Assessing Quality in Volcanic Ash Soils

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Abstract

Forest managers must understand how changes in soil quality resulting from project implementation affect long-term productivity and watershed health. Volcanic ash soils have unique properties that affect their quality and function; and which may warrant soil quality standards and assessment techniques that are different from other soils. We discuss the concept of soil quality and how it may be altered by activity-induced soil disturbances. A practical application of the use of soil disturbance categories and physical soil indices used to perform operational soil monitoring on an ash cap soil is also discussed.

Introduction

Soil disturbance resulting from forest management activities is of concern to both land managers and the public. On National Forest System lands in the Northwest many current projects are being administratively appealed or litigated based on the assumption they will result in soil degradation. Some claim that when implementing ground disturbing activities, the Forest Service commonly exceeds its own standards intended to maintain soil quality. There is a need for objective and accurate measures of change in soil quality caused by management activities. Assessing change in soil quality is difficult and can be influenced by a number of complicating factors. Properties of volcanic ash soils may also require development and application of unique soil quality standards and assessment protocols.

Properties of Volcanic Ash Soils that May Affect Quality and Function

Many soils in the Inland Northwest have been influenced by ashfall deposits from the eruption of Mt. Mazama (now Crater Lake) as well as other Cascade volcanoes (Harward and Youngblood 1969). These deposits are found in most soils of the Columbia Plateau of central and eastern Oregon and Washington. Soils range in texture from "popcorn pumice" near Crater Lake to sands and silts as distance from source increases. Volcanic ash soils have physical and chemical properties that affect their quality and function; and that make them unique when compared to other soil parent materials.

A study conducted by Geist and Strickler (1978) compared some physical and chemical properties of volcanic ash soils to residual soils derived from basalt in the Blue Mountains of northeastern Oregon. In summary, volcanic ash soils had:

- Lower bulk density
- Higher porosity
- Weaker structural development
- Lower cohesion
- Lower coarse fragment (>2mm) content

Such properties are described in detail by others in these Proceedings.

This paper focuses on soils with a distinct "ash cap" or surface layer of volcanic ash deposits. Such deposits vary from a few centimeters to over a meter in depth depending on distance from the source, topography, wind patterns and subsequent erosion.

Volcanic ash soils have a relatively uniform undisturbed surface soil bulk density (0.67) and a disproportionate concentration of nutrients (total OM, N, K) in the upper 30 cm of the soil profile. These properties tend to make volcanic ash soils more susceptible to surface (sheet, rill, wind) erosion when exposed; and to displacement by ground-based equipment. They store more water but yield a larger proportion of it in the low suction ranges. Volcanic ash soils also seem to compact to the same degree over a wide-range of moisture contents.

Pumice soils have many of the same properties as other volcanic ash soils. Like other volcanic ash soils the low density, lack of cohesion, and concentration of soil nutrients in the upper soil profile of pumice soils, make pumice soils susceptible to soil compaction and the loss of nutrients through soil displacement. Because of their low cohesion between individual pumice particles, compaction in pumice soils can result from both compression and vibration. Pumice soils also have been found to be most susceptible to compaction when they are very dry or at or near saturation. Soil moisture contents between these two extremes appear to provide some cohesion between soil particles reducing susceptibility to compaction. Amounts of soil organic matter is also important when determining their susceptibility to compaction.

When compaction does occur, soil strength (as measured by resistance to penetration) has been found to increase exponentially with an increase in soil bulk density (Chitwood 1994). In compacted soils soil strength has also been shown to increase quickly as the soil dries out over the growing season (Craigg 2006). Thus measurements of soil strength and soil bulk density are providing different information about changes occurring in the soil when compaction occurs. Since there is not a simple linear relationship between measurements of soil strength and soil bulk density when soil conditions change it would be difficult to readily substitute one measurement for the other.

Consideration of these properties, along with ash/pumice depth and underlying soil material, is important in developing soil management objectives/prescriptions, in evaluating potential impacts of proposed activities, and in establishing meaningful soil quality standards.

Soil Disturbance and its Relationship to Soil Quality

Definitions of soil quality differ greatly depending on whom one asks. Most would say they recognize a high quality soil *"when they see it"* but when asked to define soil quality, each would most likely provide a different answer depending on their individual objectives and personal biases (Karlen and others 1997). The quality of an individual soil may vary for differing purposes: a high quality soil for production of trees or forage may have low quality for production of cotton or wheat. To say that one soil is of higher quality or "better" than another is not proper without qualification.

There are some who use the terms "soil quality" and "soil health" interchangeably (Warkentin 1995). Each soil has inherent physical, chemical, and biological properties that affect its ability to *function* as a medium for plant growth, to regulate and partition water flow, or to serve as an effective environmental filter. When any or a combination of these inherent factors is altered to a point where a soil can no longer *function* at its maximum *potential* for any of these purposes, then its quality or health is said to be reduced or impaired (Larson and Pierce 1991).

Many factors enter into making determinations of soil quality. Some of these factors can be changed by disturbance (Larson and Pierce 1991; Seybold and others 1997; Grossman and others 2001). Alteration of soil properties through disturbance mechanisms is not necessarily harmful. Tillage is an extreme form of soil disturbance often used to improve soil quality or "tilth" for production of agricultural crops. In forestry applications, site preparation to improve regeneration success or soil restoration work often involve soil disturbance to some degree (surface soil exposure, scalping, subsoiling). What sets these apart from other forms of soil disturbance is that they are planned and are, or should be, carried out with specific objectives in mind under prescribed conditions.

Management activities on forest and rangelands often result in various forms of disturbance that can alter soil function. Commonly, land managers are concerned about how changes in soil quality or function resulting from unplanned, activity-induced disturbance affect the long-term productivity and hydrologic response of watersheds. In wildland situations, concern usually focuses on disturbance-related departures from natural soil conditions (considered to be maximum potential or best possible conditions), occurring as either legacy impacts or those caused by current management activities. Understandably, there are differences of opinion among soil scientists and land managers about when and where "significant" thresholds are reached. This is complicated by the fact that soils differ in their ability to resist and recover from disturbance effects (Seybold and others 1999).

Disturbance may have negative, neutral, or even positive effects on a soil depending on its inherent properties. Meaningful soil disturbance standards or objectives must be based on measured and documented relationships between the degree of soil disturbance and subsequent tree growth, forage yield, or sediment production. Studies designed to determine these relationships are commonly carried out as part of controlled and replicated research projects. The paucity of such information has caused problems in determining threshold levels for, or defining when, detrimental soil disturbance exists; and in determining how much disturbance can be tolerated on a given area of land before unacceptable changes in soil function (productive potential or hydrologic response) occur. Given natural variability of soil properties across the landscape, a single set of standards for assessing detrimental disturbance seems inappropriate.

Defining Detrimental Soil Disturbance

Soil disturbance exists in a number of forms. In forest, range, and watershed management applications, it most commonly occurs as compaction, displacement, and puddling resulting from use of ground-based harvesting and slash disposal equipment. The removal of above ground organic matter is also a result of this type of disturbance. Soil disturbance can also occur in the form of sheet and rill erosion or charred soil in intensely burned areas.

Effects of soil disturbance on site productivity or hydrologic function of watersheds is dependent on its degree, extent, distribution, and duration (Froehlich 1976; Snider and Miller 1985; Clayton and others 1987). **Degree** refers to the amount of change in a particular soil property such as porosity, bulk density, or strength and the depth to which that change occurs. **Extent** refers to the amount of land surface occupied by that change expressed as a *percentage of a specified area*. **Distribution** of soil disturbance within a management area may likely be more important than the actual estimated extent. Disturbance can occur as small evenly-distributed polygons, or in large polygons in one or a few locations. **Duration** is the length of time disturbance effects persist. For example, compaction effects have been measured over 30 years following timber harvest activities on some soils (Froehlich and others 1985).

Degree and duration of effects are largely determined by inherent soil properties that influence resistance to, and ability to recover from, disturbance. Extent, distribution, and, in some instances, degree of disturbance can be controlled by imposing management constraints such as limiting season of operation, spacing of skid roads and trails, and number of equipment passes.

A challenge has been to establish meaningful soil quality standards given the inherent variability of soils across the landscape. Simply stating a single threshold beyond which detrimental soil conditions are thought to exist may not be enough. Most forest land managers do not wish to damage their productive base or cause impaired watershed function. However, they also do not want to unnecessarily limit management opportunities.

Current Status and Needs

Soil quality can be improved, maintained, or degraded by forest management activities. In order to identify and quantify such changes, a scientifically rigorous protocol is required. It must quantify types and amounts of soil disturbances within a specified area; and identify areas of disturbance considered to be detrimental. Protocols must be:

- Statistically valid
- Relatively easy to implement
- Cost effective
- Usable at different scales
- Able to determine if soil quality is being maintained, improved or degraded.

Numerous methods exist for sampling soil disturbance in both operational and research settings. Methods differ with respect to sampling objectives, soil variables considered, and assessment protocols. Inconsistent application of soil disturbance measurement techniques across a variety of land ownerships has led, in some cases, to unreliable and incomparable results. More effective and efficient (cost, utility of data) soil disturbance assessment and monitoring programs could be achieved through use of common soil disturbance class definitions and consistent use of statistically reliable sampling protocols (Curran and others 2005).

Defined soil disturbance categories must be related to physical indices of soil quality and documented changes in vegetation growth or hydrologic function. A determination needs to be made if, in fact or at what point, these disturbance categories represent "detrimental" changes in soil function. In order to evaluate impacts of forest management activities on soil quality, three distinct levels of information are needed. The first two are commonly generated through agency or company soil monitoring programs. The last one is primarily a research function.

Initial assessments can be as simple as determining if specified soil conservation or best management practices (BMP) have been implemented as planned or if contractual/legal requirements relating to soil disturbance have been met. This is often referred to as **compliance** or **implementation** monitoring.

After the initial compliance monitoring, soil disturbance assessment and monitoring projects are commonly done to evaluate effectiveness of management practices. These assessments evaluate pre-determined, usually provisional, soil disturbance standards or objectives based on best available knowledge. This is commonly referred to as **operational** or **effectiveness** monitoring.

Soil disturbance standards or objectives must also be tested or validated to determine if they result in unacceptable reductions in productivity or watershed function, are appropriate for local site conditions, or if adjustments are needed. This process is usually referred to as **validation** monitoring. Validation is best accomplished in a research environment under carefully controlled conditions. Ideally, research would be completed before standards were developed and implemented.

Cost-effective approaches are needed for operational soil disturbance assessments or monitoring that provides statistically valid and scientifically relevant data. Monitoring must meet specified quality-control standards and contribute to regional strategic databases relating tree growth or hydrologic function to defined classes of disturbance. Our current ability to compare results from operational and research studies requires more common or standardized soil disturbance definitions and assessment protocols.

To be cost-effective, operational soil disturbance monitoring protocols must meet several criteria. Protocols (1) must provide scientifically and technically sound information, (2) must be reliable, pertinent, and obtained with minimum investments, (3) must be clearly communicated and understood by all affected parties, and (4) must be consistently and efficiently implemented (Curran and others 2005).

USDA Forest Service Approach to Operational Soil Monitoring

In Forest Service Region 6, initial assessments of activity-induced changes in soil quality are typically made through a stratification process in which visually recognizable soil disturbance categories and disturbances that can be easily detected by probing the soil are described and quantified within an activity area. This is commonly accomplished using a point grid system in combination with point observations along a series of randomly oriented transects. This process is described in detail by Howes and others (1983).

More recently, point observations are being replaced by visual soil disturbance categories, developed and used to describe areas with a combination of soil disturbances that repeat across an activity area and which are likely large enough in extent and distribution to affect soil function. Visual categories also account for the fact that various forms of disturbance are not mutually exclusive. For example, compaction and displacement often occur together. An interim protocol of this process that is based on procedures described by Scott and others (1979) is currently being used on national forests in the Blue Mountains.

The process of quantifying different soil disturbance categories across a landscape provides a relatively rapid and inexpensive method for quantifying different types of soil disturbances over large acreages and is recognized by the FS as an essential step in the soil assessment process. **This process, however, is often stopped at this point and the incorrect assumption made that any soil disturbance is detrimental**.

To avoid this potential problem, visual soil disturbance categories must be further evaluated to determine if they do, in fact, adequately represent detrimental soil conditions. The first step in evaluating a disturbance category is to identify the soil function(s) that may be negatively affected by a soil disturbance. For example, if surface soils have been displaced, a soil's ability to supply nutrients may be reduced. In compacted skidroads and landings, changes in soil resistance to root penetration as well as air and water movement in the soil may be the most important consideration. Identification of soil function(s) affected by disturbance allows for the selection of the most appropriate soil indicators which can then be used to assess a change in the ability of the soil to function. Care must be taken when developing and interpreting such indices. Environmental factors such as macro- and micro-climate can mask changes in soil function due to disturbance.

Soil indicators or indices are soil parameters that can be quantitatively measured using standardized methods and compared between disturbed and undisturbed sites. On National Forest System lands in the Northwest, soil disturbance is considered to be detrimental when a soil index is either higher or lower than a defined threshold.

Development and Application of Forest Service Soil Quality Standards

The USDA Forest Service is directed by law to sustain productivity at current or enhanced levels and to protect and improve the soils for which it is responsible. Recognizing this responsibility, the Pacific Northwest Region (R6) issued a Forest Service Manual Supplement dealing with soil productivity protection in 1979. It has been revised a number of times since then (current version FSM 2520. R-6 Supplement 2500.98-1, Effective August 24, 1998). This direction specifies threshold values (degree) for estimating when detrimental soil disturbance occurs and also sets area limits (extent) for detrimental soil disturbance on an activity area basis. Most national forests within R6 have incorporated these values, with minor modifications, as standards in their forest land and resource management plans. Other Forest Service Regions subsequently developed similar policy and direction (Powers and others 1998). Thresholds for estimating detrimental soil compaction, displacement, puddling, and severely burned soils were developed based on applicable research results available at the time.

Standards emphasize both observable and measurable soil characteristics that field personnel can use to monitor effectiveness of activities in meeting soil management objectives. All forms of detrimental soil disturbance, including permanent features of the transportation system such as roads and landings, are limited in extent to no more than 20 percent of an activity area. In activity areas that exceed this extent limit either as a result of previous or current activities, restoration plans must be in place before new projects are implemented. **These standards are applied to all soils regardless of their inherent properties and ability to resist or recover from disturbance.** The only special consideration given volcanic ash soils is an allowable 20 percent increase in soil bulk density before they are considered detrimentally compacted. The reason for this is their relatively low undisturbed bulk densities when compared to soils developed in other parent materials.

Application of Operational Soil Monitoring Techniques

The following is an example of the use of an operational soil monitoring procedure that was used to evaluate the effects of a forest thinning operation on the soil resource. The procedure illustrates the application of soil disturbance categories and physical soil indices.

Overview

During the winter of 2005, the Sisters Ranger District of the Deschutes National Forest in central Oregon implemented a thinning project designed to reduce hazardous fuels in pine stands within the wildland urban interface. A *Timberjack* cut-to-length harvester and a *Timberjack* forwarder were used to remove trees 12 inches in diameter and smaller, resulting in a stand with irregular tree spacing of about 20x20 ft.

Project objectives included:

- Reduce risk of wildfire to the nearby community of Black Butte Ranch.
- Promote residual tree growth and move stand toward larger diameter trees.
- Produce a biomass product that could be used to help offset the cost of the thinning operation.

Thinning operations occurred during February and March of 2005. During much of this time, the surface 2 to 4 inches of soil was frozen. There were, however, times when temperatures rose and soils were moist but not frozen. Several snow storms also occurred during this period, depositing from a few inches to over a foot of snow. Soil conditions were favorable for most of the two month period during which operations occurred.

Soil functions potentially affected by the project included:

- Ability of the soil to supply water and nutrients to residual trees.
- Ability of the soil to absorb and transmit water.
- Ability of the soil to resist other detrimental soil impacts including displacement, puddling, severe burning, and surface erosion.

Mitigation measures used to reduce potentially detrimental soil impacts included operating over frozen ground, snow, and slash; use of harvest equipment designed to have low ground pressure; designating spacing of equipment trails; and hand piling slash.

Forest managers wished to know if these practices were effective in meeting soil quality objectives on this and other similar projects. In this case, managers wished to know if soil disturbance resulting from the above suite of practices exceeded 20 percent of the activity area. They also wished to know if different categories of disturbance contained detrimental soil impacts as defined in (FSM 2520. R-6 Supplement 2500.98-1).

Project Area Soils

Soils in the project area were mapped as part of the Soil Survey of the Upper Deschutes River Area, Oregon (NRCS 2002). They are described as the Sisters-Yapoah complex 0-15 percent slopes. Soils are classified as:

Sisters soil series – Ashy over loamy, mixed, frigid Humic Vitrixerands
Yapoah soil series – Ashy-skeletal, frigid Humic Vitrixerands

Harvester/Forwarder Transportation System

The *Timberjack* cut-to-length harvester used in this operation was equipped with a cutting head mounted on a 30 foot boom. This allowed the harvester to cut and process materials while making parallel passes across the harvest unit at a spacing of approximately 60 feet. Harvested materials are positioned so they can be reached from alternate harvester trails by the forwarder machine. This results in two types of trails within the harvest unit (1) those that been driven across only one time by the harvester (ghost trails) and (2) trails that have been driven across by the harvester followed by the forwarder (harvester-forwarder trails). Because trees are limbed and topped at the time of felling there are no landings within the harvest unit. Once the forwarder has collected harvested materials they are piled next to a haul road prior to loading on log trucks.

Description of Visual Soil Disturbance Categories

A combination of visual observations and probing of the soil with a tile spade or metal rod was used to identify and describe four categories of soil disturbance within activity areas. These categories are:

Condition Class 1: Undisturbed state, natural.
- No evidence of past equipment operation.
- No wheel tracks or depressions evident.
- Litter and duff layers intact.
- No soil displacement evident.

Condition Class 2: Trails used by the harvester machine only. *Ghost trails*.
- Two track trails created by one pass of a *Timberjack* cut-to-length harvester.
- Faint wheel tracks with a slight depression evident and are < 4 inches deep.
- Litter and duff layers intact.
- Surface soil has not been displaced and shows minimal mixing with subsoil.

Condition Class 3: Trails used by both harvester and forwarder.
- Two track trails created by one or more passes of a *Timberjack* cut-to-length harvester and one or more passes of a *Timberjack* forwarder.

- Wheel tracks evident and are 4 to 6 inches deep with the exception of areas where operator was able to lay down enough slash to mitigate soil impacts.
- Litter and duff layers are partially intact or missing.

Condition Class 4: Skid trails from previous entries. All were re-used during current entry.

- Old skid trails created in the early part of 20th century when selective harvest occurred.
- Trails appear to have high levels of soil compaction across the entire trail.
- Evidence of topsoil removal.

Soil Functions Affected by Soil Disturbances

Based on visual observations described above, it was determined that soil compaction was the most prevalent form of soil disturbance within the harvested area. When compaction occurs, there are alterations of basic soil properties such as soil density, total pore volume, pore size distribution, macropore continuity, and soil strength (Greacen and Sands 1980). Soils vary in their susceptibility to compaction (Seybold and others 1999). Once a soil becomes compacted, the condition can persist for decades (Froehlich and others 1985). This, in turn, affects soil function.

A number of researchers have measured reductions in site productivity attributed to soil compaction (Froehlich and others 1986; Cochran and Brock 1985; Helms and Hipken 1986). Effects of soil compaction on site productivity, however, are not universally negative. Gomez and others (2002) looked at a range of forest soil types in California and found compaction to be detrimental, neutral, or beneficial depending on soil texture and water regime.

Quantifying Visual Soil Disturbance within an Activity Area

To assist with quantifying the amount of soil compaction, a recording penetrometer was used to determine the average width of compacted soils across both the ghost trails and the harvester-forwarder trails (figs. 1 and 2). A threshold level for the increased soil strength of 2.5 MPa was used to identify compacted areas. Soil strengths beyond this level were considered to be high enough to begin to inhibit plant root growth. Based on results harvester ghost trails were initially considered to consist of two detrimentally compacted tracks, each approximately three feet in width. Harvester forwarder trails were considered to consist of two detrimentally compacted tracks, each approximately four feet wide.

A randomly oriented square grid with one grid intersection every two acres was next overlain on the activity area and used to locate sample points for determining areal extent of soil disturbance categories (fig. 3). At each of the grid intersections, a randomly oriented, 100-ft transect was established. The four defined disturbance categories were measured along each transect and lengths occupied by each category recorded. A mean for each category was then computed for the entire activity area. Sampling in this manner ensured an unbiased, representative sample. It was determined that 17 percent of the activity area was occupied by soil disturbance (total of categories 2-4). A 95 percent confidence interval around this estimate was calculated to be plus or minus 2 percent.

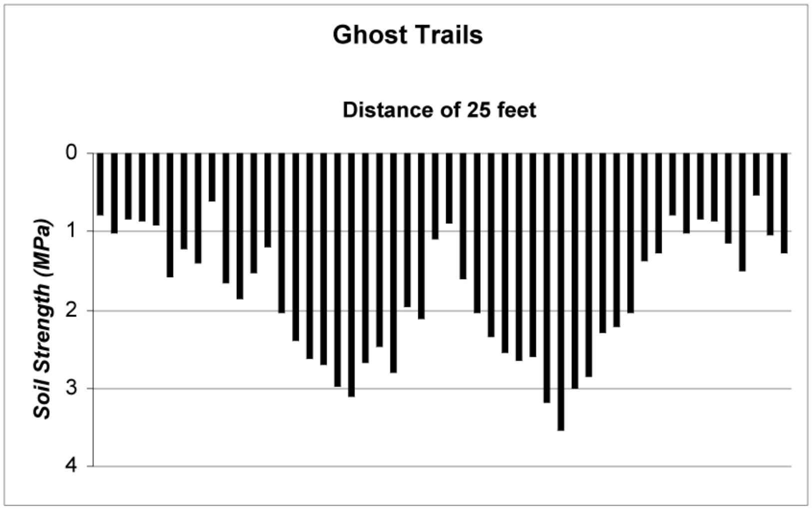

Figure 1—Average soil resistance measured for the 10 to 25 cm soil depth. Measurements were made perpendicular to the harvester ghost trails.

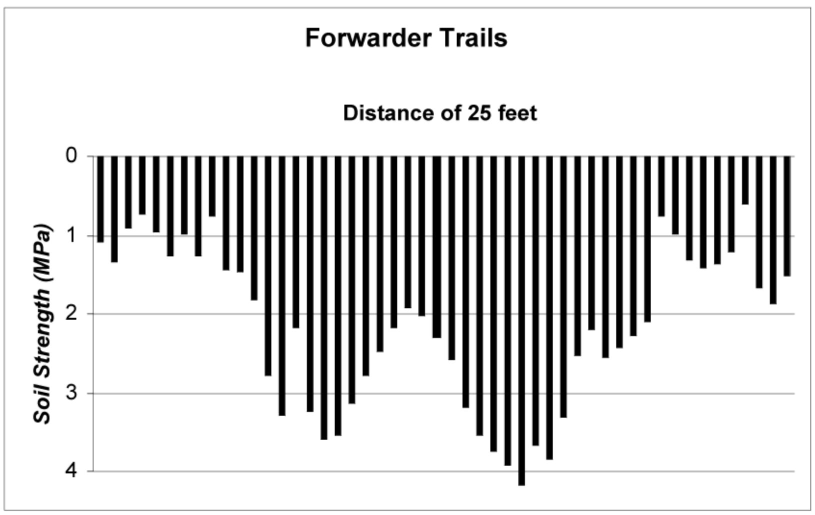

Figure 2—Average soil resistance measured for the 10 to 25 cm soil depth. Measurements were made perpendicular to the harvester forwarder trails.

Use of Soil Indices to Interpret Visual Soil Disturbance Categories

Three physical soil indices used by the Forest Service to assess changes in soil physical properties attributed to compaction are increases in soil bulk density, increases in soil strength (resistance to penetration), and changes in soil pore size distribution.

Soil Bulk Density

Soil bulk density is defined as the mass per unit volume of soil and represents the ratio of the mass of solids to the total or bulk volume of the soil (Soil Survey Staff 1996). The direct measurement of an increase in soil bulk density from soil compaction requires a minimum amount of sampling equipment and is the most commonly made measurement of soil compaction used by the Forest Service. Physical factors that affect soil bulk density and compactability include soil

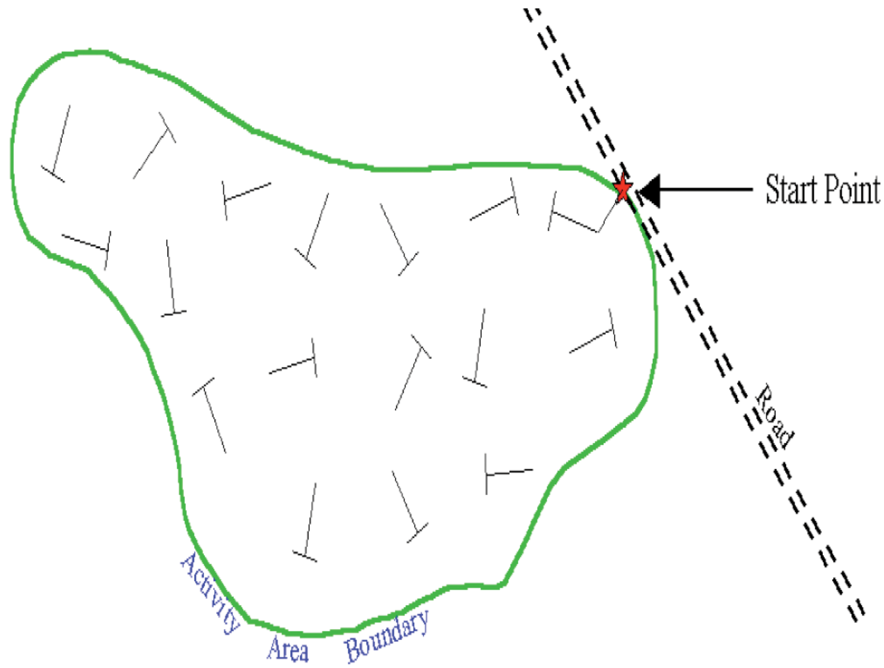

Figure 3—Example of a pre-established grid (randomly oriented) with transects oriented along random azimuths.

particle sizes and density, organic matter content, and mineralogy (Howard and others 1981).

Soil bulk density samples were collected in the spring of the year using a hammer-driven soil core sampler. Table 1 shows soil bulk densities reported for both the whole soil and for the fine fraction of soil (soil particles <2mm removed). Determining soil BD based on the fine fraction of soil results in a lower BD value compared to that determined on a whole soil basis. This is due to the higher weight to volume ratio of soil coarse fragments in the soil core, compared to an equal volume of soil material. When determined on a whole soil basis, soil compaction resulted in a significant increase in soil bulk density in both the ghost trails and the forwarder trails. Soil bulk densities determined for the fine fractions of soil were significantly greater in the forwarder trails but not in the ghost trails.

Table 1—Soil bulk density measurements determined based on the whole soil (including soil coarse fragments >2mm) and based on the fine fraction of soil.

Soil Condition Class	% Volume Soil Coarse Fragments	Soil Bulk Density Whole Soil (Mg/m^3)	Soil Bulk Density Fine Fraction Soil (Mg/m^3)
1	1	0.93a	0.92a
2	2	1.02b	1.00ab
3	2	1.08b	1.06b

Columns within a soil bulk density analysis method are not significant at p = 0.05 if followed by the same letter.
n = 3

In this case, few coarse fragments were encountered and there was little difference in soil BD between results obtained using cores with and without coarse fragments. If there had been more coarse fragments in cores or a large variation in coarse fragments between cores, it would have had a greater influence on calculated soil bulk densities and on the way in which the soil functions. To correctly interpret soil bulk density measurements, it is necessary to report soil bulk densities for whole soil and the fine fraction of soil. It is also necessary to know the amounts of coarse fragments in the soil cores.

Forest Service soil quality standards identify a change in soil bulk density of 20 percent or more above undisturbed levels as a threshold for determining detrimental compaction in Andisols (soils derived from volcanic ash). When calculated on both a whole soil and fine fraction of soil basis, no measured increases in soil bulk density exceeded the 20 percent relative increase threshold. Therefore, none of the soil bulk density changes in any of the visual soil disturbance categories met the Forest Service definition of a detrimentally compacted soil table 2.

Soil Strength

Soil strength describes the soil hardness or the soils resistance to penetration. Soil probes and spades can be used to detect changes in soil strength resulting from soil compaction. This technique can be quantified by using a recording soil penetrometer. Measured soil strengths can vary depending on soil particle size distribution and shape, clay and organic matter content (Byrd and Cassel 1980). Within a soil type changes in soil water content and structure can also affect soil strength (Gerard 1965).

Changes in soil strength resulting from soil compaction were measured within different disturbance categories using a recording soil cone penetrometer, which is capable of recording, at predetermined intervals, the force required to push a cone into the ground (Miller and others 2001). Measurements were made in early spring, shortly after harvest operations were complete. Field measurements of gravimetric soil moisture, based on the fine fraction of soil, ranged from 0.19 to 0.22 g/g and were slightly less than the 0.23 g/g estimate of soil field capacity that was obtained from soil core samples used to determine soil pore size distribution. The penetrometer was set to record soil resistance at 1.5 cm increments between 0 and 60 cm soil depth. Readings were then down loaded to a Microsoft Excel Spreadsheet for analysis.

Table 2—Absolute and relative percentage increase in soil bulk density as a result of soil compaction.

Soil Condition Class	Soil Bulk Density Determination Method	Soil Bulk Density (Mg/m^3)	Absolute Increase in Soil Bulk Density (Mg/m^3)	Relative % Increase in Soil Bulk Density
1	Whole Soil	0.93		
2	Whole Soil	1.02	0.09	10
3	Whole Soil	1.08	0.15	16
1	Fine Fraction	0.92		
2	Fine Fraction	1.00	0.08	9
3	Fine Fraction	1.06	0.14	15

Soil texture and seasonal changes in soil moisture can greatly influence soil strength measurements. Resistance to penetration has been shown to increase for both uncompacted and compacted soils as they dry out over the growing season. The increase in resistance to penetration with decreasing soil moisture, however, tends to occur more rapidly in compacted soils than in uncompacted soils (Craigg 2006). Therefore, soil moisture relationships should be considered when interpreting soil resistance measurements.

Measurements of soil resistance in the undisturbed areas gradually increased with soil depth reaching a resistance of 1 MPa in the first 10 cm and a final soil resistance of 2 MPa at approximately 60 cm soil depth. In the forwarder trails soil resistance increased much faster, reaching a resistance of 3 MPa within the first 10 cm soil depth and retaining that high strength throughout the 60 cm depth. Increases in soil resistance in the ghost trails were higher than the undisturbed but less than the forwarder trails (fig. 4). During the thinning operation efforts were made to limb harvested trees on the equipment trails and then drive on the slash mat to mitigate soil compaction. Soil penetrometer measurements indicated that the slash mat did have at least some affect on mitigating soil compaction (fig. 5).

Currently, Forest Service Region 6 does not have a soil quality index threshold for increases in soil resistance resulting from compaction. Research results suggest that soil resistances of 2 MPa and greater can begin to affect plant root growth (Siegel-Issem and others 2005). Thus these results suggest differences in soil function between the different soil condition classes, in particular the ability of roots to penetrate compacted soils.

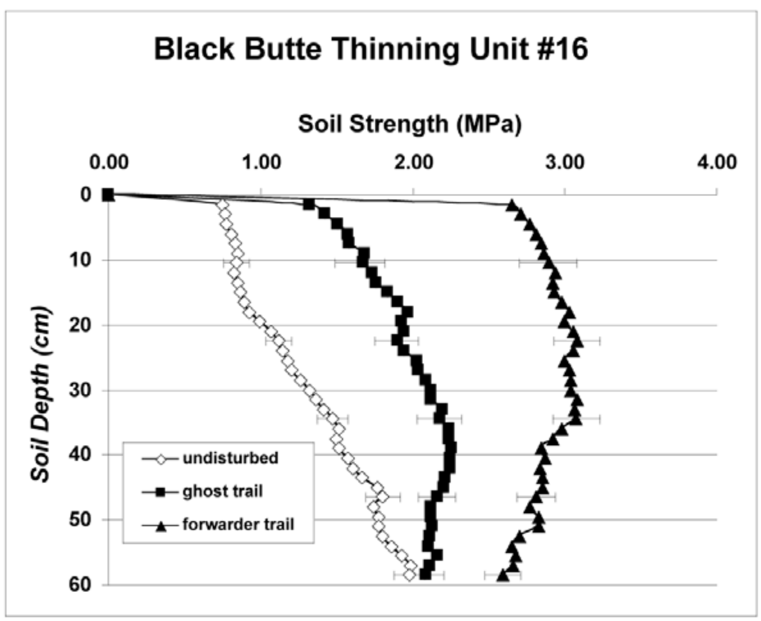

Figure 4—Soil strength measured in the spring of 2005 for different soil disturbance classes. Horizontal bars indicate one standard error. n = 30.

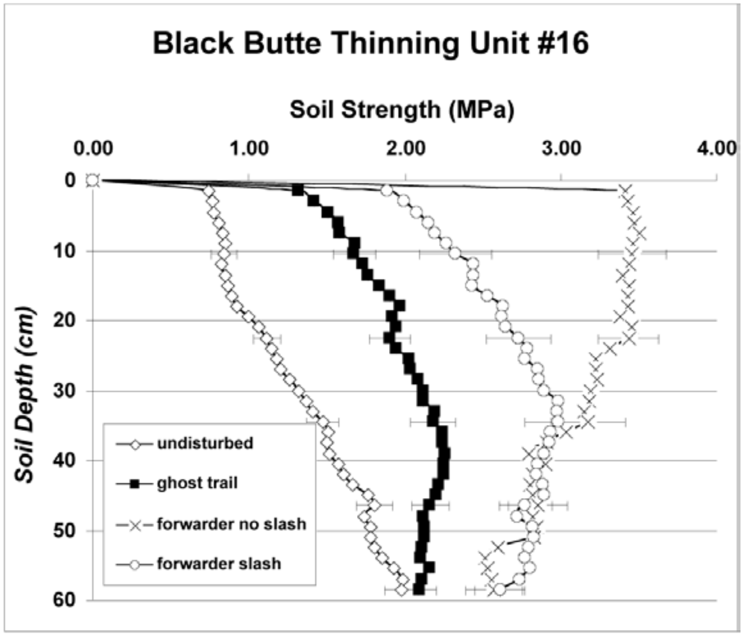

Figure 5—Soil strength measured in the spring of 2005 for different soil disturbance classes with measurements on harvester forwarder trails separated depending upon whether or not slash was present. Horizontal bars indicate one standard error. n = 30 (undisturbed and ghost trails)
n = 15 (forwarder trails)

Soil Pore Size Distribution

Soil pore space accounts for approximately half of the total volume of mineral soil. Changes in total soil porosity and pore size distribution that may result from soil compaction can affect soil functions by altering air and water flow into and through the soil. Changes in soil porosity can also affect the amounts of water storage in the soil (Scott 2000).

Measuring a full range of soil pore sizes requires relatively sophisticated laboratory equipment compared to that needed for measuring soil bulk density or soil strength. Although total soil porosity can be estimated from bulk density and soil particle density, this calculation provides no information about pore size distribution changes occurring in the soil. To better understand changes in soil pore size distribution resulting from soil compaction, a relatively simple method was used which does not require the use of sophisticated laboratory equipment. This technique measures mainly the porosity changes occurring in the larger soil pore sizes (soil pores > 30µm).

Intact soil cores for measuring soil pore size distribution were collected using the same hammer-driven core sampler used to sample soil bulk density. Following collection of intact soil cores, soil pore size distribution was determined using a modification of the water desorption method described in (Danielson and Sutherland 1986). Briefly, a hanging water column was created by connecting a Buchner funnel with a porous ceramic plate in the bottom to approximately 3 meters of plastic tubing with a burette connected to the other end. A soil core was then placed in the funnel and saturated with water by raising the burette and creating a slight head of water. A series of suctions were next applied to the saturated soil core by raising the funnel above a predetermined mark on the burette. Volumes of water removed from the soil cores were recorded for a series of applied suctions and the equivalent radius of the largest soil pores filled with water determined by the capillary equation (Scott 2000).

Results indicated a shift in soil pore size distribution from larger pore sizes or macropores (soil pores > 30μm) to smaller pore sizes (soil pores < 30μm) when soils became compacted (fig. 6). While soil compaction did result in a significant decrease in macropores and a significant increase in smaller soil pore sizes, there was not a significant change in total soil porosity between the different disturbance categories (table 3). Although standards have been established in Forest Service Region 6 for macropore space reductions in residual soils, none have yet been established for ash-derived soils.

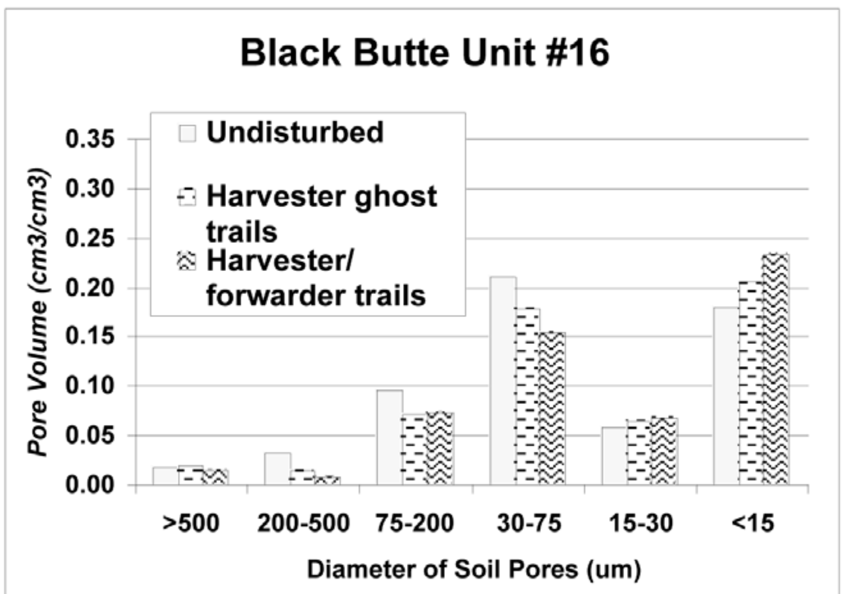

Figure 6—Shift in soil pore size distributions for different soil disturbance classes following soil compaction.

Table 3—Changes in soil pore size distribution and total soil porosity resulting from soil compaction.

Soil condition Class	Pore volume >30μm (cm^3/cm^3)	Pore volume <30μm (cm^3/cm^3)	Total pore volume (cm^3/cm^3)
1	0.36a	0.24a	0.59a
2	0.29b	0.27b	0.55a
3	0.25b	0.30c	0.55a

n = 3
Columns within a pore size class are not significant at p = 0.05 if followed by the same letter.

Interpretation of Results

Extent of soil disturbance within the project area was initially determined by first describing and quantifying visual soil disturbance categories and then measuring a suite of indices within each category. Soil index measurements that were made within disturbed areas were then compared to those measurements made in undisturbed areas. Degree of change in specified soil indices was next compared to defined thresholds for determining if the change is considered "detrimental" or "undesirable."

All measured increases in soil bulk density were below threshold values defined by the Pacific Northwest Region for soils derived from volcanic ash. Although increases in soil strength were measured for ghost trails and for harvester-forwarder trails, no threshold value or soil quality standard has yet been established in the Pacific Northwest Region for soil strength. Reductions in macropore space were also measured in ghost trails and for harvester-forwarder trails. Forest Service Region 6 does not currently have a soil quality index threshold established for macropore space reductions in ash-derived soils. Soil strength and reductions in macropore space appear to be reliable and easily measurable indices of soil function. They also provide additional information about changes occurring in the soil when compaction occurs. Validation work needs to be completed to determine appropriate thresholds for each of these indices.

Summary

Soil quality can be defined in a number of ways depending on one's point of view. For forest practitioners, management-induced changes in soil quality are of concern when site productivity is measurably reduced or water quality is impaired. Soil disturbance can be accurately described and quantified using consistent visual categories and sound, cost-effective sampling protocols. Assessments of soil quality must relate visual disturbance categories to changes in the ability of the soil to provide nutrients or to absorb and transmit water. A number of physical soil indices (soil bulk density, soil strength, soil pore size distribution) are available to help define such relationships.

Soils vary across the landscape and respond differently to management practices. Care must be taken when making soil quality assessments to select the most appropriate soil indices, to follow proper sampling protocols, and to interpret results correctly. Finally, without knowing effects of soil disturbance on site productivity and sediment yield, meaningful assessments of soil quality cannot be made. Validation of such cause and effect relationships is a step in the process that is often never completed.

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Timberjack cut-to-length harvester

Timberjack forwarder machine

Harvester forwarder trail

Quantification of soil disturbance categories using randomly oriented 100 foot transects.

Measuring soil resistance using the recording soil penetrometer.