.987	1.350	0.283	1.067	1.338	0.291	1.047
64	1.215	0.294	0.921	1.347	0.298	1.049	1.214	0.273	0.941	1.296	0.262	1.034	1.212	0.272	0.940	1.281	0.269	1.012
65	1.403	0.293	1.109	1.444	0.322	1.121	1.343	0.286	1.058	1.375	0.297	1.079	1.294	0.267	1.027	1.360	0.278	1.081
66	1.340	0.311	1.028	1.358	0.309	1.049	1.301	0.253	1.048	1.300	0.267	1.033	1.347	0.268	1.079	1.359	0.278	1.081
67	1.531	0.303	1.228	1.613	0.318	1.295	1.414	0.350	1.064	1.545	0.351	1.193	1.187	0.312	0.875	1.331	0.320	1.011
68	1.223	0.241	0.982	1.184	0.254	0.930	1.293	0.234	1.059	1.302	0.215	1.087	1.359	0.276	1.083	1.370	0.287	1.084
69	1.341	0.265	1.079	1.351	0.299	1.052	1.380	0.269	1.111	1.331	0.287	1.044	1.270	0.260	1.010	1.285	0.264	1.021
70	1.508	0.342	1.166	1.451	0.331	1.120	1.454	0.313	1.141	1.526	0.290	1.237	1.249	0.236	1.013	1.330	0.278	1.051
71	1.242	0.318	0.923	1.324	0.312	1.013	1.378	0.337	1.041	1.431	0.362	1.068	1.311	0.339	0.972	1.322	0.346	0.975
72	1.359	0.324	1.035	1.307	0.312	0.995	1.278	0.278	0.999	1.301	0.255	1.046	1.179	0.292	0.887	1.291	0.292	0.998
73	1.236	0.293	0.943	1.297	0.310	0.985	1.196	0.267	0.928	1.248	0.295	0.952	1.380	0.345	1.035	1.309	0.310	0.990
74	1.230	0.281	0.949	1.140	0.266	0.873	1.152	0.273	0.878	1.228	0.276	0.952	1.255	0.274	0.980	1.358	0.312	1.046
75	1.209	0.234	0.975	1.077	0.255	0.821	1.272	0.255	1.017	1.269	0.271	0.98	1.471	0.312	1.158	1.406	0.308	1.098
76	1.252	0.230	1.022	1.297	0.240	1.057	1.219	0.231	0.988	1.211	0.214	0.997	1.203	0.237	0.966	1.200	0.217	0.983
77	1.078	0.186	0.891	1.100	0.183	0.916	1.228	0.222	1.006	1.302	0.229	1.074	1.249	0.236	1.013	1.257	0.224	1.032
78	1.289	0.249	1.045	1.246	0.208	1.038	1.217	0.189	1.028	1.235	0.199	1.036	1.210	0.218	0.991	1.240	0.221	1.018
79	1.267	0.202	1.065	1.259	0.194	1.064	1.143	0.176	0.967	1.189	0.199	0.989	1.172	0.198	0.974	1.165	0.209	0.956
80	0.744	0.183	0.561	0.944	0.196	0.748	1.174	0.167	1.007	1.225	0.189	1.036	1.265	0.223	1.042	1.286	0.238	1.048
81	1.096	0.154	0.941	1.217	0.187	1.030	1.274	0.208	1.066	1.271	0.198	1.073	1.188	0.169	1.019	1.180	0.180	0.999
82	1.251	0.200	1.051	1.294	0.199	1.095	1.109	0.156	0.952	1.132	0.171	0.960	1.243	0.210	1.033	1.260	0.229	1.031
83	1.318	0.236	1.082	1.133	0.227	0.905	1.197	0.188	1.009	1.214	0.224	0.989	1.285	0.222	1.063	1.319	0.230	1.089
84	1.032	0.200	0.831	1.028	0.198	0.829	1.406	0.237	1.170	1.385	0.243	1.142	1.416	0.266	1.190	1.342	0.239	1.103
85	1.233	0.214	1.019	1.298	0.253	1.045	1.350	0.229	1.121	1.333	0.240	1.092	1.193	0.229	0.964	1.214	0.217	0.996
86	1.249	0.199	1.050	1.362	0.192	1.169	1.228	0.203	1.024	1.283	0.197	1.086	1.332	0.250	1.081	1.393	0.274	1.120
87	1.269	0.171	1.098	1.227	0.169	1.057	1.203	0.173	1.030	1.391	0.183	1.208	1.268	0.156	1.112	1.290	0.191	1.099
88	1.171	0.153	1.018	1.208	0.178	1.030	1.189	0.186	1.003	1.204	0.166	1.038	1.278	0.163	1.115	1.215	0.166	1.049
89	1.238	0.170	1.067	1.181	0.159	1.022	1.231	0.180	1.051	1.236	0.186	1.050	1.198	0.198	1.001	1.273	0.218	1.055
90	1.490	0.288	1.202	1.516	0.287	1.229	1.382	0.294	1.088	1.453	0.316	1.137	1.506	0.306	1.202	1.521	0.343	1.178
91	1.209	0.224	0.985	1.332	0.286	1.045	1.322	0.276	1.046	1.476	0.384	1.172	1.329	0.266	1.063	1.385	0.289	1.096
92	1.195	0.253	0.941	1.206	0.239	0.966	0.899	0.233	0.666	1.080	0.235	0.844	1.252	0.257	0.995	1.356	0.256	1.100
93	1.284	0.261	1.023	1.373	0.280	1.093	1.274	0.265	1.008	1.364	0.291	1.072	1.206	0.294	0.911	1.172	0.318	0.854
94	1.341	0.295	1.046	1.361	0.305	1.056	1.193	0.257	0.935	1.183	0.245	0.938	1.415	0.270	1.145	1.435	0.232	1.202
95	1.149	0.256	0.893	1.253	0.254	0.998	1.344	0.251	1.092	1.308	0.246	1.061	1.484	0.341	1.142	1.515	0.346	1.169
96	1.395	0.315	1.081	1.431	0.352	1.079	1.363	0.278	1.084	1.334	0.271	1.063	1.408	0.319	1.089	1.375	0.285	1.091
97	1.497	0.354	1.143	1.554	0.380	1.174	1.237	0.253	0.983	1.212	0.272	0.940	1.130	0.230	0.891	1.124	0.241	0.882
98	1.125	0.253	0.871	1.091	0.227	0.863	1.346	0.287	1.058	1.352	0.295	1.057	1.298	0.269	1.029	1.372	0.293	1.078
99	1.204	0.271	0.933	1.129	0.279	0.850	1.311	0.272	1.038	1.401	0.253	1.148	1.372	0.255	1.117	1.372	0.240	1.132
100	1.329	0.276	1.053	1.381	0.308	1.073	1.354	0.268	1.086	1.341	0.281	1.060	1.176	0.214	0.962	1.268	0.239	1.029
101	1.210	0.272	0.942	1.217	0.262	0.954	1.279	0.265	1.014	1.289	0.249	1.040	1.337	0.279	1.058	1.366	0.273	1.093
102	1.098	0.164	0.934	1.165	0.220	0.945	1.387	0.330	1.057	1.446	0.325	1.120	1.316	0.281	1.035	1.297	0.259	1.038
103	1.373	0.253	1.120	1.335	0.232	1.102	1.360	0.272	1.089	1.417	0.280	1.136	1.153	0.265	0.888	1.232	0.245	1.037
104	1.209	0.261	0.958	1.135	0.238	0.896	1.050	0.233	0.817	1.086	0.221	0.865	1.139	0.217	0.921	1.137	0.237	0.899
105	1.259	0.285	0.973	1.322	0.234	1.088	1.205	0.250	0.954	1.303	0.254	1.049	1.143	0.195	0.947	1.111	0.210	0.901
106	1.286	0.254	1.032	1.265	0.264	1.001	1.276	0.244	1.032	1.279	0.252	1.027	0.752	0.169	0.582	0.767	0.185	0.581
107	1.237	0.249	0.987	1.290	0.243	1.046	1.392	0.260	1.132	1.365	0.259	1.105	1.365	0.281	1.084	1.394	0.304	1.090
108	1.155	0.231	0.924	1.185	0.236	0.949	1.443	0.328	1.115	1.376	0.303	1.073	1.534	0.329	1.204	1.456	0.265	1.191
109	1.354	0.261	1.093	1.342	0.240	1.102	1.290	0.238	1.051	1.300	0.266	1.033	1.049	0.212	0.837	1.051	0.201	0.849
110	1.234	0.298	0.936	1.271	0.278	0.992	1.458	0.306	1.152	1.504	0.311	1.193	1.255	0.290	0.965	1.225	0.249	0.976
111	1.341	0.249	1.092	1.405	0.264	1.141	1.179	0.258	0.921	1.108	0.236	0.972	1.380	0.241	1.138	1.277	0.244	1.053
112	1.174	0.212	0.961	1.220	0.226	0.994	1.275	0.255	1.020	1.289	0.234	1.054	1.253	0.281	0.972	1.212	0.255	0.957
113	1.179	0.231	0.947	1.223	0.240	0.983	1.267	0.212	1.055	1.211	0.249	0.961	1.207	0.227	0.980	1.340	0.276	1.064
114	1.175	0.234	0.941	1.281	0.261	1.020	1.231	0.308	0.923	1.185	0.249	0.935	1.240	0.204	1.036	1.204	0.207	0.997
115	1.287	0.283	1.004	1.298	0.297	1.000	1.187	0.204	0.982	1.234	0.214	1.020	1.276	0.272	1.004	1.171	0.225	0.945
116	1.270	0.259	1.010	1.219	0.264	0.954	1.267	0.277	0.990	1.156	0.267	0.888	1.142	0.243	0.899	1.251	0.280	0.971
117	1.113	0.190	0.922	1.168	0.202	0.965	1.002	0.187	0.815	1.188	0.200	0.987	1.002	0.220	0.782	1.160	0.228	0.932
118	1.303	0.244	1.059	1.264	0.245	1.019	1.283	0.272	1.011	1.289	0.259	1.031	1.174	0.219	0.954	1.226	0.216	1.010
119	1.302	0.284	1.017	1.279	0.289	0.989	1.292	0.266	1.026	1.309	0.251	1.058	1.343	0.233	1.082	1.356	0.292	1.065

Appendix 2.

Growth Study Variables

Variables

Treatment: Control (C,1), Tilled (T, 2) and Untilled (U,3)
Trail: the position of the trees in the trails, two numbers separated by a slash means that the trees are between two of them.
CurrentDBH: current diameter at breast height in cm.
DBH7yearsago: diameter at breast height seven years ago.
CrownClass: Codominant (C), Dominant (D) and Intermediate (I).
AveageCrownRadius: average crown radius in meters
BasalAreaRatio
PreThCSI: pre-thinning CSI
PostThCSI: post-thinning CSI
ChThCSI: change in CSI

Study Variables

Tree	TreatNum	Treatment	Trail	CurrentDBH(cm)	DBH7yearsago(cm)	CrownClass	AverageCrownRadius(m	BasalAreaRatio	PreThCSI	PostThCSI	ChangeThCSI
1	1	C	2/3	44.45	15.7	C	3.2832	1.74	256.00	141.00	115.00
2	1	C	2/3	46.99	17.5	C	3.7392	1.26	196.00	137.00	59.00
3	1	C	2/3	40.39	14.4	C	3.8	1.21	374.00	165.00	209.00
4	1	C	2/3	32.51	10.9	C	2.28	1.70	304.00	99.00	205.00
5	1	C	2/3	46.23	16.9	C	4.1952	1.00	168.00	106.00	62.00
6	1	C	3/4	45.97	16.9	C	4.1952	1.29	212.00	65.00	147.00
7	1	C	3/4	48.26	17.4	C	4.6512	1.24	93.00	91.00	2.00
8	1	C	3/4	36.58	13.0	C	3.192	1.60	170.00	39.00	131.00
9	1	C	3/4	34.04	12.3	C	2.888	1.40	250.00	63.00	187.00
10	1	C	3/4	33.27	12.2	C	2.9792	1.21	237.00	123.00	114.00
11	1	C	3/4	42.16	15.2	C	3.648	1.05	279.00	112.00	167.00
12	1	C	4/5	43.43	15.6	C	3.496	1.51	259.00	48.00	211.00
13	1	C	4/5	34.54	12.1	C	2.9792	1.63	158.00	45.00	113.00
14	1	C	4/5	43.43	15.8	C	3.344	1.22	252.00	98.00	154.00
15	1	C	4/5	49.02	17.3	C	4.4992	1.69	254.00	103.00	151.00
16	1	C	4/5	51.31	18.0	C	3.8912	1.18	161.00	92.00	69.00
17	1	C	4/5	37.34	13.6	C	2.6752	1.50	286.00	157.00	129.00
18	1	C	4/5	71.37	26.2	D	4.4992	1.13	318.00	152.00	166.00
19	1	C	5/6	28.70	10.5	I	3.192	1.55	308.00	118.00	190.00
20	1	C	5/6	57.66	20.4	D	4.0432	1.34	226.00	83.00	143.00
21	1	C	5/6	36.07	13.1	C	3.344	1.33	86.00	35.00	51.00
22	1	C	5/6	41.91	15.3	C	3.496	1.65	209.00	102.00	107.00
23	1	C	5/6	32.77	11.9	C	3.192	1.30	348.00	138.00	210.00
24	1	C	5/6	48.01	17.6	C	3.648	1.07	327.00	154.00	173.00
25	1	C	5/6	44.20	16.0	C	3.192	1.18	273.00	126.00	147.00
26	1	C	5/6	42.16	15.9	I	4.6512	1.08	205.00	177.00	28.00
27	1	C	6/7	30.48	11.0	I	2.8272	1.19	271.00	179.00	92.00
28	1	C	6/7	52.07	18.3	C	3.7392	1.30	277.00	184.00	93.00
29	1	C	6/7	33.53	12.1	C	2.8272	1.53	240.00	142.00	98.00
30	1	C	6/7	56.39	17.9	C	3.4352	1.19	221.00	118.00	103.00
31	1	C	6/7	43.43	15.7	C	3.1312	1.16	225.00	108.00	117.00
32	1	C	6/7	54.61	19.7	D	3.5872	1.07	230.00	125.00	105.00
33	1	C	6/7	28.96	10.6	I	3.04	1.26	230.00	129.00	101.00
34	1	C	6/7	25.40	9.1	I	2.736	2.14	184.00	56.00	128.00
35	1	C	7/8	49.02	18.2	C	3.648	0.79	229.00	219.00	10.00
36	1	C	7/8	30.99	11.3	I	3.2832	1.63	156.00	133.00	23.00
37	1	C	7/8	40.89	15.3	C	3.192	1.55	241.00	146.00	95.00
38	1	C	7/8	43.69	15.9	C	2.736	1.27	272.00	135.00	137.00
39	1	C	7/8	50.04	18.7	C	3.192	1.26	230.00	151.00	79.00
40	1	C	7/8	47.75	17.4	D	3.4352	1.14	199.00	97.00	102.00
41	3	U	1	69.60	25.2	D	4.864	1.02	141.00	74.00	67.00
42	3	U	1	39.88	13.9	C	3.192	1.54	237.00	83.00	154.00
43	3	U	1	44.96	16.6	C	3.648	1.14	280.00	121.00	159.00
44	2	T	2	56.90	20.4	D	4.56	1.10	159.00	86.00	73.00
45	2	T	2	59.44	22.3	D	4.4992	0.98	118.00	95.00	23.00
46	2	T	2	53.59	19.8	C	4.256	1.02	285.00	183.00	102.00
47	2	T	2	52.32	18.7	C	3.2832	1.50	263.00	96.00	167.00
48	2	T	2	29.72	10.8	C	2.5232	1.30	228.00	134.00	94.00
49	2	U	2	51.05	18.6	C	3.04	1.60	301.00	109.00	192.00
50	2	U	2	38.35	13.7	C	2.888	1.92	311.00	100.00	211.00
51	2	T	3	51.05	17.8	D	4.104	1.45	172.00	72.00	100.00
52	2	T	3	38.86	14.1	C	3.04	1.39	329.00	110.00	219.00
53	2	T	3	34.54	12.2	C	3.2832	1.43	277.00	66.00	211.00
54	2	T	3	50.29	18.4	C	3.952	1.18	133.00	72.00	61.00
55	2	T	3	37.34	13.5	C	2.888	1.40	249.00	156.00	93.00
56	2	T	3	45.47	16.4	C	3.192	1.52	320.00	145.00	175.00
57	2	T	3	36.83	16.2	C	2.6752	0.86	315.00	151.00	164.00
58	2	T	3	45.47	16.9	C	2.8272	1.06	273.00	143.00	130.00
59	2	T	3	33.27	12.1	C	2.6752	1.21	280.00	108.00	172.00

Study Variables

Tree	TreatNum	Treatment	Trail	CurrentDBH(cm)	DBH7yearsago(cm)	CrownClass	AverageCrownRadius(m	BasalAreaRatio	PreThCSI	PostThCSI	ChangeThCSI
60	2	T	3	36.32	12.7	C	2.8272	1.63	216.00	94.00	122.00
61	2	T	3	31.75	11.0	C	2.6752	1.36	377.00	46.00	331.00
62	2	T	3	41.91	15.9	C	3.192	1.42	232.00	94.00	138.00
63	3	U	4	41.66	14.6	D	3.2832	2.76	238.00	50.00	188.00
64	3	U	4	43.94	15.4	C	3.648	2.11	248.00	64.00	184.00
65	3	U	4	28.19	10.5	C	2.6752	1.41	171.00	60.00	111.00
66	3	U	4	48.51	17.0	C	3.648	1.23	350.00	74.00	276.00
67	3	U	4	35.31	13.0	C	3.192	2.19	250.00	96.00	154.00
68	3	U	4	47.24	17.2	C	3.648	1.07	184.00	125.00	59.00
69	3	U	4	38.61	14.0	C	3.2832	1.40	131.00	99.00	32.00
70	3	U	4	32.77	12.0	C	3.2832	2.06	270.00	104.00	166.00
71	3	U	4	59.94	21.3	D	3.648	1.38	245.00	61.00	164.00
72	3	U	4	28.96	10.6	I	2.736	1.29	247.00	101.00	146.00
73	3	U	4	39.37	14.0	C	3.192	1.41	217.00	56.00	161.00
74	3	U	4	33.27	11.2	C	3.4352	1.70	304.00	60.00	244.00
75	3	U	4	31.50	11.2	I	2.3712	1.36	180.00	50.00	130.00
76	3	U	4	54.61	19.6	C	3.8	1.24	371.00	68.00	303.00
77	3	U	4	47.75	17.7	C	2.9792	1.03	344.00	184.00	160.00
78	2	T	5	66.04	25.0	D	3.8912	1.05	186.00	74.00	112.00
79	2	T	5	46.23	16.9	C	3.8	1.14	179.00	68.00	111.00
80	2	T	5	29.72	11.1	I	2.2192	3.67	258.00	91.00	167.00
81	2	T	5	52.32	18.8	C	3.648	1.32	211.00	96.00	115.00
82	2	T	5	42.42	15.6	C	3.4352	1.20	299.00	78.00	221.00
83	2	T	5	46.99	17.3	C	3.648	0.94	227.00	87.00	140.00
64	2	T	5	40.13	14.6	C	3.5872	1.45	384.00	98.00	286.00
85	2	T	5	53.09	19.4	C	3.8912	1.13	253.00	33.00	220.00
86	2	T	5	45.47	16.2	C	3.04	1.29	369.00	155.00	214.00
87	2	T	5	47.24	17.5	C	3.7392	1.16	346.00	180.00	166.00
88	2	T	5	46.99	16.8	C	3.8	1.23	251.00	159.00	92.00
89	2	T	5	46.48	16.9	C	3.1312	1.16	317.00	156.00	161.00
90	3	U	6	36.83	14.2	I	2.432	1.06	264.00	171.00	93.00
91	3	U	6	41.15	14.2	C	2.9792	1.50	274.00	62.00	212.00
92	3	U	6	47.24	17.0	C	3.2832	1.59	306.00	98.00	208.00
93	3	U	6	49.28	17.8	C	3.192	1.32	214.00	59.00	155.00
94	3	U	6	41.15	15.2	C	3.952	1.04	202.00	87.00	115.00
95	3	U	6	40.64	15.0	C	3.1312	1.28	195.00	69.00	126.00
96	3	U	6	46.99	16.3	C	3.952	1.68	312.00	57.00	255.00
97	3	U	6	44.20	15.9	C	2.736	2.92	325.00	79.00	246.00
98	3	U	6	44.45	15.9	C	3.344	1.33	280.00	100.00	180.00
99	3	U	6	34.80	12.3	I	2.9792	1.51	348.00	128.00	220.00
100	3	U	6	41.91	15.2	C	2.8272	1.80	301.00	122.00	179.00
101	3	U	6	44.96	16.1	C	3.496	1.46	282.00	64.00	218.00
102	3	U	6	46.74	16.1	C	3.4352	1.24	339.00	143.00	196.00
103	3	U	6	47.24	16.7	C	3.344	1.72	181.00	64.00	117.00
104	3	U	6	48.51	17.4	C	2.736	1.50	260.00	99.00	161.00
105	3	U	6	36.83	12.4	C	3.192	2.24	225.00	69.00	156.00
106	3	U	6	44.45	15.8	C	3.4352	1.59	230.00	66.00	164.00
107	3	U	6	36.83	12.7	C	3.04	2.13	238.00	50.00	188.00
108	3	U	6	48.01	17.0	C	3.8	1.40	292.00	128.00	164.00
109	3	U	6	42.67	15.7	C	2.8272	1.02	277.00	154.00	123.00
110	3	U	6	41.91	15.1	C	3.4352	1.33	272.00	112.00	160.00
111	2	T	7	33.27	12.6	I	2.8272	0.96	274.00	186.00	88.00
112	2	T	7	52.32	19.6	C	3.2832	0.92	250.00	111.00	139.00
113	2	T	7	37.34	13.6	C	2.432	1.22	295.00	191.00	104.00
114	2	T	7	46.99	17.0	C	3.4352	1.73	162.00	112.00	50.00
115	2	T	7	38.35	13.9	C	3.4352	1.23	247.00	112.00	135.00
116	2	T	7	60.96	22.6	D	4.9552	1.18	234.00	109.00	125.00
117	2	T	7	54.61	20.5	C	4.1952	0.68	248.00	182.00	66.00
118	2	T	7	57.15	21.0	D	3.4352	1.11	230.00	92.00	138.00
119	2	T	7	49.28	17.4	C	3.4352	1.30	222.00	72.00	150.00

Appendix 3.

Tree Heights

Heights

#Tree	HEIGHT (feet)	Heights (6 years before)	#Tree	HEIGHT (feet)	Heights (6 years before)	#Tree	HEIGHT (feet)	Heights (6 years before)	#Tree	HEIGHT (feet)	Heights (6 years before)
1	126	113	31	114	109	61	113	107	91	130	119
2	122	118	32	137	123	62	122	117	92	133	109
3	133	117	33	109	103	63	114	103	93	128	118
4	107	102	34	96	89	64	127	116	94	134	117
5	124	115	35	143	129	65	103	94	95	136	118
6	126	112	36	98	94	66	138	123	96	129	117
7	123	117	37	127	115	67	107	97	97	121	108
8	111	100	38	126	113	68	127	111	98	128	116
9	109	105	39	124	117	69	126	109	99	114	107
10	122	108	40	128	114	70	108	100	100	136	118
11	124	120	41	141	123	71	140	120	101	131	110
12	112	119	42	127	112	72	111	107	102	123	118
13	104	113	43	131	122	73	129	113	103	135	117
14	114	118	44	132	117	74	116	109	104	129	120
15	132	117	45	140	125	75	111	106	105	125	118
16	140	120	46	144	133	76	134	127	106	122	111
17	114	108	47	126	113	77	129	124	107	117	109
18	154	140	48	114	101	78	147	130	108	135	120
19	104	95	49	133	117	79	129	115	109	124	113
20	148	135	50	117	110	80	110	100	110	127	114
21	115	106	51	138	128	81	142	120	111	118	108
22	126	110	52	124	110	82	128	113	112	130	124
23	116	118	53	108	99	83	136	118	113	134	118
24	133	121	54	131	118	84	122	113	114	117	108
25	125	109	55	118	104	85	133	123	115	126	112
26	123	108	56	133	118	86	123	116	116	138	129
27	108	110	57	122	108	87	132	123	117	138	127
28	124	117	58	140	123	88	115	117	118	139	119
29	114	105	59	115	99	89	118	122	119	135	119
30	133	123	60	124	116	90	108	101			

Appendix 4.

Volumes

Stem Volumes (cubic feet)

Tree	Treatment	VolumeIncrement(Weyerh)	VolumeIncr(Bruce)	Average	Tree	TreatNum	VolumeIncrement(Weyerh)	VolumeIncr(Bruce)	Average
1	C	20.53	21.46	20.99	31	C	12.48	12.87	12.67
2	C	10.41	10.78	10.59	32	C	27.78	29.18	28.48
3	C	18.52	19.48	19.00	33	C	5.48	5.61	5.54
4	C	10.93	11.18	11.05	34	C	4.89	4.93	4.91
5	C	15.34	16.01	15.68	35	C	19.98	21.35	20.67
6	C	17.64	18.56	18.10	36	C	5.24	5.33	5.29
7	C	16.25	16.78	16.51	37	C	11.78	12.41	12.10
8	C	12.42	12.82	12.62	38	C	17.15	18.02	17.59
9	C	7.28	7.47	7.37	39	C	13.45	14.04	13.74
10	C	10.41	10.82	10.62	40	C	20.18	21.22	20.70
11	C	11.99	12.43	12.21	41	U	46.98	48.75	47.87
12	C	6.39	6.29	6.34	42	U	19.05	19.90	19.47
13	C	4.98	5.03	5.00	43	U	13.98	14.71	14.35
14	C	6.92	6.93	6.93	44	T	30.96	32.30	31.63
15	C	26.65	27.98	27.31	45	T	26.44	28.24	27.34
16	C	33.61	35.51	34.56	46	T	21.20	22.46	21.83
17	C	9.37	9.69	9.53	47	T	25.87	26.97	26.42
18	C	41.83	43.45	42.64	48	T	8.28	8.50	8.39
19	C	6.19	6.31	6.25	49	T	24.57	25.96	25.26
20	C	34.75	36.44	35.60	50	T	12.11	12.55	12.33
21	C	9.95	10.30	10.13	51	T	27.60	28.86	28.23
22	C	16.73	17.59	17.16	52	T	14.39	15.05	14.72
23	C	5.14	5.29	5.22	53	T	10.55	10.83	10.69
24	C	18.90	19.94	19.42	54	T	21.27	22.41	21.84
25	C	19.62	20.62	20.12	55	T	13.55	14.10	13.82
26	C	13.58	14.36	13.97	56	T	21.13	22.31	21.72
27	C	4.49	4.59	4.54	57	T	-3.76	-3.49	-3.62
28	C	22.77	23.35	23.06	58	T	18.95	20.25	19.60
29	C	9.35	9.65	9.50	59	T	11.00	11.37	11.18
30	C	45.49	46.64	46.06	60	T	13.49	14.03	13.76

Stem Volumes (cubic feet)

Tree	Treatment	VolumeIncrement(Weyerh)	VolumeIncr(Bruce)	Average	Tree	TreatNum	VolumeIncrement(Weyerh)	VolumeIncr(Bruce)	Average
61	T	9.65	9.92	9.78	91	U	19.85	20.76	20.30
62	T	7.19	7.54	7.36	92	U	28.01	29.68	28.85
63	U	16.85	17.42	17.13	93	U	20.14	21.04	20.59
64	U	19.81	20.67	20.24	94	U	16.02	16.96	16.49
65	U	4.98	5.07	5.03	95	U	16.64	17.65	17.15
66	U	27.30	28.74	28.02	96	U	24.79	25.89	25.34
67	U	9.04	9.32	9.18	97	U	17.77	18.54	18.16
68	U	21.37	22.51	21.94	98	U	18.62	19.50	19.06
69	U	15.96	16.73	16.34	99	U	10.69	11.03	10.86
70	U	7.34	7.55	7.44	100	U	19.47	20.61	20.04
71	U	41.15	43.21	42.18	101	U	24.39	25.74	25.06
72	U	4.94	5.06	5.00	102	U	20.59	21.24	20.91
73	U	17.58	18.42	18.00	103	U	26.60	28.05	27.33
74	U	12.78	13.16	12.97	104	U	20.03	20.90	20.46
75	U	7.80	8.01	7.91	105	U	16.24	16.87	16.55
76	U	23.25	24.06	23.65	106	U	18.29	19.03	18.66
77	U	12.52	13.06	12.79	107	U	14.23	14.71	14.47
78	T	31.66	34.06	32.86	108	U	25.08	26.38	25.73
79	T	18.92	19.94	19.43	109	U	13.75	14.42	14.09
80	T	5.99	6.14	6.07	110	U	16.72	17.53	17.12
81	T	32.86	34.96	33.91	111	T	6.71	6.98	6.85
82	T	16.31	17.20	16.75	112	T	13.71	14.32	14.01
83	T	21.93	23.35	22.64	113	T	14.72	15.50	15.11
84	T	12.39	12.91	12.65	114	T	16.80	17.41	17.11
85	T	21.64	22.67	22.15	115	T	14.09	14.75	14.42
86	T	16.64	17.25	16.94	116	T	23.00	23.89	23.45
87	T	14.87	15.66	15.27	117	T	18.57	19.70	19.14
88	T	11.21	11.26	11.23	118	T	32.90	35.06	33.98
89	T	7.79	7.73	7.76	119	T	27.54	28.98	28.26
90	U	4.74	4.94	4.84					

Appendix 5.

Statistical Outputs

Statistical outputs.

1. ANOVA for the off-trail not-averaged BD

```
      ***  One-Way ANOVA for data in Densities.off.trail by Treatment ***

Call:
   Aov Model = Densities.off.trail ~ Treatment,

Terms:
                Treatment Residuals
 Sum of Squares  0.029152  2.066736
Deg. of Freedom         1       355

Residual standard error: 0.07630066
Estimated effects may be unbalanced

           Df Sum of Sq    Mean Sq F Value      Pr(F)
Treatment   1  0.029152 0.02915198 5.00739 0.02585915
Residuals 355  2.066736 0.00582179
```

2. ANOVA for the off-trail averaged BD

```
***  One-Way ANOVA for data in AveCurrentBDOFF by Treatment ***

Call:
   Aov(Model =  AveCurrentBDOFF ~ Treatment)

Terms:
                Treatment Residuals
 Sum of Squares 0.0097061 0.3628382
Deg. of Freedom         1       117

Residual standard error: 0.05568825
Estimated effects may be unbalanced

           Df Sum of Sq     Mean Sq  F Value      Pr(F)
Treatment   1 0.0097061 0.009706144 3.129821 0.07947776
Residuals 117 0.3628382 0.003101181
```

3. ANOVA for the in-trail non-averaged BD

```
***  One-Way ANOVA for data in Densities.In.Trail by Treatment ***

Call:
   aov( Model = Densities.In.Trail ~ Treatment)

Terms:
                Treatment Residuals
 Sum of Squares  0.068993  2.205881
Deg. of Freedom         1       235

Residual standard error: 0.09688513
Estimated effects may be unbalanced

           Df Sum of Sq    Mean Sq  F Value       Pr(F)
Treatment   1  0.068993 0.06899254 7.350009 0.007201278
Residuals 235  2.205881 0.00938673
```

```
Standard Two-Sample t-Test

 x: In-trail Non-averaged BD with Treatment = Tilled , and y: In-trail Non-
averaged BD with Treatment = Untilled
t = -2.7111, df = 235, p-value = 0.0072
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
 -0.058925729 -0.009327262
sample estimates:
 mean of x mean of y
 0.9847667  1.018893
```

4. Two-sample t-test for averaged in-trail BD

```
Standard Two-Sample t-Test

data:  x: In-trail averaged BD with Treatment = Tilled , and y: In-trail
averaged BD with Treatment = Untilled
t = -2.4308, df = 77, p-value = 0.0174
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
 -0.062081960 -0.006171031
sample estimates:
 mean of x mean of y
 0.9847667  1.018893
```

5. Kruskal-Wallis non-parametric rank sum test for BAR

```
       Kruskal-Wallis rank sum test

 BAR and Treatment
Kruskal-Wallis chi-square = 9.2164, df = 2, p-value = 0.01
alternative hypothesis: two.sided
```

6. Two-sample Wilcoxon rank-sum test for Control and Tilled trees.

```
              Exact Wilcoxon rank-sum test

 x: BAR with Treatment = Control , and y: BAR with Treatment = Tilled
rank-sum statistic W = 1751, n = 40, m = 40, p-value = 0.2105
alternative hypothesis: true mu is not equal to 0
```

7. Two-sample Wilcoxon rank-sum test for Control and Untilled trees.

```
       Exact Wilcoxon rank-sum test

x: BAR with Treatment = Control , and y: BAR with Treatment = Untilled
rank-sum statistic W = 1399, n = 40, m = 39, p-value = 0.0489
alternative hypothesis: true mu is not equal to 0
```

8. Two-sample Wilcoxon rank-sum test for Tilled and Untilled trees.

```
        Exact Wilcoxon rank-sum test

x: BAR with Treatment = Tilled , and y: BAR with Treatment = Untilled
rank-sum statistic W = 1855, n = 39, m = 40, p-value = 0.0035
alternative hypothesis: true mu is not equal to 0
```

9. Kruskal-wallis rank-sum test for Volume

```
        Kruskal-Wallis rank sum test

data:  Average and TreatNum from data frame VolumeFinal
Kruskal-Wallis chi-square = 4.1065, df = 2, p-value = 0.1283
alternative hypothesis: two.sided
```