# Effects of Machine Traffic on the Physical Properties of Ash-Cap Soils

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**Abstract**

With pressure and vibration on a soil, air spaces between soil particles can be reduced by displaced soil particles. Activity associated with heavy machine traffic increases the density of the soil and can also increase the resistance of the soil to penetration. This paper reviews research related to disturbance of forest soils with a primary focus on compaction in ash-cap soils. The general process of compaction is described along with physical properties of ash-cap soils that relate to compaction. Ash-cap soils have physical soil properties most closely aligned to silt-loam soils. Undisturbed ash-cap soils often have low bulk densities to variable depths. Under moisture conditions near field capacity, these soils are susceptible to significant disturbance from machine traffic, and when the disturbance causes increases in bulk density, the soils are not likely to recover from this disturbed condition for many years. Machine traffic on forest soils generally occurs as a result of some form of active stand management including precommercial thinning, intermediate and final timber harvest, and site preparation activities involving slash disposal and treatment. The direct contact between equipment and the forest soil will result in some type of soil disturbance. The degree and extent of the soil disturbance is most often controlled through guidelines on the selection and operation of equipment and by restricting the location and operating season for equipment.

## Introduction

### General Process of Compaction

Compaction of soils is created through the energy exerted on the soil, usually through vehicular traffic in harvesting and site preparation operations. It results in the reduction of air spaces in the soil with a corresponding increase in the bulk density of the soil (weight per unit of volume). Erosion can also result from forest operations. Erosion generally occurs as a result of soil displacement and is most often associated with harvest and site preparation activities on steeper slopes.

Although generally viewed in a negative context with respect to forest soils, compaction is often a desirable process in construction activities. Many engineering projects involving earthwork in earthen dams, structural foundations, and roads require predictable strength in the soils that are at the foundation of the construction projects. Various compaction methods have been developed to achieve a desired level of soil strength and density. Some of the principles derived from research in civil engineering and soil mechanics on achieving desired levels of compaction can also be applied to forest soils in determining conditions where natural soils are at the greatest risk of compaction.

Cullen and Montagne (1981) conducted an extensive summary of literature on the general relationships between soil properties and compaction. Their review includes the general relationship between the soil properties of texture, fragment content, structure, moisture content at the time of compaction, and organic matter and the susceptibility of the soil to compaction. A more recent review by Miller and others (2004) summarized current literature on the effects of heavy equipment on soils and productivity. The discussion in this section draws heavily on these literature reviews.

## Engineering Compaction Methods

Compression or kneading compaction is generally achieved in the field with equipment that exerts gradually increasing pressure on the soil. Pressure is gradually increased to a maximum and then is gradually decreased. A device commonly used to accomplish this task in construction is called a sheepsfoot roller. Rubber tired rollers also exhibit the characteristics of this kneading action. The interaction of the tires of rubber-tired skidders used in forest operations with the soil seems to resemble that of kneading compaction machines, but with far less pressure than the equipment designed for that purpose.

Vibratory compactors usually combine pressure on the soil with vibration. Hand-held models utilize a vibrating plate. Larger versions combine a large steel roller with a vibratory impulse. There is some conjecture that tracked equipment used in forest operations can duplicate this action, but, again, with far less compactive energy than equipment designed for that purpose.

Engineering properties of soils are important to compaction. In addition to moisture content, important factors include initial soil strength or bulk density, distribution of particle sizes, percent organic matter, rock-fragment content, and percent sand, silt or clay (soil texture). The presence and influence of clay in the soil will usually determine whether it is classified as cohesive or non-cohesive. Clay influences the susceptibility of soils to compaction because of the small particle sizes of clay, clay mineralogy, and through its effect on shear strength. With small clay particles, the shear strength on soils can be partially attributed to the chemical bonding and electro-chemical resistance between particles (Brown 1977).

Soil type, texture and structure will influence the equipment that is most effective in achieving the highest level of compaction. Means and Parcher (1963) found that "maximum densities for soils with coarse texture were achieved with a heavy smooth-wheeled roller with some vibratory effects." Coarse textured soils, usually those very low in clay content, are non-cohesive and these generally require vibratory compactors. Fine-textured soils and soils with a high content of clay are usually not compacted well through vibratory compactors and require the kneading action of a mechanism similar to a sheepsfoot roller (Ingersoll-Rand 1975). Kryine (1951) noted that, in general, the maximum soil densities achieved by several methods of laboratory and field compaction decrease with decreasing soil particle size. The highest densities generally occur in soils with a wide range in particle sizes where particles can be reoriented in ways that allow the small particles to pack into the voids between the larger particles (Li 1956; Cullen and Montagne 1981; Miller and others 2004).

Ash-cap soils have unique characteristics that affect their response to the various compaction methods. While the particle size is relatively small, ash-cap soils are also considered non-cohesive and non-plastic (Cullen and others 1991). Because of their non-cohesive nature, they are likely to be susceptible to vibratory compaction (Cullen and Montagne 1981). While the kneading action of a sheepsfoot roller would probably exceed the shear strength of ash-cap soils and would not be effective for compaction, the pressure and more subtle kneading action produced by rubber-tired and tracked vehicles could increase bulk densities.

Froehlich and others (1980) completed a general report for the Equipment Development Center of the U.S. Forest Service to provide a basis for predicting soil compaction on forested land. Observed soil types included sandy loam, clay loam and loam. The study developed equations to predict absolute and percent changes in bulk density with vehicular traffic. While specific values associated with the equations may not be useful in a broad sense, the statistically significant factors are of interest. These include the number of trips by equipment, initial soil strength (cone index), initial soil density, machine derived pressure of the vehicle in kilograms per square centimeter, soil organic matter in percent, soil moisture content in percent, and forest floor depth. The most significant of these factors were number of trips and the initial cone index of the soil, reflecting a measure of initial soil strength and the level of machine activity as two primary factors in determining changes in soil characteristics.

## Optimum Moisture Content

The optimum moisture content for compaction is related to the energy generated in the compaction effort. As compaction effort increases, soils will be compacted to higher soil strength and bulk density. The maximum bulk density will also occur at lower optimum moisture content. Soils below the optimum moisture content will not be compacted to as high a bulk density as when they are at the optimum moisture content (Håkansson and Lipiec 2000). Up to and including the optimum moisture content, water can lubricate particles and allow their reorientation with respect to each other. Most compaction is seen in wet conditions, particularly near soil field moisture capacity (Alexander and Poff 1985). When soil moisture exceeds the optimum moisture content of the soil, soils begin to become plastic or the incompressibility of the water prevents reorientation and packing of the soil particles. According to the review by Cullen and Montagne (1981), optimum moisture content for compaction tends to increase as soil texture becomes finer (Felt 1965). The less dense the initial soil sample, the greater the moisture content required to reach maximum soil density for a given compactive effort (Lull 1959).

Optimum moisture content for compaction is determined for engineering purposes by a laboratory analysis called the Proctor test. The standard proctor test involves 25 blows of a 2.5 kg hammer dropped from a height of 30.5 cm. Because this test did not generate sufficient energy to predict compaction efforts of most modern construction equipment, a modified proctor test was developed. The modified test increased the compaction energy, using 25 blows of a 4.5 kg hammer dropped from a height of 45.7 cm. Both the standard and modified Proctor tests created too much compaction energy to effectively predict compaction from equipment used in forest operations (Froehlich and others 1980). A light proctor test using 8% of the energy of the standard Proctor test appeared to be effective in predicting the compaction effort of harvesting and site preparation equipment. It involved 10 blows of a hammer weighing 0.5 kg dropped from a height of 30.5 cm. The general relationship between optimum moisture content, maximum bulk density and level of compaction effort are illustrated in Figure 1. As compaction energy increases, the optimum moisture content for compaction decreases.

Soil texture can also affect the response of the soil to compaction efforts and its sensitivity to moisture content. Figure 2 illustrates theoretical differences in maximum bulk density and sensitivity to moisture for well graded and uniform soils when other factors of the soil are held constant. Although the light Proctor test could be used to predict maximum bulk densities that might result from forest operations for some soil types, it also showed that the soils were less sensitive to moisture content when there was less compaction energy applied. The compaction curve was flatter and, in some cases, U-shaped as illustrated in Figure 3 (Froehlich and others 1980).

Davis (1992) used the light Proctor test in his studies of bulk density changes in two central Oregon soils. He found the light proctor test to be adequate for describing a cobbly loam soil, but found a test using the heavier hammer of the standard proctor test with 5 to10 blows of the hammer (rather than 25) to be more accurate in predicting compaction for the ash-cap soil with sandy loam texture. His Proctor tests showed gradually increasing bulk densities as compaction effort increased, but there was not a high sensitivity to soil moisture content.

Total organic matter content in the soil is closely related to aggregate size and stability. Thus a reduction in organic matter content will result in a loss of aggregate stability and a subsequent increase in a soil's potential for compaction (Alderfer and Merkle 1941). Working with four soils in New York, Free and others (1947) concluded that soil samples containing the most organic matter would be compacted the least at given moisture contents and compactive efforts. This relationship between organic matter and compactibility of soils was also confirmed in the review conducted by Miller and others (2004).

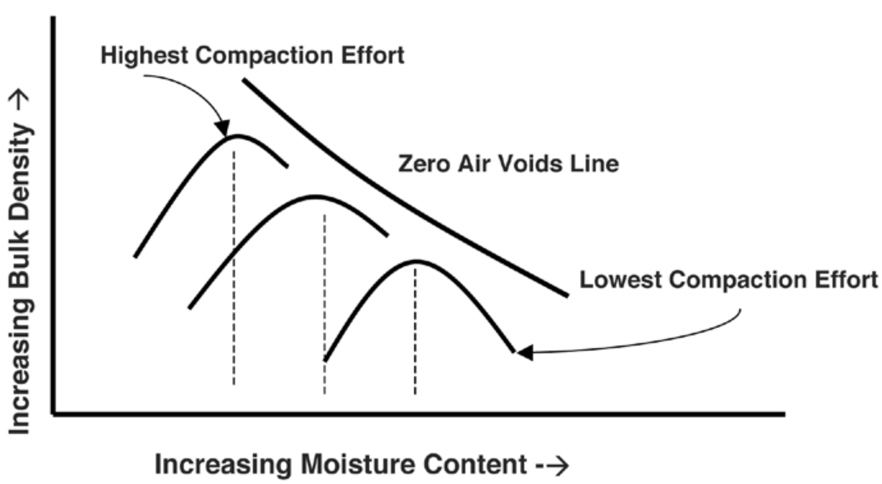


**Figure 1**—General relationships between moisture content, compaction effort and maximum bulk density.

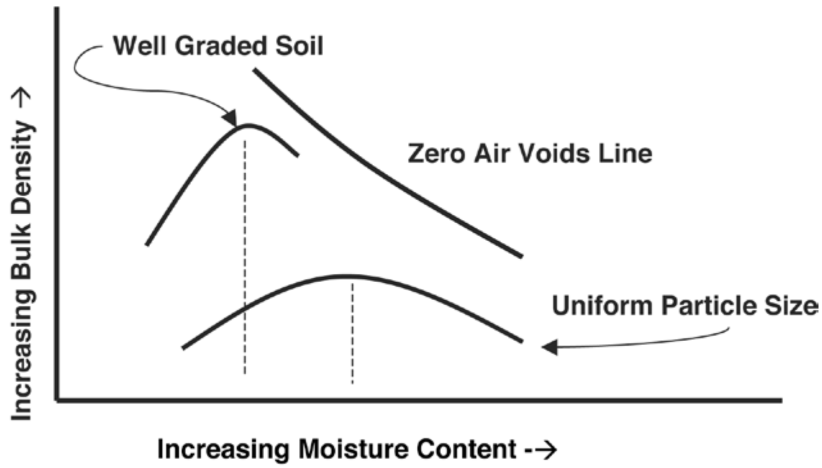


**Figure 2**—General relationships of optimum moisture content and maximum bulk density for well graded and uniform textured soils.

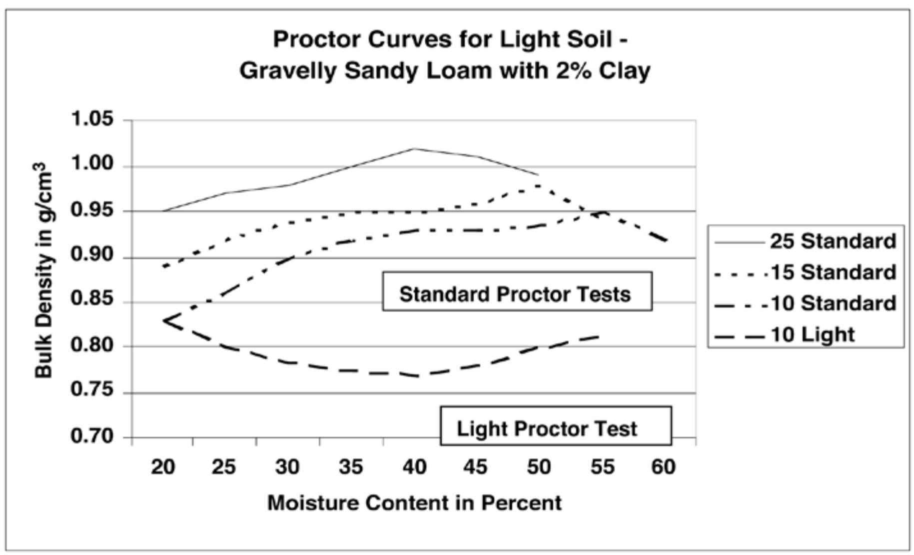


**Figure 3**—Proctor test results on light soil gravelly sandy loam soil with initial bulk density near 0.70 g/cm$^3$ (Mg/m$^3$ ) and 2% clay content adapted from Froehlich and others (1980).

## Methods and Limitations of Measuring Compaction

There are several methods available to measure compaction, but all have limitations in forest soils. Two of the most common include: (1) the bulk density of the soil and (2) soil strength as often measured by the resistance of the soil to penetration with a calibrated penetrometer. While measurement of bulk density or soil strength before and after vehicular traffic is ideal because it reduces sampling error, it is seldom done. Most often the measurements are taken "on and off" compacted areas. If the soil disturbance has also displaced soils in compacted areas, this leads to the risk of comparing soil characteristics in one soil horizon with those in another.

## Bulk Density

Bulk density, the dry mass of a unit volume of soil (Blake and Hartge 1986), is commonly used to measure soil compaction. Bulk density and rock content measurements are required to convert soil nutrient, water, and microbial measures to a mass-per-area basis to compare between sites with different bulk densities and within-site processes (McNabb and others 1986). Although rocks are often not a large component of ash-cap soils, roots and steep slopes make it extremely difficult to accurately determine soil bulk density. A number of different methods have been used to determine bulk density in soils. These can generally be categorized as (1) core sampling, (2) excavation and volume displacement and (3) radiation.

*Core sampling* is a simple, straightforward method for measuring bulk density. Cylinders of a known volume are driven into the soil and the resultant soil core dried and weighed. In some cases, narrow and small core samplers may overestimate bulk density by compacting soil into the cylinder when it is hammered into the soil.

*Volume excavation* is an appealing alternative to core techniques because it allows for flexibility in volume of soil sampled based on the size of soil coarse-fragments, roots or hardpans. A hole is excavated to the desired depth and width, all soil material is removed and collected for weight determination and the volume of the hole measured. Various methods have been used to measure hole volume including known quantities of sand or styrofoam balls, water as measured in a plastic bag lining the hole (Kohl 1988), and expanding polyurethane foam (Page-Dumroese and others 1999).

*Radiation methods* are instantaneous, produce minimal soil disturbance, allow accessibility to subsoil measurements without excavation, do not have to be on a level site, and have the option of continuous or repeated measurements of the same point (Blake and Hartge 1986). With a nuclear moisture-density gauge, the source probe is lowered to selected soil depths through access tubes and the average density between the source and surface-located detector is obtained. However, using a nuclear gauge is not common on forest sites far from a road since it weighs about 18 kg. In addition, the equipment operator much be certified to handle and transport radioactive material (Flint and Childs 1984).

## Penetrometer

Soil penetrability is a measure of the ease with which a probe can be pushed or driven into the soil (Vaz and others 2001). The resistance to penetration is related to the pressure required to form a spherical cavity in the soil, large enough to accommodate the cone of the penetrometer, and allowing for the frictional resistance between the cone and its surrounding soil. Ease of penetration by the probe is influenced by both soil and probe characteristics. Soil-to-probe friction is governed by probe factors such as cone angle, diameter, roughness and rate of penetration. Soil factors influencing penetration resistance are matric water potential (water content), bulk density, soil compressibility, soil texture, and organic matter content (Smith and others 1997; Vaz and others 2001).

Major factors that limit the use and interpretation of penetrometers as field indicators of excessive compaction are the influences of water content and initial bulk density, mostly because there is an insufficient data base to allow adjustments for these factors (Gupta and Allmara 1987; Bennie and Burger 1988). A widely accepted method is to measure penetrometer resistance at or near field moisture capacity.

Penetrometer-measured soil strength has been principally linked with soil bulk density, water content, clay content, and organic carbon. Usually soil strength increases with increasing bulk density and decreasing water content, except at lower levels of compaction when soil strength declines as soils dry out (Smith and others 1997). Since soil strength is strongly related to water content, it varies considerably throughout the year with each wetting and drying cycle (Busscher and others 1997). This relationship is also influenced by the degree of compaction (Mirreh and Ketcheson 1972). Increasing clay contents appears to reduce the rate at which soil strength increases as soils dry to wilting point. With increasing organic matter content, soil strength values are high at field capacity, especially at higher bulk densities (Smith and others 1997).

### Correlation between methods of measuring compaction

Increases in bulk density generally have a positive correlation to increases in the resistance to penetration as measured by a penetrometer, but specific, statistical relationships between these two types of measurement have been much more difficult to establish. Efforts to correlate bulk density measurements to penetrometer readings through regression analysis have often failed or resulted in an extremely low correlation coefficient (Landsberg and others 2003; Froese 2004). Allbrook (1986) was reasonably successful in developing a statistical relationship between bulk density and soil strength ($R^2$=0.67) when the soil strength was measured at or near field capacity moisture content. The study was conducted on volcanic soils in central Oregon and compared bulk densities and soil strength in skid ruts and in adjacent undisturbed areas. Soils had initial soil bulk densities averaging 0.80 Mg/m$^3$. At the 5 cm depth he found a 23.2% increase in bulk densities measured with a nuclear densimeter and a 143% increase in soil strength as measured with a penetrometer. It appears that the soil strength measurements were more sensitive and responsive to changes in soil conditions, but it is also clear that a standard of detrimental soil disturbance that dictates less than a 15% change in bulk density will not be the appropriate percentage standard when comparing soil strength (penetrometer) readings. The USDA Forest Service uses a threshold value of a 15% increase in bulk density for determining when soil compaction has reached a level that is detrimental to biomass production (Powers and others 1998).

## Characterization of Ash-Cap Soils

Soils characterized as ash-cap soils are often derived from a variety of volcanic eruptions, the most common being the eruption of Mount Mazama at Crater Lake, Oregon. These soils are often considered surficial deposits, overlaying the soil derived from the base rock by depths that vary from 15 cm to several meters. They are frequently characterized in the silt loam or sandy loam textural categories of soils. Most ash-cap soils are characterized by low bulk densities, generally less than 0.75 g/cm$^3$, and by high porosity and low shear strength (Page-Dumroese 1993; Cullen and Montagne 1981; Davis 1992). The predominance of silica (glass fragments) in the soil contributes to the water holding capacity of the soil. The distribution of micro- and macro-pore spaces provides many areas for holding water, especially in the micro- pore spaces. One effect of compaction may be to decrease the macro-pore space that is easily assessable to plants, but not the micro-pore space. Ash-cap soils can also be characterized by relatively low clay content. This generally means that there will be very little cohesion and internal bonding in the soil. Without clay, there will be very little shrinking and swelling and this may affect the rate of soil recovery from compaction.

Although ash-cap influenced soils are non-cohesive, they do not seem to recover easily from compaction. Froehlich and others (1985) observed compaction on and off skid trails on several harvested sites in central Idaho. For soils of volcanic origin, there was a reduction in the percent difference in density on and off trails with time, but they also found that soil bulk density on volcanic soils were still 26% higher at 15 cm depth in the trails than off trails 20-25 years after harvesting. One risk with soil recovery studies that consider bulk densities in disturbed and undisturbed areas is that they may not be comparing the same soil types and texture. For example, if the disturbance also displaced soil on a skid trail, the comparison may be between the surface horizon of the undisturbed soil and a sub-horizon of the soil on the skid trail.

There are several hypotheses on why ash-cap soils do not recover more quickly. One is that the compaction activity breaks down the soil particles and/or realigns them into more of a platy structure that allows them to fit closer together after traffic. Another is that the jagged edges of the silica dominated ash-cap soil particles are physically locked during compaction. Since clay content is low, there is little natural shrinkage and swelling in the soil. Other factors may be related to the high initial percent change in bulk density that generally occurs and the lack of a significant freeze-thaw cycles in the drier regions of the intermountain western USA.

Cullen and others (1991) characterized two ash-cap soils in their work in western Montana. Using a standard Proctor test they determined the optimum moisture content for compaction of ash cap soils to be about 228 g/kg (22.8%) and 256 g/kg (25.6%) in the surface layer with a projected maximum bulk density at this moisture content of 1.50 $Mg/m^3$ and 1.36 $Mg/m^3$ for ash over quartzite or limestone till, respectively. These bulk densities are much higher than those encountered in even heavily compacted forest soils as a result of forest operations. Given the results of the work of Froehlich and others (1980), one would expect the optimum water content for compaction from forest operations to be higher than the value observed in the Montana tests and the resulting maximum compaction to be lower. Field observations in the Montana soils showed their severely compacted sites to have average bulk densities at the 5 cm depth of 1.01 $Mg/m^3$ and 0.97 $Mg/m^3$ for ash over quartzite or limestone till, respectively.

Although the relatively low bulk densities of ash cap soils make them very susceptible to compaction, the resulting bulk densities of compacted soils seldom exceed 1.0 $Mg/m^3$. The impact of this degree of change in bulk density on future forest productivity is not the subject of this paper but the general impact of compaction on tree growth has been studied in a number of different settings over the years (Froehlich 1979; Davis 1992; Powers and others 2004). While increased bulk density associated with machine traffic has generally been shown to reduce tree growth, the extent of the growth reduction in ash-cap soils is not well documented. Growth reduction can possibly be attributed to a reduction in the water holding capacity of the soil, but the change in pore-size distribution within the ash-cap soils after compaction may also affect tree growth (Powers and others 2004). The use of 15% percent change that is used as a threshold value for determining detrimental soil compaction by the USDA Forest Service may be ineffective for all soils since each soil textural class varies in initial bulk density value and biological significance of that change (Williamson and Neilsen 2000). Block and others (2002) suggest that combining soil bulk density or soil strength measurements with a surface disturbance regime can be a useful method for monitoring harvesting impacts on soil.

## Case Studies of Operations on Ash-Cap Soils

Compaction on some ash-cap soils has been found to persist for long periods of time, particularly at depths of 15 cm and greater. Geist and others (1989) found significant compaction on study sites sampled 14 to 23 years after harvest in the Blue Mountains of Oregon. Although average bulk densities did not vary greatly between harvested and undisturbed area for most sites, 0.67 $Mg/m^3$ on undisturbed versus 0.71 $Mg/m^3$ on harvested, there was a much wider range of bulk densities in the disturbed areas indicating areas of significant compaction and areas of likely displacement. In the most disturbed unit, average bulk density was 0.66 $Mg/m^3$ on the undisturbed area and 0.80 $Mg/m^3$ on the harvested area, but the range of observed bulk densities on the disturbed sites was even wider.

Davis (1992) observed difference in bulk densities on disturbed and undisturbed areas in an ash-cap soil with sandy loam texture. He found the average bulk density of disturbed volcanic ash soils to be 35% higher than the undisturbed, 0.73 $g/cm^3$ versus 0.98 $g/cm^3$. He conducted standard and light Proctor tests on the soil and determined a maximum bulk density with the standard Proctor test of 1.07 $g/cm^3$ at a moisture content of about 35%. He also found a relatively flat curve across a range of moisture contents for lighter Proctor tests.

Another study conducted in the Blue Mountains of Oregon (Snider and Miller 1985) illustrates the impact of soil moisture content on operational results. They established a statistical split-plot design to look at soil characteristics on skid trails, on berms of trails, in obvious fire rings where slash had been piled and burned, in areas with some general disturbance, and in undisturbed areas five years after the last harvest/site preparation activity. Bulk densities in the control area averaged 0.68 $Mg/m^3$ at the 3.2 cm depth, 0.89 $Mg/m^3$ at the 10.8 cm depth and 0.92 $Mg/m^3$ at the 18.4 cm depth. Generally there were no significant differences in bulk densities at any depth among the four variations and the control. The authors suggest that the reduced level of compaction may have been a function of dry soil conditions during the period of operations.

An experiment on the Colville National Forest in northeastern Washington involved analysis of harvesting economics and soil impacts for a number variations in harvesting systems and trail spacing for harvesting equipment on both steep and gentle slopes. The steep slope units involved use of a cable yarding system coupled with mechanized harvesting equipment. One unit allowed downhill forwarding with a ground-based cut-to-length forwarder. Gentle slope units were designed with variations in the designated trail spacing with some allowance for the felling machine to travel off trail in some units (Johnson 1999; Keatley 2000; Johnson 2002).

Soil analysis involved bulk density and penetrometer measurements before and after harvest operations (Landsberg and others 2003). Study conclusions suggest that compaction resulting from an earlier fire-salvage harvesting operation has remained for at least 70 years. Conclusions note that compaction was not as great on steep terrain where the cable based systems were used, but also note that the soils were sandier in that area and were likely to be more resistant to changes in soil strength. Changes in soil strength, as measured with a recording penetrometer, showed an average of 127% increase in resistance to penetration in the surface layer (0 to 10 cm) and an 89% increase in resistance to penetration at depths of 15 to 25 cm on skid trails in the ground based units. This contrasts to changes of –3% for the surface layer and 43% at depths of 15 to 25 cm in the steeper units. Differences on and off skid trails at the 0 to 10 cm depth averaged 63% in the ground based units and 10% in the steep slopes. Differences at the 15-25 cm depth averaged 26% for both units. There were significant differences between the types of harvesting system, however. For example, the differences between on and off trail resistance to penetration for the cut-to-length system was 15% at the 0 - 10 cm depth and 3% at the 15 - 25 cm depth. Soil conditions after harvesting that remained within limits of the specified guidelines, but results also reflected difficulties associated with interpretation of penetrometer results when readings are taken over a full field season that includes significant changes in soil moisture content (Landsberg and others 2003).

In one study, ash-cap soils in northern Idaho were shown to reach their maximum bulk density after 4 trips with a rubber-tired skidder. Subsequent trips did not result in further increases in bulk density. However, pore-size distribution continued to change after 4 or more trips (Lenhard 1986). Although bulk density does not appear to change after several passes, other physical properties may continue to change to the detriment of soil productivity. If soil pore-size distribution continues to change, then plant-water relationships are likely to be altered or soil puddling will occur for longer periods of time.

The results reported on dry soils in northern Idaho by Froese (2004) were similar to those reported in northeastern Oregon (Snider and Miller 1985). Froese' thesis work involved study of a cut-to-length system operating on ash cap soils. Bulk densities in the control averaged 0.95 $Mg/m^3$ at the 10 cm depth, 1.10 $Mg/m^3$ at the 20 cm depth and 1.21 $Mg/m^3$ at the 30 cm depth. These values are higher than typical bulk densities for ash-cap soils with minimal disturbance and may have contributed to the lack of change after operations. They are also typical of bulk densities measured on skid trails after machine operations as illustrated in the case study for Western Montana (Cullen and others 1991). There was virtually no change in bulk density after the passage of the harvester and one pass of the forwarder. Some increase in bulk density was detected at the surface layer with increased numbers of forwarder passes. Operations were also conducted in late summer when soils were quite dry.

Cullen and others (1991) reported changes in bulk density as a result of traffic at three soil depths on soils in Western Montana. Bulk density in the surface layer of ash over a limestone till at 5 cm changed from 0.61 $Mg/m^3$ with no traffic to 0.84 $Mg/m^3$ with moderate traffic and to 0.97 $Mg/m^3$ with severe traffic. The changes at 15 cm were also significant, changing from 0.53 $Mg/m^3$ in the undisturbed case to 0.97 $Mg/m^3$ and 0.93 $Mg/m^3$ for moderate and severe traffic respectively. In their conclusions they note that the volcanic surface horizon overlying the glacial till soils was well-graded, cohesionless, and was prone to vibratory compaction.

## Controlling Compaction

Methods of limiting compaction impacts on soils generally involve control of the traffic patterns of equipment, restriction of vehicles to designated trails and areas, and control over the seasons of operation. Since topography plays a major role in the redistribution of water on a site, depressions in the landscape may have higher moisture content and be more prone to compaction damage than areas higher on the landscape. Designated trails can avoid these sites when needed.

The use of low ground pressure machines and covering of trails with slash mats such as those generated with cut-to-length systems can limit the consequences of one or two passes of equipment, but do not appear to be effective in minimizing soil compaction when equipment must use trails multiple times (Froese 2004; Han 2005). In several studies of mechanized equipment, one pass of the harvesting machine did not appear to significantly change bulk density in the soils (Froese 2004; Han 2005). Subsequent passes of the skidding or forwarding equipment did increase soil bulk densities, but compaction was limited to the percent of the area in major trails or just in the ruts of well defined forwarder trails.

Increasing spacing between operational trails can decrease the overall impact on an area, but can also have negative economic consequences because of the increased cost of moving cut logs and trees increased distances to the operational trails (Johnson 2002). Careful operational planning can mitigate some of the higher costs associated with increased trail spacing, however. It may also be possible to allow the felling equipment to operate in a limited fashion off established trails and to bunch harvested material to the trail for processing and/or forwarding.

Limiting operations during periods of high soil moisture content will also limit soil impacts. This generally will translate into seasonal restrictions on equipment, with most operations taking place in late summer and early fall. Dry soils (<15% soil moisture content) can effectively support higher ground pressures and result in more limited soil compaction to the surface mineral soil (>10 cm) (Han 2005). Winter operations may be possible with minimal soil impact if the ground is frozen to depths of 10 to 15 cm (Flatten 2002) or has sufficient snow cover (at least 15 cm).

Another option for minimizing soil compaction, but which can also have significant economic consequences is to shift from ground-based harvesting to cable or helicopter harvesting systems. Both of these options can be structured to have minimal soil impacts, but will generally incur higher costs than ground-based systems.

## Summary and Suggested Areas of Future Research

Ash-cap soils are derived from a variety of volcanic eruptions and are most often classified in the silt or sandy loam categories. They are also characterized with low bulk density, high porosity, and high water holding capacity. They tend to be non-cohesive and because of their relatively low strength, are highly susceptible to both vibratory and compressive compaction. Compaction is generally viewed in a negative context with respect to long-term site productivity and sustainable forest management. The results of several studies in the intermountain west illustrate that both bulk density and soil strength values were significantly increased during ground-based harvest operations, but that the resulting bulk densities of compacted ash-cap soils are often below the initial bulk densities of other soil textures. The long-term effects of the changes in factors on site productivity still need to be studied through controlled experiments.

Since ash-cap soils have relatively low bulk densities before operations, they may experience a very high percent change in soil strength and bulk density. In setting standards, it is not clear whether the focus should be on the final bulk density or soil strength reading, the absolute amount of change, or the percent change. If soil strength, as measured by the penetrometer, is recommended as a standard method for soil measurement, corresponding threshold levels of percent and absolute change will need to be established.

The process of soil compaction can be explained by engineering properties of soils, but the degree of soil compaction created in field settings is highly influenced by a variety of factors including distribution of particle sizes, presence of organic matter, soil moisture content, and soil texture. Bulk density and soil strength are commonly used to measure the degree of soil compaction, but the statistical correlations between two variables can be very low when soil strength is not measured near field capacity of the soil. The relationships between bulk density and soil strength and the other critical soil factors such as water holding capacity is less clear, however. Additional work is also needed to determine the effect of the depth of the ash-cap on soil response to machine traffic.

Although ash-cap soils are susceptible to both vibratory and compression forces, the specific vibratory and compressive force potential of the equipment operating in various harvesting and site preparation functions (cutting, transporting) is not known. Research on the vibratory effects of equipment and whether changes in machine design could reduce this effect would be very useful to forest management strategies.

Several studies also found that changes in bulk density and soil strength in ash-cap are long term (>70 years) and that recovery time for ash-cap soils is expected to be slow. These studies noted that soil compaction was generally limited to skid trails and top soil layers (<30 cm). Harvesting equipment used, season of operation and harvest planning were major factors in affecting soil compaction. Controlling compaction often involves use of low impact equipment selection, use of designated skid trails, and limitation of operations to dry seasons or when the ground is frozen. The use of low ground pressure machines and covering trails with slash in a cut-to-length logging may help reduce impacts on soils, especially soil displacement.

## References

Alexander, E.; Poff, R. 1985. Soil disturbance and compaction in wildland management. U.S. Department of Agriculture, Forest Service, Pacific Southwest Region, Earth Resources Monograph B. 158 p.

Alderfer, R. B.; Merkle, F. G. 1941. Structural stability and permeability of native forest soils compared with cultivated areas of the same soil type. Soil Sci Soc Am Proc. 6: 98-103.

Allbrook, R. F. 1986. Effect of skid trail compaction on a volcanic soil in central Oregon. Soil Sci. Soc. Am. J. 50: 1344-1346.

Bennie, A. T. P.; Burger, R. D. T. 1988. Penetration resistance of fine sandy apedal soils as affected by relative bulk density, water content and texture. S. Afr. J. Plant Soil 5: 5-10.

Blake, G. R.; Hartge, K. H. 1986. Bulk Density. In: Klute, A., ed. Methods of soil analysis. Part 1. Agronomy Mongr. 9. Madison, WI: ASA: 363-375.

Block, R.; K.; VanRees, C. J.; Pennock, D. J. 2002. Quantifying harvesting impacts using soil compaction and disturbance regimes at a landscape scale. Soil Sci. Soc. Am. J. 66: 1669-1676.

Brown, K. W. 1977. Shrinking and swelling of clay, clay strength, and other properties of clay soils and clays. In: Minerals in soil environments. Soil Sci. Soc. of Am. 948 p.

Busscher, W. J.; Bauer, P. J.; Camp, C. R.; Sojka, R. E. 1997. Correction of cone index for soil water content differences in a coastal plain soil. Soil Tillage Res. 43: 205-217.

Cullen, S.; Montagne, C. 1981. Final Report to the United States Forest Service (Region 1) — Soil Compaction Study. Unpublished report on file at: U.S. Department of Agriculture, Forest Service. 243 p.

Cullen, S. J; Montagne, C.; Ferguson, H. 1991. Timber harvest trafficking and soil compaction in western Montana. Soil Sci. Soc. Am. J. 55: 1416-1421.

Davis, S. 1992. Bulk density changes in two central Oregon soils following tractor logging and slash piling. Western Journal of Applied Forestry. 7(3): 86-88.

Felt, E. J. 1965. Compactibility. In: Black, C. A. and others, eds. Methods of soil analysis. Part 1. Agronomy. Madison, WI: Am. Soc. of Agron. 9: 400-412.

Flatten, B. 2002. Determining appropriate winter logging conditions for protection of the soil resource. Presented to SALHI-W (Sale Area Layout & Harvesting Institute - West) Ground-based Systems Session; 2002 June; Moscow, ID. 14 p.

Flint, A. L.; Childs, S. 1984. Development and calibration of an irregular hole bulk density sampler. Soil Sci. Soc. Am. J. 48: 374-378.

Free, G. R.; John, Lamb, J. Jr.; Carleton, E. A. 1947. Compactibility of certain soils as related to organic matter and erosion. J. Am. Soc. of Agron. 39:1068-1076.

Froehlich, Henry A. 1979. Soil compaction from logging equipment: effects on growth of young ponderosa pine. Journal of Soil and Water Conservation. 34: 276-278.

Froehlich, H. A.; Azevedo, J.; Cafferata, P.; Lysne, D. 1980. Predicting soil compaction on forested land. Final Project Report. Missoula, MT: U.S. Department of Agriculture, Forest Service. Equipment Development Center. 120 p.

Froehlich, H. A.; Miles, D. W.; Robbins, R. W. 1985. Soil bulk density recovery on compacted skid trails in central Idaho. Soil Sci Soc Am J. 49: 1015-1017.

Froese, K. 2004. Bulk density, soil strength, and soil disturbance impacts from a cut-to-length harvest operation in north central Idaho. Unpublished: Moscow, ID: University of Idaho. 72 p. M.S. Thesis.

Geist, J. M.; Hazard, J. W.; Seidel, K. W. 1989. Assessing physical conditions of some pacific northwest volcanic ash soils after forest harvest. Soil Sci. Soc. Am. J. 53: 946-950.

Gupta, S. C.; Allmaras, R. R. 1987. Models to assess the susceptibility of soils to excessive compaction. Adv. Soil Sci. New York: Springer-Verlag.

Håkansson, I.; Lipiec, J. 2000. A review of the usefulness of relative bulk density values in studies of soil structure and compaction. Soil & Tillage Research. 53: 71-85.

Han, H.-S. 2005. Compaction of forest soils. Presented at: 22nd Inland Empire Forest Engineering Conference; 2005 March 8-9; Moscow, ID.

Ingersoll-Rand. 1975. Compaction data handbook. Ingersoll-Rand Co. Shippensburg, PA. 68 p.

Johnson, L. R. 1999. Combining cut-to-length and cable yarding systems. In: Proceedings of the International Mountain Logging and 10th Pacific Northwest Skyline Symposium; 1999 March; Corvallis, OR: Oregon State University: 43-52.

Johnson, L. R. 2002. Adapting conventional harvesting equipment to small diameter stands – the Fritz experiments. Unpublished report on file at: College of Natural Resources, University of Idaho, Moscow, ID. 16 p.

Keatly, T. A. 2000. Harvesting options in small diameter stands operating on gentle slopes. Moscow, ID: University of Idaho. 199 p. M.S. Thesis.

Kohl, K. D. 1988. Mechanics of rill headcutting. Ames, IA: Iowa State University. PhD. Dissertation.

Krynine, D. P. 1951. Some comments on earth compaction. National Resource Council Highway Research Board Bulletin. 42: 14-20.

Landsberg, J. D.; Miller, R. E.; Anderson, H. W.; Tepp, J. S. 2003. Bulk density and soil resistance to penetration as affected by commercial thinning in northeastern Washington. Research Paper PNW-RP-551. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 35 p.

Lenhard, R. J. 1986. Changes in void distribution and volume during compaction of a forest soil. Soil Sci. Soc. Am J. 50: 462-464.

Li, C. Y. 1956. Basic concepts on the compaction of soil. Proceedings of the American Society of Civil Engineers, Journal of Soil Mechanics and Foundations Division. Paper 862. 82: 1-20.

Lull, H. W. 1959. Soil compaction on forest and range lands. Misc Pub No 768. U.S. Department of Agriculture. 33 p.

McNabb, D. H.; Cromack, K. Jr.; Fredricksen, R. L. 1986. Variability of nitrogen and carbon in surface soils of six forest types in the Oregon Cascades. Soil Sci. Soc. Am. J. 50: 1037-1041.

Means, R. E.; Parcher, J. V. 1963. Physical properties of soils. Columbus, Ohio: Charles E. Merrill Books, Inc. 464 p.

Miller, R. E.; Colbert, S. R.; Morris, L. A. 2004. Effects of heavy equipment on physical properties of soils and on long-term productivity: a review of literature and current research. NCASI Technical Bulletin 887. National Council for Air and Stream Improvement.

Mirreh, H. F.; Ketcheson, J. W. 1972. Influence of bulk density and matric pressure on soil resistance to penetration. Can. J. Soil Sci. 52: 477-483.

Page-Dumroese, D. S. 1993. Susceptibility of volcanic ash-influenced soil in Northern Idaho to mechanical compaction. Research Note INT-409. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 5 p.

Page-Dumroese, D. S.; Jurgensen, M. F.; Brown, R. E.; Mroz, G. D. 1999. Comparison of methods for determining bulk densities of rocky forest soils. Soil Sci. Soc. Am. J. 63: 379-383.

Powers, R. F.; Tiarks, A. E.; Boyle, J. R. 1998. Assessing soil quality: Practicable standards for sustainable forest productivity in the United States. In: Davidson, E. A.; Adams, M. B.; Ramakrishna, K., eds. The contribution of soil science to the development of and implementation of criteria and indicators of sustainable forest management. Madison, WI: SSSA Spec. Publ. 53: 53-80.

Powers, R. F.; Sanchez, F. G.; Scott, D. A.; Page-Dumroese, D. 2004. The North American Long-Term Soil Productivity Experiment: coast-to-coast findings from the first decade. RMRS-P-34. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 191-206.

Smith, C. W.; Johnston, M. A.; Lorentz, S. 1997. Assessing the compaction susceptibility of South African forest soils. I. The effect of soil type, water content, and applied pressure on uniaxial compaction. Soil Tillage Res. 41: 53-73.

Snider, M. D.; Miller, R. F. 1985. Effects of tractor logging on soils and vegetation in eastern Oregon. Soil Sci. Soc. Am. J. 49: 1280-1282.

Vaz, C. M. P.; Bassoi, L. H.; Hopmans, J. W. 2001. Contribution of water content and bulk density to field soil penetration resistance as measured by a combined cone penetrometer-TDR probe. Soil & Tillage. 60: 35-42.

Williamson, J. R.; Neilsen, W. A. 2000. The influence of forest site on rate and extent of soil compaction and profile disturbance of skid trails during ground-based harvesting. Can. J. For. Res. 30: 1196-1205.