Physical Characteristics of Forest Soils After Timber Harvest and Tillage in Central Oregon: A Case Study

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1. Abstract

This study examined the effects of timber harvest and subsoiling on soil physical properties considered important to forest productivity and hydrologic concerns. Ground based mechanical timber harvesting on some soil types can cause soil disturbance including compaction. These effects in turn can influence multiple important soil physical properties that affect forest productivity and watershed processes. On Federal forest lands in the Pacific Northwest, forest tillage, or subsoiling, is often used to ameliorate compacted soils. This case study examines multiple soil physical properties in a subsection of four harvest units that were clearcut harvested followed by subsoiling of skid trails, and in four adjacent control areas, in the Deschutes National Forest east of the Cascade crest in central Oregon. Subsections were biased towards areas of heavy machine traffic, generally next to a landing, and were tested for differences based on whether the sites were sloped versus flat, or "disturbed" versus "undisturbed." Soil properties tested were: bulk density, total porosity, pore size distribution, available water capacity, soil strength, and infiltration. Significant differences were seen between harvested-subsoiled areas and undisturbed controls for bulk density, total porosity, soil strength in the 12.5-25.0 and 25.0-37.5 cm depths, and infiltration at very high rainfall rates. Significant differences between flat and sloped areas were observed in soil strength at the 12.5-25.0 and 25.0-37.5 cm depth classes. However, given the limited scale and variable nature of the observed differences it appears that tillage of compacted areas mitigated most of the negative physical effects. Physical soil productivity and hydrologic behavior comparable to the undisturbed areas is expected.

2. Problem Definition and Justification for Research

Tillage is a common practice on western Federal forest lands to mitigate the effects of soil compaction, but its effectiveness has not been widely documented. Current management policy on USDA Forest Service lands in the Pacific Northwest Region 6 requires leaving a minimum of 80% of an activity area in acceptable soil condition and avoiding detrimental conditions. Often - as is the case in the Metolius River Basin where this study was conducted - tilling with a subsoiler is used as a restoration measure to help return soil productivity and hydrologic functions within the soil profile.

One of the data gaps listed in the Metolius Watershed Analysis Update (2004) was to a need to "*assess the effect of past subsoiling operations on residual tree health and growth, planted or natural regeneration tree rooting and growth, and biotic and ecologic soil processes within the profile.*" This study will help fill that gap for managers and resource specialists concerned about the topic, including foresters, soil scientists, hydrologists and silvicuturalists. Although results would not be directly applicable beyond the specific or similar site and soil conditions, the new information gained will shed light on the dynamics of compaction and soil tillage in contemporary forest practices. The study could also be continued in the future by revisiting sampling sites 5, 10 or 15 years in the future to gain further knowledge about temporal trends.

3. Literature Review

3.1 Soil Disturbance

The mechanization of timber harvesting operations, particularly with ground-based vehicles, can be an important cause of soil disturbance. Serious soil impacts that may be caused by intensive forest management practices and ground-based machines include compaction, puddling and displacement (NCASI 2004). The following discussion will focus on compaction disturbance since it is most relevant to this case study.

The type of machine used in forest operations combined with logged terrain and timber characteristics will determine the total load and ground pressure applied to the soil (Lysne and Burditt, 1983), and in turn influence the distribution of immediate effects on physical properties of soil. When combined with repeated traffic, immediate effects to the soil can consist of an increase in soil penetration resistance, reduced air and water conductivity due to decreased size and total volume of pores, and reduced number and size of structural aggregates (Greacen and Sands 1980). Secondary effects that can result from exposed soil include reduced infiltration and gas exchange from displaced soil particles that fill soil pores, and a higher susceptibility to impacts from equipment, rain and snowmelt. Soil characteristics such as texture and moisture will also determine the vulnerability to compaction. When compaction effects persist through time, longer-term consequences may arise and affect soil processes and forest productivity (NCASI 2004).

The negative effects of compaction on site productivity and plant growth are well documented and it is often perceived as one of the leading types of soil degradation from forest operations (Froehlich and McNabb, 1983). Roots of many forest species cannot easily penetrate well-compacted soil and reduced growth will occur if the availability of resources is low in the restricted root zone and occupied soil volume (Childs *et al*. 1991). Severe soil compaction can lead to physiological dysfunctions in plants including reduced water absorption and leaf water deficits. Inhibited seed germination, impeded growth of seedlings, and increased seedling mortality can also occur and adversely affect the regeneration of forest stands. Beyond the seedling stage, woody-plant growth can be inhibited due to the combined effects of increased soil strength and decreased water infiltration and aeration (Kozlowski 1999).

3.1.1. Assessment Methods

Bulk density is often used as a quantitative index of relative compaction (Table 1). For certain sites and soil conditions there is a clear and reasonably strong relationship between bulk density or soil strength and factors that affect plant growth, (Froehlich 1979, Froelich and McNabb 1983). However, despite its popularity in characterizing compaction, there is no direct biological influence. In a study on ponderosa pine in California's Sierra Nevada Gomez *et al*. (2002) found that the significance of changes in bulk density to plant growth depends greatly on soil texture. It was found that increased bulk density on a sandy loam soil produced an increase in ponderosa pine seedling growth, decreased growth on a clay soil, and had no significant effect in a loamy soil. Plant responses apparently depended more on how soil-water relationships were affected by compaction than absolute changes in bulk density.

Soil strength, soil porosity or organic matter content are additional variables that can be used to assess the different types of soil disturbance as they relate more directly to biological processes. Soil strength links to plant growth as an index of the resistance to elongating root tips, while porosity is important because it correlates with the proportion of soil volume that holds air and water (Powers *et al*. 1999). Loss of surface organic matter and exposure of mineral soil surface due to some forest management practices may reduce nutrient supply and affect water and energy fluxes. Erosion and mass displacement such as landslides can not only decrease nutrient content and soil microbial activity, but also may decrease the available soil volume for root development and water or gas storage (Childs *et al*. 1991). Sediment supply and transport processes such as these may affect the timing, volume and quality of sediment at the outlet of a catchment.

The response of a forest system to soil compaction will vary widely and one single physical parameter will be insufficient to quantify soil quality across a large scale. Integrated approaches that reflect dominant vegetation processes and soil-water relationships can be more useful in assessing the extent and effects of soil disturbance (Powers *et al*. 1998). Miller and Anderson (2002) noted that for the many places in the Northwest where tree response and soil compaction have been measured, tree response ranged from mostly negative through none to positive. The positive responses occurred on soils associated with low compressibility and sandy loam textures.

Table 1. Summary of some Interior Pacific Northwest studies of soil compaction after timber harvest.

Area	Soil Texture	Parent Material	Results	Reference
Eastern Oregon	silt loam	Ash over basalt	No significant change between disturbed and control areas	Snider and Miller (1985)
West Central Idaho	loam	Volcanic material over weathered basalt	26% increase in Db *	Froehlich et al. (1985)
Central Oregon	loam	Ash over residuum or collivium from volcanic rocks	38% of samples showed >15% increase in Db	Cochran and Brock (1985)
Eastern Oregon	sandy loam	Colluvial mixture of Rhyolitic and tuffaceous sediment	23% increase in Db 220% increase in soil strength	Allbrook (1986)
Eastern Oregon, Washington	silt loam	Ash over buried soil	19% of harvest area >20% increase in Db	Geist et al. (1989)
Central Oregon	sandy loam	Ash over buried soil	35% increase in Db	Davis (1992)
Northern Idaho	silt loam	Ash over mixed alluvium	20% increase in Db	Page-Dumroese (1993)
Northern Idaho	silt loam	Ash over mixed alluvium	Significant increase in Db at all depths after compaction treatment	Page Dumroese et al. (1997)
Northeastern Oregon	silt loam	Ash over basalt	No significant difference in Db between yarding-corridor, between - corridor, and undisturbed areas	Allen et al. (1999)

*Db = bulk density.

3.2 Infiltration

The entry of rain or snowmelt into the soil at the ground surface is commonly expressed by the term infiltration. Water typically penetrates at the soil-atmosphere interface and is successively absorbed into deeper soil horizons. The rate of entry, or the infiltration rate, depends on the intrinsic characteristics of the soil, initial soil water content, and the rate of water application to the soil surface (Fisher and Binkley 2000). The infiltration process is largely responsible for determining how much water will reach the root zone. If rainfall rates or snowmelt exceed the ability of the surface soil conditions to absorb water, overland flow will occur and plants may be without sufficient moisture for growth (Hillel 1998).

At the point when snowmelt or rainfall rate equals the capability of a soil to absorb it, infiltration will proceed at a maximum rate or *infiltration capacity* (Horton 1940). As this infiltration capacity is exceeded, ponding and overland flow will occur at the soil surface. At high enough velocities and volumes, overland flow can cause surface erosion. Infiltration capacity and its relationship with time are dependent on the initial moisture content of the soil, texture, structure and layering of the profile. Generally, if the soil is initially relatively dry, infiltration starts off high and decreases to a steady state infiltration capacity. This decrease results for several reasons. The primary one is that the matric suction gradient declines as infiltration proceeds. What begins as a very steep potential gradient caused by the difference of potential between the wet soil surface and dry soil below, lessens considerably as the wetted zone depth increases over time and the same difference in potential acts over a much larger distance. In some cases, the decrease results from the entrapment of air bubbles, swelling of clay, detachment of pore-blocking particles, or bulk compression of original soil air that was prevented from escaping initially when infiltration began (Hillel 1998).

Undisturbed forest soils in many areas of the Pacific Northwest generally have infiltration capacities that exceed precipitation rates (Rothacher *et al*. 1967, Harr 1977) and overland flow is uncommon. Forest watersheds where disturbance is managed, can maintain rapid infiltration rates attributable to a porous litter layer that absorbs much water, lessens raindrop impact, discourages the formation of surface crusts, and prevents displacement of the mineral surface soil. Increased porosity, from the incorporation of significant organic matter into the mineral soil naturally increases a soil's permeability to water (Fisher and Binkley 2000). Another distinguishing characteristic of many Pacific

Northwest forest soils are that a large percentage of their total porosity are macropores, which can act as rapid conduits for large quantities of water. Macropores often result from the decay of old roots, or are tunnels and burrows made by worms, animals, or insects (Fisher and Binkley 2000).

Soil disturbance from logging activities can change infiltration capacities by altering the physical characteristics of the surface soil; skidding can compact soil, raindrop splash may erode wet particles and clog macropores, and burning of slash may form hydrophobic surfaces (Johnson and Beschta 1980). The intensity, duration, and energy of a rainstorm, combined with slope steepness and length, will determine its erosive power on the soil surface. Intensity can be highly variable spatially and over the course of a rainstorm. Duration is defined as the length of time from start to finish of the rainstorm. The energy of a storm is determined by the total sum of kinetic energy falling raindrops have over a unit area. When a raindrop falls it is subject to gravitational acceleration and air resistance as its speed increases. As the resistance becomes equal to the accelerating force, the drop reaches terminal velocity and falls at a constant speed. Raindrop energy when it hits exposed soil is responsible for some detachment and transportation of surface particles. However, actual erosion of the soil surface to rainfall or runoff is also dependent on soil erodibility which is strongly influenced by texture and structure (Hillel 1998).

3.2.1 Hydrophobicity

Hydrophobicity is a property of soils that results in a resistance to wetting over some period of time due to a reduced physical affinity of the soil to water. It can have major implications for surface and subsurface water processes, erosion, and consequently plant growth. Some significant hydrological implications include enhanced overland flow and accelerated erosion, uneven wetting patterns, development of preferential flow patterns, and reduced infiltration capacity of the soil. The link between water repellency and the accumulation of long-chained organic compounds, released from decomposing or burning plant litter, between or on soil particles is widely accepted but the nature of their attachment to particle surfaces and their exact chemical composition are lacking (Doerr 2000).

Hydrophobicity is largely considered a seasonal occurrence that changes with variations in soil moisture. It is usually low or completely absent during wet periods and high or severe during extended dry conditions. Repellency has also been found to vary depending on soil type and plant species, and increase after the burning of plant litter and heating of the soil (Doerr 2000). In a study conducted by McNabb *et al*. (1989) on a harvested mixed-evergreen forest in southwest Oregon, broadcast burning was found to increase water repellency and decrease the infiltration rate of the surface soil for up to 5 months. This increase was not long-lasting as after the first fall rains in late November, hydrophobicity on burned plots decreased to levels that differed insignificantly from unburned ones. The role of more severe fire related repellency has also been established and its long lasting effects are still being investigated by scientists.

MacDonald and Huffman (2004) found a burned ponderosa and lodgepole pine forest in the northern Colorado Front Range where soil water repellency was spatially variable, decreased with depth, and was strongest in areas that burned at moderate and high intensities. One year after the burn, fire-induced hydrophobicity was undetectable.

In determining a soil moisture threshold where hydrophobic areas become hydrophilic the authors suggest, 26% for moderate to high burn sites, 13% for areas burned at low severity, and 10% for unburned sites. Determination of thresholds are important for rehabilitation treatments and post-fire erosion risk (MacDonald *et al.* 2004).

3.2.2 Rainfall Simulators

To study erosion, infiltration or overland flow, rainfall simulators are often used. They consist of a standardized spray or drip application generated by a sprinkler head or table; some include a pressure regulator for more uniform applications. The application is made to a plot of known area surrounded by a frame meant to prevent the lateral movement of water from the test plot to the surrounding soil, inserted with limited disturbance into the soil. Attached to the plot frame is either an opening or gutter that leads to a sampling bottle to catch surface runoff. Some simulators can be suspended above ground by placing them on supports to allow simulated raindrops to gain more velocity and more closely imitate rainfall (Van Es *et al*. 2005).

Advanced rainfall simulator designs are helpful because they allow the option to vary and regulate many rainfall characteristics such as the intensity, duration, drop size distribution and kinetic energy. Depending on their size and related water requirements (which can differ greatly) their ease of transport and operation is variable. Where spatial variability is high, simulation measurements need to be replicated and distributed over a greater area, and a simulator that can be operated and moved easily is essential (Kamphorst 1987).

A rainfall simulator placed close to the soil surface may overestimate actual infiltration capacities where mineral soil is exposed. Simulated raindrops falling from a short distance above the soil surface may infiltrate quicker than those falling from the sky at terminal velocity (Johnson and Beschta 1980). Even if that is the case, a rainfall simulation setup can still effectively index differences or changes in surface erodibility and infiltration capacity.

When estimating infiltration capacity of the soil from a ring infiltrometer, the most consistent data are observed when steady-state conditions occur. If the apparatus has a single ring setup, analytical adjustments will be needed to account for three-dimensional flow at the bottom of the ring. Reynolds and Elrick (1990) used numerical modeling to estimate these effects depending on depth of ring insertion, ring radius, and other soil hydraulic properties.

3.2.3. Snowmelt

In some locations a significant portion of precipitation falls as snowfall. When that happens, snow is stored on the land surface for a variable period of time, from hours to months, before melting. In the western U.S. snowmelt is a major contributor to ground water recharge and surface water supply. Snowmelt is a process that progresses intermittently between three phases; *warming*: the average snowpack temperature increases steadily until it is isothermal at 0º C, *ripening*: melting occurs but is retained in snowpack and *output*: when further input of energy produces water output. The time it takes to undergo the phases depends on various energy inputs (Dingman 2002).

When water arrives at the bottom of the snowpack it will either accumulate to form a saturated zone at the base of the snowpack that moves towards a surface-water body and/or it will infiltrate into the soil. Three snowmelt-runoff generation scenarios are possible. If the ground surface is unsaturated and the water table is at depth, water output from the snowpack will infiltrate and move as subsurface flow towards a surface water body or deep aquifer. If the ground surface cannot accept water input, a basal-saturated zone develops at the bottom of the snowpack in which water flows towards a stream or other water body. Lastly, if the water table has risen above the ground surface at lower parts of a slope, water will move streamward by surface and subsurface routes (Dingman 2002).

Hayashi *et al*. (2003), discuss the importance of small surface depressions in snowmelt and infiltration dynamics of a landscape. Depression-focused recharge can be an important source of groundwater and in some places store large amounts of water and thereby keeping it out of rivers as runoff. At sites in Saskatchewan, Canada where hydraulic conductivity was low and the soil is frozen in early spring, significant snowmelt resulted and large portions collected in small depressions. Subsequent infiltration was limited by the thawing front and in turn by the saturated hydraulic conductivity of the soil (Hayashi et al. 2003).

3.3 Volcanic Ash Soils

Soils that form from relatively fine volcanic ejecta have many features that distinguish them from other soils. They are generally characterized by a combination of low bulk density, high phosphate sorption capacity, oxalate-extractible aluminum and iron, and volcanic glass (Buol *et al.* 2005). Most are very stable and will resist erosion from water when undisturbed because of their high permeability. However, their low undisturbed bulk densities make fine ash soils susceptible to compaction. Multiple studies of logging vehicle traffic on skid trails have shown significant effects on physical properties of these soils, including reduced infiltration, increased bulk density and soil strength (Cullen *et al*. 1991, Page-Dumroese 1993, 1997).

Ash, pumice and cinders from volcanic eruptions are primary parent materials for soils in the Deschutes National Forest. In many locations, previously developed soils were buried as materials fell upon them during the eruption of Mount Mazama about 6,000 years ago. Mazama ash deposits are the most widespread soil material in the forest and the distribution of volcanic materials varies depending on distance from Mount Mazama (Crater Lake). In the Sisters District where this study was located, volcanic ash 10-40" thick from Mazama and other close volcanoes and cinder cones are common (Larson 1976). Near Mt. Washington and Santiam Pass a black uniform sand, believed to be from Nash crater and Sand Mountain is found in varying thicknesses. Deposits six feet thick just west of the Cascade crest diminish moving eastwards and can be found influencing soils to the northern boundary of the forest. Additional deposits in the Forest from Newberry and Devil's Hill are younger and overlie Mazama pumice but are not as extensive and are more localized around Newberry Crater and Devil's Hill respectively. Concerns about soil impacts in the area mainly focus on soil compaction and displacement as well as erosion associated with compacted skid trails and forest roads and higher wildfire burn intensities (Craigg 2000).

3.4 Natural Recovery from Soil Disturbance

Major processes responsible for naturally loosening compacted soil include biological activity, frost heaving, freezing-thawing and wetting-drying. The effectiveness of these processes in ameliorating soil properties depend on climate and subsequent moisture and temperature regimes, as well as the frequency of the cycles (Froehlich and McNabb, 1983). Changes in bulk density during freeze-thaw cycles are attributed to the packing and displacement of soil during the growth of ice lenses fed by capillary movement. This alone does not result in large volume changes but can when combined with soil drying that occurs when soil pore water freezes and aggregate water potential decreases (NCASI 2004).

The times required for soils to naturally recover from the negative effects of compaction are variable but multiple investigations into bulk density recovery in the Pacific Northwest show that decades are needed for deep loosening of heavily compacted soil (Wert and Thomas 1981, Froehlich *et al*. 1985, Geist *et al*. 1989, Craigg 2000). Heninger *et al*. (1997) in a comprehensive study of bulk density and seedling growth at eight locations in Oregon over 10 years found that skid trail rut depths averaged 15 cm below the original soil surface and bulk densities exceeded the control areas by 14% four and five years after skidding,

3.5 Management of Soil Compaction Impacts

Reducing the amount of area covered by skidtrails during forest operations can lessen soil disturbance and compaction problems. With modest effort, it is possible to plan and efficiently use a skid trail system that significantly limits the area (e.g. 15% or less) of compacted soil. Designated skid trails can also be used for later entries into the timber stand for further management activities (Garland 1993).

Site preparation and harvesting can also be scheduled for times when soil moisture conditions are favorable as wet soils with significant clay content are often more prone to compaction and puddling. However, it is important to recognize that the relationship between compaction and soil moisture is not the same for all soil types and can vary depending on the amount of ground pressure applied. Soil moisture variability is high on many sites making moisture-based management complex. In most cases, under both moist and dry soil conditions, logging vehicles can cause significant soil compaction after multiple trips (Adams undated). Clayey forest soils can also be treated with elevated caution because a small number of trips can cause mixing or compaction (NCASI 2004).

Another procedure for dampening the effect of machine traffic is to prepare and maintain a layer of organic matter either in the form of slash or other available vegetation to cushion the effects of heavy machinery. If the harvest unit is logged from the end of a skid trail towards a landing, slash will collect on the trail behind the skidding operation (Garland 1993). After a thinning in the western Oregon Cascades (Allen *et al*. 1997) where slash levels were intentionally varied on skid trails, soil bulk densities were about 7 percent lower in skid trails with high slash levels (8-18” deep) than those with low levels (4-7” deep).

Not only can the schedule and layout of the operation be planned to reduce the severity and extent of compaction, but the choice of equipment and logging system is an important consideration as well. Although generally more costly than ground-based systems, skyline cable or aerial systems typically produce minor soil compaction. For ground operations machines must be heavy and strong enough to perform the task efficiently but can be chosen to reduce local disturbance. Specific suggestions listed in Garland (1993) and NCASI (2004) for reducing the impacts of ground operations include: using low ground pressure skidders or track machines, winching logs from stump to skidder rather than moving to the stump, suspension systems to minimize compaction, and matching equipment to the size of logged material.

3.5.1. Soil Tillage

Where compaction is unavoidable and extensive enough to be a management concern, trails can be tilled to help restore favorable soil conditions. When soils compact, basic soil properties such as pore size distribution, pore volume, macropore continuity, and soil strength are altered and can have a significant negative influence on vegetation growth by preventing plant root elongation or water, air, or heat transport. Effective tillage breaks soil into various-sized clods, reduces soil strength, and rearranges aggregates to promote air and water movement; thus providing favorable conditions for more rapid soil recovery (NCASI 2004).

Andrus and Froehlich (1983) evaluated the design and performance of four tillage implements used in the Pacific Northwest to till compacted forest soil. Among the implements studied were brush blades, disk harrows, rock rippers and winged subsoilers. All but the subsoiler were relatively ineffective in loosening varied conditions of compacted forest soil to desirable levels. In most cases this was because the tilling was too shallow to loosen most of the compacted soil within the skid trail. A winged subsoiler uses long ripper shanks with wings attached to the base of each tine so that it increases the effective tillage depth. The tilled volume produced was significantly greater than that produced by tines without wings. Since the time of this study winged subsoiler design has continued to evolve and is the most common method of ameliorating soil compaction in the Pacific Northwest, particularly on Federal lands.

Tree harvest and subsequent site preparation produce different short-term and long term effects that might be limiting to early tree growth, establishment and productivity over the long term. Effects that are initially negative or positive could disappear or even reverse over time. Specific effects of soil tillage will depend on multiple components including regional climate and soil texture. Soil tillage can ameliorate growth losses after replanting but exactly to what extent is still being investigated. Effects on productivity require long-term monitoring for validation and can vary depending on location, as droughty or alpine areas are often slower growing (Curran *et al* 2005).

Heninger and others (2002) quantified soil properties and seedling growth on tilled and untilled skid trails and off-trail plots in western Oregon and observed mean bulk densities in tilled skid trails similar to that of “logged only” (off-trail) soil. Average height growth the first 7 years after planting was slower on non-tilled trails but for years 8-10 height growth was similar for all treatments. Height growth recovered after soil tillage preceded by spreading berms into deep ruts. From an earlier investigation in coastal Washington by Heninger and others, reduced height growth in nontilled trails lasted only for 2 years, and after 7, 8, and 18 years, there were no differences in total tree height among non tilled, tilled and logged only treatments. The authors concluded that, tillage of skid trails was ineffective in coastal Washington likely because of favorable soil and climatic conditions. In Oregon however, tillage allowed for full recovery from potential growth losses resulting from compacted skid trails.

A retrospective study in British Columbia comparing soil conditions with forest productivity after 5 years showed that rehabilitation of landings with a winged subsoiler resulted in good stocking and plot samples having greater than 1000 stems per hectare 63-95% of the time. The authors suggest that a commercial tree crop will likely result and that in future rehabilitation efforts even better growth could occur with topsoil spreading (Plotnikoff et al. 2000).

In the Deschutes National Forest, improvement in survival, growth and seedling plantability after subsoiling has been noted by resource specialists (Craigg 2000). Additional benefits of tillage noted by Craigg (2000) include increased slash left on site for nutrient cycling and reduced competing vegetation in plantation stands, producing improved seedling growth and survival on drier sites. A potential lowering of fuel hazard risk by breaking up the fuel load continuity is possible through tillage in addition to increased protection of soil and water resources by limiting vehicle access. However, limited funding and questions about long-term effects of soil tillage have led to the development of criteria for determining where and when to till (Craigg 2000). Dates of the next planned entry into a harvest area and sensitivity of a soil type to compaction are two of those factors. Studies of forest soil tillage and its effects on site productivity are lacking and more research is needed in this region. Monitoring of tree growth over time to verify long-term effects is essential for effective management and decision making. Site disturbances can vary dramatically depending on location, soil texture and climate and more long-term data are needed before extended trends can be assessed.

3.6 Soil Protection Policy

Acknowledging forest soils as a resource worth conserving became more prevalent in recent decades. As the understanding of soils and their dynamic interactions with forest species increased, so did awareness for protecting them. One of the first major Federal laws to address forest soils within its sections was the National Forest Management Act (NFMA) of 1976. It amended, reorganized and expanded the Forest and Rangeland Renewable Resources Planning Act of 1974, which required the management of renewable resources on National Forest lands. Based on sustained yield and multiple-use principles, the Secretary of Agriculture is required to develop a management program for Forest lands. To meet objectives contained in the Act, Forest Service Handbooks and Forest Service manuals have been created and frequently amended to provide guidance on executing programs and activities to protect resources.

Initial policies and guidelines designed to manage compaction were limited, but as related research expanded through the 1970's and 80's broader interest spread among forest managers (Adams 2005). The 1983 Region 6, USDA Forest Service supplement set forth standards addressing soil productivity and protection that are still applied today. Some of those standards include limits on how much of an area should be impacted by operations and what qualifies as detrimental compaction: "*A minimum of 80 percent of an activity area should be left in a condition of acceptable productivity potential*…" On volcanic ash/pumice soils, detrimental compaction is described as "*an increase in soil bulk density of 20 percent or more over the undisturbed level*." And on other soils as "*An increase in soil bulk density of 15 percent or more over the undisturbed level, a macropore space reduction of 50 percent or more*…"

Further amendments to the Region 6 Supplement have been issued since 1983 to provide guidance on soil inventory and mapping, organic matter management and moisture regimes. Compaction, displacement, puddling and severely burned detrimental limits remain the same as those set in 1983 as well as the requirement to maintain a minimum of 80% of an activity area in acceptable soil quality condition. While the scientific data was limited to support many of these limits, operational threshold values were needed for effective administration and thus the levels were based on best professional judgment (Powers *et al.* 1998).

More recently in the 1980's, USDA Forest Service researchers proposed a soil monitoring strategy based on the following three rationale: management practices create soil disturbances, soil disturbances affect soil and site processes, and soil and site processes control site productivity. It was also based on measurable soil variables that are correlated with important site processes. Each Forest Service Region developed threshold-monitoring standards to detect when significant changes have occurred in potential forest productivity, and as a result an extensive long-term study was developed to create calibration curves for major soil and forest types throughout the nation. Primary objectives include validation of operational regional standards and establishment of more effective monitoring variables. The project is called the Long-Term Soil Productivity Study and although results remain preliminary, it is expected that soil quality standards will continue to evolve as the research findings help direct new policy guidelines (Powers *et al*. 1998).

4. Study Objectives

The primary objectives of this study were to characterize and compare several soil physical characteristics in high traffic areas on recent and past subsoiled harvest units and on adjacent control locations in Central Oregon. Two harvest units, one sloped and one flat, from 1998 and 2004 were chosen, along with adjacent control locations because of similar geologic formation, soil type, aspect, and slope. Although there has been considerable study of soil compaction on harvest areas, this research focuses on less studied physical characteristics that can better explain watershed and plant growth responses. The following questions further explain the nature of the objectives and what this study is intended to accomplish:

1. How do soil physical properties in high traffic areas after tillage compare with soil conditions in relatively undisturbed adjacent areas?

2. Does the Cornell Sprinkle Infiltrometer provide a good measure of infiltration on an Oregon volcanic ash soil? How do the observed infiltration data compare with estimated storm levels for this general location? Does application rate affect runoff? If so, how?

3. Are there major differences or other patterns in soil physical properties in sloping versus level harvest units?

4. What are the effects of tree harvest and soil tillage on porosity and soil water holding capacity? What implications might this and other changes in soil-physical characteristics have for subsequent plant growth?

5. Within constraints of the study design, is there a suggestion of major differences or other patterns in soil physical properties in older versus newer harvest units?

These particular questions were asked both to gain insight for future research and to help address management concerns, because parts of this area in central Oregon have extensive forest health and fuels problems.

5. Study Location

The study sites are located on the Sisters Ranger District of the Deschutes National Forest east of the Cascade Mountain crest in central Oregon. They are in Deschutes County approximately 30 miles northwest of Bend, Oregon within a few miles of Oregon Highway 20. Harvest units are in the subwatersheds of First and Jack Creeks located on the western flanks of the Metolius River Basin.

5.1. Harvest Unit Criteria and Selection

Initially it was hoped that a chronosequence of harvested sites could be established to look at soil characteristics more closely over a wider range of time. However, after considering possible influential unknown variables and visiting many potential sites, only harvest units from two different years were selected. In addition to time limitations imposed by summer field seasons and the scope of this project, it was felt that the site variability among many years would be too great.

Primary site selection criteria for harvest units were: 1) sites that had been either clearcut or heavily harvested using similar ground-based methods and followed by tillage of compacted skid trails, 2) similar slope and aspect with paired sites from the earlier year, 3) very similar soil type throughout the sampling area and with other studied sites, and 4) relatively easy access from forest roads in good condition. Unit 3 (sloped) and 5 (flat) were chosen from the 1998 Davis Thin and Unit 85 (sloped) and 118 (flat) were selected from the Lower Jack Sale in 2004. From each of these selected harvest units, a smaller subsection under an acre in size was chosen and laid out into a numbered grid to intensely sample and characterize areas of heavy traffic and subsoiling. The subsections were located near where a landing had been and from visible evidence and soil probing it was clear that multiple skid trails had existed.

5.2 Harvest Unit Descriptions

All study sites have a northerly aspect and sloped units average 17%. Climate in the area is characterized by hot, dry summers and cold, wet winters. Average annual precipitation is 110-150 cm with the majority falling November through April and often as snow. Native vegetation consists primarily of ponderosa pine, white fir, snowbrush, chinkapin and pinegrass.

Soils consisted primarily of Typic Vitricryands, but also included Alfic Vitrixerands and Aquic Vitrixerands. Profiles are made up of a fine sandy loam that is influenced partially to entirely by volcanic ejecta including ash, cinders and pumice.

Beneath them at depths of 50-100 cm lie soils that had previously been developed from older parent materials such as glacial till and glacial outwash. These were buried as volcanic materials fell during multiple volcanic events. All bedrock materials are extrusive volcanic rocks and can be found at depths of 150 cm or more (Larsen 1976).

Historically, fire intensities at low elevation locations within the Metolius watershed were low and forests survived and thrived along the Metolius River. However, in the past decade, many portions of the forests including large segments of the study sites, experienced fires that were uncharacteristic in size and intensity. The B&B fire of 2003 was unprecedented in size compared to fires in the past century and burned over the studied harvest units at different intensities. Harvest units from 2004 were generally more affected by the burn. According to the Metolius Watershed Analysis Update (USDA Forest Service 2004) vegetation mortality was mixed and the direct effect of wildfires to the soil resource is minimal. Productivity is expected to be the same except in areas where elevated temperatures lasted for extended periods of time (places where down woody debris or stumps were completely combusted). These areas are less than 4% of the total burn area. Negative changes to the soil from nutrient volatilization or altered mineral compositions were not observed to a large extent.

Units 85 (sloped) and 118 (flat) from the Lower Jack Timber Sale were part of a timber sale that was affected by the B&B fire. Unit 118 had been thinned prior to the fire but 85 had not. Following the fire in 2004, both units were removed of dead and dying trees, which for Unit 85 was almost the entire stand because it was nearly all dead. Trees were felled with tracked machines, and skidded with rubber tired grapple skidders.

Following completion of operation, tillage of skid trails was done with a winged subsoiler that had three shanks spaced 3-4 feet apart.

6. Methods

The research questions posed were addressed through the collection and analysis of data from four harvest units and their respective adjacent unharvested control areas. These sites were located in the Deschutes National Forest and used to represent typical harvest units in a managed landscape within the area (Table 2). Data were gathered manually in the field and stored electronically. The data were statistically analyzed using SAS software.

Table 2. Summary characteristics of harvest units where a smaller high-traffic area was sampled.

Unit ID	Location	Area (hectares)	Slope (%)	Treatment(s)	Year
3	44º27'56"N 121º44'14"W	16.6	17	Clearcut	1998
5	44º27'57"N 121º43'13"W	5.9	0	Clearcut	1998
118	44º29'28"N 121º42'45"W	8.1	0	Thin prior to salvage	2004
85	44º30'15"N 121º42'39"W	12.9	17	Salvage	2004

For each harvest unit, a numbered grid was laid out purposely across a portion of the most heavily trafficked areas (generally immediately adjacent to a main roadside landing) and varied from 0.26-0.30 hectares in size. Measurements were then taken at random points on the grid generated from a random number table to well characterize the disturbed area. Diagrams depicting the grid and sampling layout for each harvest unit can be found in Appendix A.

Adjacent to each sampled harvest unit, an "undisturbed" control area was selected and sampled for the same properties as the harvest units. These areas were reforested stands that had not been harvested for several decades. While these areas were not true "undisturbed" controls, they did represent the closest approximate of a control in this part of the Deschutes Forest. Most land in this area has seen substantial timber harvest and other management as well as recreational traffic, which makes it nearly impossible to find totally undisturbed areas that are comparable in soil type, aspect, slope, and geologic formation. The control areas were sampled for identical variables, but not in an identical systematic random grid-point method due to the variable ground conditions and size of these areas. Sampling sites were biased towards spots that were very likely to not have been covered by any machine traffic. These areas included patches of uncut trees, or in-between larger habitat trees where there was not enough space for a vehicle to travel through. While true "undisturbed" conditions are almost impossible to find in such a historically heavily used public forest, the sampled areas were seen as a reasonable approximation for undisturbed controls because they had not been harvested or otherwise trafficked in several decades, and had nearly identical soil types, aspects and slopes.

6.1 Bulk Density

Core sampling was used to determine the average dry whole soil bulk density of each harvest unit. Seventeen - 5 cm diameter cores (96.2 cm^3 volume) were taken from each unit vertically at the 10-15 cm depth. This depth was considered suitable for evaluating trends in the upper horizons of the soil that could occur with management while avoiding anomalies of soil conditions right near the surface. In the undisturbed adjacent control sections for each harvest unit, seventeen cores were selectively taken at the same depth from areas that seemed to have had little or no traffic on them in recent times.

Core sampling for bulk density is a straightforward method that involves driving cores of a known volume into the soil to a certain depth followed by careful removal, and subsequent weighing of the core after it has been oven dried (Blake and Hartge 1986). Often the measurement of bulk density in forest soils is hampered by the presence of coarse fragments. In gravelly or stony soils, under representation of this fraction and lower than actual bulk density values can occur if the core size is too small in diameter. In other cases, overestimated values of density can occur if the soil is compacted when the core is driven into the soil (Page-Dumroese 1999). These potential concerns were not deemed to be serious problems because during sampling, it was observed that the soil was not overly gravelly or stony. The 5 cm diameter cores were considered effective in representing all particle fractions and were collected in ways to minimize disturbance to the best extent possible. However, with all core sampling some minimal disruption is inevitable.

6.2 Soil Water Retention and Pore Size Distribution

From the set of collected bulk density cores at the 10-15 cm depth, four cores were selected randomly from each harvest unit and adjacent control units. They were subjected to a stepwise series of incremental laboratory pressure chamber and membrane extraction pressures, 10, 33, 50, 100, 500 and 1500 kPa, to generate data points for moisture retention curves.

Soil water retention curves, or desorption curves as they are often called, are useful in characterizing multiple soil physical characteristics that can be interpreted in relation to water availability for plants, infiltration into soil, and water flow. For this study, pore size distribution and macroporosity are the characteristics sought with the desorption curves. These parameters were expected to provide a useful index for gauging soil physical responses to different tillage and management systems.

Desorption curves are created after determining a set of equilibrium pressures and tensions that will best fit the intended use of data. Minimally disturbed cores are collected and covered with cheesecloth on their bottom end and held in place with a rubber band. The cores are saturated and placed on ceramic plates being sure to establish good hydraulic contact with the tension medium. Pressure within an enclosed chamber is increased to the selected value and water drains from the soil over time in response to the imposed pressure until equilibrium is established. A point on the desorption curve represents the water remaining in the soil at equilibrium with the applied pressure (Klute, 1986). This process is repeated until all the desired points on the curve have been collected. Capillary theory is used to obtain the equivalent pore size distribution.

6.3 Soil Strength

Soil strength is commonly measured by penetrometer, which typically consists of a cylindrical shaft with a conical tip at one end, and a force measuring device at the other. Penetrometers provide rapid point estimates of soil resistance to penetration as the probe is driven into the soil at a constant speed. Resistance depends on soil type, bulk density, water content, and structure of the soil. Penetration resistance generally increases with increasing bulk density and decreases with increasing soil water content (Bengough *et al*. 2001).

For this study, a CP20 Rimik Cone Penetrometer was used in the field to assess soil strength in each harvest unit and control area during August of 2005. Settings were adjusted to provide point estimates of soil resistance every 25 mm, down to a target depth of 400 mm. For the harvested units, two strength measurements 1 m apart were collected every 12.2 m along the numbered grid for each harvest unit. As penetration resistance readings can be extremely variable, a large sample size was used in order to effectively characterize the trafficked area and account for expected variability. Small diameter soil samples were taken for determination of soil moisture content and soil surface descriptions were collected at each sampling site for later reference purposes.

For the control locations, 12 meter transects were laid out in a random azimuth direction from each infiltration measuring location (see next section). Strength was measured twice (perpendicular to the transect, three feet apart) every two meters out from the infiltration site for a total of 12 penetrometer readings per transect (see Appendix A).

6.4 Infiltration

A small and durable portable rainfall simulator was used to measure infiltration on the selected study sites. In this way, many replicate field measurements could be collected relatively quickly and inexpensively. The Cornell Sprinkle Infiltrometer consists of an airtight reservoir with adjustable Mariotte-type air entry tube for controlling pressure head and coiled capillary drip tubes at the bottom (Ogden et al. 1997). A range of rainfall intensities from 0.5 cm/min to 0.65cm/min can be achieved by placing the bubbling tube at various heights.

To operate the device, an infiltration ring is inserted into the soil to a depth of 7 cm. The outflow hole is oriented downslope where overland flow would run naturally and a hole dug to place a beaker to collect outflow. The rainfall simulator is filled with water and then placed on top of the infiltration ring and the initial water level height in the simulator is measured. The air-entry tube is opened while concurrently starting a stopwatch and any outflow from the ring is measured. Once steady state conditions have been reached (generally within one hour), or once the water level in the simulator is nearly empty, the measurement period ends and water level height within the reservoir is recorded again.

12 rainfall simulation and infiltration measurement pairs were taken at each harvest area at randomly selected grid points. Of the 12 rain applications, 6 were at a high intensity rainfall (6.9cm/hr) and 6 were at very-high intensity rainfall (27.8cm/hr). Infiltration rate was measured along with any potential runoff. At control sites identical measurements were conducted but sampling sites were not random, and instead biased toward locations where past disturbance was most unlikely. Measured infiltration rates were later adjusted to account for lateral flow at the bottom of the ring using conversion factors for field-saturated conditions (based on manufacturer instructions and Reynolds and Elrick, 1990).

6.5 Data Analysis

Data analysis for this case study was conducted using a split plot design with year as the blocking factor. An analysis of variance (ANOVA) procedure was conducted using SAS v9.1 statistical software. The CLASS, MODEL, and RANDOM statements were used within the PROC MIXED procedure to test what was labeled topography, disturbance and topography × disturbance effects. The term "topography" denotes whether the sampling area was either flat or sloped and "disturbance" defines whether the area was harvested and tilled or if it was an undisturbed control. Topography and disturbance were fixed effects and block was the random effect. A Bonferroni adjustment was made to modify the desired alpha level downward in order to compensate for the increased probability of error that occurs when multiple tests are performed on the same data set. To do this the alpha level of 0.05 was divided by the number of separate statistical comparisons. Mean values for each measured soil physical characteristic are summarized in Appendix B.

In analyzing soil strength data, the REPEATED statement was added to the PROC MIXED procedure to perform a repeated measures analysis. This is because strength measurements were collected at the same sampling point but at different depths. Proper covariance structure was determined using a macro and each proposed covariance structure was ranked by Akaike's Information Criterion (AIC) and Bayesian Criterion (BIC). The structure with the lowest AIC and BIC value was chosen as the most appropriate. Lastly, in order to simplify the analysis, the 15 depth intervals were grouped into three depth classes to minimize the number of individual measures per replicate.

The study design of this case study has some limitations for data analysis and as a result not all initially desired comparisons are statistically robust. Due to the lack of replication of the year variable there is not enough power to support the results when comparing data from one year to another. However, despite this two-sample t-tests were conducted (Appendix D) for each topography × disturbance class combination between the years of 1998 and 2004 to simply observe the results and potential insights for where further research might be promising.

7.0 Results and Discussion

7.1 Bulk Density

17 bulk density cores of a known volume (96.2 cm^3) were collected, dried and weighed to obtain dry bulk densities for the whole soil fraction at each sampling location. Means were calculated for each group from values that ranged from 0.67 to 1.18 g/cm^3 (Figure 1). The obtained bulk density values match up well with previous work done in the area by the Sisters Ranger District of the Deschutes National Forest (USDA Forest Service 2005). That analysis showed that in 2004, Salvage Unit 85, the same unit subsampled in 2005 (2004-S in Fig. 1), mean whole soil bulk density at comparable depths on untilled skid trails and non-impacted areas was 1.10 g/cm^3 and 0.90 g/cm^3 respectively.

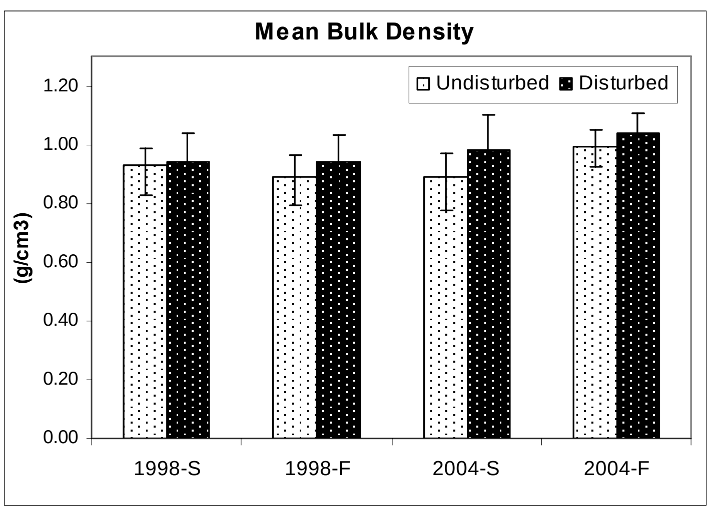

Figure 1. Mean bulk density values ± one standard deviation for disturbed and undisturbed locations.

From tests analyzing topography and disturbance relationships with bulk density in high traffic portions of harvest units and their respective undisturbed counterparts there was not enough evidence to support an interaction effect between these variables ($F_{1,131}$ = 0.02, P = 0.8970). This suggests that overall the mean bulk density of the sampled sites does not depend on this specific combination of topography and disturbance classes. Units with different slopes or operations could show some patterns.

There was also not enough evidence to support a significant difference in bulk density between flat and sloped locations ($F_{1,131}$ = 3.86, P = 0.0514, Bonferroni adjusted α = 0.025). The estimated mean bulk density of flat sites was 0.96 g/cm^3 (95% CI: 0.90, 1.03 g/cm^3) and 0.93 g/cm^3 for sloped sites (95% CI: 0.87, 1.00 g/cm^3). This is a 3% difference (95% CI: 0.0, 6.5%) between flat and sloped areas. Soil forming factors acting in the area (i.e., climate, organisms, parent material and time) all appear relatively uniform between sites. Relief is the only thing that varies and perhaps due to the recent formation of surface soils in the area (volcanic deposition 6000 years ago) and their high permeability and ability to resist erosion, minimal transport has occurred and soil profiles are relatively similar. In addition, the similar management of forests at the flat and these moderately sloped locations could have contributed to similar surface soil densities.

While there was no evidence suggesting a topographic control on bulk density, there was strong statistical evidence that bulk density in disturbed areas was greater than undisturbed areas ($F_{1,131}$ = 10.90, P = 0.0012). The estimated mean bulk density on the disturbed sites was 0.97 g/cm^3 (95% CI: 0.91, 1.03 g/cm^3) and 0.92 g/cm^3 for undisturbed areas (95% CI: 0.86, 0.98 g/cm^3). This is a 5% difference (95% CI: 1.6, 8.6%) between these areas.

While a difference of 5% between disturbed and undisturbed areas was deemed significant in this statistical analysis, it is only slightly larger than the 3% difference between flat and sloped sites which was statistically insignificant. The percentage difference between disturbed and undisturbed areas is also less than the USDA Forest Service Region 6 definition of detrimental compaction (20% in ash/pumice soils) and sampled areas were those exposed to heavy machine traffic. Mean bulk density on disturbed sites, 0.97 g/cm^3, was not as high as the 1.10 g/cm^3 measured on untilled skid trails by USDA Forest Service (2005) suggesting that some amelioration of compaction resulted from the tillage.

7.2 Soil Water Retention and Pore Size Distribution

From the seventeen bulk density cores collected from each harvest unit and control location, four were chosen randomly to undergo further soil-water retention analysis. A total of 32 cores, which was the maximum that could be fit into the pressure chamber at one time, was subject to a series of incremental pressures, 10, 33, 50, 100, 500, and 1500 kPa, to generate points for a moisture retention curve. Mean volumetric moisture content was determined at each matric potential (Figure 2 and Appendix C).

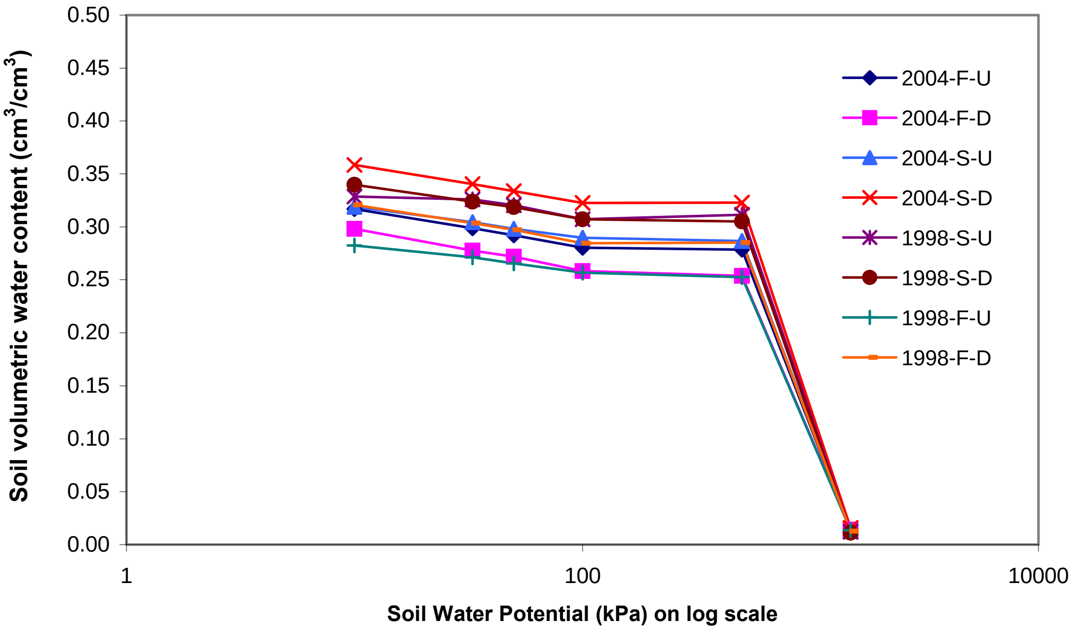

Fig 2. Mean volumetric water content in the soil (m^3/m^3) at each matric potential on a log scale for each sample site. (S=Sloped, F=flat, D=disturbed, U=undisturbed)

By determining the volume of water removed from the soil in response to changes in matric potential and using assumptions from the capillary model, the volume of pores above a specific diameter can be determined (Klute 1986). The approximate volume of pore space for a specific pore size range equals the volume of water removed between two specific pore sizes. Pore volumes for two different diameter size ranges, ≤30 µm, and >30 µm, were estimated (Figure 3) from the release curve.

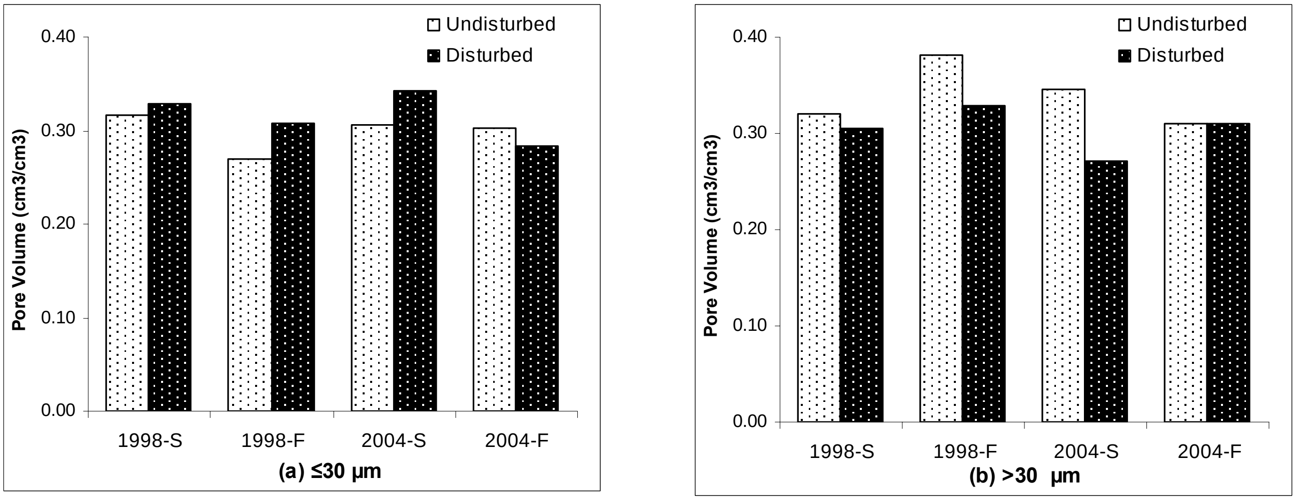

Figure 3 (a and b) – Pore volume for two diameter classes (a) ≤30 μm and (b) >30 μm according to sample site using the desorption method.

From ANOVA's conducted on each size class (Appendix D), there was no evidence that suggested either individual fixed effects from topography or disturbance class or interaction effects between the two factors were associated with the distributions of any of the pore diameter size classes. From the different size classes, macroporosity (which for this case was considered as pores greater than 30μm diameter), is of great interest because it contributes to unique characteristics that many forest soils exhibit including high infiltration and hydraulic conductivity (Greacen and Sands 1980). The estimated mean macroporosity for flat and sloped locations was 0.33 $cm^3/cm^3$and 0.31 cm^3/cm^3 respectively; a relative difference of 6% (95% CI: -0.02, 0.06 %). On disturbed and undisturbed areas, mean macroporosity was 0.31 $cm^3/cm^3$and 0.34 cm^3/cm^3respectively, a relative difference of 9%, (95% CI: -0.07, 0.01 %).

The USDA Forest Service investigation (2005) of salvage unit 85, showed that macroporosity on skid trails and non-impacted sites were 0.21 g/cm^3 and 0.33 g/cm^3 respectively; a relative 37% difference. The larger difference between the skid trail and undisturbed values in that study than that seen in this study is likely because the Forest Service skid trails were measured in 2004 prior to tillage of the trails. One of the management concerns related to compaction from logging machines is a major shift in pore size distribution from macropores (larger diameters), to micropores (smaller diameters). This shift can cause the soil to behave as if it were of a finer texture and alter plant soil-water relationships and affect site productivity. No significant difference in pore size distribution was observed on the 2005 harvest unit sampling subsets after harvest and tillage of skid trails (Appendix A).

7.3 Total porosity

Total porosity was calculated for each sampled bulk density core using volumetric water content and an assumed particle density of 2.65 g/cm^3. Porosities of individual samples ranged from 0.55 cm^3/cm^3 to 0.75 cm^3/cm^3 and means were determined for each treatment group (Figure 4).

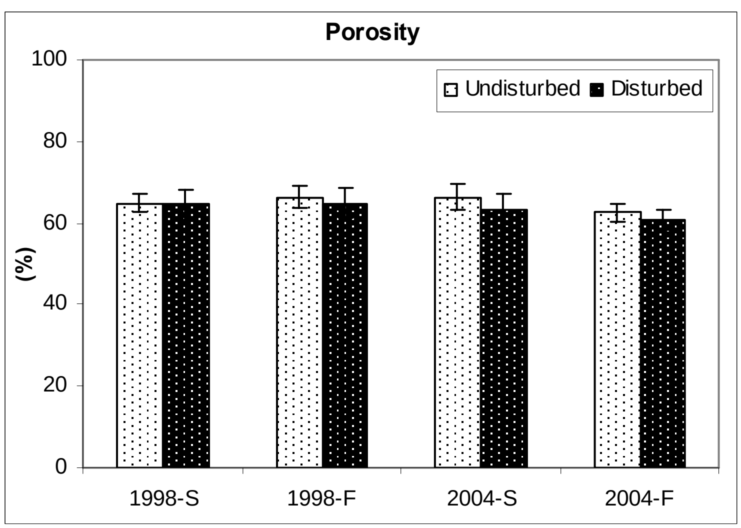

Figure 4: Mean total porosity as percent of total soil volume according to treatment unit ± one standard deviation

Since porosities were calculated using bulk densities for each sample group, the results are very similar in terms of main and interaction effects. Again, there was not enough evidence to support an interaction between topography and disturbance ($F_{1,131}$ = 10.90, P = 0.8970) implying that the total porosity at a site is not associated with this combination of topography and disturbance.

For individual fixed effects, there was no evidence of any difference in porosity between flat and sloped locations ($F_{1,131}$ = 3.86, P = 0.0514, Bonferroni adjusted α = 0.025). The estimated mean porosity on sloped locations was 1.7% greater than flat locations (95% CI: 3.7, -0.3 %). Because porosities were determined using bulk density values, reasons for the lack of porosity-topography relationship are similar. Soils have similar parent material, organism interactions, management and experience the same climate. Major differentiation of sites between the top 10-15 cm of soil were not observed in the soil profiles.

On the other hand, evidence was strong that total porosity in disturbed areas was less than undisturbed areas ($F_{1,131}$ = 10.90, P = 0.0012). The estimated mean difference in porosity between disturbed and undisturbed locations was -1.9 % (95% CI: -3.2, -0.6 %). Although statistically significant, the relative percentage differences between flat versus sloped locations and disturbed versus undisturbed are small. Further exploration into porosity is needed to confirm the relationship of porosity values as the sample size was relatively small and variability high.

Values determined by the USDA Forest Service (2005) for untilled skid trails and non-impacted areas were 0.56 cm^3/cm^3 and 0.64 cm^3/cm^3 respectively. Mean porosity values determined for disturbed and undisturbed sites in this case study were 0.63

cm^3/cm^3 and 0.65 cm^3/cm^3 respectively. The fact that these porosity values were measured after the tillage of existing skid trails in high traffic areas are suggestive of the idea that the tillage practices helped restore porosities to levels similar to undisturbed areas.

7.4 Available Water Capacity

Available water capacity (AWC) is the water retained in the soil after gravity drainage has occurred and generally available to plants. It is bound in the soils by a tension greater than that of field capacity and below the permanent wilting point. Water held more loosely than at field capacity is quickly drained by gravity. Field capacity for this fine sandy loam soil was considered to occur at -33kPa and wilting point at -1500 kPa. This value is only an approximation as the permanent wilting point can vary with plant species and soil type. AWC was determined as the amount of moisture held between these two tensions (Figure 5).

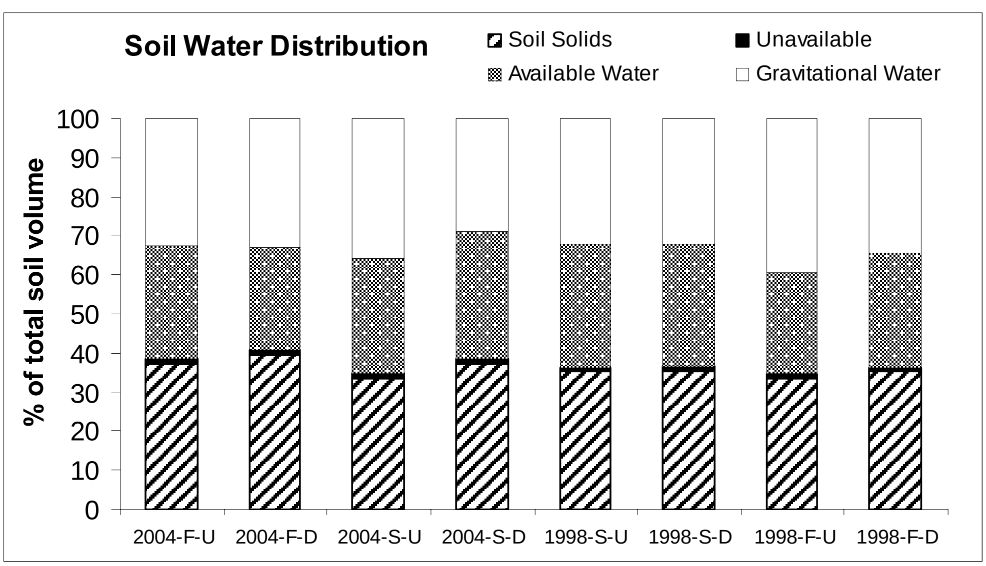

Figure 5. Estimated volumetric distribution of soil solids, available water, gravitational water, and water unavailable to plants based on pressure chamber tests with soil cores.

From tests of main effects and interactions there was not enough evidence to support an interaction between topography and disturbance on available water ($F_{1,27}$ = 1.62, P = 0.2136) implying that the available water capacity of a site is not associated with these combinations of topography and disturbance.

There was no evidence of any statistically significant difference in AWC between flat and sloped locations ($F_{1,27}$ = 0.39, P = 0.5401) or between disturbed and undisturbed locations ($F_{1,27}$ = 0.02, P = 0.8910) as individual tests on fixed effects (Figure 6). The estimated mean difference between flat and sloped locations was 0.2 %, (95% CI: -3.9, 4.3 %) and the estimated mean difference in available water capacity between disturbed and undisturbed areas was 1.1 % (95% CI: -3.1, 5.2 %). These findings seem to correspond well with those of macroporosity and total porosity because available water is a function of the two. However, sample size for this analysis was very small with only four soil cores per sample group. In Figure 6 there is some suggestion of available water increases for some group pairs but high sample variability could mask significant differences. More study is needed into AWC to comment with greater certainty.

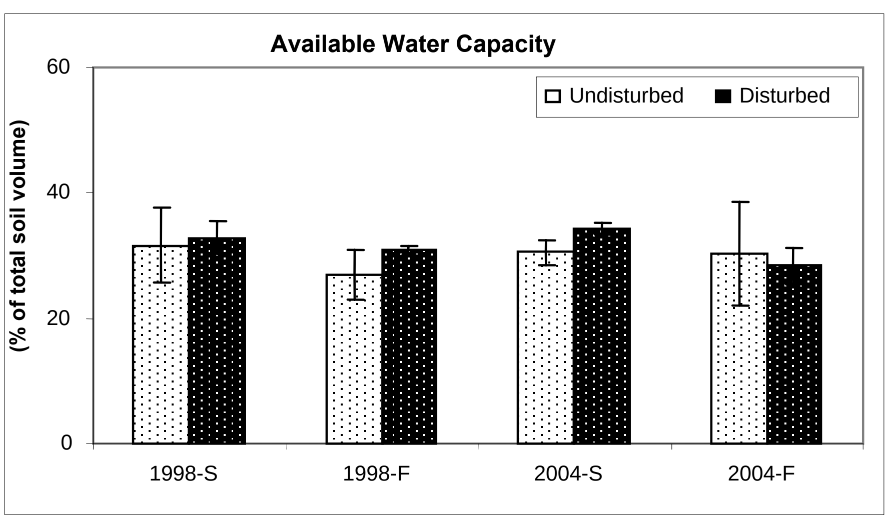

Figure 6. Mean available water capacity for each treatment unit ± one standard deviation.

7.5 Soil Strength

Soil strength profiles measured by the penetrometer were downloaded onto a computer and any bad data caused by equipment difficulties such as machine malfunctions or hitting subsurface rocks were removed. To facilitate the data analysis, groups were reassigned "profiletype" numbers in the following manner for analysis: (1) sloped-disturbed areas, (2) flat-disturbed areas, (3) sloped-undisturbed areas, and (4) flat-undisturbed. In addition, due to the high amount of repeated measures per individual profile (16 strength readings), the profile data were grouped into three depth classes: (Depth Class 1) 0.0-12.5 cm, (Depth Class 2) 12.5.0-25.0 cm, and (Depth Class 3) 25.0-37.5 cm. The last strength reading at 40.0 cm below the surface was removed from the statistical analysis in order to create three comparable depth classes and because of some questionable and missing readings at 40 cm. Soil moisture determined by small diameter soil cores averaged between 7 and 9 % across all units.

Sample size corrected AIC and BIC values for each considered covariance structure were determined (Appendix B) and the AR(1) structure was chosen for the final repeated measures statistical model.

There was strong evidence of an interaction effect between profile type and depth class ($F_{2,2017}$ = 17.91, P = <0.0001) implying that soil strength at each depth class will depend on profile type.

For the main effects, Depth Class was statistically significant as expected ($F_{2,2017}$ = 723.05, P = <0.0001) implying that soil strength changes with depth. All depth classes were significantly different from each other. With profiletype, all types were statistically different from each other except for the sloped × disturbed and flat × disturbed types (P=0.4153)

To elaborate on the interaction effects, in Depth Class 1, there was no significant difference between any of the four profile types (Table 3, Fig 7). In Depth Class 2, soil strength was significantly higher on disturbed sites compared to undisturbed sites and there was no evidence of a difference between flat and sloped areas within the disturbed (P=0.3623) or undisturbed (P = 0.1377) conditions. For Depth Class 3, each location was significantly different from the other except for on disturbed locations where there was not enough evidence to suggest a difference between flat and sloped sites (P=0.3813).

	Profile type			
Depthclass	Sloped × Disturbed (1)	Flat × Disturbed (2)	Sloped × Undisturbed (3)	Flat × Undisturbed (4)
1 (0-12.5 cm)	679 (82) a a	555 (82) a b	634 (87) a c	618 (86) a d
2 (12.5-25.0 cm)	1402 (83) a a	1345 (82) a b	1027 (87) b c	1135 (86) b d
3 (25.0 – 37.5 cm)	1745 (84) a a	1805 (85) a b	1194 (87) b c	1480 (87) c d

Table 3 – Soil strength (kPa) as related to profile type and soil depth. Values are means of 1998 and 2004 units (± one standard deviation). The first letter after each mean refers to comparisons within depth classes and the second letter refers to comparisons between depths. Pairs with different letters are significantly different at 0.05 level.

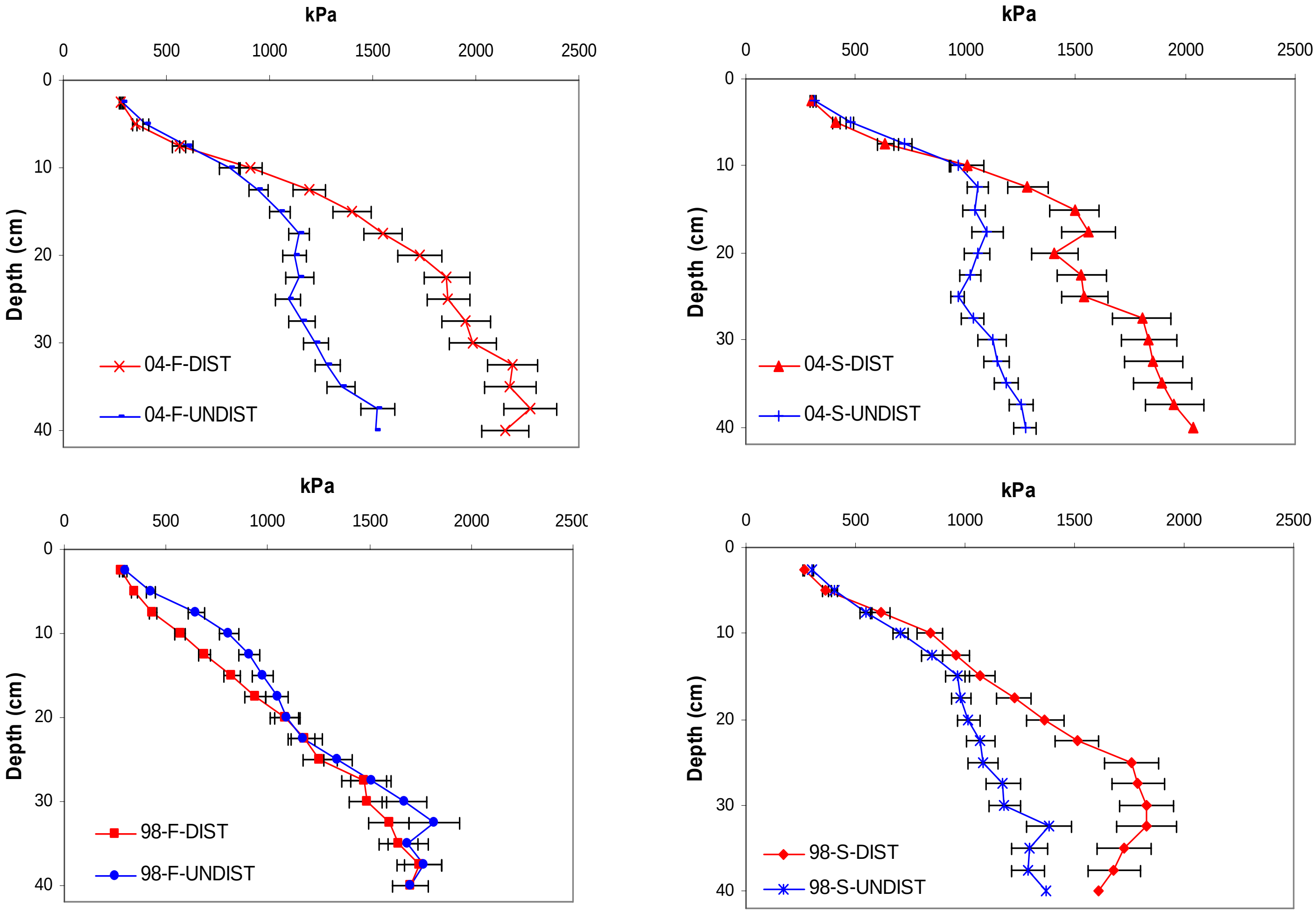

Figure 7: Soil strength by profile type ± one standard deviation.

7.6 Infiltration

Six high intensity and 6 very-high intensity rainfall simulations were conducted at each harvest unit and respective control. Soil moisture prior to beginning the simulations determined by small diameter soil cores was between 7 and 9 %. The average high rainfall intensity was 6.9 cm/hr (2.7 in/hr) and the average very-high intensity rainfall simulation was 27.8 cm/hr (10.9 in/hr). These values are averages because consistent rainfall was hard to achieve with the simulator and as a result rainfall varied slightly from simulation to simulation.

From the NOAA Atlas 2 (Oregon) precipitation frequency map various rainstorm intensities for the area could be calculated using latitude and longitude. According to the NOAA website that interpolates distances and calculates intensities (*http://www.nws.noaa.gov/oh/hdsc/noaaatlas2.htm*), for the Metolius Basin at 3500 ft elevation the 2-year, 30-minute storm intensity is 1.0 cm (0.40 in) and the 100-year, 30-minute storm was 2.7 cm (1.05 in). It is clear that both rainfall intensities tested here are much greater than would likely be experienced naturally at the study locations.

The nature of the Cornell infiltrometer makes low rainfall intensities difficult to achieve and even more difficult to repeat consistently. At the lower-intensity range of the instrument, tiny changes in height of the air-entry tube corresponded to bigger than desirable changes in precipitation intensity. Infiltration rate and runoff rate were also measured during each simulation. It is important to remember that these measured rates are only indices of real rates that could occur during an actual rain event. Also, in this general location rain-on-snow events were possible, but were not investigated.

Infiltration at high intensity rainfall simulations

During the high intensity rainfall simulations infiltration rates ranged from 3 cm/hr to 9 cm/hr and there was not enough statistical evidence to support an interaction effect between topography and disturbance ($F_{1,42}$ = 0.09, P = 0.7602). This implies that the infiltration rate of a site at rainfall intensities roughly 6.9 cm/hr does is not associated with this combination of topography and disturbance (Figure 8).

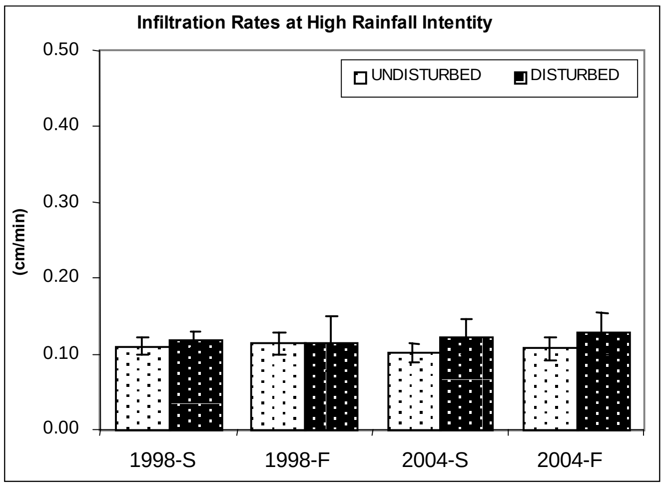

Figure 8. Average infiltration under high rainfall intensity simulations (± one standard deviation).

There was also no evidence of any difference in infiltration rate between flat and sloped locations at the high intensity rainfall simulations ($F_{1,42}$ = 0.16, P = 0.6870). The estimated mean difference between flat and sloped locations was 0.00 cm/min (95% CI: --0.01, 0.01). There was no difference in infiltration rate between disturbed and undisturbed areas ($F_{1,42}$ = 4.72, P = 0.0354); the Bonferroni adjusted alpha level in this case was 0.025. The estimated mean difference in infiltration rate between disturbed and undisturbed areas was 0.01 cm/min (95% CI: 0.0, 0.2).

While rainfall rates in this case were not typical of the area and if anything, most closely resemble a 100-yr 30-minute storm, runoff occurred one time across all 47 high intensity rainfall simulations on disturbed and undisturbed sites. The ability of the soil to allow water to infiltrate far exceeded the rainfall rate the majority of the time. Overland flow is not likely to occur and there is a low risk of erosion as a result.

Infiltration at very-high intensity rainfall simulations

Rainfall rates at the very-high intensities ranged from 20.4 cm/hr to 36.6 cm/hr. There was fairly strong evidence to support an interaction effect between topography and disturbance ($F_{1,59}$ = 8.27, P = 0.0056) implying that the infiltration rate of a site at very high rainfall intensities is associated with this combination of topography and disturbance class (Figure 9).

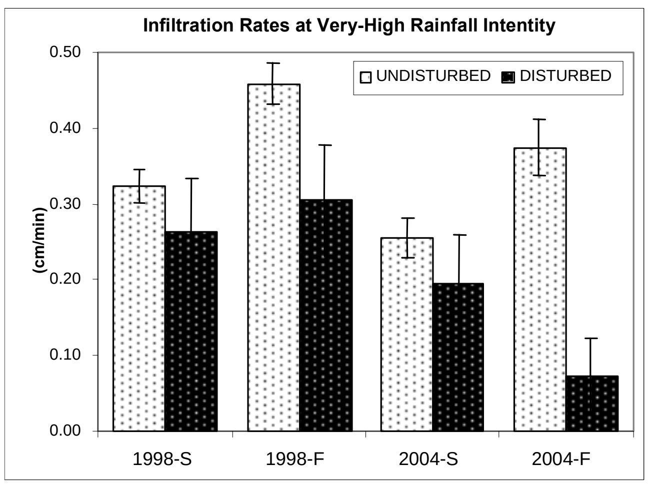

Figure 9. Average infiltration under very-high rainfall intensity simulations (± one standard deviation)

There was no evidence of a topography effect alone on infiltration rates ($F_{1,59}$ = 0.99, P = 0.3230) with the estimated mean difference between flat and sloped locations at 0.03 cm/min (95% CI: -0.04, 0.11 cm/min).

There was fairly strong evidence of a disturbance effect on infiltration rates ($F_{1,59}$ = 19.09, P = <0.0001). The estimated mean difference in infiltration rate between disturbed and undisturbed areas was -0.14 cm/min (95% CI: -0.22, -0.07 cm/min). However, these very-high rainfall rates would be highly unlikely in the study areas so the data simply suggest the physical limits of these soils under extreme conditions.

8.0 Conclusions

Under the course of this field study, it was possible to characterize and compare several soil physical characteristics on a portion of several harvest units and adjacent control locations in Central Oregon with some of the heaviest traffic and soil disturbance, including soil tillage. To organize the discussion and conclusion of findings, topics will be addressed following the questions posed initially in the study objectives.

How do soil physical properties in high traffic areas after tillage compare with soil conditions in relatively undisturbed adjacent areas?

From a management and policy standpoint no major differences of concern were observed in whole soil bulk density, available water content, total porosity, infiltration, or pore size distribution between tilled high-traffic areas and undisturbed adjacent areas. Differences between groups for each of these characteristics were insignificant or less than 9% keeping them below limits set for "detrimental compaction" by the USDA Forest Service Region 6 guidelines. It appears that skid trail subsoiling after tree removal was an effective management tool in these areas for ameliorating the negative effects of compaction.

From a statistical standpoint, some significant differences were observed and could warrant further investigation. Bulk density was significantly greater and total porosity significantly less in disturbed areas than that in undisturbed areas. However, available water content, and pore size distribution were not significantly different between tilled sites and undisturbed controls. Small sample sizes and large variability for some properties could have masked potential relationships and more sampling is needed in those cases to confirm the results. It is also important to remember that these results only characterize an area under one acre in size and not the entire harvest unit. Sampling was biased to areas of high traffic generally adjacent to a landing. Interpolation to areas larger than this is not advised because if the entire harvest unit was sampled, differences would likely be reduced due to a smaller total area of disturbed and tilled soil.

While some differences were seen in infiltration rate at the highest rainfall simulations, realistically these results do not raise management concerns because they were obtained under rainfall intensities that were far greater than would likely ever occur in this study area. This was mainly due to operating constraints of the equipment used. Convective storms of short duration and high intensity do occur in the Deschutes National Forest, however, even the 100-yr 1-hour intensity for the study area is not as great as the simulated high rainfall application rate.

Soil strength on tilled high traffic areas compared to undisturbed locations exhibited no significant differences at the 0-12.5 cm depth. However, at the 12.5-25.0 cm and 25.0-37.5 cm depths, soil strength values at disturbed sites were significantly greater than undisturbed locations. Some possible reasons for this are that while tillage was successful to a certain extent in ameliorating soil strength impacts, some portions of the harvest units could have remained untreated by the subsoiler, or if they had been tilled, were not restored enough to match natural undisturbed values.

Does the Cornell Sprinkle Infiltrometer provide a good measure of infiltration on an Oregon volcanic ash soil? How do the observed infiltration data compare with estimated storm levels for this general location? Does application rate affect runoff? If so, how?

The Cornell Infiltrometer provides a good measure of infiltration dependant on the rainfall application rate. However, given the climate in the area of the studied soil type, the tool does not provide low enough application rates to refine our understanding of rainfall-runoff mechanisms and possible subsequent erosion. Attainment of soil infiltration capacity data is not possible with the Infiltrometer if runoff does not occur. That is because to obtain it, one must subtract the measured runoff rate from the known rainfall application rate. If runoff does not occur, the infiltration rate will equal the rainfall rate and infiltration capacity will remain unknown.

Precipitation-runoff events in the study area consist of convective rainstorms, snowmelt, and rain-on-snow events. In the Metolius Basin at an elevation of 3500 ft the 2-year, 30-minute storm intensity is 1.0 cm (0.40 in) and the 100-year, 30-minute storm is 2.7 cm (1.05 in). These values were not adequately tested in this study due to the sometimes capricious nature of the instrument at low rainfall intensities. However, with infiltration capacity of the soil exceeding the rainfall rate the majority of the time at the high rainfall simulations, I feel it is safe to assume that that the same would have occurred had the rainfall application rate been lower and more realistic.

Are there major differences or other patterns in soil physical properties in sloping versus level harvest units?

Although these permeable soils generally have low natural runoff potentials (Larsen 1976), concerns are raised about runoff and erosion from slopes disturbed by management or natural events (such as the B&B Fires that exposed large areas of mineral soils). Higher peak flows and potential sediment transport to streams from storm runoff also raises water quality and channel erosion concerns. Skid trails can be a potential source of sediment if located near streams because of reduced porosity and infiltration and increased bulk density that inhibits plant cover. However, few, if any, studies have investigated how runoff or erosion potential is affected when forest skid trails are subsoiled on either level or sloped locations. Results from this case study show no major patterns or differences in soil physical properties between the sloped versus level harvest units. Differences in available water content, total porosity, pore size distribution, bulk density, soil strength and infiltration were not great enough to be statistically significant and neither flat nor sloped areas had consistently greater or smaller differences. It is important to note that the slopes studied did not exceed 16-17% and were only on a small section of an entire harvest unit, which may have limited the establishment of a direct association between skid trail tillage and relief.

It is also likely that the minor differences observed were influenced by the fact that the soils were very similar on level and sloped areas despite their difference in relief. All of the factors aside from soil strength were measured within the top 15 cm of the soil profiles and to this depth the soil profiles were very similar, consisting of a very dark brown fine sandy loam to a depth of at least 50 cm. Soil forming factors such as parent material, climate, organisms, and time apparently all acted similarly across the landscape and downslope soil movement is likely minimal due to the high permeability of the soils and consequent resistance to erosion. Forest management has also been similar across sites, suggesting that the treatment with a winged subsoiler helped ameliorate the possible increase in runoff and sediment transport following these timber harvests.

Infiltration rates typically exceeded even the very-high rainfall rate, limiting the possibility of overland flow and sediment transport. Assuming infiltration and permeability of the upper soil profile remains high, erosions risks should remain low.

What are the effects of tree harvest and soil tillage on porosity and soil water holding capacity? What implications might this and other changes in soil-physical characteristics have for subsequent plant growth?

Root growth is a complex activity that depends on favorable levels of water and nutrient availability, gas exchange, and soil strength. Differences in total porosity or soil water holding capacity resulting from slope or tillage of skid trails were not evident from this analysis. The same is true for bulk density, pore size distribution, infiltration and soil strength at the 0-12.5 cm depth. This evidence suggests that root growth impacts would not be a significant concern because gas exchange and available water is similar after skid trail tillage to that of undisturbed locations. This agrees with findings by Gomez *et al*. (2002) and their study on the effects of soil compaction on ponderosa pine. They found that the extent of soil compaction effects were defined by soil water-root and soil air-root processes.

While the exact relationships between soil strength and root elongation for Douglas-fir and ponderosa pine are unknown for this study area, Cochran and Brock (1985) found a negative correlation in the Sisters Ranger District between ponderosa pine seedling growth in clearcuts and increases in soil bulk density. Declines in growth were observed at densities higher than those measured in this case study. Greacen and Sands (1980) summarized that for many pine species, abundant roots were reported in soils of strengths less than 1700 kPa but were limited above 2500 kPa. For this investigation mean soil strength for each group at the 12.5-25.0 cm and 25.0-37.5 cm depth classes remained below 1745 kPa and suggest that soil strength would also not be a limiting factor even though it was greater on disturbed sites.

Subsequent plant growth and possible effects on future site productivity and stem volume are almost impossible to predict based on the limited extent of this study in scope and size. Given the relatively small changes of the sampled physical characteristics, it could be suggested that no major effects on productivity would occur. However, in order to verify any conclusions on productivity, vegetation measurements would need to be collected.

Within constraints of the study design, is there a suggestion of major differences or other patterns in soil physical properties in older versus newer harvest units?

Comparisons between older and more recent harvest units were conducted using two sample t-tests but are not statistically robust due to the lack of replicates. In Appendix B a table of p-values can be seen for multiple soil physical characteristics from comparisons between old and recent harvest units. The only characteristics where a potential significant difference between the two years can be seen, is with whole soil bulk density, and total porosity on the flat harvest units; density was greater and porosity was lower on the units harvested in 2004 than in 1998. However, without replication and multiple comparisons occurring on the same small sample set this relationship cannot be certain. Additional testing is needed on more harvest units from the same years and of similar soil type to improve the comparisons, or repeated sampling or a chronosequence of similar sites could be used to evaluate temporal trends.

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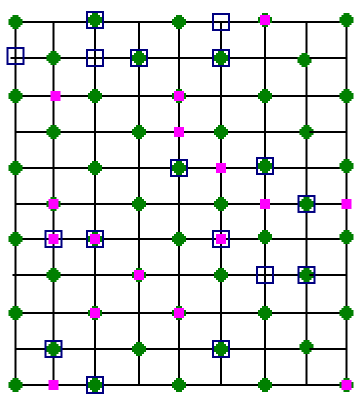
Appendix A:
Sampling Design

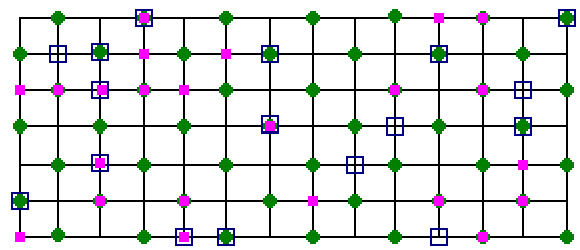
Grid Layout on Harvest Units

Legend: Penetrometer
Infiltration
Bulk Density

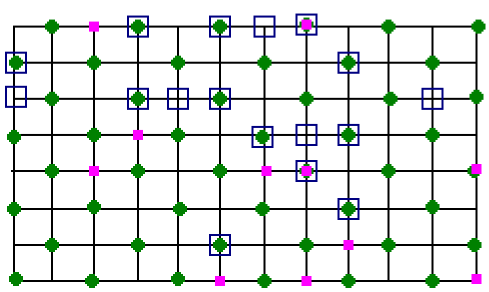
Unit 118: Salvage harvest in 2004.
160 ft. x 200 ft.
Flat topography



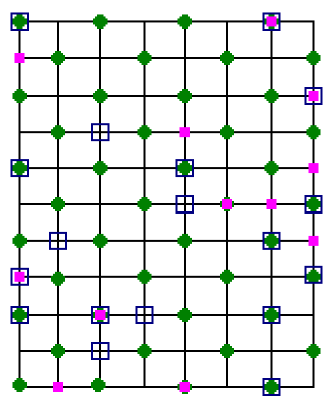
Unit 85: Salvage harvest in 2004.
230 ft. x 120 ft.
17% slope.



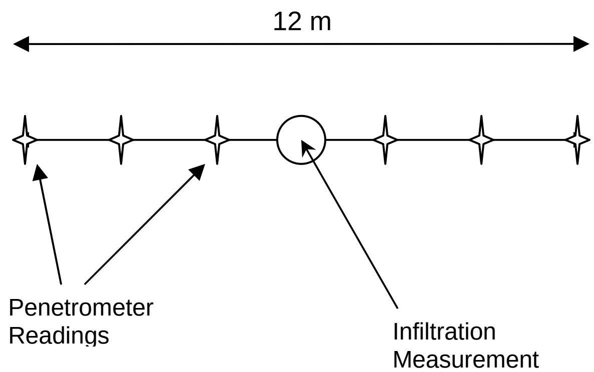
Unit 5: Clearcut in 1998
220 ft. x 140 ft.
Flat topography



Unit 3: Clearcut in 1998
140 ft. x 200 ft.
17% slope



Unharvested - Control Area Layout



Appendix B:
Soil Physical Characteristic Summary Table
(Values are means ± one standard deviation)

						Soil Strength (kPa)			Infiltration (cm/min)	
Year	**Topography**	**Disturbance**	**Density (kg/m^3)**	**Porosity (%)**	**AWC (%)**	**DepthClass 1 (0-12.5cm)**	**DepthClass 2 (12.5-25.0 cm)**	**DepthClass 3 (25.0-37.5 cm)**	**High Rainfall Rate**	**Very High Rainfall Rate**
1998	Flat	Disturbed	0.94 (0.09)	65 (4)	31 (2)	464 (180)	1057 (652)	1589 (962)	0.11 (0.04)	0.30 (0.07)
2004	Flat	Disturbed	1.04 (0.07)	61 (3)	26 (6)	656 (392)	1681 (1012)	2110 (1074)	0.13 (0.03)	0.07 (0.05)
1998	Flat	Control	0.89 (0.07)	66 (3)	31 (4)	618 (293)	1127 (519)	1691 (898)	0.11 (0.02)	0.46 (0.03)
2004	Flat	Control	0.99 (0.06)	63 (2)	28 (8)	608 (242)	1110 (463)	1306 (552)	0.11 (0.02)	0.37 (0.04)
1998	Sloped	Disturbed	0.94 (0.10)	65 (4)	29 (5)	609 (349)	1386 (901)	1770 (1190)	0.12 (0.01)	0.26 (0.07)
2004	Sloped	Disturbed	0.98 (0.12)	63 (4)	32 (2)	727 (464)	1506 (1073)	1867 (1160)	0.12 (0.02)	0.20 (0.06)
1998	Sloped	Control	0.93 (0.06)	65 (2)	26 (6)	561 (207)	1023 (484)	1263 (690)	0.11 (0.01)	0.32 (0.02)
2004	Sloped	Control	0.89 (0.08)	66 (3)	29 (2)	708 (241)	1036 (435)	1147 (471)	0.10 (0.01)	0.26 (0.03)

Appendix C:

Average incremental volumetric moisture content (cm^3/cm^3) for soil-water retention analysis

Applied Pressure	Harvest Unit							
(kPa)	**2004-F-U**	**2004-F-D**	**2004-S-U**	**2004-S-D**	**1998-S-U**	**1998-S-D**	**1998-F-U**	**1998-F-D**
1500	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01
500	0.28	0.25	0.29	0.32	0.31	0.30	0.25	0.29
100	0.28	0.26	0.29	0.32	0.31	0.31	0.26	0.28
50	0.29	0.27	0.30	0.33	0.32	0.32	0.27	0.30
33	0.30	0.28	0.30	0.34	0.33	0.32	0.27	0.30
10	0.32	0.30	0.32	0.36	0.33	0.34	0.28	0.32

Appendix D:
Statistical Output

Bulk Density ANOVA F test of main effects and interactions

Effect	Num DF	Den DF	F Value	Pr > F
Topo	1	131	3.86	0.0514
DistClass	1	131	10.90	0.0012
Topo*DistClass	1	131	0.02	0.8970

Porosity ANOVA F test of main effects and interactions

Effect	Num DF	Den DF	F Value	Pr > F
Topo	1	131	3.86	0.0514
DistClass	1	131	10.90	0.0012
Topo*DistClass	1	131	0.02	0.8970

Available Water Content ANOVA F test of main effects and interactions

Effect	Num DF	Den DF	F Value	Pr > F
Topo	1	27	0.02	0.8910
Distclass	1	27	0.39	0.5401
Topo*Distclass	1	27	1.62	0.2136

Infiltration ANOVA F test of main effects and interactions at high rainfall simulations

Effect	Num DF	Den DF	F Value	Pr > F
Topo	1	42	0.16	0.6870
DistClass	1	42	4.72	0.0354
Topo*DistClass	1	42	0.09	0.7602

Infiltration ANOVA F test of main effects and interactions at very high rainfall simulations

Effect	Num DF	Den DF	F Value	Pr > F
Topo	1	59	0.99	0.3230
DistClass	1	59	19.09	<.0001
Topo*DistClass	1	59	8.27	0.0056

Soil Strength ANOVA Table of F statistics and main effects

Effect	Num DF	Den DF	F Value	Pr > F
DepthClass	2	2017	723.05	<.0001
profiletype	3	2017	14.51	<.0001
profilety*DepthClass	6	2017	17.91	<.0001

Covariance structure AIC and BIC values

Covariance Structure	AICc	BIC
CS	31547.3	31543.4
UN (3)	N/A	N/A
UN (2)	N/A	N/A
UN (1)	N/A	N/A
AR (1)	**31281.6**	**31277.7**
TOEP (3)	31295.8	31290.5
TOEP (2)	31293.8	31287.8
TOEP (1)	31545.3	31542.3

This first-order autoregressive model considers observations in the same depthclass to be more highly correlated than measurements taken at different depths

P-value table from two sample t-tests between 1998 and 2004 units for multiple sampled variables. Values in bold indicate significance at the 0.05 level.

Topography	**Disturbance**	**Density**	**Porosity**	**AWC**	**Infiltration (High Rainfall Rate)**	**Infiltration (Very High Rainfall Rate)**
Flat	Disturbed	**0.0013**	**0.0013**	0.1604	0.5261	**0.0082**
Flat	Control	**<0.0001**	**<0.0001**	0.5580	0.4608	0.0846
Sloped	Disturbed	0.2500	0.2500	0.2543	0.7228	0.2270
Sloped	Control	0.1465	0.1465	0.3184	0.2634	0.3816