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Volcanic-Ash-Derived Forest Soils of the Inland Northwest: Properties and Implications for Management and Restoration

9-10 November 2005
Coeur d'Alene, ID

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Abstract

Volcanic ash from the eruption of Mt. Mazama ~7,700 years ago has a strong influence on many forested landscapes of the Pacific Northwest and Intermountain regions of the USA and Canada. Because of the unique biological, physical and chemical properties of the ash, it is closely tied to plant communities and forest productivity, and should therefore be considered as a resource to protect when harvesting, burning, or site preparation activities occur on it. How did this symposium get started? There has been a steady stream of questions, problems, and research on volcanic ash-cap soils for many decades. This symposium was designed to assemble experts to discuss our state-of-knowledge about volcanic ash-cap soil management and restoration. About 200 scientists and natural resource managers participated in this conference, which was held at the Coeur d'Alene Resort, Coeur d'Alene, ID in November 2005.

The Technical Committee

Deborah S. Page-Dumroese is a Research Soil Scientist and Project Leader, Rocky Mountain Research Station. Debbie's research has focused on long-term soil productivity after management activities, including belowground chemical, physical, and biological properties.

Richard E. Miller is a retired Research Soil Scientist from the Pacific Northwest Research Station. Dick is still actively involved in soil research and is currently working to address issues of soil quality and monitoring.

Jim Mital is the Forest Ecologist, Soil Scientist, and Weed Coordinator on the Clearwater National Forest. Jim has worked to help design "soil friendly" management options for resource managers.

Paul McDaniel is Professor of Soil Science in the College of Agricultural and Life Sciences at the University of Idaho. Paul's research activities have included elucidating the unique chemical and physical properties of ash-cap soils.

Dan Miller is Silviculture Manager for Potlatch Forest Holdings, Inc., Lewiston, ID. Dan has been instrumental in working with logging contractors to reduce soil impacts during harvesting.

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Contents

Properties, Characteristics, and Distribution of Ash-cap Soils

Past Activities and Their Consequences on Ash-cap Soils

Management Alternatives for Ash-cap Soils

Special Topic— Grand Fir Mosaic

Summaries of Poster Papers

Properties, Characteristics, and Distribution of Ash-cap Soils

Volcanic Ash-cap Forest Soils of the Inland Northwest Properties and Implications for Management and Restoration

Steven B. Daley-Laursen

In: Page-Dumroese, Deborah; Miller, Richard; Mital, Jim; McDaniel, Paul; Miller, Dan, tech. eds. 2007. Volcanic-Ash-Derived Forest Soils of the Inland Northwest: Properties and Implications for Management and Restoration. 9-10 November 2005; Coeur d'Alene, ID. Proceedings RMRS-P-44; Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

***Steven B. Daley-Laursen**, Dean and Professor, College of Natural Resources, University of Idaho.*

Good Morning and Welcome. My task today is to set the stage for a productive conference by providing an historical context, an overview of the subject matter to be covered, and a challenge for next steps by interested scientists and practitioners.

An Historical Perspective

Volcanoes have been part of the Earth's history ever since it has had a solid surface. And, volcanoes have been a part of human culture for thousands of years. In some ways, our reactions to the magnitude of a volcanic explosion haven't evolved as much as one might think. Ranging from ancient cultures who believed that victims should be sacrificed in response to volcanic eruption, to Harry Truman who stubbornly sacrificed himself during the most recent eruption in the continental United States, volcanoes have impacted our lives in many ways and will continue to do so in the future.

But disaster sometimes brings fortune. Here on the West Coast where some volcanoes erupt violently every 20-30 years or so, we live in one of the grandest ash-cap locations in the world. Soils throughout the Inland Northwest region of the United States extending from the Cascade Mountains of Oregon and Washington to Northern Idaho and Western Montana have been influenced and overlain by tephra from cataclysmic eruptions of Mount Mazama.

About 6,850 years ago Mount Mazama, a strato-volcano, collapsed to produce Crater Lake, one of the world's best known calderas. The caldera is about 6 miles (10 km) wide. The catastrophic pyroclastic eruption released about 12 cubic miles (50 cubic km) of magma to the surface. It was one of the largest eruptions in the last 10,000 years.

The Mazama eruption was followed by the May 18, 1980 eruption of Mount St. Helens in west-central Washington. This eruption spread less than 1/100th of the Mazama ash volume over areas of eastern Washington and Northern Idaho. The St. Helens ash plume carried by the jet stream took 2 weeks to circle the globe! Though considerably smaller in volume output than the Mazama eruption, the Mount St. Helens eruption and deposition had effects on soils and productivity in our region that are still visible and proudly measurable.

On a personal note, these volcanoes and the consequence of their eruptions have had a direct impact on my life and career in three ways. As an Oregonian by birth I was a visitor to Crater Lake learning about local geology and forests. As a resident of Moscow, Idaho during the May 1980 eruption of St. Helens (and the nearly 1-year aftermath) I had the experience of being blanketed with ash and having life's pace slow to a walk with a mask and goggles in a snowy white haze. And, as a student of the Habitat Type at UI and a researcher developing stand growth simulation models in the Grand fir, Douglas-fir and cedar hemlock systems of the Inland Northwest, I learned first hand about the impact of ash on soil properties and chemistry and site productivity and potential vegetation. So, I have for some time been awed by the power of these profound phenomena—the volcanoes that produce the ash, and the ash caps that add value to the region's soils.

My experience with the aftermath of volcanic eruption was expanded and deepened this past year, when I had the opportunity to tour Las Valles Caldera in northern New Mexico. This is a 50 mile wide caldera that blew its top 1.2 million years ago, leaving behind an inspiring landscape of biological diversity. I went there to meet up with scientists from three New Mexico universities conducting research on watershed dynamics and carbon-water relations. This is a remarkable place at 10,000 feet in the Southern Rocky Mountains. Don't miss your opportunity to visit and learn about the past and present conditions of Las Valles Caldera.

These major volcanic eruptions and depositions all created the same wondrous outcome; ash-cap soils. As a result of frequent volcanic activity, the soils of the Northwest are unique and behave differently than anywhere else in the United States. As you'll hear from a dozen researchers and land managers over the next 2 days, we now know much about the properties and characteristics of these deposited soils and the effects of our activity on them.

An Overview of Our State of Knowledge— Preview of the Conference

We know the distribution of Andic soils, and Mark will tell you more. We know about the chemical and physical properties of Andisols. They are light and fluffy, low density and have remarkable water-holding capacity. Paul will tell us more about all of this, drawing from his 2005 treatise on Andisols. We know something about Andic soil quality and will hear more about that from Steve later this afternoon.

We know that the most significant glass accumulations are found in forested areas. It has been suggested that outside a forest structure like the Douglas-fir, or the more mesic Grand fir and cedar hemlock ecosystems, volcanic ash is not retained against erosion, certainly not under extreme conditions of management that exacerbate erosion.

We also know there is a strong link between Andisol distribution and forest productivity; reference my earlier comments about habitat type as a predictor variable in stand growth simulation models. In the 1970s, Habitat Type was explaining much variation in our tree growth and forest stand simulation models, acting as an effective integrator of slope, aspect, elevation, moisture and temperature in the prediction of species occurrence and abundance as well as tree and shrub growth rate. At that time, many scientists and managers were beginning to believe that the one factor not adequately stratified in Daubenmire's Habitat Type scheme was soil type.

Ash-cap soils play a critical role in water relations and nutritional ecology, and thus, plant diversity in forested ecosystems. Later attempts at habitat typing in the United States have taken soil type much more seriously.

In more recent science on forest nutrition, soil parent material has taken on celebrity status as a predictor variable in site productivity. Researchers and land managers now speak of *good and bad rocks* (parent material) and acknowledge through empirical and laboratory science the characteristics of ash soils and their direct impact on nutritional ecology. Through cooperative research and outreach, this has had a direct influence on management prescriptions on both public and private forest ownerships.

From this body of research and practice, we know that properly managed Andic soils can be some of the most productive on earth. Dennis and Larry will share their knowledge on management regimes on forested systems with ash-cap soils. Marianne will share ways to improve tree performance through nutritional augmentation and site decisions. Pete will tell you about the effects of different fire regimes on Andic soil types.

We know these soils are susceptible to compaction, and decrease in value and volume under intense and frequent fire and erosion following irresponsible forest management practices. Han and Leonard will review the effects of machine traffic, plans for a lighter footprint during forest operations, and the overall economics of timber operations with an eye to ecological and economic sustainability. Chuck will introduce us to restoration schemes for degraded soils. And, Mike will share best management practices relating to insect and disease populations and harvest operations.

The Challenge to Scientists and Practitioners— Where We Go From Here

We know much, and you've gathered an impressive crew of scientists and practitioners to share the current knowledge base. But, the conference is about more than just dumping all the current knowledge on the table. It's about synthesizing current knowledge into a more coherent perspective on these soils and the management they can tolerate. And, just as important, it's about framing the next set of questions…laying out your science road map for the future, and doing it together.

In interviewing soils folks and managers in preparation for this presentation, I was told by more than one person that most of the studies on Andisols have occurred in the Midwest and overseas—in Japan, Iceland, and New Zealand for example, and that the body of information available in the U.S. is fleeting and incomplete. It would be good to organize a list of highest priority research to be conducted on Andic soils in this region.

Most also agree that around the edges of this spotting science base, there are mental volumes of endemic, practitioner knowledge about Andic soils stored in the expert systems that are our experienced local forest managers. It would be useful to all of you to organize this endemic knowledge and subject it to scientific scrutiny, invalidation and confirmation. That's why you're here—to match the insights and experience of forest managers with the curiosity of forest researchers…to develop a coherent research agenda that will lead to best practices for protection and sustainability of this important Andic soil resource.

That's the real reason I accepted the invitation to be with you today. Obviously, I can't stand toe to toe with you on the science of soils or the intricacies and art-form of management. But, I have spent my career straddling the research and outreach worlds of academia, striving to bring the researcher and practitioner together around a coherent and integrated science and management agenda. The best outcomes of science are achieved when the scientist and practitioner conceptualize a problem and research question together and I'm passionate about making this type of connection a reality. The rewards are profound for all who subscribe.

So, my closing statement is an admonition in that spirit of collaboration and coordination.

Soils are taken for granted and underrated by the average person. Just dirt, you know—uncorruptable and forever static in the average mind's eye. But, you and I know this isn't true. They are in fact the substrate on which most life and biodiversity resides, they are the physical base on which the water system self-regulates, they are often the defining factor in what you can and cannot do well on a particular site. And they are fragile, corruptible and degradable. In many cases, if you screw them up once, you don't get a second chance. In extreme cases of erodibility, when they're gone, they're gone.

The Andic soil is particularly erodible. Studies of Andic soils can give clues to other highly erodible soils in even more critical regions of biodiversity, like the topics.

As we continue to grow our understanding of the working processes and functions of ecosystems, and as a society, we recognize and attempt to quantify, and even trade, the values of natural capital, soil and it's relationship to water and carbon will be key areas of inquiry, value, credit and trade.

Most climate modelers and carbon scientists now agree that the Inland Northwest, in fact the Grand fir and cedar hemlock ecosystems with moist, relatively warm temperature regimes and at low to mid elevations, may be one of North America's biggest carbon sponges. Andic soils definitely play a role in this equation. In the marketplace that characterizes our economy and society, our valuing of these soils will follow on our understanding of these soils.

Scientists and managers in western North America have in their backyard a living laboratory in which to study the Andic soil. You're in the driver's seat for advancing the world's knowledge on these soils, their properties and characteristics, their additions to ecological potential and production, and their responses to the regimes of human activity. And, you're gathered here to ponder this.

So, listen well to what you and your colleagues know and chart a course together that will fill in the blanks. Identify the key management questions and issues relating to ash cap soils. Identify the categories of inquiry that are important to pursue. Identify areas where you need to go beyond anecdote to science and make some plans to test and invalidate your mental models. Let the practitioners influence the research agenda, and hold the scientists accountable for getting the science out in usable form to managers on the ground.

The University of Idaho is a land grant institution with a mission to advance both science and practice in natural resource management. We will be looking for ways to partner in your noble pursuit.

Good luck with your meeting and thanks again for the invitation to participate.

Ecological and Topographic Features of Volcanic Ash-Influenced Forest Soils

Mark Kimsey, Brian Gardner, and Alan Busacca

In: Page-Dumroese, Deborah; Miller, Richard; Mital, Jim; McDaniel, Paul; Miller, Dan, tech. eds. 2007. Volcanic-Ash-Derived Forest Soils of the Inland Northwest: Properties and Implications for Management and Restoration. 9-10 November 2005; Coeur d'Alene, ID. Proceedings RMRS-P-44; Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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Abstract

Volcanic ash distribution and thickness were determined for a forested region of north-central Idaho. Mean ash thickness and multiple linear regression analyses were used to model the effect of environmental variables on ash thickness. Slope and slope curvature relationships with volcanic ash thickness varied on a local spatial scale across the study area. Ash distribution and aspect showed weak correlation. Elevation and ecologically based plant associations accounted for about 54 percent of the observed variation in volcanic ash thickness. Climax plant associations moister than grand fir/queen cup beadlily (*Abies grandis/Clintonia uniflora*) had consistently thick ash mantles and soils that would be classified as either Andisols or andic subgroups using Soil Taxonomy. The statistical model error of 10.7 cm was significantly lower than the >20 cm variation often found in local soil series. This model quantitatively assesses ash distribution and can be integrated into other local ecological models.

Introduction

Volcanic ash from eruptions along the Pacific Northwest Cascade Range has significantly influenced forest soils of the Inland Northwest, U.S.A. (Mullineaux 1986; Shipley and Sarna-Wojcicki 1983). The Holocene era eruption of Mt. Mazama (now Crater Lake, OR) distributed >116 km^3 of volcanic tephra across this region (Bacon 1983; Zdanowicz and others 1999). Soils influenced by the deposition of Mt. Mazama tephra can be found throughout the western United States and into southwestern Canada (fig. 1). Soils formed in, or influenced by volcanic ash are important to forest management. Volcanic ash-influenced soils have lower bulk density, higher porosity, and higher water infiltration and retention than soils less influenced or unaffected by ash (McDaniel and others 2005; Nanzyo and others 1993; Nimlos 1980; Warkentin and Maeda 1980). Among the benefits of these properties is the reduction in drought stress on plant communities during extended summer dry periods.

Figure 1—Estimated spatial distribution of Mt. Mazama volcanic ash across the western United States and southwestern Canada. The study area for this research project is located within the boxed area of north-central Idaho (Mt. Mazama ash distribution adapted from Williams and Goles 1968).

Regional deposition following the eruption of Mt. Mazama was estimated at approximately 15-20 cm thick in eastern Washington, with thinning in areas more distal to the eruption (Busacca and others 2001). The current distribution pattern of volcanic glass derived from the Mazama event is much different than this original deposition pattern. A map depicting the prevalence of volcanic glass in modern surface soils of Eastern Washington indicates only weak tephra influence in soils of the southwest Columbia Plateau even though these areas are closest to the volcanic source of the tephra (fig. 2) (Busacca and others 2001). Instead, glass content of the surface soils increases with increasing downwind distance from the source volcano. Also, none of the modern tephra-influenced surface soils are composed of pure volcanic ejecta. Soils of the Blue Mountains, OR, and Clearwater Mountains, ID, have some of the best-expressed andic soil properties

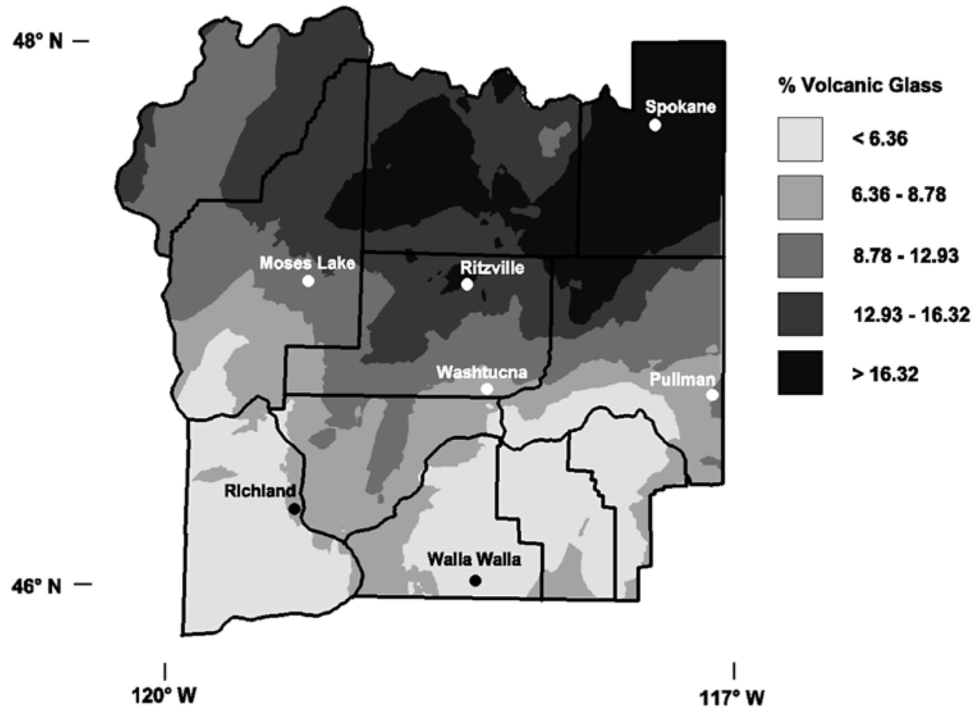

Figure 2—Volcanic glass content of modern surface soils in eastern Washington (from Busacca and others 2001).

in the region, yet these soils generally have glass contents of 20 to 50 percent in their surface layers.

Several mechanisms have been proposed as factors in the transformation of the original tephra sheet into the mixed distribution patterns that we see. These include: 1) a partial re-entrainment of ash by wind with resulting redeposition further downwind (i.e. to the northeast); 2) burial of ash material by subsequent episodes of loess deposition; 3) bioturbation of the tephra by soil fauna, which served to mix the volcanic glass into the surrounding soil mass; and 4) reduced erosion loss and enhanced capture of remobilized air-fall material under coniferous vegetation such as is found at the northern and eastern margins of the Columbia Plateau (Busacca and others 2001; Hunter 1988).

Recent Natural Resource Conservation Service (NRCS) soil surveys have extensively mapped volcanic ash-influenced forest soils in portions of the Inland Northwest. From these surveys, ash distribution and ecological/topographic relationships can be assessed. However, these soil survey relationships are often presented as a range in ash thickness. For example, volcanic ash thicknesses in Hugus and Bouldercreek soil series commonly found in our study area have mapped variations >20 cm (Soil Survey Division 2006). As more information is gathered on the role of volcanic ash in forest productivity and management, forest managers may need finer resolution of ash distribution than a range in ash thickness. The inherent variation of soil surveys may not provide the level of accuracy needed for decision support systems. A potentially workable alternative is a statistical re-analysis of individual soil-site descriptions created during local NRCS soil surveys.

Based on the above rationale, our objective was to select a relatively small geographic region within the Inland Northwest for which extensive soil and environmental data was available to 1) develop a dataset of volcanic ash depths, habitat types, and terrain features; 2) conduct statistical analyses to assess relationships between ash thickness and selected vegetative and topographic features; and 3) determine the precision and fit of a statistical model to estimate the thickness of volcanic ash across a landscape.

Materials and Methods

Study Area

The area chosen for this study is the NRCS ID-612 soil survey region of north-central Idaho (fig. 1). This survey area encompasses about 336,250 ha of diverse climatic factors, habitat types, and complex terrain attributes. Landscapes of this region are generally characterized as mountainous in the north and east, while the south and west are characterized as basalt plateaus/benchland incised with deep canyons. Elevation ranges from 300 m in the southwest to >1700 m in the north and east. Mean annual precipitation (MAP) roughly follows the elevational gradient, with <300 mm MAP in the southwest and >1500 mm in the northeast. Ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) habitat types dominate the southern regions of the soil survey. Western redcedar (*Thuja plicata*) and western hemlock (*Tsuga heterophylla*) dominate the warm, moist upland regions; with Subalpine fir (*Abies lasiocarpa*) and mountain hemlock (*Tsuga mertensiana*) predominant in the colder, higher elevations (Cooper and others 1991).

Data Analysis

Nine hundred and twenty-one soil-site descriptions and their XY coordinates were obtained from the Orofino, ID, NRCS field office. Field records composed of volcanic ash thickness, terrain attribute, and habitat type observations were entered into a database. The effective number of observations available for analyses varied since it was not unusual for certain field observations to not be recorded on the field form. A summary of the field descriptors and their potential influence on volcanic ash distribution is presented in table 1.

The continuous variables elevation (ELE), slope (SLP), and aspect (ASP) were grouped into discrete classes to facilitate the comparison of incremental changes in ash thickness with terrain attributes. ELE was classed into 200-m intervals, SLP at 10 percent breaks, and ASP in 45-degree quadrants. Curvature values were derived from a United States Geological Survey (USGS) 30-m digital elevation model (DEM) using grid algebra in a geographic information system (GIS). The numerical curvature values were then grouped into their respective linear (L), concave (C), and convex (C) classes.

Average ash thickness by class was computed for each of the variables described above. Standard errors were computed and *t*-tests performed to test for significant differences in ash thickness using an α-level of 0.1. Variables that showed significant class differences in volcanic ash thickness were subsequently tested for use as predictor variables in a volcanic ash distribution model. A stepwise variable

Table 1—Selected ecological and topographic features used in this study and their potential significance in determining volcanic ash distribution patterns (Cooper and others, 1991; Gallant, 2000).

Ecological/Topographic Features	Significance
Elevation (meters): ELE	Climate, vegetation type, potential energy
200-400	
400-600	
600-800	
800-1000	
1000-1200	
1200-1400	
1400+	
Slope (%): SLP	Overland and subsurface flow, velocity, and runoff
0-10	
10-20	
20-30	
30-40	
40-50	
50-60	
60+	
Aspect (°): ASP	Solar irradiation, wind erosion/deposition
Flat	
N (342.6-27.5)	
NE (27.6-72.5)	
E (72.6-117.5)	
SE (117.6-162.5)	
S (162.6-207.5)	
SW (207.6-252.5)	
W (272.6-297.5)	
NW (297.6-342.5)	
Up/Across Slope Curvature: PRCU/PLCU	Flow acceleration, erosion/deposition rate, converging/diverging flow, soil water content
Linear	
Concave	
Convex	
Plant Associations:	Climate, topography, site productivity, disturbance
Vegetation Series: VS	
Pinus ponderosa (PIPO)	
Pseudotsuga menziesii (PSME)	
Abies grandis (ABGR)	
Thuja plicata (THPL)	
Tsuga heterophylla (TSHE)	
Tsuga mertensiana (TSME)	
Abies lasiocarpa (ABLA)	
Habitat Type: HT	
Festuca idahoensis (FEID)	
Physocarpus malvaceus (PHMA)	
Symphoricarpus albus (SYAL)	
Linnaea borealis (LIBO)	
Clintonia uniflora (CLUN)	
Asarum caudatum (ASCA)	
Adiantum pedatum (ADPE)	
Gymnocarpium dryopteris (GYDR)	

selection procedure was used within the framework of a general linear model (GLM) to assess which variables explained the greatest variation in volcanic ash thickness. Variables that were within the upper 0.1 percentile of a Type III sums-of-squares *F*-distribution were retained within the model. The prediction equation was deemed reliable if it produced a high coefficient of determination (R^2) and low root mean square error (RMSE).

Results

Topographic and Vegetative Indicators

Volcanic ash is highly correlated with ELE (fig. 2). Each 200-m increment is significantly different up to 1200 m ($p < 0.1$). Above 1200 m, there is no significant difference in mean ash thickness. Forest soils below 600 m in elevation have ash thicknesses ≤10 cm. Many low elevation soils exhibit significant mixing of the shallow ash mantle with underlying soil material. These lower elevation forest soils are classified as vitrandic subgroups of a soil order (Soil Survey Staff 1999). Forest soils located at elevations between 600 m and 1200 m have mean ash thicknesses 24 to 35 cm. These soils are classified as andic subgroups. Volcanic ash mantles have a mean thickness of about 45 cm above 1200 m elevation. Ash mantles deeper than 36 cm that meet several other NRCS criteria are considered members of the order Andisols (Soil Survey Staff 1999) or Andosols of the World Reference Base (FAO/ISRIC/ISSS 1998).

Mean ash thickness showed no significant decrease with increasing slope gradient (fig. 3). Mean ash thickness showed relatively little variation with a small range of 25 to 34 cm across all slope classes. Slopes <10 percent showed significantly less volcanic ash than all classes except the 60 percent class. Ash depth increases up

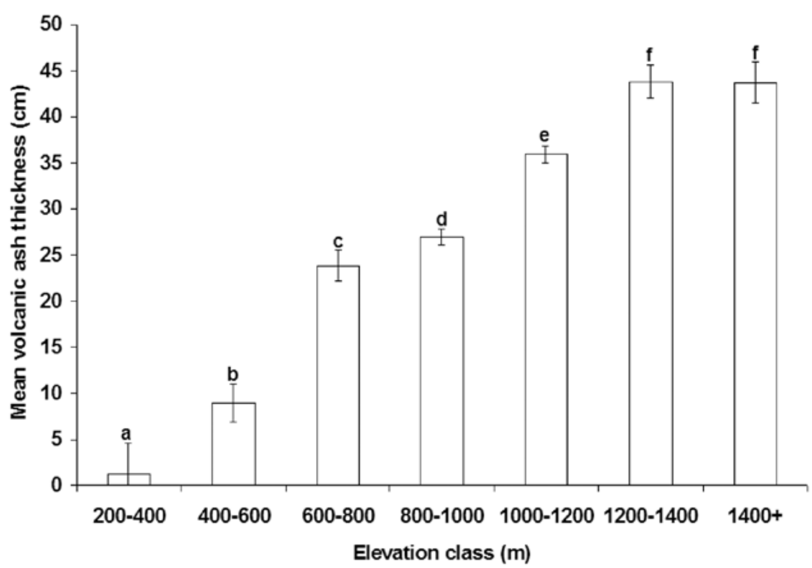

Figure 3—Mean volcanic ash thickness as a function of elevation (ELE) class. Y-axis bars represent standard errors, with letters indicating significant differences ($p < 0.1$).

to the 20 to 30 percent SLP class; after which, there are no significant differences in ash thickness by SLP class. The 20 to 30 percent class had significantly greater ash depths than all slope classes and was marginally greater than the 40 to 50 percent class ($p = 0.12$).

North aspects generally exhibit thicker ash mantles than south facing aspects (fig. 4). N, NW, and SE aspects show mean ash depths >32 cm. NE and W facing aspects have thinner ash caps (~30 cm), but are not significantly different than N, NW, or SE aspects. S, SW, and E aspects have significantly thinner ash mantles of about 27 cm.

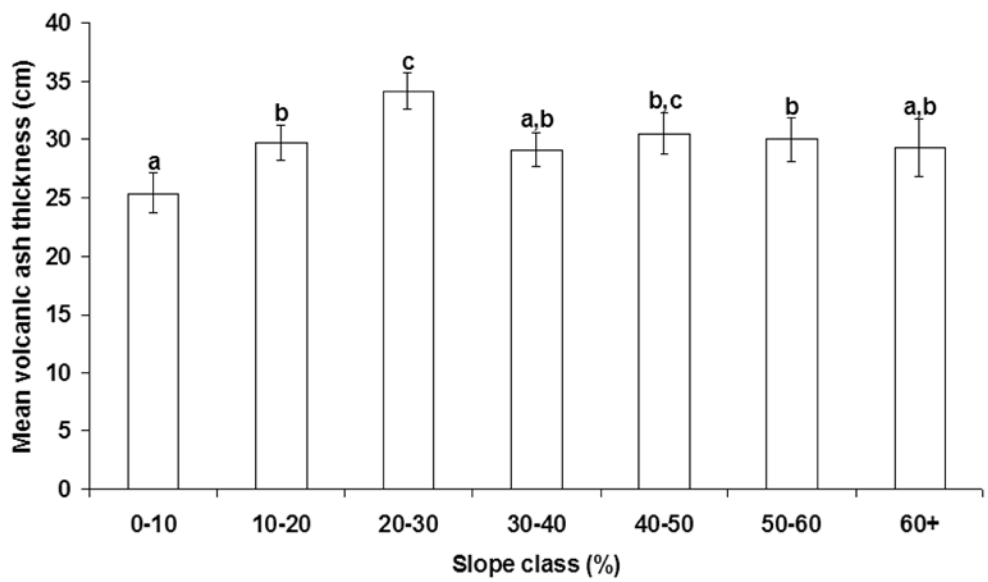

Figure 4—Mean volcanic ash thickness as a function of slope (SLP) class. Y-axis bars represent standard errors, with letters indicating significant differences ($p < 0.1$).

Slope curvature shows that nonlinear surfaces retain a greater thickness of volcanic ash compared to linear surfaces (fig. 5). Concave and convex surfaces show mean ash depths >30 cm for both upslope (PRCU) and across slope (PLCU) surface curvature. Linear surfaces in both PRCU and PLCU are significantly lower (<25 cm) than either convex or concave surfaces. There was no statistical difference between concave and convex in either PRCU or PLCU slope curvature.

Vegetation series and habitat type plant associations showed the strongest relationship with volcanic ash thickness (fig. 6). Overall, the ponderosa pine (PIPO) and Douglas-fir (PSME) vegetation series have very thin volcanic ash mantles (<3 cm) and show no significant change by habitat type within series. Grand fir (*Abies grandis* – ABGR) has the widest range in ash-influence of all vegetation series. Mean ash thickness ranges from 0 to 40 cm depending on the underlying habitat type within series. The moist twinflower (*Linnaea borealis* – LIBO) habitat

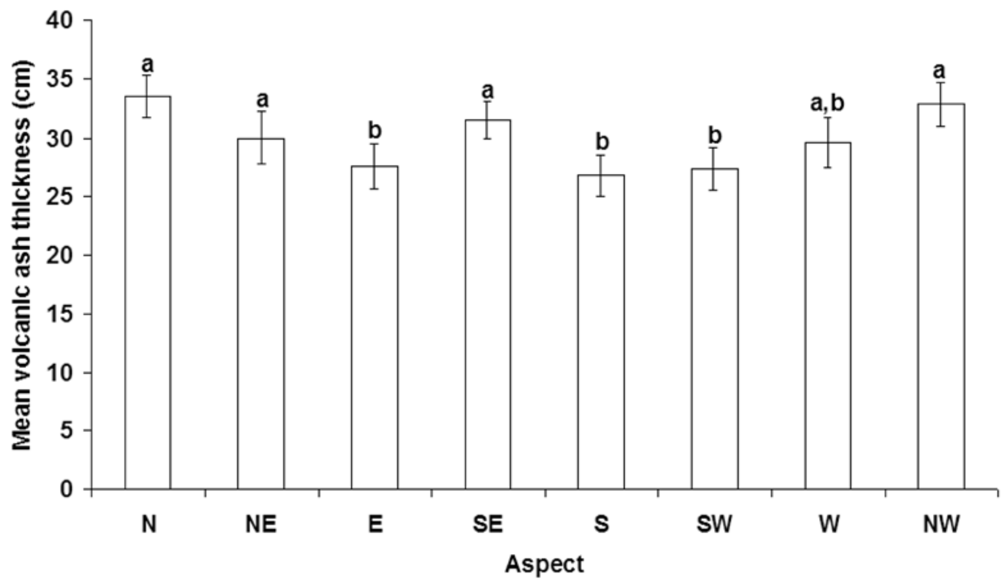

Figure 5—Mean volcanic ash thickness as a function of aspect (ASP) class. Y-axis bars represent standard errors, with letters indicating significant differences ($p < 0.1$).

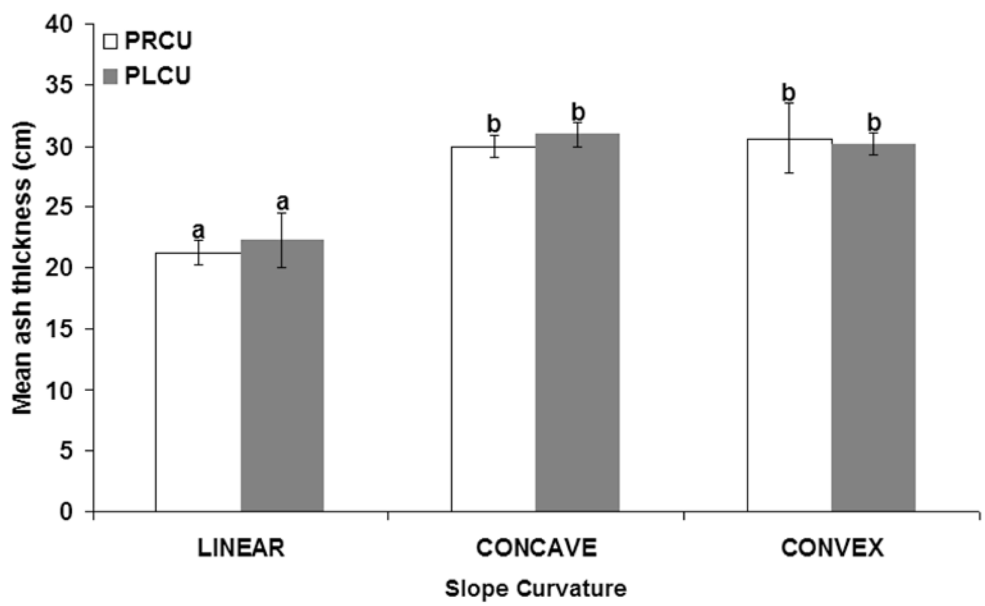

Figure 6—Mean volcanic ash thickness as a function of upslope curvature (PRCU) class. Y-axis bars represent standard errors, with letters indicating significant differences ($p < 0.1$).

type of the ABGR vegetation series surprisingly shows no significant ash mantle (mean = 0 cm). Ash thickness in ABGR habitat types can be described as a function of increasingly moist understory indicator species, with the exception of LIBO. Habitat type rankings for volcanic ash thickness would be *LIBO < PHMA/SYAL < CLUN < ASCA*, where PHMA, SYAL, CLUN, and ASCA represent ninebark (*Physocarpus malvaceus*), snowberry (*Symphoricarpus albus*), queen-cup beadlily (*Clintonia uniflora*), and wild ginger (*Asarum caudatum*), respectively. These rankings suggest that vitrandic intergrades would be more prevalent on PHMA/SYAL and LIBO habitat types, andic intergrades on CLUN, and Andisols on ASCA.

Changing from an ABGR to a western redcedar (THPL) vegetation series is accompanied by a 5-cm increase in mean ash thickness when comparing across CLUN habitat types. This shift is not evident for the ASCA habitat type, which shows no significant differences between ABGR and THPL vegetation series. Maidenhair fern (*Adiantum pedatum* – ADPE) and oak-fern (*Gymnocarpium dryopteris* – GYDR) habitat types show a reduction of >7 cm in mean ash thickness over ABGR/THPL-ASCA. Mean ash thickness for CLUN and ADPE/GYDR habitat types suggest that andic intergrades would be most common, with Andisols (in other words, ash mantle >36 cm) occurring primarily under an ASCA habitat type. Based on these observations, understory rankings of habitat type by increasing ash thickness would be *CLUN = ADPE/GYDR < ASCA*.

The western hemlock (TSHE) series displayed the largest difference in volcanic ash thickness between CLUN and ASCA habitat types (about 28 cm). TSHE-CLUN habitat types show at least a 6-cm decrease in mean ash thickness when compared to THPL-CLUN; however, a TSHE-CLUN habitat type would still fall within the andic intergrade classification associated with other CLUN habitat types. Ash thickness in the ASCA habitat type is significantly greater for TSHE vegetation series than for any other series with observed ASCA habitat types. Mean ash depths on TSHE-ASCA are 54 cm, which would place them well within the Andisol soil order.

Mountain hemlock (TSME) and subalpine fir (ABLA) series are typically found at higher elevations where air temperatures are relatively low and annual precipitation high. The warmer, moister ASCA habitat was not observed. Mean ash thickness is greater on TSME-CLUN than ABLA-CLUN, but the difference is insignificant. Volcanic ash-thickness on these vegetation series is >36 cm, thus placing them into the Andisol order.

Volcanic Ash Distribution Modeling

The class variables listed in table 1 were added stepwise into a multiple linear regression equation. Variables were assumed to be independent and normally distributed. The final model, with selected variables acting as fixed effects on volcanic ash thickness, is:

$$AT_{jklmno} = \mu + PRCU_j + ASP_k + SLP_l + ELE_m + VS{*}HT_n + \varepsilon_{jklmno}$$

where,

AT_{jklmno} is the predicted value for observation *o* with vegetation series*habitat type interaction *n* at elevation *m* on slope *l* with aspect *k* and upslope curvature *j*,

μ is overall volcanic ash thickness mean,
$PRCU_j$ is the fixed effect of upslope curvature (concave, convex, or linear),
ASP_k is the fixed effect of aspect (N, NE, E, SE, S, SW, W, NW, or FLAT),
SLP_l is the fixed effect of percent slope (0-10, 10-20, 20-30, 30-40, 40-50, 50-60,or 60+),
ELE_m is the fixed effect of elevation in meters (200-400, 400-600, 600-800, 800-1000, 1000-1200, 1200-1400, 1400+),
$VS*HT_n$ is the fixed effect of vegetation series*habitat interaction (where, VS are ponderosa pine, Douglas-fir, grand fir, western redcedar, western hemlock, mountain hemlock, or subalpine fir; and HT are Idaho fescue, ninebark/snowberry, twinflower, queen-cup beadlily, wild ginger, or maidenhair fern/oak-fern),
ε_{jklmno} is the error term;

where, j = 3 for upslope curvature, k = 9 for aspect, l = 7 for slope, m = 7 for elevation, n = 13 for vegetation series*habitat type interaction, and o = 1 for number of observations per location.

All class variables, except PLCU, explained a significant portion of variation in volcanic ash thickness ($p < 0.1$) (table 2). Variables ranked from least to most in variance explained are *PRCU < ASP < SLP < ELE < VS*HT*. The interaction term, VS*HT, accounted for the largest percentage of explained variance at 71.2 percent. ELE was the second largest at 18.2 percent. SLP and ASP accounted for 8.9 percent combined, and PRCU explained the least at 1.7 percent. The overall model was significant (p <0.001) and accounted for 60 percent of the observed variation in ash thickness. A model RMSE of 10.7 cm and CV of 36 percent indicate that there is a significant amount of variation still unaccounted for; however, the predictive error is significantly lower than the variation found in local soil series.

Table 2—General linear model variables retained in an ash prediction analysis. Partial variance indicates the percent of the model R2 explained by each retained variable.

	Elevation	Slope	Aspect	Upslope Curvature	Vegetation Series* Habitat Type
Partial Variance (%)	18.2	4.7	4.2	1.7	71.2
Significance[a]	<0.0001	0.006	0.04	0.03	<0.0001

[a]Significance level tested at α = 0.1.

Discussion

Ecological and Topographic Indicators

It is evident from the broad relationships presented that volcanic ash distribution is strongly associated with vegetation patterns and less dependent on terrain attributes. Elevation, although a topographic feature, shows strong collinearity with local precipitation gradients and vegetative cover (data not shown). This situation suggests that elevation serves locally as a proxy variable for interactions between precipitation and vegetation patterns and their subsequent effect on ash distribution.

Slope class did not have a negative impact on mean ash thickness with slopes >60 percent showing no significant decline in ash depths (fig. 3). This result supports other research on slope stability of volcanic ash. In a review of volcanic ash soils, Warkentin and Maeda (1980) note that volcanic ash on free-standing slopes up to 70 degrees are common in regions of high rainfall. They attribute this high degree of stability to the unique permeability of volcanic ash.

The significantly lower mean ash thickness in the 0-to-10 percent slope class may be due to the geographic location of these observations. A majority of these observations for nearly flat terrain were on the benchlands of the south and southwest portion of the study area. This region is characterized by low elevation PSME and ABGR vegetation series, which often exhibit thin or mixed volcanic ash mantles.

The prevalence of thicker ash mantles on north aspects may be attributable to several factors (fig. 4). North aspects typically support moister plant communities in our study area (Cooper and others 1991). These moist plant communities may provide greater soil surface cover, which would decrease the impact of precipitation and overland water flow on volcanic ash redistribution. Additionally, the moisture retained within the soils after precipitation events would be less susceptible to evaporation from solar radiation. Giest and Strickler (1978) found volcanic ash soils of Oregon to be susceptible to wind erosion once in a dry state. Assuming that current southwesterly prevailing wind patterns were similar to historic post-eruption patterns, dry volcanic ash on south-facing slopes would be expected to be more susceptible to redistribution by wind than north aspects. The significant increase in ash thickness on southeast slopes is anomalous to this theory and suggests that the overall effect of aspect on ash distribution is local and intricately tied with surrounding topographic and environmental factors.

The significant decrease in ash thickness on linear surfaces shown in figure 5 is partially correlated with the slope class these observations share. A review of the dataset shows that about 67 percent of the linear surfaces occur on slopes <10 percent with the remainder unevenly divided among several steeper slope classes. As detailed in the previous discussion of slope classes, observations with gradients <10 percent are found primarily in the drier benchland portions of the study area. The correlation between slope steepness and slope surface curvature within the dataset may mask local effects of slope curvature on ash thickness. Surprisingly, convex surfaces in both upslope and across slope positions displayed no significant decrease in mean ash thickness over concave surfaces. Other research on volcanic ash deposition after the eruption of Mt. St. Helens has shown that concave surfaces support thicker ash mantles than convex (Zobel and Antos 1991). Our conflicting results may be due to the level of variation found within these classes. Standard errors were small because of large sample sizes, but the standard deviations were often large within the surface classes, reflecting significant variation within the data.

Cooper and others (1991) associate shifts in climax plant associations to distinctive soil and/or topographic microclimate features. Habitat type shifts and differing soil ash depth are evident across the broad habitat type associations observed in our study area (fig. 7). These strong relationships may be attributed to many combinations of topographic, climatic, or edaphic factors. Steele and others (1981) noted that the influence of volcanic ash contributed to distinct shifts in Idaho plant communities. However, it is still an open question as to whether

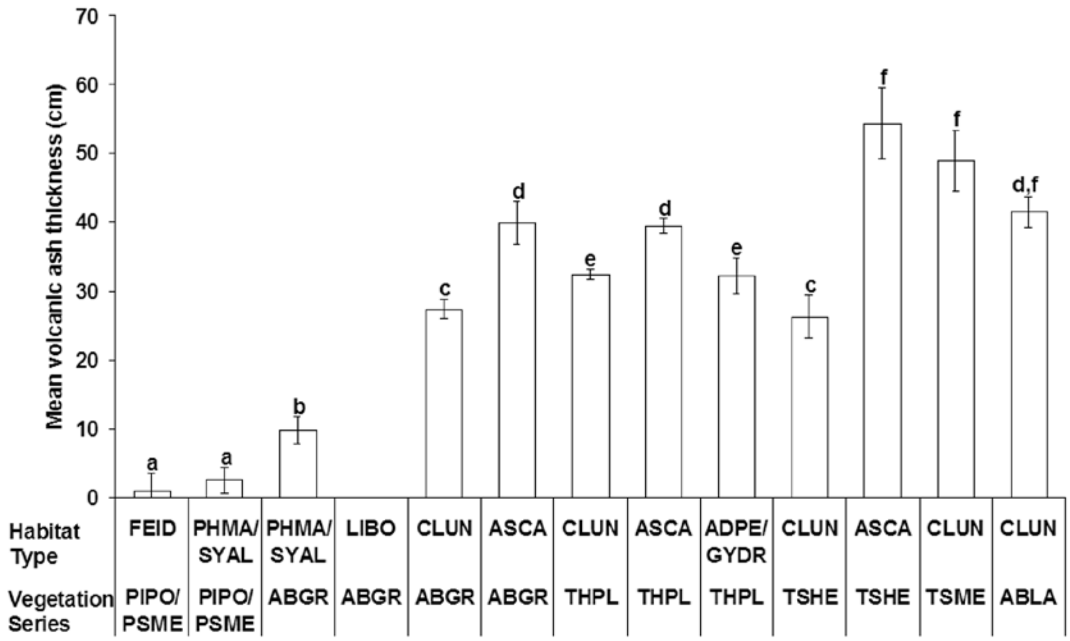

Figure 7—Mean volcanic ash thickness as a function of overstory (VS) and understory (HT) indicator plant species. Y-axis bars represent standard errors, with letters indicating significant differences ($p < 0.1$) (Cooper and others 1991).

the presence of volcanic ash is responsible for shifts in plant associations, or that variations in plant community were responsible for differential ash retention. Despite this uncertainty, volcanic ash thickness is highly correlated with plant associations and can be used to assess ash distribution patterns.

PSME and PIPO vegetation series show the least ash thickness within our data. Shifts to moister habitat types within these vegetation series show no significant dependence on volcanic ash. It has been suggested that these vegetation series now reside on landscapes that, post-Mazama eruption, were drier and did not support forest vegetation cover. Lack of overstory cover and dry climatic conditions prevented these landscapes from retaining volcanic ash mantles subsequent to the eruption.

Volcanic ash thickness in ABGR communities is highly variable. Unlike successively moister plant associations, an ABGR vegetation series does not always indicate the presence of significant volcanic ash influence. This variability is partly attributable to the transition zone that ABGR inhabits between xeric and udic soil moisture regimes. Near the dry end of the spectrum, ABGR plant communities would be associated with minimal to no ash influence. This suggests that an increase in plant available soil moisture would shift the understory plant community towards moister habitat types. Thus, drier habitat types (PHMA/SYAL) often exhibit less ash influence in the soil than the CLUN and ASCA types.

An exception to this pattern is the ABGR-LIBO association. LIBO is considered to inhabit moister environments than PHMA, suggesting that volcanic ash might be present on this habitat type. The absence of volcanic ash on LIBO habitat types may be attributable to the fact that only five observations were collected within this habitat type, providing for a poor representation of the range in ash thickness.

All remaining plant associations moister than ABGR show significant ash influence in the soil. The presence of a thick ash mantle is often identified by the presence of these climax species. Increasing ash thickness in the soil is evident in the habitat type gradients within the THPL series; however, habitat type differences are minimal.

The TSHE vegetation series occupies a narrow ecological range in north Idaho forests and primarily inhabits moist, moderate temperature sites and are intolerant to drought, excess moisture, and frost (Cooper and others 1991). The narrow ecological range suggests that other edaphic and climatic factors might play a larger role in TSHE distribution than volcanic ash influence in the soil. Such factors may also explain why TSHE-CLUN plant associations have thinner ash mantles than THPL-CLUN. TSHE-ASCA sites do show significant increases in volcanic ash thickness. This result suggests that volcanic ash is associated with a shift to moister understory plant communities within the TSHE vegetation series.

TSME and ABLA plant communities occupy high elevation sites with up to 1500 mm of annual precipitation within our study area. Vegetation series within these zones are probably not dependent on the presence of volcanic ash for their establishment. The high precipitation and dense vegetative cover of these plant communities retained volcanic ash subsequent to original ash deposition.

Volcanic Ash Distribution Modeling

The strength of the relationships between elevation, plant communities, and volcanic ash produces a strong predictive ability for our ash distribution model. An R^2 value of 0.6 is considered an excellent improvement over the limited regional volcanic ash modeling attempts (Nimlos and Zuuring 1982). Predictions from this model allow quantitative ash assessments with a known error within the study area. Forest managers can use this model to integrate the predictions into a geographic information system (GIS). One motivation behind developing a quantitative ash distribution model was to overcome the variation inherent within mapping units generated through a soil survey. Volcanic ash thicknesses in Hugus and Bouldercreek soil series commonly found in our study area have mapped variations >20 cm (Soil Survey Division 2006). The predictive model's RMSE of 10.7 cm significantly improves on this level of variation, thus providing a finer resolution support tool for local forest soil management.

Further research should be conducted to determine local affects of topographic features on ash distribution despite the significant improvement this model provides in predicting ash depth and distribution. Global statistical procedures such as multiple linear regression may mask local topographic influence. Adjusting a statistical model to perform a more local analysis may yield improved results. A more costly, but perhaps informative method, would be a detailed survey of a finite landscape. Research at local levels may reveal topographic and volcanic ash relationships otherwise masked by large conventional soil surveys. Regardless of which approach is used, modeling ash distribution seems to be inherently a local exercise. The extrapolation of model results outside a study area is not recommended. The concepts behind the model presented in this paper may be applicable elsewhere, but the relationships as reflected in the model parameter estimates are unique.

Summary

This study's findings suggest that volcanic ash distribution is intricately linked with elevation and plant community associations. Elevation increases precipitation, which in turn supports different climax plant communities. Increasing plant density at each successive climax community may serve to retain ash deposits subsequent to volcanic eruptions and entrap wind-transported volcanic ash from drier, lower elevation sites. Topographic variables show relatively little impact on ash thickness patterns. Several of the terrain attributes showed clustering by geographic location within our study area. Gentler slopes, which were predominately found at drier, lower elevations, supported thinner ash mantles. The slope curvature variable was also linked to geographic location. Nonlinear slopes were most often found in the mountainous region of the study area. The strong effect of elevation and vegetation habitat type series reduced the ability to distinguish mean ash thickness differences between convex and concave surfaces.

Statistical modeling accounted for 60 percent of the observed variation in ash thickness and returned an RMSE of 10.7 cm. These model statistics indicate a significant development in the prediction capability of volcanic ash thickness. Model error is significantly lower than the variation of >20 cm often observed in local ash-influenced soil series. However, it became evident during our analyses that ash distribution and thickness is heavily influenced by local ecological and topographic attributes that cannot be assumed to affect ash depth uniformly across a study area. Future ash modeling efforts must focus on assessing local environmental influences and account for nonstationarity in the independent variables. Such an analysis may clarify the ecological and topographic effects on ash distribution and thickness that are otherwise generalized in a global regression analysis.

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Field Identification of Andic Soil Properties for Soils of North-central Idaho

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Introduction

Currently, laboratory measurements are definitive for identifying andic soil properties in both the USDA Soil Taxonomy (Soil Survey Staff 1999) and the World Reference Base for Soil Resources (FAO/ISRIC/ISSS 1998). Andic soil properties, as described in Soil Taxonomy, result mainly from the presence of significant amounts of allophone, imogolite, ferrihydrite or aluminum-humus complexes in soils. The required properties are high acid-oxalate extractable aluminum and iron percentages, low bulk density, and high phosphate retention. In addition, glass is a common component of andic soils of the Inland Northwest region (McDaniel and others 2005).

A large body of work has been devoted to characterizing ash soils for classification and management purposes. Summaries of this work include Shoji and others (1993) and Dahlgren and others (2004). However none of these efforts have addressed the problem of identifying soils with andic soil properties directly in the field. Most soil mapping professionals working with ashy materials are able to identify andic properties under field conditions. However, there is currently no summary of the methods used by individuals to accomplish this identification. A procedure for recognizing andic materials using field characteristics would assist both those lacking experience with these materials and those assessing soils from written descriptions. Also, a logically derived set of selection criteria for detecting andic properties could help even experienced professionals in areas where volcanic ash influence has been diluted by mixing with other materials.

This paper will examine two alternatives for detecting andic soil properties. The first is the development of an empirical model using routinely observed soil features as recorded in soil descriptions from north-central Idaho. The second is the use of sodium-fluoride (NaF) pH to detect the presence of allophane or similar amorphous materials in soils. The objectives of this project were to: 1) identify a set of field-observable characteristics that can reliably identify soils derived from Mount Mazama tephra; 2) develop a simple model using these characteristics to evaluate samples as to whether they meet andic criteria or not; and, 3) evaluate use of NaF-pH in this region as a test for recognizing ash influence.

Methods and Materials

A set of 323 Natural Resources Conservation Service (NRCS) pedon descriptions (or 945 separate soil horizons) from Latah County, Idaho was used to evaluate how well a set of field observations allows an observer to distinguish andic materials from other soil materials. Only horizons having a complete set of observations for all properties and occurring within 50cm of the soil surface were used. Each horizon had been designated as ashy or non-ashy according to the expert opinion of the NRCS soil scientist recording the soil description. The dataset contains 468 horizons designated as ashy and 477 horizons designated non-ashy.

The set of field observable characteristics proposed for recognizing andic materials are soil color (dry and moist), structure, consistence (consistence is the set of stickiness, plasticity, rupture resistance dry and rupture resistance moist), and root abundance. Soil color is described using standard Munsell notation. Structure, consistence and root abundance are described using the methods and nomenclature found in Schoeneberger and others (2002).

Most of the soil properties are described using a number of component elements. For example, soil color is described by the six components of dry hue, dry value, dry chroma, moist hue, moist value and moist chroma (see table 1). This subdivision of properties resulted in a list of 17 properties and/or components that could be used to distinguish between ashy and non-ashy soil horizons. Each component of a property has been assigned one of several possible classes that describe the component for a given soil. For example, dry soil hue could be 5YR, 7.5YR or 10YR. Tables 2 through 6 show the relative frequency distribution for each class used to describe the components of each soil property by tephra or non-tephra parent materials.

The relative frequencies observed for the classes describing the components of each soil property were used to evaluate which components would be useful in discriminating andic from non andic (or "other") materials. A useful discriminator was defined as one that showed: 1) a clustering of 60 percent or more of observations for the tephra material on one component class, and 2) less than 35 percent of observations for the 'other ' materials occurring in that same class.

The pH of a suspension containing 1 g soil in 50 mL 1 M NaF is used as a test for the presence of short-range order minerals. These minerals are commonly early products of the weathering of pyroclastic materials. The action of 1 M NaF on these minerals releases hydroxide ions (OH^-) to the soil solution and increases the pH. A 1 M NaF pH of more than 9.4 at 2 minutes after the NaF solution is added is a strong indicator (in non-calcareous soils) that short-range order minerals dominate the soil exchange complex (Burt 2004).

Table 1—Soil properties proposed as useful for field recognition of tephra derived soil materials with their component elements and descriptive classes.

Property	Component elements	Descriptive classes
Soil color	dry hue	5YR, 7.5YR, 10YR
	dry value	2, 2.5, 3, 4, 5, 6, 7
	dry chroma	2, 3, 4, 6
	moist hue	5YR, 7.5YR, 10YR
	moist value	2, 2.5, 3, 4, 5, 6, 7
	moist chroma	2, 3, 4, 6
Structure	grade	weak, moderate, strong
	size[a]	1, 2, 3, 4, 5
	kind[b]	abk, gr, pl, pr, sbk, massive
Consistence	dry rupture resistance	soft, slightly hard, moderately hard, hard, very hard
	moist rupture resistance	very friable, friable, firm
	stickiness	nonsticky, slightly sticky, moderately sticky, very sticky
	plasticity	nonplastic, slightly plastic, moderately plastic, very plastic
Root abundance[c]	very fine and fine roots	few, common, many
	medium and coarse roots	few, common, many
Texture[d]	none	1, 2, 3, 4 ,5 6, 7

[a] Structure size classes are: 1 = very fine, very fine and fine or fine; 2 = very fine to medium or fine and medium; 3 = medium; 4 = fine to coarse or medium and coarse; 5 = coarse.
[b] Structure kinds are: abk = angular blocky; gr = granular; pl = platy; pr = prismatic and sbk = subangular blocky.
[c] Root abundance classes are: few = <2%, common = 2 to 20% and many = >20%.
[d] Texture classes are: 1 = sil; 2 = l; 3 = fsl, vfsl; 4 = sicl; 5 = cl; 6 = sl; 7 = cosl, lcos for definitions of class terms see Schoenberger and others 2002.

Table 2—Observed frequencies for the components of soil color by moisture status and parent material.

Color component	Classes	Moist tephra count	Freq	Other count	Freq	Dry tephra count	Freq	Other count	Freq
		(no.)		*(no.)*		*(no.)*		*(no.)*	
Hue	10yr	145	0.39	120	0.73	240	0.74	138	0.90
	7.5yr	229	0.61	43	0.26	84	0.26	14	0.09[a]
	5yr	0	0	2	0.01	0	0	2	0.01
Value	2	0	0	3	0.02	0	0	0	0
	2.5	5	0.01	2	0.01	0	0	0	0
	3	181	0.48	45	0.27	0	0	0	0
	4	184	0.49	101	0.60	2	0.01	11	0.07
	5	5	0.01	16	0.10	127	0.39	19	0.12
	6	0	0	1	0.01	181	0.56	104	0.68
	7	0	0	0	0	14	0.04	20	0.13
Chroma	2	2	0.01	4	0.03	3	0.01	5	0.03
	3	52	0.14	63	0.41	21	0.07	66	0.43
	4	255	0.68	82	0.53	261	0.81	78	0.51
	6	66	0.18	5	0.03	38	0.12	5	0.03

[a] Component meets criteria for useful ashy soil identifier.

Table 3—Observed frequencies for the components of soil structure by soil parent material.

Structure component	Classes	Tephra count	Freq	Other count	Freq
		(no.)		*(no.)*	
Structure grade	weak	419	0.83	148	0.29[a]
	moderate	83	0.16	349	0.68
	strong	3	0.01	20	0.04
Structure size	1	261	0.52	125	0.24
	2	204	0.40	290	0.56
	3	29	0.06	60	0.12
	4	1	0	29	0.06
	5	9	0.02	11	0.02
Structure kind	abk	0	0	2	0
	gr	196	0.39	91	0.17
	pl	0	0	11	0.02
	pr	0	0	16	0.03
	sbk	311	0.61	395	0.75
	massive	1	0.00	15	0.03

[a] Component meets criteria for useful ashy soil identifier.

Table 4—Observed frequencies for the components of soil consistence by soil parent material.

Consistence component	Classes	Tephra count	Freq	Other count	Freq
		(no.)		*(no.)*	
Dry consistence	soft(so)	474	0.96	19	0.15[a]
	slightly hard (sh)	17	0.03	32	0.24
	moderately hard (mh)	1	0.00	32	0.24
	hard (ha)	0	0.00	42	0.32
	very hard(vh)	1	0.00	6	0.05
Moist consistence	very friable(vfr)	507	0.98	25	0.19[a]
	friable(fr)	11	0.02	97	0.72
	firm(fi)	0	0.00	12	0.09
Stickiness	nonsticky(so)	474	0.93	34	0.25[a]
	slightly sticky(ss)	34	0.07	85	0.62
	moderately sticky(ms)	0	0.00	18	0.13
	very sticky(vs)	0	0.00	1	0.01
Plasticity	nonplastic(po)	465	0.91	16	0.12[a]
	slightly plastic(sp)	43	0.08	51	0.38
	moderately plastic(mp)	1	0.00	54	0.40
	very plastic(vp)	0	0.00	15	0.11

[a] Component meets criteria for useful ashy soil identifier.

Table 5—Observed frequencies for root abundance by root size class and soil parent material.

Root abundance	Classes	Tephra count	Freq	Other count	Freq
		(no.)		*(no.)*	
Very fine and fine roots	none	2	0	4	0.01
	few	12	0.03	33	0.07
	common	93	0.20	223	0.47
	many	366	0.77	216	0.45
Medium and coarse roots	none	95	0.20	171	0.36
	few	158	0.33	199	0.42
	common	207	0.44	88	0.18
	many	13	0.03	18	0.04

Table 6—Observed frequencies of soil textures (for the <2mm fraction) by parent material

Soil texture name	Tephra count	Freq	Other count	Freq
	(no.)		*(no.)*	
sil (1)	465	0.99	320	0.67
l (2)	3	0.01	112	0.23
fsl, vfsl (3)	0	0	10	0.02
sicl (4)	0	0	7	0.01
cl (5)	0	0	4	0.01
sl (6)	0	0	19	0.04
cosl, lcos (7)	0	0	5	0.01

While each of these variables is important in recognizing ash soils, the classification criteria allow for interaction between the two so that no single value serves to discriminate andic from nonandic horizons. In an attempt to define such a threshold value for NaF-pH, a dataset of laboratory measurements from Clearwater County, Idaho was obtained for analysis. The dataset contained 267 horizons with NaF-pH information. These were then grouped into andic (73 horizons) and nonandic (194 horizons) soils. Table 7 reports the mean and standard deviation for these two sample populations. Assuming a normal distribution, it is possible to use these means and standard deviations to calculate a NaF-pH value that corresponds to the critical value for the Z statistic at a chosen level of probability. Table 7 reports these critical values as NaF-pH values at P=.95 and P=.99.

Table 7—Mean, standard deviation and NaF-pH values that are equivalent to the critical values of Z at two levels of probability.

	Mean	Standard deviation	NaF-pH at P=.95	NaF-pH at P=.99
Nonandic	8.58	0.60	9.56	9.97
Andic	10.56	0.36	9.97	9.73

Results and Discussion

Soil color is strongly influenced by parent material (Richardson and Daniels 1993). Table 2 indicates that the only component of soil color useful for recognizing ash influenced soils in north-central Idaho is the moist hue. The ash-influenced materials are noticeably redder in hue (7.5YR vs. 10YR) than other materials for most samples. This is assumed to be a result of the prevalence of ferrihydrite in ashy materials (Dahlgren and others 2004; Ugolini and Dahlgren 2002). Ferrihydrite-containing soils have hues of 5-7.5YR while soils with hues between 7.5YR and 2.5Y tend to contain significant amounts of goethite (Schwertmann 1993).

Soil structure is a complex phenomenon that depends in part on factors such as parent material, climate and the physical and biochemical processes of soil formation (Brady and Weil 2001). Andic soils have a tendency to have weak fine structure that is granular in A horizons and subangular blocky in B horizons (table 3). Soils derived from other materials have similar structure size and kind but exhibit stronger development with a grade of moderate being dominant. Therefore, structure grade is recognized as a suitable identifier for ash-influenced soils.

Consistence is a description of a soil's physical condition at various moisture contents as evidenced by the response of the soil to mechanical stress or manipulation. The consistence of a soil is determined to a large extent by the particle-size distribution of the soil, but is also related to other properties such as organic matter content and mineralogy (http://organiclifestyles.tamu.edu /soilbasics/soilphysical.html). Andic soils have unique consistence properties displaying low rupture resistance (in both dry and moist states), little stickiness and low plasticity (table 4). Each of these components of consistence is useful to separate ash influenced from other materials. They are a reflection of the very low clay contents and unique mineralogy of the ashy material.

Field observations have noted a high degree of root proliferation in ashy surface horizons in north-central Idaho. While the data show a slight trend toward greater root abundance in the ashy materials, the difference compared to the other parent materials was not sufficient to allow use of this characteristic as a discriminator (table 5). The recording of root abundance as broad classes rather than actual counts per area may have reduced the usefulness of this comparison.

A series of simple models for recognizing ash-influenced soil materials were created using the components identified as useful discriminators of ashy material. They were tested through a process of trial and error. During this testing it was discovered that soil texture could be used to help improve model performance. This is true even though that property did not meet the criteria set for recognition as a useful discriminator. Soil texture proved to be a special case where the high degree of clustering on the silt loam class (99.6 percent of observations) for the ash-influenced material helped the model to recognize these materials. This improved performance results from better separation of the ash-influenced materials from low plasticity materials of other origins. During this phase, it was also determined that moist rupture resistance would not be used in the final model. Even though this component met the criteria for a useful discriminator, it is strongly related to dry rupture resistance. The addition of moist rupture resistance did not improve the model. Dry rupture resistance was preferred because it had more-easily recognized classes and greater consistency in application by different observers.

A final model was created for evaluating whether a soil sample classifies as andic material. The model scores a soil based on the six identified properties and /or components as follows:

moist hue – 7.5YR=1, other=0;
structure grade – weak=1, other=0;
dry rupture resistance – soft=2, other=0;
stickiness – nonsticky=2, other=0;
plasticity – nonplastic=2, other=0;
texture – silt loam=2, other=0.
A score >= 8 is andic material while <8 is nonandic.

This model was used to evaluate the original dataset and returned an error rate of 7.6 percent. There were approximately equal percentages of false positives and false negatives. Of the 468 horizons designated ashy by the expert observers, the model failed to recognize 37. These 37 false negatives were due primarily to their lack of the expected moist hue and plasticity characteristics. Of the 477 horizons designated-non-ashy by expert observers, 35 were misidentified by the model as andic materials. These 35 horizons are silt loams that are low in clay and that have rupture resistance, stickiness and plasticity characteristics similar to andic materials. The model correctly discriminated between andic and nonandic materials in 92.4 percent of cases.

NaF-pH has been identified as a simple and convenient index for the presence of andic materials (Fieldes and Perrott 1966). Work by Kimsey and others (2005) found a strong (R^2 =.82) correlation between NaF-pH and acid oxalate extractable Al and Fe. Another study by Brownfield and others (2005) reported a good correlation (R^2 =.66) between tephra percent (based on grain counts) and NaF-pH. A critical pH value of 9.4 has been suggested as the threshold for recognition of tephra dominated materials (Soil Survey Staff 1995). The calculations shown in table 7 indicate that, for the Clearwater County data, this threshold value is too low. The table shows that 95 percent of the distribution of NaF-pH values for andic horizons is greater than or equal to 9.97. Interestingly, the same NaF-pH value of 9.97 is the upper bound below which 99 percent of the distribution of nonandic values is found. Rounding to one decimal place gives a NaF-pH of 10.0 as a suggested threshold for recognizing andic materials. When applied to the Clearwater County data, this threshold causes an error rate of about 10 percent (7 out of 73 horizons misidentified) for andic horizons and about 3 percent (6 out of 194 horizons misidentified) for nonandic horizons. Using a threshold pH value of 10.0 allowed for correct classification of horizons in about 95 percent of cases.

Summary

Two methods for field identification of volcanic ash influenced soil horizons were explored. A simple empirical model was developed for ash recognition using the easily observable qualitative properties of moist hue, structure grade, dry rupture resistance, stickiness, plasticity and texture. This model successfully discriminated between tephra and other materials in about 92 percent of cases. A model like this can be used to help those not expert in soil classification to recognize andic soil materials, to evaluate written descriptions when soil samples are not available and to help more experienced soil classifiers in conditions where the tephra is highly mixed with other materials. One principal weakness of this model is that it is developed for Mount Mazama ash in north-central Idaho. Soils formed in volcanic ejecta in other areas may have a different set of identifying characteristics.

The second method for identification of andic materials was the use of NaF-pH. While the analysis used here depended on laboratory measurements, the NaF-pH can be readily measured in the field. Data from Clearwater County, Idaho showed that using a threshold value of 10.0 pH units correctly classified soil horizons in about 95 percent of cases. The use of NaF-pH to detect allophanic material has broad application to many different volcanic materials. However, identification of the most useful threshold value may be subject to regional variation.

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Physical and Chemical Characteristics of Ash-influenced Soils of Inland Northwest Forests

P. A. McDaniel and M. A. Wilson

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Abstract

Holocene ash from the cataclysmic eruption of Mount Mazama (now Crater Lake) in southeastern Oregon is a major component of many forest soils that lie to the east of Cascade Mountains in the Pacific Northwest region. The relatively high productivity of the region's ecosystems is closely linked to this volcanic ash component. This paper reports on the ecologically important properties of these ash-influenced soils by examining soil characterization data from over 500 soil horizons of the region contained in the National Soil Survey database. Volcanic ash-cap textures are generally silty in areas distal to the eruption. Volumetric water-holding capacity of ash-cap horizons is as much as twice that of underlying horizons and underscores the importance of ash caps in seasonally dry, forested ecosystems of the Inland Northwest region. Cation exchange capacity (CEC) determined at field pH (ECEC) averages 8.0 $cmol_c\ kg^{-1}$ and is less than one-third the CEC determined at pH 8.2, indicating considerable variable charge. These data suggest that ash-influenced soils have limited ability to store and exchange nutrient cations such as Ca, Mg, and K. In addition, strong sorption of SO_4 and PO_4 significantly limits the bioavailability of these nutrients. Erosion and compaction of ash caps are major management concerns, but relationships between these processes and ash-cap performance remain unclear.

Introduction

Soils formed entirely or partially in volcanic ejecta such as ash (glassy particles <2mm in size), cinders (glassy particles >2mm in size), and pumice (highly vesicular fragments) are fundamentally different from other soils in terms of their physical, chemical, and mineralogical properties. Because of this, Andisols were established as the 11th soil order in U.S. Soil Taxonomy in 1989. The World Reference Base of Soil Resources (WRB) also recognizes these soils as Andosols, one of the 30 soil reference groups (FAO/ISRIC/ISSS 1998). Soils formed in volcanic ash, such as the ash-cap soils found in the Pacific Northwest region, are characterized by what are referred to as *andic properties* in Soil Taxonomy (Soil Survey Staff 2003). Andic properties refer to a combination of characteristics, including the presence of glass, short-range-order or poorly crystalline weathering products with high surface reactivity, and low bulk density.

Volcanic ash from the eruption of Mt. Mazama (now Crater Lake, OR) ~7,700 years BP (Zdanowicz and others 1999) has influenced many mid- to high-elevation forest soils in the Pacific Northwest region. The unique properties of these ash-caps are intricately linked to forest productivity across the region (Geist and Cochran 1991; Meurisse and others 1991). As such, these soils represent a valuable regional resource from both an economic and ecologic perspective. Moreover, ash-cap soils respond differently to use and management than do soils formed in other parent materials, and it is therefore important to recognize and understand the basic differences in properties. In this paper, we describe some of the important characteristics of volcanic ash-influenced soils.

We used the Natural Resources Conservation Service (NRCS) — Soil Survey Laboratory characterization database for Washington, Oregon, Idaho, and Montana to provide an overview of physical and chemical characteristics of volcanic ash-cap soils of the region. The soils in this database are representative of the dominant mapping unit components in soil survey areas, and have properties that are considered typical of soils across the region. For inclusion in the database, we identified all horizons meeting either the criteria for andic soil properties or andic subgroups in Soil Taxonomy (Soil Survey Staff 2003). All characterization data were obtained using standard methods (Burt 2004) and have been summarized in McDaniel and others (2005).

Soil Morphology

The thickness of ash caps across the Inland Northwest region is variable, but follows a general trend of thinning with increasing distance from Crater Lake (fig. 1a). Data presented by McDaniel and others (2005) showed a range in thickness of 2 to 152 cm across the region, with an average thickness of 38 cm. It should be noted that these reported thicknesses include ash caps thinned by erosion as well as those in which other soil parent materials have been mixed with the volcanic ash after initial deposition. In the latter case, the reported thicknesses represent those of *ash-influenced* mantles rather than pure ash mantles. It is important to realize that the ash caps found across the region have been mixed to varying degrees by post-depositional processes and represent a range in composition. For purposes of this paper and others contained in these proceedings, the term *ash cap* will be used to include all ash mantles, regardless of degree of mixing.

Most of the official soil series descriptions (Soil Survey Division 2005) for ash-cap soils of the region include forest litter layers that are underlain by A horizons having thicknesses typically ranging from 2.5-7.5 cm (1-3 inches). The development of A horizons formed in volcanic ash in the Inland Northwest is usually weak despite the fact that ash-cap soils generally contain relatively large amounts of organic matter compared to other mineral soils (Dahlgren and others 2004). This weak development is probably due to the fact that most ash-influenced soils are forest soils, where the majority of carbon is contained in litter layers and relatively small quantities are added to A horizons in the form of roots. This factor results in relatively thin, light-colored A horizons. Very dark-colored A horizons can form in volcanic-influenced soils that support grasses or understory vegetation with extensive root systems. Deep, dark A horizons have been described under bracken fern (*Pteridium aquilinum*) communities in northern Idaho (Johnson-Maynard and others 1997). These communities may have as much as 3,500 g/m^2 of belowground biomass in the form of rhizomes and fine roots (Jimenez 2005).

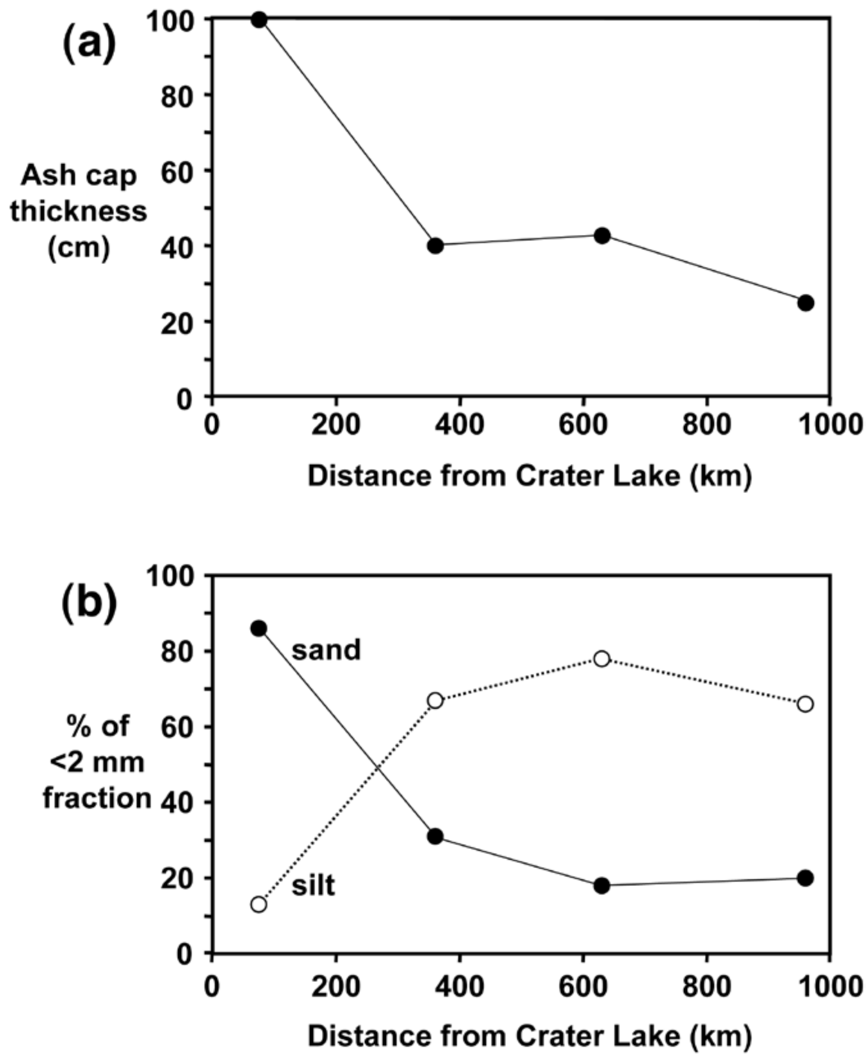

Figure 1—Change in (a) ash-cap thickness and (b) particle-size distribution of Mazama tephra as a function of distance from Crater Lake, OR. Particle-size data represent averages for the ash caps of Lapine, Angelpeak, Threebear, and Jimlake soils and are adapted from McDaniel and others (2005).

Underlying the A horizons are reddish- to yellowish-brown Bw horizons that do not exhibit significant increases in clay content. Hues of these subsoil horizons are typically 7.5YR to 10YR with chromas of 4 or 6. These characteristic colors reflect the weathering of ash to form poorly crystalline Fe oxides such as ferrihydrite (McDaniel and others 2005).

In some higher-elevation areas, ash-cap soils may have undergone sufficient podzolization to develop E-Bh, Bhs horizon sequences. These soils are typically in high-precipitation environments and have extremely acid E horizons. In the Selkirk Mountains of northern Idaho, pH values as low as 3.7 having been reported (McDaniel and others 1997), the lowest pH values found anywhere in the region for native soils.

Physical Properties

Particle-Size Distribution

Much of the tephra distributed throughout the Pacific Northwest was carried in suspension by prevailing westerly winds, a process that has resulted in fairly distinct ranges of particle sizes associated with ash caps. Examination of ash cap textures across the region shows a decrease in overall particle size with increasing distance from the source (fig. 1b). The pumice regions of central Oregon are in closer proximity to Crater Lake, and sand-sized pumice dominates in soils like Lapine. However, ash caps from the Blue Mountains (e.g. Angelpeak soil), northern Idaho (Threebear soil), and western Montana (Jimlake soil) are predominantly silt-sized, reflecting the greater distance of transport. Fine-earth fractions of these ash caps typically have silt loam or loam textures, which can substantially enhance the water-holding capacity of soil profiles.

Bulk Density

Bulk density of Andisols tends to be relatively low, and this is one of the defining characteristics of these soils in Soil Taxonomy and the WRB. Of the 271 horizons examined across the region, the average bulk density is 0.90 g cm^{-3} (fig. 2). However, only ~60 perecent of the horizons have bulk densities of $\leq$0.90 g cm^{-3}, suggesting that mixing and/or compaction, both of which would tend to increase bulk density, have occurred since deposition. Because bulk density is inversely related to porosity, an ash cap with a bulk density of 0.90 g cm^{-3} may have ~40 percent more porosity than a typical mineral soil with a bulk density of 1.3 g cm^{-3}.

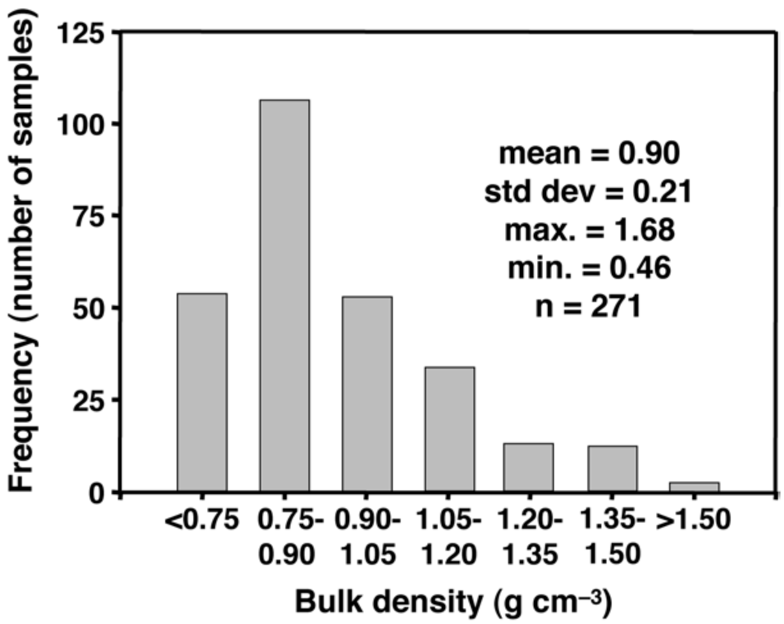

Figure 2—Bulk density data for andic soil horizons of the Pacific Northwest region. Taken from McDaniel and others (2005).

Water-Holding Capacity

Andisols typically are able to retain large amounts of water (Dahlgren and others 2004). In the Inland Northwest region where extended dry periods often occur during the growing season, this water-holding capacity is arguably the most important property from an ecological standpoint. Additional water-holding capacity associated with ash-cap soils may be critical to the establishment and maintenance of some plant communities. The basis for the additional water-holding capacity imparted to soils by volcanic ash stems from three factors. First, as discussed previously, ash caps have relatively high porosity. Secondly, much of the distal ash is silt-sized, which is desirable from the standpoint of water retention characteristics. This is especially true in many mountainous areas where volcanic ash overlies coarser-textured, often rocky soils with relatively little plant-available-water-holding capacity. Finally, weathering of volcanic ash gives rise to a colloidal fraction that has high surface area and is able to retain considerable quantities of water (Wada 1989; Kimble and others 2000; Dahlgren and others 2004).

The effect of a volcanic ash cap on the water-holding capacity of a north Idaho soil is illustrated in figure 3. The ash cap consists of the top two horizons, which have more than twice the water-holding capacity (on a volume basis) of the underlying coarser-textured horizon that has formed in outwash. In this example, the ash mantle contributes 8.6 cm (~3.4 inches) of plant-available water to the soil profile. Ash-caps of the region have an average water retention of ~11 percent (by weight) at 1,500 kPa of soil moisture tension (wilting point) (McDaniel and others 2005), or roughly twice that of sandy soils (Brady and Weil 2004).

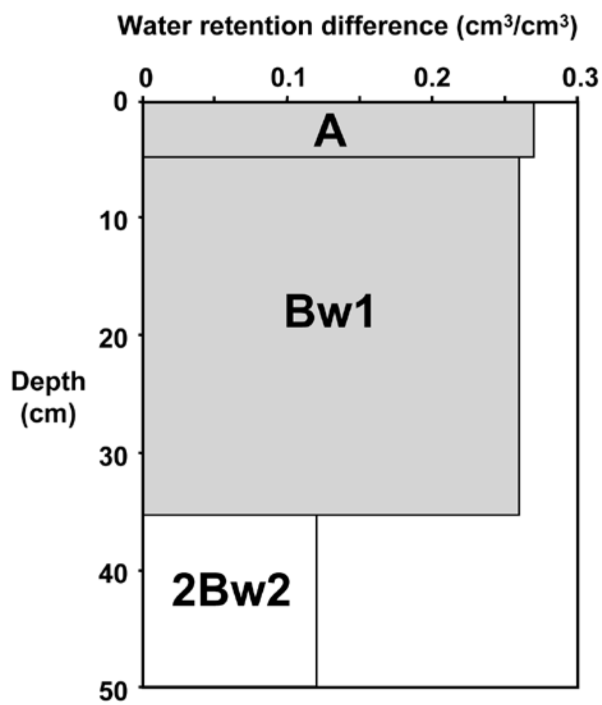

Figure 3—Water retention difference in the top 50 cm of the Bonner series (86ID017002) from north Idaho. Bars represent the difference in water content between –1,500 and –33 kPa, expressed on a volume basis and corrected for rock fragment content. Shaded bars are for andic materials.

When comparing or interpreting water retention data, it is important to distinguish between data reported on a gravimetric (weight) and those reported on a volume basis. Because soil horizons formed in volcanic ash typically have bulk densities <1.0 g/cm^3, water contents will be greater when expressed on a weight basis rather than a volume basis. The opposite is true for other mineral soils with bulk densities >1.0 g/cm^3.

A mantle or cap of volcanic ash also contributes to a more-favorable soil moisture regime through a mulching effect. Some of the increases in crop yields observed after the 1980 Mount St. Helens eruption were attributed to the deposition of fresh ash and its role in reducing evaporative water losses (Dahlgren and others 2004).

Other Physical Properties

Some Andisols exhibit thixotropy, which is described as a reversible gel-sol-gel transformation (Nanzyo and others 1993b). Upon application of pressure or vibration, a wet soil mass will experience a sudden reversible loss of strength and begin to flow. It can easily be observed in a well-moistened ash-cap sample. By applying pressure to the material between the thumb and forefinger, water can be forced out of the soil mass; release of pressure will cause then water to be re-absorbed. On a larger scale, thixotropy can result in soil collapse under roadways and building foundations (Brady and Weil 2004). Thixotropy is most pronounced in highly weathered soils formed in volcanic ash (Buol and others 2003), and therefore is not often well expressed in the relatively less-weathered ash-cap soils of the Inland Northwest region. Soils formed in volcanic ash also have a low bearing capacity because of their low bulk density (Kimble and others 2000), and this makes them susceptible to compaction and can create problems for trafficking and building foundations.

Mineralogical Properties

Volcanic Glass

The principal component of Mazama volcanic ash is glass, which was formed by the very rapid cooling of rhyodacitic magma as it was ejected from the volcano during the climatic eruption (fig. 4) (Bacon 1983). The amount of glass in volcanic ash mantles across the region is variable, and most likely reflects post-depositional redistribution. In the Blue Mountains of northeastern Oregon and southeastern Washington, relatively undisturbed ash mantles contain 60-90 percent volcanic glass and are found in moister landscape positions with lower fire frequency (Wilson and others 2002). In other areas with more active surficial processes such as erosion after fire, glass contents ranges from 25-60 percent, and these are referred to as mixed mantles (Wilson and others 2002). The glass content of 528 ash-cap soil horizons of the region that meet andic soil requirements in Soil Taxonomy averages ~42 percent and exhibits a bimodal distribution (McDaniel and others 2005). This suggests that mixed mantles are common across the region, and that locally, underlying soils have at least some influence on ash cap properties.

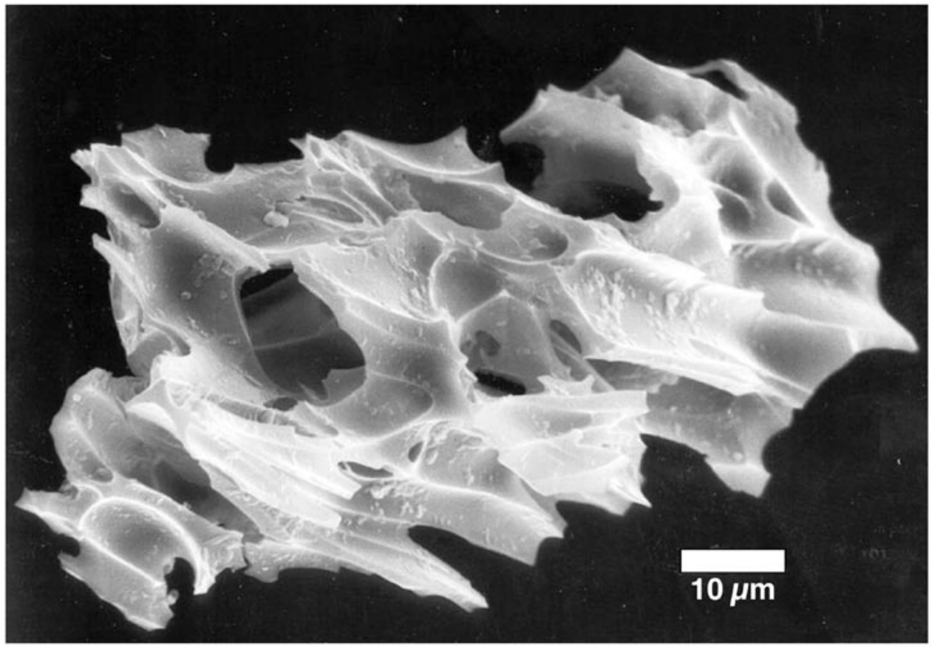

Figure 4—Volcanic glass shard from north Idaho soil. Glass is from the Mazama eruption and measures ~0.1 mm across. Photo from University of Idaho.

Analysis of Mazama ash deposits shows an elemental composition of 70-72 percent SiO_2 (Bacon 1983). In addition, McDaniel and others (1997) reported that the combined Al_2O_3 and SiO_2 content of Mazama glass was ~87.5 percent, with the CaO, MgO, and K_2O contents comprising only 4.9 percent by weight. For comparative purposes, Bohn and others (2001) report an average CaO, MgO, and K_2O content for a variety of igneous rocks of 12 percent. It is clear from these data that volcanic glass is not a rich source of plant nutrients and should not be thought of as a having remarkable fertility. Minor amounts of plant nutrients such as SO_4^{2-}, Ca^{2+}, and PO_4^{2-} present in the original Mazama ash fall may have provided short-term fertility inputs, as was the case with the 1980 eruption of Mount St. Helens (Fosberg and others 1982; Mahler and others 1984). However, long-term fertility of the glass is relatively low.

Clay Mineralogy

Because of the lack of a crystalline structure, glass weathers relatively rapidly to form poorly crystalline or non-crystalline minerals in the clay fraction. In slightly to moderately weathered Andisols such as those found in the Pacific Northwest region, there are three mineral assemblages that tend to dominate: (1) Al-humus complexes, often with Al-hydroxy-interlayered 2:1 minerals; (2) allophane and imogolite, and; (3) poorly crystalline Fe oxides (ferrihydrite) (Dahlgren and others 2004). As ash weathers, Al and Fe released into soil solution in surface horizons can form stable organic complexes, especially at soil pH < 5 (Parfitt and Kimble 1989); these pH values are common under coniferous forest vegetation at higher elevation in the Inland Pacific Northwest. Al-humus complexes represent active forms of Al and may contribute to Al toxicity (Dahlgren and others 2004). In the relative absence of humus and less acid conditions, such as in B and C horizons, Al and Si precipitate to form allophane and imogolite. These two aluminosilicate minerals may have similar chemical composition, but allophane typically consists of spherical units while imogolite appears as threads or tubes (Kimble and others 2000). Allophane and imogolite both have relatively high surface area. Using data presented by Harsh and others (2002), White and Dixon (2002), and Malla (2002), the surface area of imogolite is as much as 100 times greater than that of kaolinite and 40 percent greater than that of vermiculite. This important property is directly related to both the high water-holding capacity and chemical reactivity of these minerals.

Chemical Properties

Soil Reaction

The majority of andic soil horizons of the region are moderately to slightly acid. Approximately 70 percent of the horizons examined have pH values between 5.6 and 6.5, with an average pH of 6.02 (fig. 5). This pH range is generally suitable for plant growth, as many nutrients are present in plant-available forms within this range and the potential for aluminum toxicity is low (Brady and Weil 2004).

Cation/Anion Exchange

One of the important features of soils formed in volcanic ash is the variable charge associated with the colloidal fraction. Variable charge, also sometimes referred to as pH-dependent charge, means that the net surface charge depends

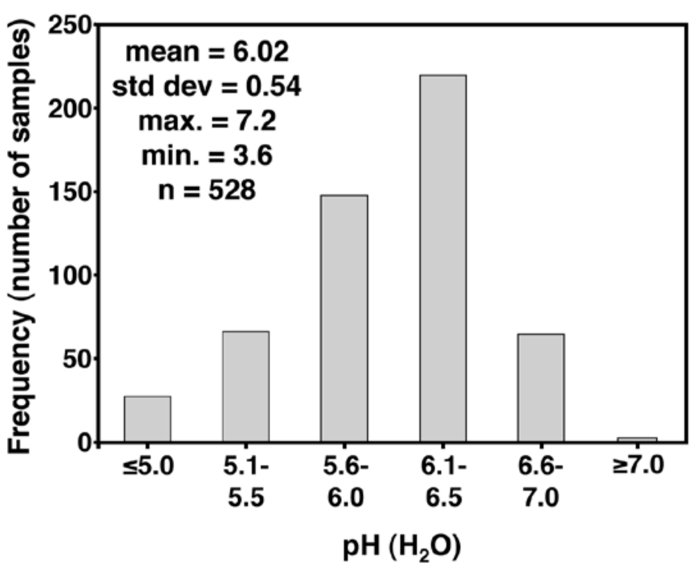

Figure 5—Soil pH data for ash-cap soil horizons from the Inland Pacific Northwest region.

on the pH of the soil solution (Soil Science Society of America 2001). It is this net surface charge that determines the cation exchange capacity (CEC) of a soil and its ability to retain and exchange nutrient cations such as Ca^{2+}, Mg^{2+}, and K^{+}. The CEC of andic soils decreases with decreasing pH, and may in fact, be quite low at the acidic pH values that characterize many forest soils. Moreover, some andic soils may have substantial anion exchange capacity (AEC) at acidic field pH values (Kimble and others 2000), influencing the retention of ions such as chloride and nitrate. Although PO_4^{2-} and SO_4^{2-} ions are sorbed through anion exchange, fixation of these ions (described below) is much greater than this exchange reaction.

The effect of variable surface charge is illustrated by CEC and base cation data from ash-cap soils across the region. Table 1 shows CEC values determined for 515 horizons using three procedures. The lowest values are for effective cation exchange capacity (ECEC), where the CEC is determined at the pH of the soil. The highest values are for CEC determined at pH 8.2 ($CEC_{pH\ 8.2}$), which is considerably higher than the soil pH of the region. Although this latter method overestimates the CEC that exists in the field, the difference in ECEC and $CEC_{pH\ 8.2}$ values illustrates the potential variable charge that exists in these soils. On average, $CEC_{pH\ 8.2}$ values are approximately four times greater than ECEC values.

Table 1—Exchange properties of andic soil horizons of the Inland Northwest Region. Adapted from McDaniel and others (2005).

	Ca^{2+}	Mg^{2+}	K^{+}	Base saturation[1]	ECEC[2]	$CEC_{pH\ 7}$	$CEC_{pH\ 8.2}$
	- - - - *($cmol_c$/kg)*		- - - -	*(%)*	- - - - - - - - *($cmol_c$/kg)*		- - - - - - - -
Average	7.2	1.3	0.8	46.0	6.5	19.1	26.4
n	515	515	514	514	113	515	513
Std. deviation	8.7	2.0	0.7	26.6	5.4	11.3	13.6
Minimum	0	0	0	1	0.5	3.4	7.0
Maximum	88.2	24.0	9.1	100	46.7	101.0	126.2

Another important characteristic of ash-cap soils is their ability to strongly adsorb and immobilize plant-available forms of P and S. This process, known as fixation, results in low concentrations of PO_4^{2-} and SO_4^{2-} in soil solution and available for plant use (fig. 6). The ability to fix PO_4^{2-} results from the strong attraction between PO_4^{2-} and the edges of allophane, imogolite, and ferrihydrite, and there are probably several sorption mechanisms involved (Wada 1989). High PO_4^{2-} sorption is one of the characteristics used to define andic soil properties in Soil Taxonomy and andic horizons in WRB.

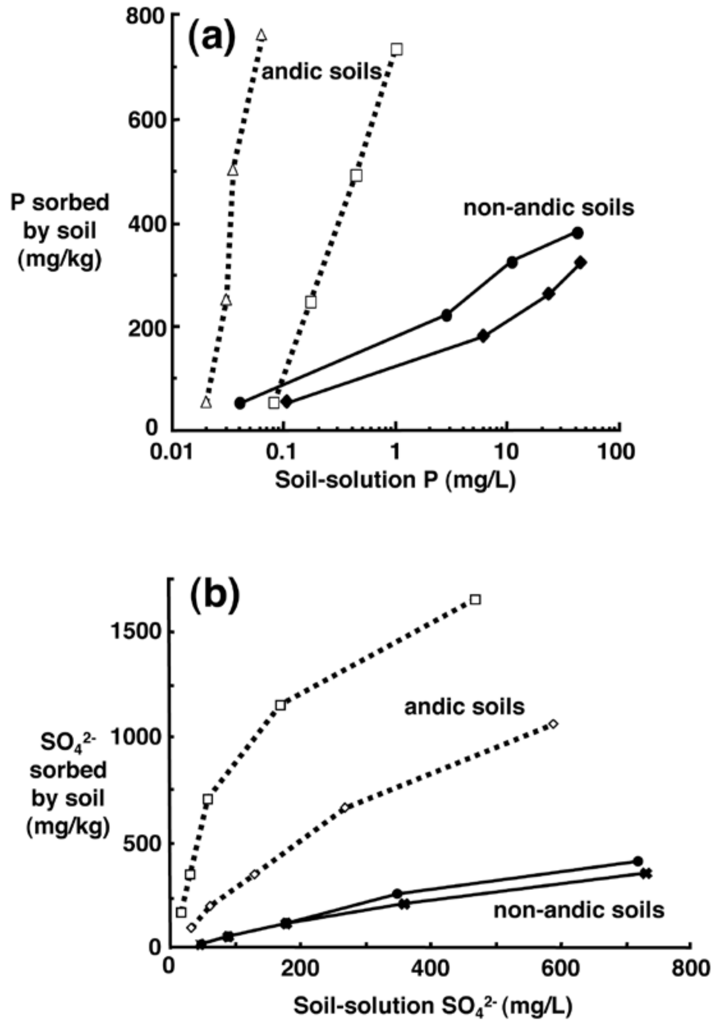

Figure 6—Sorption isotherms for (a) phosphorus additions (adapted from Jones and others 1979), and (b) sulfate additions (adapted from Kimsey and others 2005). Data points represent the proportions of sorbed (plant unavailable) and soluble (plant available) forms with additions of increasing quantities of phosphorus and sulfate.

Allophanic and Non-allophanic Andisols

Because of the range in characteristics of volcanic ash-cap soils, a relatively simple classification scheme has been devised that recognizes these differences from a management perspective. This system classifies soils as either allophanic or non-allophanic (Nanzyo and others 1993a; Dahlgren and others 2004). Allophanic Andisols are those that are dominated by inorganic weathering products such as allophane and imogolite. In contrast, organically bound complexes are much more important in non-allophanic Andisols. Properties of these two classes of ash-derived soils are summarized in table 2. In general, non-allophanic soils present more management challenges. These soils have several properties that may inhibit plant growth — greater acidity and greater potential for Al^{3+} toxicity

Table 2—Comparison of properties of allophanic and non-allophanic Andisols (adapted from Dahlgren and others 2004; Nanzyo and others 1993a).

Property	Allophanic	Non-allophanic
pH	slightly to moderately acid	strongly acid
Dominant mineralogy	allophane/imogolite	Al-interlayered 2:1 layer silicates and Al-organic complexes
Organic matter content	moderate	moderate to high
Al toxicity	rare	common
Compaction potential	slight	moderate

are two of the most important. Most of the soils in the Inland Northwest region are classified as allophanic (McDaniel and others 2005). However, research has shown that shifts from allophanic to non-allophanic properties and vice versa can occur relatively quickly with changes in vegetation. An example of this from northern Idaho is described in the following section.

Response to Management

Erosion

The scientific literature contains sometimes-contradictory information about susceptibility of ash-cap soils to erosion. Soils formed in volcanic ash are typically described as having strong resistance to erosion, largely as a function of stable aggregation and high infiltration rates (Nanzyo and others 1993b; Dahlgren and others 2004). However, because of their low bulk density they may be very susceptible to wind and water erosion when vegetative cover is removed (Kimble and others 2000; Arnalds and others 2001). In the Inland Northwest region, maintenance of forest cover, including both canopy and litter layers, has been an important factor in the retention of Mazama ash caps over the millennia since deposition (McDaniel and others 2005). These factors suggest that erodibility of volcanic ash caps is related to degree of disturbance; disturbance that destroys or removes canopy and litter layers will likely lead to severe erosion.

Compaction

Perhaps one of the best-documented responses of ash-cap soils to land-use activities is compaction. As described earlier, andic soils are defined in part by a bulk density of $\leq$0.90 g/cm^3. Numerous studies have shown significant increases in ash-cap bulk density as a result of timber harvest trafficking. In the Blue Mountains of eastern Oregon and Washington, average bulk density increased from 0.669 g cm^{-3} in unharvested areas to 0.725 g cm^{-3} in harvested areas, representing an average increase of ~9 percent (Geist and others 1989). However, larger bulk density increases were associated with skid trails and landings. Similarly, Cullen and others (1991) reported significant increases in ash-cap bulk density in moderately and severely trafficked areas as compared to non-harvested controls. In addition, they were able to quantify changes in soil hydrologic properties accompanying bulk density increases. Water content at relatively low soil moisture tensions decreased significantly in trafficked areas compared to the controls (Cullen and others 1991) (fig. 7a). One-hour infiltration decreased as well, with values decreasing from 38.5 cm in the control to 7.3 cm in the severely trafficked areas (Cullen and others 1991).

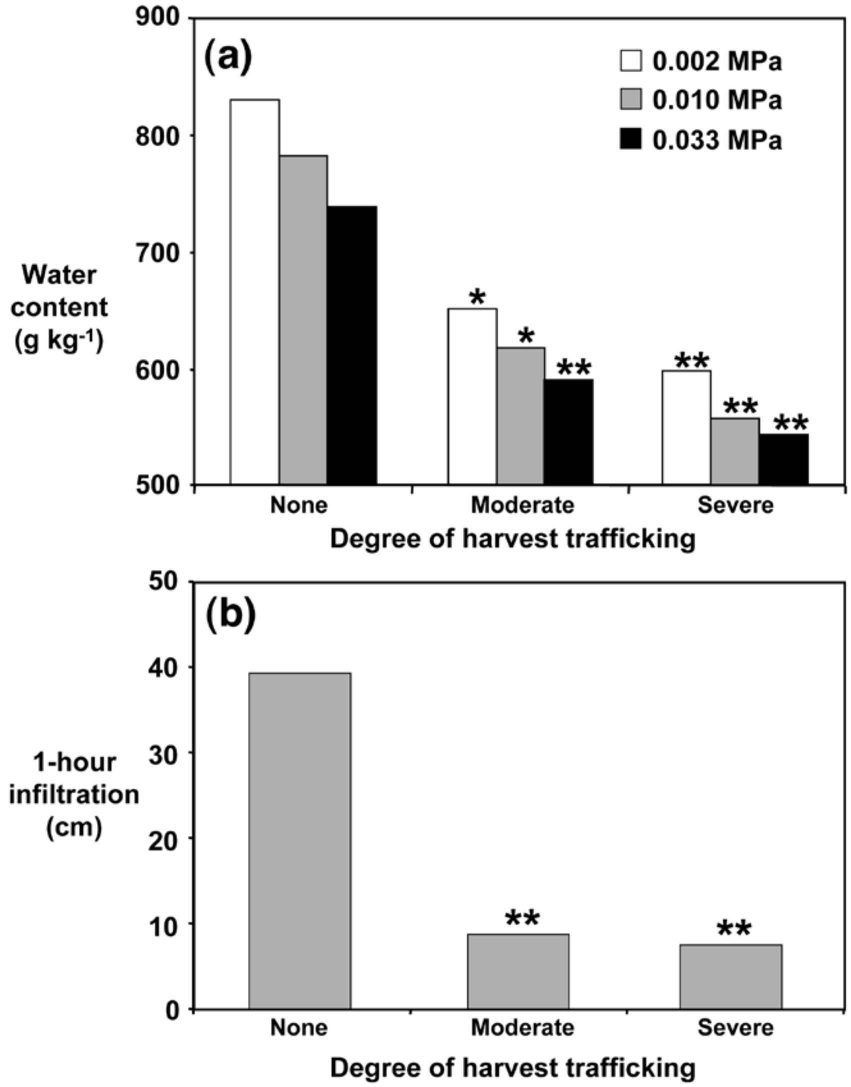

Figure 7—Changes in (a) water content of ash-cap soils due to timber harvest trafficking, and (b) 1-hour infiltration in ash-cap soils due to timber harvest trafficking. *, ** indicate values that differ from the untrafficked controls at the 0.01 and 0.05 significance levels, respectively. Data are adapted from Cullen and others (1991).

Chemical/Mineralogical Changes

Work by Johnson-Maynard and others (1997) in northern Idaho suggests that development of non-allophanic properties accompanies establishment of bracken fern communities after clearcutting in as little as 30 years and may contribute to the observed lack of timber regeneration. This subject is discussed in more detail by Ferguson and others (this proceedings). Recent literature suggests that this mineralogical conversion is not irreversible. Takahashi and others (2006) reported that additions of lime to non-allophanic soils will raise pH and reduce the active forms of Al^{3+}, thereby representing a potential reclamation strategy.

Knowledge Gaps

Two major questions related to the properties and management of ash-cap soils in the Inland Pacific Northwest region remain. The first question is: *How much ash is there and where is it?* This seems like a basic question, yet it is one for which a good answer does not currently exist. The National Cooperative Soil Survey program has produced in ~1:24,000-scale soil surveys for parts of the region, and these provide sufficient detail to assess the extent and spatial distribution of ash-cap soils. However, much of the forested land area where ash-cap soils are found has not been subject to this type of soil mapping. As a result, detailed information about the quantities and spatial distribution of ash across the region is often lacking, poorly documented, and/or not readily accessible. Development of models that predict ash cap depth and distribution will likely be greatly enhanced by new technologies in remote sensing. However, in the absence of more detailed mapping or predictive models, a test such as the NaF pH measurement can provide a quick and easy indicator of ash-cap soils. An NaF pH value $\geq$9.4 generally indicates the presence of weathered volcanic ash (Fieldes and Perrott 1966; Wilson and others 2002) and serves as a guideline for identifying ash-cap soils.

A second question is: *What is the relationship between ash-cap soil properties and soil performance?* The majority of research to date has focused on measurement of ash-cap properties rather than performance. For example, compaction of ash-cap soils has been well documented, but compacted bulk densities are typically well within the range considered to be acceptable for other mineral soils. So with regard to performance, does an ash cap with bulk density 1.1 g cm^3 behave differently than a soil without an ash cap having the same bulk density? An answer to this question will require a better understanding of the changes in pore size and connectivity that occur with compaction in ash-cap soils. Efforts should be focused on determining critical thresholds in andic soil properties at which tree growth and the hydrologic performance will be adversely affected. Long-term studies will be needed to address these issues, and successful management will ultimately require an understanding of the mechanisms involved.

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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.

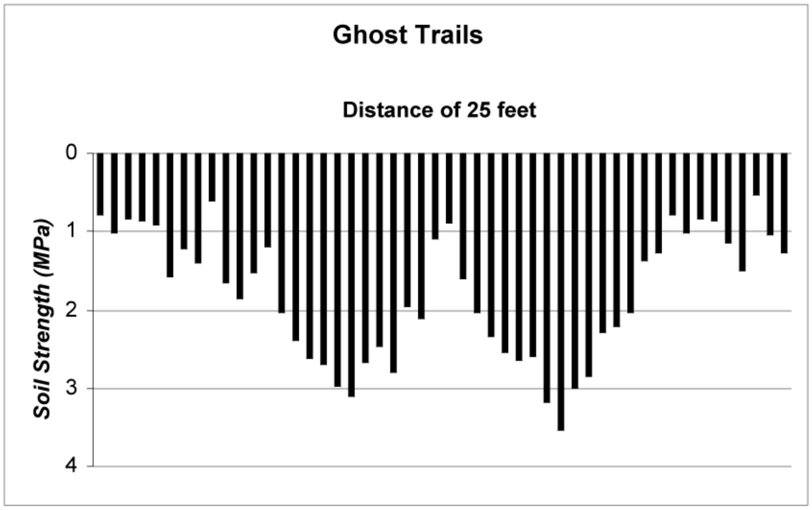

Figure 1—Average soil resistance measured for the 10 to 25 cm soil depth. Measurements were made perpendicular to the harvester ghost trails.

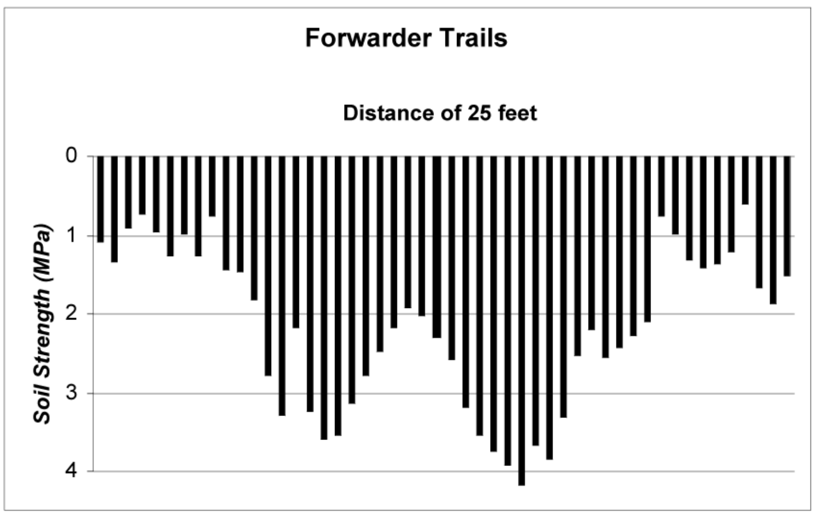

Figure 2—Average soil resistance measured for the 10 to 25 cm soil depth. Measurements were made perpendicular to the harvester forwarder trails.

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

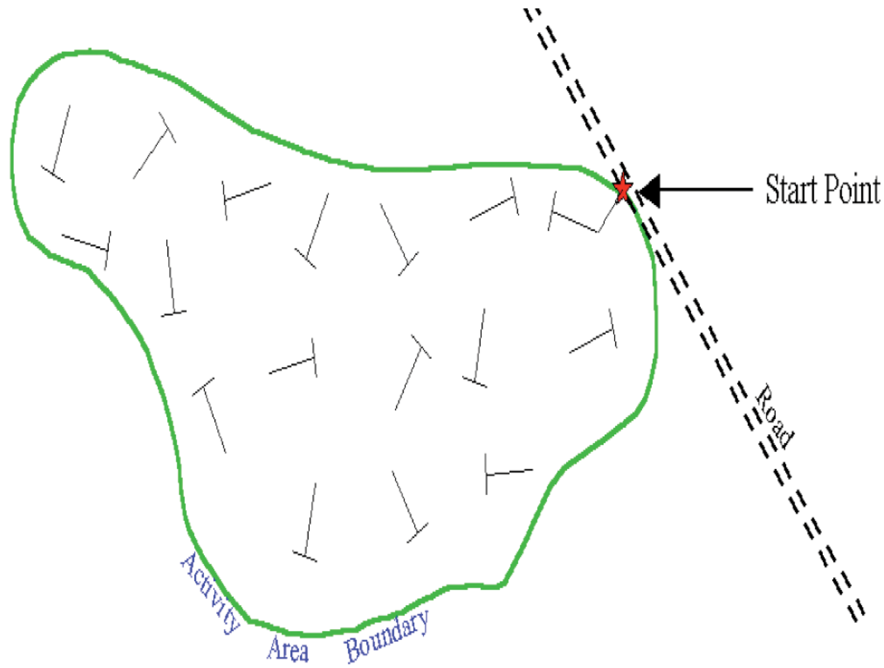

Figure 3—Example of a pre-established grid (randomly oriented) with transects oriented along random azimuths.

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.

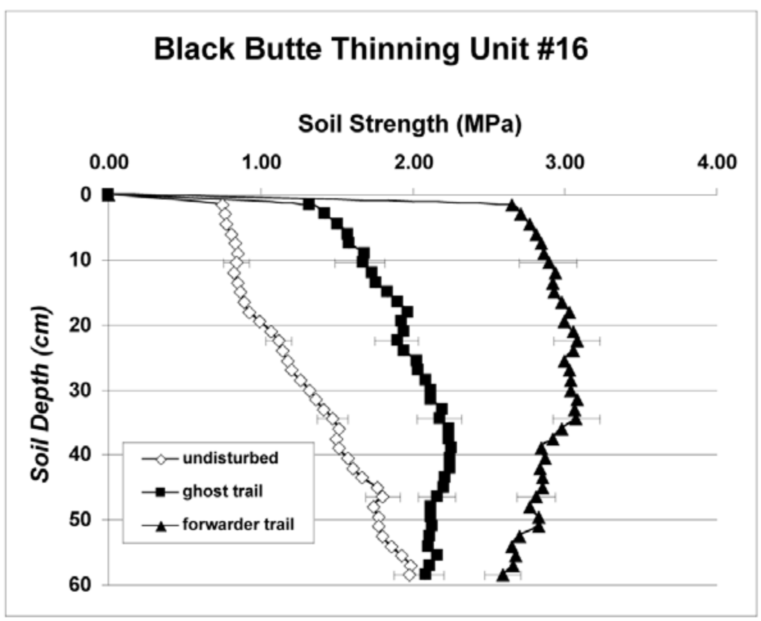

Figure 4—Soil strength measured in the spring of 2005 for different soil disturbance classes. Horizontal bars indicate one standard error. n = 30.

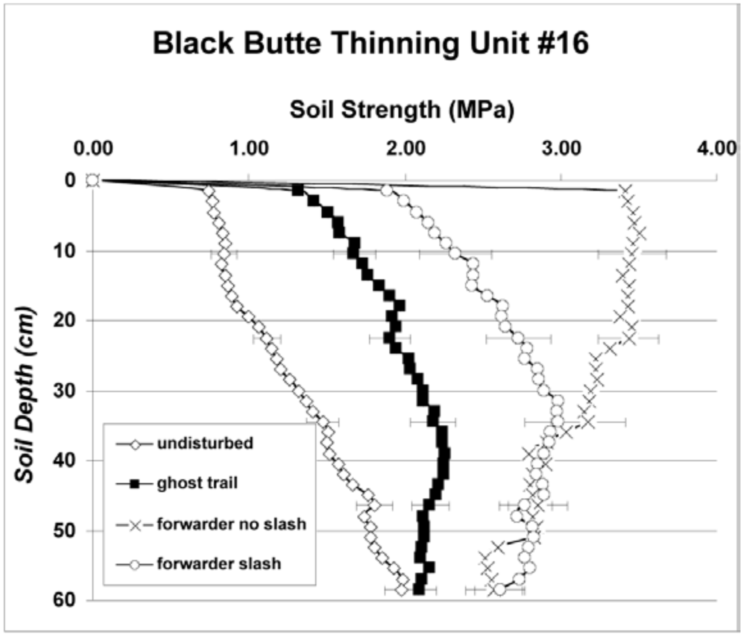

Figure 5—Soil strength measured in the spring of 2005 for different soil disturbance classes with measurements on harvester forwarder trails separated depending upon whether or not slash was present. Horizontal bars indicate one standard error. n = 30 (undisturbed and ghost trails)
n = 15 (forwarder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

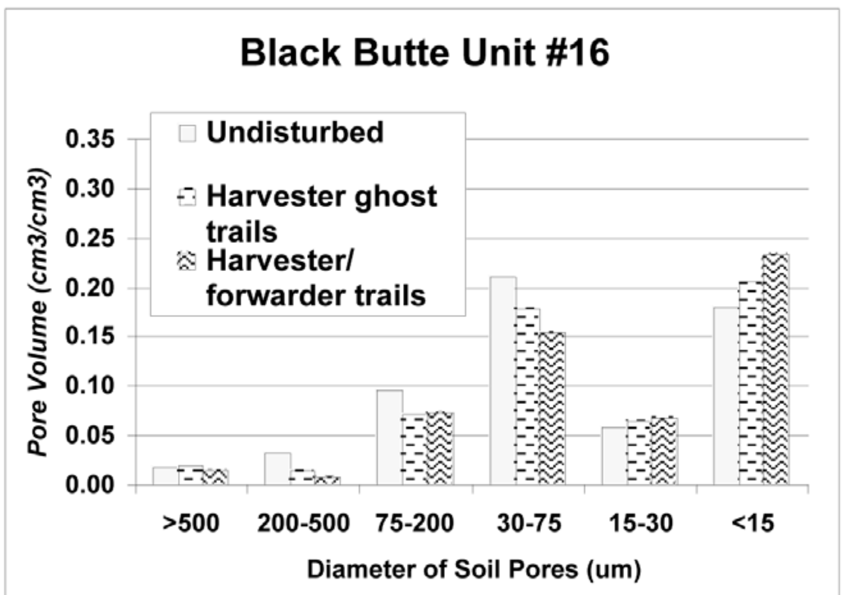

Figure 6—Shift in soil pore size distributions for different soil disturbance classes following soil compaction.

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.

Past Activities and Their Consequences on Ash-cap Soils

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

Leonard R. Johnson, Debbie Page-Dumroese and Han-Sup Han

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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).

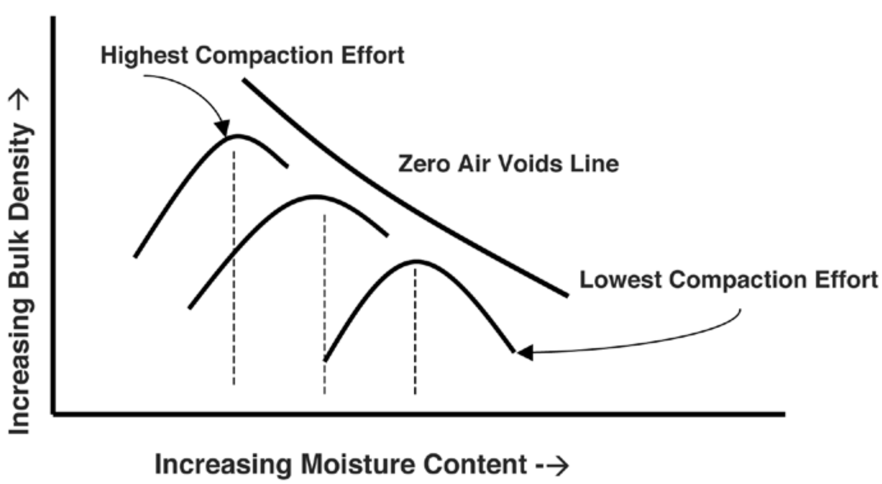

Figure 1—General relationships between moisture content, compaction effort and maximum bulk density.

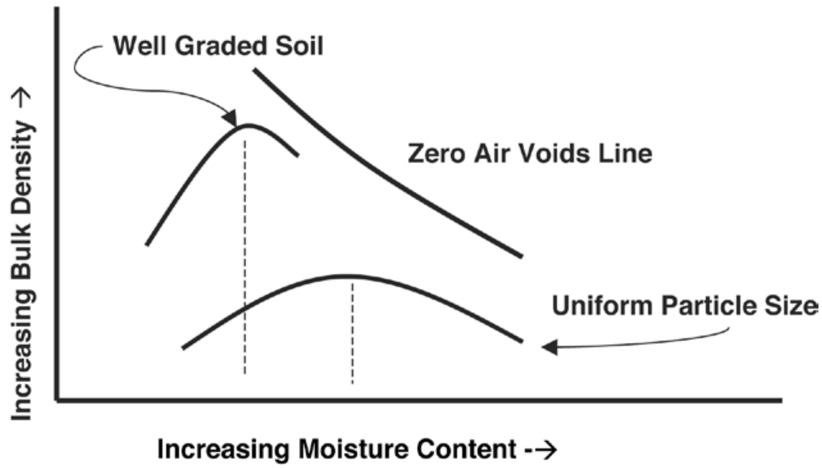

Figure 2—General relationships of optimum moisture content and maximum bulk density for well graded and uniform textured soils.

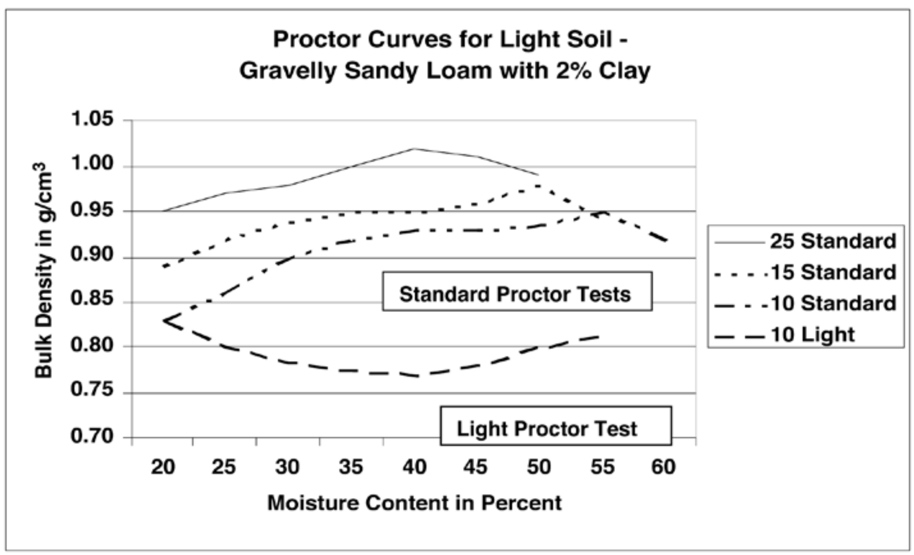

Figure 3—Proctor test results on light soil gravelly sandy loam soil with initial bulk density near 0.70 g/cm^3 (Mg/m^3) and 2% clay content adapted from Froehlich and others (1980).

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.

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Runoff and Erosion Effects after Prescribed Fire and Wildfire on Volcanic Ash-Cap Soils

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Abstract

After prescribed burns at three locations and one wildfire, rainfall simulations studies were completed to compare postfire runoff rates and sediment yields on ash-cap soil in conifer forest regions of northern Idaho and western Montana. The measured fire effects were differentiated by burn severity (unburned, low, moderate, and high).

Results indicate that this dry, undisturbed ash-cap soil exhibits high runoff rates and is naturally water repellent at the surface. However, the unburned, undisturbed ash-cap soil is not highly erodible due the protective duff layer on the surface. When ash-cap soil was exposed to prolonged soil heating (high severity burn), surface water repellency was destroyed and a strong water repellent layer occurred a few centimeters beneath the soil surface. With the simulated rainfall, the non-water repellent surface layer became saturated; thus making the soil above the water repellent layer highly erodible—especially during high intensity rainfall.

Keywords: water repellent soils, rainfall simulation, burn severity, runoff, erosion.

Introduction

Fire is a natural and an important part of disturbance regime for forest ecosystems and many landscapes are well-adapted to this natural fire cycle. Wildfire suppression has dominated forest management for the past century and has interfered with these natural fire regimes causing unnatural accumulations of forest fuels. Although managed forests burn less frequently than the unmanaged forests, the wildfires that do occur are larger and more severe than in the past, causing more severe and long-lasting effects. Fire effects on forest soil may include fire-induced soil water repellency, reduced infiltration rates, increased overland flow, and increased peak flow, which often result in increased water and sediment yields.

Burn Severity

Burn severity, a qualitative measure of the effects of fire on site resources, is a useful concept for comparing fires (Hartford and Frandsen 1992; Ryan and Noste 1983). A range of fire and postfire conditions, such as fire intensity, fire duration, crown consumption, soil color, and proportion of litter remaining, are typically used to classify burned areas into discrete classes of high, moderate, or low burn severity. Although some aspects of burn severity can be quantified, no single number can be determined to measure 'resource impact'.

The component of burn severity that results in the most damage to soils is fire duration, because duration generally determines the temperature and depth of soil heating. Ryan and Noste (1983) created a burn severity classification system (expanded by Jain (2004)) that estimates the amount of soil heating that likely occurred during the fire based on postfire litter amounts and mineral soil coloration. Because it is specific to soil, the Ryan and Noste (1983) definition of burn severity was used to evaluate burn severity at research sites discussed in this paper.

Water Repellency

Naturally occurring water repellent soils occur in every continent and have different infiltration properties than wettable soils (Letey 2005). Fire creates or enhances water repellency in soils (Doerr and others 2000). As surface vegetation is burned and the soil is heated, organic matter in and on the soil is volatilized, and a significant fraction of these vaporized organic compounds move from the surface into the soil profile (DeBano and others 1976). These aliphatic hydrocarbon vapors condense on soil particles in the cooler layers beneath the surface to form a water repellent layer. This water repellent layer is generally within the top 5 cm of the soil profile, non-continuous, and roughly parallel to the surface (Clothier and others 2000; DeBano 2000). In general, coarse soils (low clay content) are more susceptible to becoming water repellent than finer soils (high clay content) due to the lower specific surface area of coarse soil particles. However, when water repellency is established in fine-grained soils, it can be equally or more severe than in a coarse-textured soil (Doerr and others 2000; Robichaud and Hungerford 2000).

Fire-induced soil water repellency has high temporal and spatial variability (Letey 2005). The degree and depth of postfire water repellency is related to soil heating during the fire, which, because of its dependence on antecedent soil moisture, forest floor thickness, burn duration, postfire smoldering, etc., is highly variable. Fire-induced soil water repellency has been found to vary both in the horizontal and the vertical directions at the 1 cm scale (Hallett and others 2004; Gerke and others 2001). Fire-induced water repellency is most often detected at 1 to 3 cm below the surface (Huffmann and others 2001). In addition, soil water repellency is transient and is related to soil moisture. Generally, both natural and fire-induced soil water repellency is lost during long wet periods and is re-established upon drying, causing short-term or seasonal variations (Robichaud and Hungerford 2000). Fire-induced soil water repellency is temporary because the hydrophobic substances responsible for water repellency are slightly water-soluble and slowly dissolve such that water repellent soil conditions are broken up or washed away within several years after the fire.

Infiltration

In water repellent soils, water may move through a wettable surface layer, and upon reaching a water repellent layer, flow laterally below the surface (DeBano 1981). Given the spatial variability of water repellency, water may flow preferentially, via columns, or 'fingers,' through the less water repellent areas forming an uneven wetting front (Ritsema and Dekker 1994, 1995). Infiltration on water repellent soils is also dependent on the type and distribution of plants over the surface (Shakesby and others 2000). Some plants, such as chaparral, decrease infiltration by adding hydrophobic compounds to the soil directly under the canopy (DeBano 1981). Conversely, infiltration can be enhanced by root channels and macropores (remaining after roots decay or burn) that can act as pathways for infiltrating water through water repellent layers (Meeuwig 1971; Sevink and others 1989; Burch and others 1989; Shakesby and others 2000).

Overland Flow and Erosion

Overland flow and soil erosion rates are dependent on a range of inter-related factors that include rainfall (e.g., amount, intensity, duration), soil (e.g., erodibility, particle size, pore size, bulk density, water repellency), topography (e.g., slope, aspect), and biotic (e.g., vegetation, ground cover, animal use, natural and human disturbances). Because of the reduction in infiltration capacity in water repellent soils, postfire increases in overland flow and erosion are often attributed to fire-induced water repellency (Doerr and others 2000). However, it is difficult to determine the proportion of postfire increased erosion that can be attributed to soil water repellency. Fire can also increase the erodibility of soil through reduction of protective ground cover and soil organic matter, sealing of soil pores, loss of water storage capacity in the litter and duff, loss of soil moisture, break down soil aggregates, and reduction of soil particle size (DeBano and others 1998). Thus, the contribution of soil water repellency on total postfire erosion is often difficult to separate from other fire impacts.

Caution must be used when extrapolating measurements of overland flow from small plots to determine the potential runoff on the hillslope- or catchment-scale where differential flow patterns may have significantly more effect (Shakesby and others 2000; Imeson and others 1992). After a Eucalyptus forest fire in Australia, Prosser and Williams (1998) found that small plots produced greater runoff and sediment transfer than was observed at the hillslope catchment outlet. The lack of spatial contiguity in soil water repellency and the existence of differential infiltration flow patterns may create scattered 'sink' areas across a hillside where water infiltrates and, as a result, does not reach the base of a catchment as overland flow (Imeson and others 1992; Prosser and Williams 1998).

Study Objectives

Small plot rain simulation data from three prescribed burns (northern Idaho) and one wildfire (western Montana) are used to compare fire effects on runoff and erosion of ash-cap soils. The two studies (prescribed fire study and the wildfire study) had common site characteristics (conifer forested environments and ash-cap soil types) and test procedures (rainfall simulation), which facilitated the comparison of first year postfire data from the four fires to: 1) examine fire-induced and natural ash-cap soil water repellency; 2) compare runoff rates; and 3) compare sediment concentrations and sediment yields.

Methods

Prescribed Fire

Site Description—The prescribed fire study was conducted in the Fernan Ranger District, Idaho Panhandle National Forest in the Coeur d'Alene Mountains (48°15′ N, 116°15′ W). Study plots were located between 950 to 1500 m elevation on 14 to 46 percent slopes. The predominant soil type is Typic Vitrandepts, a silt loam derived from volcanic ash-influenced loess 28 to 45 cm thick, over an Eutirc Glossoboralfs, a mixed loamy-skeletal formed from Precambrian Belt rock. Average annual precipitation is 34 inches with about one third of that falling as snow in the winter months (Abramovich and others 1998). Vegetation of the area is typical of the western hemlock/queencup beadlily (*Tsuga heterophylla/Clintonia uniflora*) habitat type (Cooper and others 1991).

Ignition of the first harvested unit was in the spring on April 25 (Bumble Bee). Ignition of the second burn occurred in the fall two years later on September 30 (Buckskin I). The third harvest unit was ignited in the summer on August 25 (Buckskin II). For each of the three prescribed burns, a helitorch-ignited strip headfire was started at the top of the slope with fire strips placed about every 30-40 m down the slope. Ignition was generally very rapid, and the entire unit ignited within 30 min.

Plots—Before each prescribed fire, six paired 1-m^2 plots were systematically selected in the study areas to represent the average fuel condition and average slope, with one plot designated for rainfall simulation and the other for soil temperature measurements. Four steel pins were installed flush with the forest floor surface in each plot to estimate forest floor consumption. In the temperature-measurement plots, these forest floor pins were located near thermocouples. Temperatures during the fire were recorded with eight chromel-alumel thermocouples located at the litter surface, in the humus, at the humus-mineral soil interface, and in the mineral soil at 1, 2, 4, 8, and 10 cm below the interface. Temperatures during the burn were first recorded when the surface temperature reached 80 °C and continued every minute thereafter for 36 h. Immediately before burning, samples of the woody fuels, forest floor, and mineral soil were collected to determine moisture content.

On each of the rainfall simulation plots, a four-sided sheet metal frame was installed. Three frame sides were 15 cm tall and installed with 5 cm inserted into the mineral soil, and the fourth, downslope side of the frame was 5 cm tall and inserted fully into the soil (no extension above the surface of the soil) allowing runoff and sediment to leave the plot.

Rain Simulation—Within days of the prescribed fire, a 30-min rain simulation was conducted at the existing soil moisture condition as determined from a composite soil sample was taken near the edge of the plot frame. The simulated rainfall was applied to each plot using a USDA-Forest Service modified Purdue-type oscillating nozzle rainfall simulator with specifications as described by Meyer and Harmon (1979). The rainfall simulator produced an average rainfall intensity of 38 mm h^{-1} for the Bumble Bee (spring 92) burn site. After the Bumble Bee simulations, the simulated rainfall intensity was increased to ensure that the rainfall rate exceeded the infiltration capacity of the soil. Rainfall intensity was 100 mm h^{-1} for the Buckskin I (autumn 94) and Buckskin II (summer 95) burn sites. Seven rain gauges located around the 1 m^2 plots verified the rainfall amount.

A covered trough at the lower end of each plot conducted runoff (water and sediment) through a pipe fitted with a valve that allowed for timed volume sampling. The samples were manually collected in 1000 ml bottles at 1-min intervals. At the end of the simulation run, any sediment remaining in the trough was washed into a sample bottle. All runoff samples were weighed and oven-dried to determine runoff rates and sediment concentrations.

Wildfire Study

Site Description—The wildfire study was conducted in the Bitterroot National Forest (46°4′ N, 114°0′ W) of western Montana where, in the summer of 2000, lightning strikes ignited the Bitterroot Complex Fires. These fires burned 101,000 ha—40 percent at high burn severity as determined by postfire appearance (USDA 2000). The predominant soil is derived from volcanic ash over highly weathered granite and is classified as a sandy skeletal Andic-Dystrocryept. The mean elevation is approximately 1,950 meters with slopes ranging from 25 to 55 percent and dominantly west-southwestern aspects. Vegetation of the area is typical of the subalpine fir/menziesii (*Abies lasiocarpa/Menziesia ferruginea* h.t.) forest habitat type.

Plots—Within an area of high burn severity, four study sites were selected based on comparable slope, aspect, and ground cover characteristics. On each of the four sites, 15 plots of 0.5 m^2 were randomly located and delineated by a four-sided sheet metal frame as previously described. Approximately 3 km north of the burned study area, three unburned sites were selected such that the slope, aspect, and soil type were comparable to the burned area sites and, in addition, the vegetative characteristics were comparable among the unburned study sites. In each of the three unburned sites, 7 plots of 0.5 m^2 were randomly located and defined by the installation of sheet metal plot frames as described above.

Directly adjacent to each plot frame, water repellency was measured using the water drop penetration time (WDPT) adapted from DeBano (1981). Eight water drops were placed on an exposed surface of the mineral soil and the time to infiltrate into the soil is observed. The degree of water repellency is determined by the length of time the water drop sits on the soil without being absorbed: 0 to 5 sec = none; 6 to 60 sec = slight; 61 to 180 sec = moderate; 181 to 300 or more = severe. The maximum observation time was limited to 5 minutes. If the water drops infiltrated in less than 5 seconds, the test was repeated at 1 cm depth below the surface. This process was repeated at 1 cm increments to a maximum depth of 5 cm.

Near the edge of the plot frame, a composite soil sample was taken to assess soil moisture. Ground cover within each plot was determined.

Rainfall Simulation—Within days after the fire was contained, a simulated rainfall event with a mean rainfall intensity of 100 mm h^{-1} was applied to each of the 102 plots for 60 min using the USDA-Forest Service and the USDA-Agricultural

Research Service oscillating-arm rainfall simulators with specifications as described by Meyer and Harmon (1979). Data from the first 30 minutes of each simulation were used for comparisons and analysis. During the rainfall simulation, samples of runoff and sediment were collected through a covered trough at the downslope edge of each plot as described for the prescribed burns above. The samples were manually collected at 1-min intervals for the first 14 min, then at 2-min intervals for the remainder of the 60-min run. All runoff samples were weighed and oven-dried to determine runoff volume for each interval, total runoff volume, sediment concentrations.

Analytical Methods

The data from the Bumble Bee prescribed fire site were not included in the statistical analysis because the rainfall application rate of 38 mm h^{-1} was much less than 100 mm h^{-1} rainfall application rate applied at all other sites. The total runoff and dry suspended sediment weight were calculated for the first 29 to 30 min of the first simulation for the Buckskin I and II sites and for the first 29 to 31 min of the year 2000 simulations at the Bitterroot sites. Runoff and suspended sediment were normalized by area to account for the different plot sizes. Runoff ratios are total runoff (mm) divided by total rainfall applied (mm) for each simulation; the rainfall is adjusted for the plot size.

Results and Discussion

Burn Severity

Varied antecedent conditions for the three prescribed burns resulted in differential soil heating and a range of fire effects on the soil. Bumble Bee, a spring burn, had the highest pre-fire soil and duff moisture contents (61 to 69 percent and 125 percent, respectively) and the lowest mineral soil temperatures (20 to 80 °C) and proportion of duff consumed (28 percent) during the fire (table 1). Bumble Bee was a low burn severity fire. Buckskin I was burned in the fall with the driest conditions of the three prescribed burns (table 1) and was classified moderate burn severity. Buckskin II, a summer burn, had slightly higher pre-burn fuel and soil moisture conditions than Buckskin I and was also classified moderate burn severity (table 1). The study areas within the Bitterroot Complex Fire area were in unburned and high burn severity areas. These four fires on ash-cap soils provided four burn severity conditions—unburned (Bitterroot), low burn severity (Bumble Bee), moderate burn severity (Buckskin I and II), and high burn severity (Bitterroot).

Moisture Content and Water Repellency

Soil moistures immediately prior to the rainfall simulations were higher in the prescribed fire sites than the wildfire sites (table 2), but probably not high enough to change the soil water repellency response (Robichaud and Hungerford 2000). Soil water repellency was directly assessed in the Bitterroot study, where both burned and unburned soils had strong water repellent responses at different depths. The unburned soil was severely water repellent at the surface while the burned soil

Table 1—Measured conditions before, during, and after three prescribed burns in northern Idaho.

Pre-prescribed Burn			
Fuel and soil moisture contents and weather conditions	**Bumble Bee**	**Buckskin I**	**Buckskin II**
Fine fuels (0-76 mm) (%)	20	9	10
Large fuels (77-300 mm) (%)	41	11	28
Litter (%)	64	13	11
Humus (%)	125	45	48
Soil 0-2 cm (%)	69	40	49
Soil 2-5 cm (%)	61	29	40
Ambient temperature (oC)	22	20	18
Wind speed (kph)	8-15	2-8	0-11
Relative humidity (%)	15	30	57
Prescribed Burn			
Maximum soil temperatures (°C)	**Bumble Bee**	**Buckskin I**	**Buckskin II**
Mineral soil surface	20-80	40-300	90-260
1 cm below min. soil surface	40-70	40-270	70-120
2 cm below min. soil surface	20-60	40-80	60-80
Post-prescribed Burn			
Organic material remaining (%)	**Bumble Bee**	**Buckskin I**	**Buckskin II**
Fine fuels	12	5	0
Duff	72	27	38

Table 2—Pre-rainfall simulation mean ground cover and gravimetric soil moisture content by location.

Locations	Ground cover	Gravimetric soil water content
	- - - - - - - - - - - - *(%)*	- - - - - - - - - - -
Unburned Bitterroot	100	15
Bumble Bee	100	29
Buckskin II	98	25
Buckskin I	70	30
Burned Bitterroot	10	17

had a water repellent layer at 1 to 2 cm below the surface (fig. 1). The creation of a fire-induced water repellent layer has been observed by other researchers (e.g., McNabb and others 1989; Brock and DeBano 1990; Scott and Van Wyk 1990; Doerr and others 2000). However, the high burn severity fire appeared to destroy the natural surface water repellency, and create a water repellent layer at depth. Doerr and others (in press) observed the same affect after wildfires in eucalyptus forests in Australia.

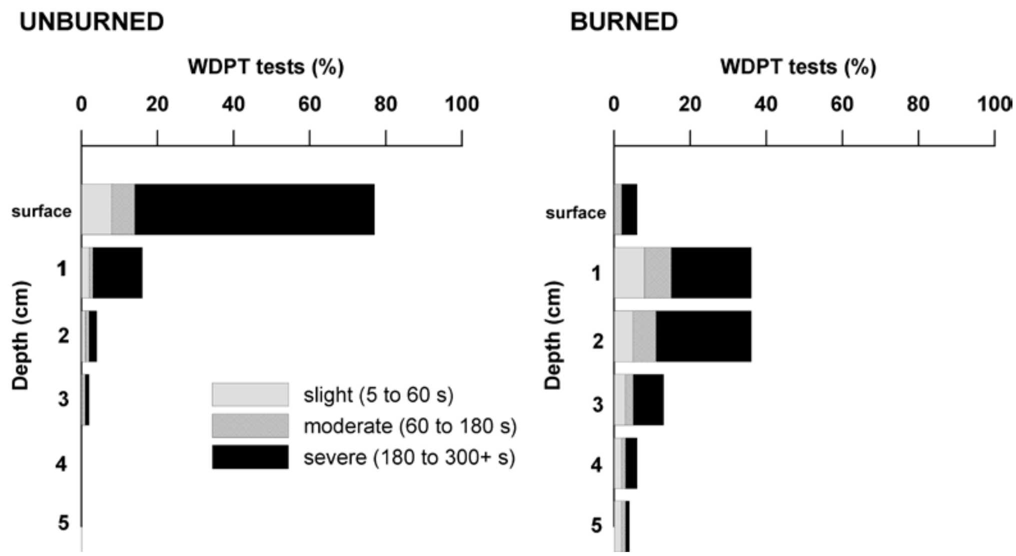

Figure 1—On the Unburned- and Burned-Bitterroot wildfire sites, the portion of water repellent soil, as measured by the Water Drop Penetration Time (WDPT) tests, are indicated for the soil surface and 1, 2, 3, 4, and 5 cm depths. The shading/hatching within each bar indicate the severity of the measured water repellency.

Runoff

The highest runoff ratio rates (fig. 2) and mean runoff amounts (33 and 32 mm) and runoff ratios (0.71 and 0.67) were measured on the high and moderate severity burn sites—Bitterroot-burned and Buckskin I, respectively (table 3). The unburned-Bitterroot sites and the moderate burn severity Buckskin II site had similar runoff ratio rates (fig. 2) and mean runoff amounts (26 and 24 mm) and runoff ratios (0.54 and 0.53) (table 3). This unexpectedly large runoff response in the unburned-Bitterroot sites is likely due to the short time frame of the simulation and the resistance to wetting of the dry organic duff material as well as the naturally water repellent dry surface soil. The Bumble Bee prescribed burn site had low runoff ratio rates (fig. 2) and a low mean runoff amount (4.7 mm) and runoff ratio (0.12) (table 3). However, these data are not directly comparable to the other sites as the lower rainfall application rate may not have exceeded the infiltration capacity of the soil.

Sediment Concentrations and Yields

Sediment concentrations and mean sediment yields generally increased with increasing burn severity (fig. 3 and table 3). Sediment concentrations in the rain simulation runoff tended to peak in the first 5 min, rapidly decrease during the second 5 min, and slowly decrease during the remaining 20 minutes of the simulation (fig. 3). The unburned-Bitterroot sites and the Bumble Bee site (low burn severity) had the lowest concentrations, peaking at 7 and 4 g L^{-1}, respectively and decreasing to less than 1 g L^{-1} at 30 min (fig. 3). These concentrations resulted in mean sediment yields of 0.027 and 0.0091 kg m^{-2}, respectively (table 3). The lower rainfall application rate on the Bumble Bee site probably had little affect on mean sediment yield (table 3) due to the high ground cover remaining after

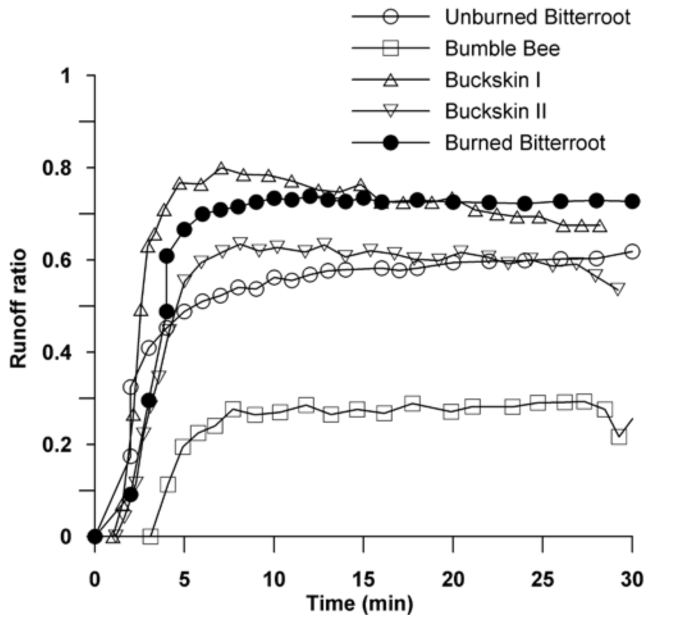

Figure 2—The runoff ratio (runoff / rainfall) rate for all study sites are plotted. The Bumble Bee sites received a lower amount of rainfall as compared to other sites.

Table 3—Mean runoff, runoff ratio, and suspended sediment yield by location. Standard errors are in parentheses. Different letters within a column indicate significant differences at α=0.05. Comparative statistics do not include the Bumble Bee data due to the lower applied rainfall at that site.

Location	Disturbance type	n	Runoff	Runoff ratio	Sediment yield
			(mm)		*(kg m^{-2})*
Unburned-Bitterroot	Undisturbed	21	26 (1.8) a	0.54 (0.032) a	0.027 (0.039) a
Bumble Bee	Prescribed fire	4	4.7 (1.4)	0.26 (0.043)	0.0091 (0.0028)
Buckskin II	Prescribed fire	6	24 (2.5) a	0.53 (0.049) a	0.26 (0.90) ab
Buckskin I	Prescribed fire	6	32 (1.3) ab	0.67 (0.19) ab	0.50 (0.80) ab
Burned-Bitterroot	Wildfire	60	33 (0.60) b	0.71 (0.12) b	0.85 (0.61) b

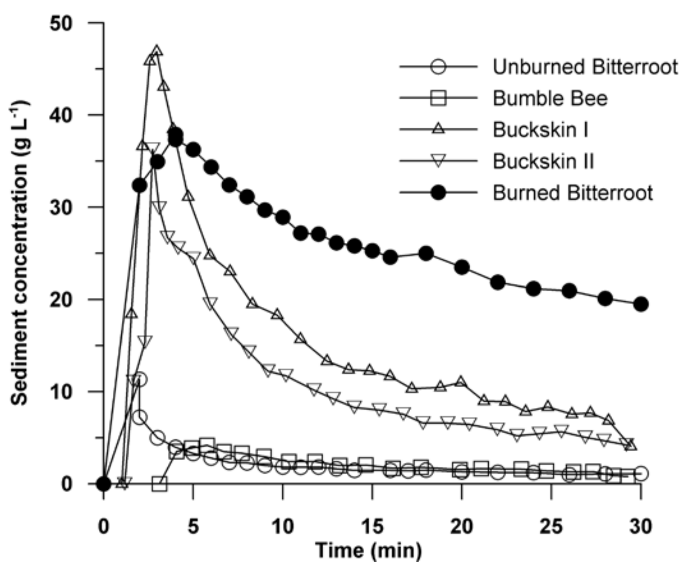

Figure 3—The sediment concentration rate for all study sites are plotted. The Bumble Bee sites received a lower amount of and less intense rainfall as compared to other sites.

the spring burn (table 2). The Buckskin I and II, both moderate burns, peaked at 47 and 36 g L^{-1}, respectively and decreased to about 1 g L^{-1} at 30 min. (fig. 3), resulting in mean sediment yields of 0.50 and 0.26 kg m^{-2}, respectively (table 3). The high severity burned-Bitterroot sites peaked at 38 g L^{-1}, and remained higher than any of the other sites through out most of the 30 min simulation, and decreased to 20 g L^{-1} at 30 min. (fig. 3), resulting in a 0.85 kg m^{-2} mean sediment yield, an order of magnitude greater than the unburned-Bitterroot sites (table 3). The higher sediment yields for the wildfire sites reflect the higher consumption of organic material during a wildfire (longer fire duration and higher soil temperatures) as compared to a prescribed fire. This difference in fires is reflected in the postfire, pre-rainfall mean ground covers, with the Burned-Bitterroot sites having 10 percent ground cover and the Buckskin I and Buckskin II sites having 70 percent and 98 percent, respectively (table 2).

Conclusions

A strong natural soil water repellency was detected at the surface of the mineral soil in the unburned, undisturbed ash-cap soil with low soil moisture content. The high burn severity wildfire appeared to destroy the surface water repellency, and cause a strong water repellent layer to develop 1 to 2 cm below the surface of the mineral soil. Soil water repellency, at the surface or slightly below the surface, increased runoff; however, below-surface water repellency results in a much larger sediment response than surface water repellency. When there is fire-induced, below-surface soil water repellency, rainfall is readily absorbed by the non-repellent surface soil (0 to 1-2 cm) which becomes saturated down to the more resistant water repellent layer. This saturated surface layer is easily detached and entrained within the subsequent overland flow. Additionally, fine roots that bind the surface soil together were likely partially consumed during the fire, making soil particles vulnerable to detachment.

Even in steep forest environments with dry conditions (i.e., severe surface water repellency), the undisturbed, unburned site with its intact duff layer was not highly erodible, despite high runoff rates. During the 30 min of high intensity rainfall, the dry duff did not absorb much water and the rainfall flowed through the duff layer and atop the water repellent mineral soil to the outlet of the plots. Consequently, the runoff rates for the unburned-Bitterroot sites were similar to those found on the moderate burn severity Buckskin II site. However, the sediment concentrations and sediment yields were less than the Buckskin II due to the protective layer of duff material. The Bumble Bee low severity prescribed fire also had minimal sediment response because of the charred, but intact, duff remaining after the fire. The fire effects on sediment concentrations and sediment yields increased with increasing burn severity.

Management Implications

Ash-cap soils are known as highly productive forest soils, and protecting this soil resource is an important land management consideration. Prescribed fires should be ignited when duff moisture content will prevent total consumption of the protective duff layer. Ash-cap soils burned at high severity are highly erodible and postfire rehabilitation decisions should take into account the potential postfire hydrological and sediment response from potential rain events.

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Management Alternatives for Ash-cap Soils

Volcanic Ash Soils: Sustainable Soil Management Practices, With Examples of Harvest Effects and Root Disease Trends

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Abstract

Sustainability protocols recognize forest soil disturbance as an important issue at national and international levels. At regional levels continual monitoring and testing of standards, practices, and effects are necessary for successful implementation of sustainable soil management. Volcanic ash-cap soils are affected by soil disturbance and changes to soil properties influence ecosystem responses such as productivity and hydrologic function. Soil disturbance from timber harvesting, reforestation, or stand tending is mainly a result of moving equipment and trees. Compaction and organic matter removal are of primary concern. The severity and extent of disturbance depend on the harvest system, soil and climatic conditions. Ash-cap soils can be susceptible to disturbance and schemes to predict compaction, displacement and erosion hazards are useful for planning forest management operations. On-site effects range from permanent loss of growing sites because of roads, to more subtle changes in soil properties that ultimately influence site productivity. Off-site effects may include erosion and landslides. Soil disturbance during operations should be regulated and monitored to minimize both on- and off-site effects, which can take years or decades to appear. Forest health issues vary on volcanic ash-cap soils. An analysis of Armillaria root disease incidence across the National Forests of the Inland Northwest indicates some potential relationships among root disease, and soil and site factors. The strong relations between presence of susceptible host and development of fungal biomass may be the strongest causal agent, with the soil and site factors supporting the presence of the pathogen and susceptible host. Thicker ash soils of more northerly areas are related to habitat types that historically supported white pine and a higher diversity of less susceptible species. After root disease mortality occurs, these more mesic environments also fill in with other species rapidly, so higher levels of root disease are more difficult to discern. Recommendations are made for soil management and about information needs for soil disturbance and root disease relations.

Key words: volcanic ash-cap soils, forest health, *Armillaria*, root disease, criteria and indicators, organic matter depletion, soil disturbance, soil compaction, sustainability protocols

The Practice of Sustainable Soil Management

Sustainable soil management can be defined as ensuring the biological, chemical and physical integrity of the soil remains for future generations. Sustainability should be addressed throughout all facets of forest management including implementation of individual harvest or stand-tending plans, development of agency or company standards and best management practices (BMPs), and third-party certification. Demonstration of sustainable soil management is promoted through reporting procedures required by applicable sustainability protocols,and by having third-party certification of forest practices and products (Curran and others 2005a).

Sustainability protocols exist at international and national levels. At the international level, the Montreal Process (MP) includes a Working Group on Criteria and Indicators for the Conservation and Sustainable Management of Temperate and Boreal Forests (Montreal Process Working Group 1997). Some countries have developed their own protocols and procedures designed to track and report progress toward meeting requirements of international protocols such as the MP. For example, the Canadian Council of Forest Ministers recently developed revised criteria and indicators for sustainable forest management (CCFM 2003).

Third-party (eco)certification of forest practices and resulting wood products arose in response to sustainability protocols and the greening of the global marketplace. Organizations such as Sustainable Forestry Initiative (American Forest and Paper Association), Canadian Standards Association, Forest Stewardship Council (FSC), and ISO 1400.1 all have documented review processes and procedures for certification. Protecting streams and natural drainage patterns, maintaining slope stability, and regulating soil disturbance are common elements considered. In addition, most require some adaptive management process to ensure continuous improvement of practices on the ground. Compliance with current soil disturbance standards is often used as a proxy for ensuring sustainability; however, a common approach to standards, and validation of the standards through research are important steps that must not be overlooked when these are used as proxies. Some certification schemes also call for more restrictive standards (e.g., FSC in British Columbia calls for lower disturbance levels than Provincial regulations).

At the local level, when managing harvest-effects on soils, tree growth and long-term productivity, soil disturbance from mechanical operations is of most concern. Soil disturbance occurring at time of operations can have negative, positive, or no detectable effect on growth or hydrologic function. Soil disturbance at the time of operations is often an indicator used in regulating long-term productivity and hydrologic effects. This is because in many NA ecosystems, we need at least 10 to 20 years data to draw conclusions about the effects of various practices on growth or hydrologic function. In discussing evidence for long-term productivity changes, Morris and Miller (1994) indicated slow-growing stands require 20 or more years of growth before long-term productivity consequences can be ascertained. Soil disturbance is the proxy that we can observe and regulate at the time of harvesting and site preparation. However, this proxy also needs to be validated and revised over time in an adaptive management process that includes standards, best management practices, monitoring (compliance, effectiveness and validation), further research and strategic direction and revision over time (Curran and others 2005b). A common approach is needed for describing soil disturbance so that results achieved in different areas are comparable (Curran and others 2005c).

Management and Communication Frameworks for Sustainable Soil Management

Just like ecosystem classification schemes (e.g., Braumandl and Curran 1992) in neighboring BC, organizing soil into mappable or otherwise describable units provides an important framework for communicating management experience, research results, and conservation efforts. Detailed soil or land type maps are available for much of the ash-cap soils in the United States, and reconnaissance-level soil mapping is available in southern BC. Maps designate soil units (e.g., soil series in detailed mapping and soil or land type associations in reconnaissance mapping) based on soil-forming factors of parent material, topography, climate and vegetation, all acting over time, which varies due to geologic events like glaciation and volcanic eruptions. As discussed above, soil disturbance can also be classified and we are working towards a common classification there as well.

Perhaps the most useful way of organizing soil units for forest management is a consideration of their risk of damage from soil disturbance. The most common disturbance of concern in forest management is from machine traffic during harvesting, site preparation, or fuel management treatments. The biggest concerns associated with machine traffic are soil compaction, soil displacement, and soil erosion. In addition, slope stability is a concern on steeper and wetter sites. To identify and mitigate the potential for landslides, terrain mapping and/or terrain stability field assessments are used on sites that exceed certain slope gradients or have indicators of potential slope instability.

Determining the soil disturbance hazards on a given site provides a framework for developing harvesting strategies by alerting the prescription developer to the specific soil disturbance concerns on that site. For example, in BC, soil disturbance default standards under the Forest and Range Practices Act (FRPA) permit up to 5 or 10% net disturbance within a cutblock area (excluding permanent access). In the Interior, the trigger for 5% is when one of the key hazards is Very High. A High rating for any hazard is primarily intended to alert the prescription developer and the operational staff of a hazard that may require special treatment to prevent problems (manage and mitigate the hazard). High compaction hazard also results in more equipment traffic disturbance types being "counted"[1] under FRPA disturbance criteria. The soil disturbance hazards also help identify site conditions that are suitable for construction of excavated and bladed trails (skid roads or backspar trails), and/or temporarily exceeding soil disturbance levels and rehabilitating slope hydrology and forest site productivity. The hazards are defined below, including brief discussions of why they are of concern.[2]

Soil Compaction Hazard

Soil compaction is the increase in soil bulk density that results from the rearrangement of soil particles in response to applied external forces. Soil puddling is the destruction of soil structure and the associated loss of macroporosity that

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[1] In BC, the term "counted" is used in reference to soil disturbance to recognize the fact that soil disturbance types or their severity vary with soil sensitivity to disturbance. More disturbance types are of concern on more sensitive soils, and less are of concern on more resilient soils (e.g., sandy soils). The net result is that more disturbance types are "counted" towards the total cumulative allowable limit on more sensitive soils.

[2] Soil degradation hazard rating keys for soil compaction, displacement, and erosion are found in Land Management Handbook 47 (Curran et al. 2000) and the *Forest Practices Code of British Columbia, Hazard Assessment Keys for Evaluating Site Sensitivity to Soil Degrading Processes Guidebook*. **The general BCMOF Web site where these and other FPC information can be located is: http://www.for.gov.bc.ca/ (look under legislation).**

results from working the soil when wet. Organic matter is often incorporated during puddling and because organic matter is lighter than mineral particles, soil bulk density may not increase; however, the other properties described below are still negatively affected. The science and rationale for the BC compaction hazard key are laid out in Carr and others (1991).

Soil moisture content is probably the best determinant of compaction hazard at any given time. In British Columbia, the soil compaction hazard key ranks the potential compaction hazard by grouping soil textures that are most susceptible to structural degradation from compaction and puddling, and are most likely to hold moisture and remain wet for longer periods. The soil compaction hazard key is a tool to help with planning of an operation, while careful monitoring of equipment effects on the soil, and hand tests for soil moisture content are the tools that help guide the operation.

Soil compaction and puddling are of concern in timber harvesting operations because of effects on roots and site water relations. Compacted soils have higher penetration resistance that can impede root growth. Compacted and puddled soils both have lower aeration porosity and lower hydraulic conductivity and infiltration rates; however, in some coarser textured soils, compaction may actually increase water holding capacity (these soils typically have lower compaction hazard ratings).

Lower aeration porosity results in reduced gas exchange that can adversely affect oxygen levels in the soil air; this reduces physiologic function of roots, which in turn can lead to root die off under wetter conditions. Lower hydraulic conductivity and infiltration rates of the compacted or puddled soil can result in increased runoff during rainfall and snowmelt events. This can lead to increased net export of water from a cutblock, which can affect downslope sites, natural drainage features, and other resource values due to erosion and sedimentation. Increased water export also means less water may be stored on site to support tree growth during summer drought. Compacted soils can also remain wetter longer, thereby further affecting seedlings because the soil may be colder and have poor aeration.

Monitoring of traditional spring harvesting on three ash-cap influenced soils in the southern Rocky Mountain Trench near Cranbrook indicated that significant declines in aeration porosity occured when evidence of equipment traffic was visible on the ground (e.g., wheel lugmarks on the soil or slight impressions with track grouser marks) (Utzig and others 1992). These sites were typical Trench soils: silt loam to silty clay loam textured surface soils low in coarse fragments, underlain by denser subsoils with more coarse fragments.

The undisturbed soils had aeration porosity values at or above the threshold recommended by the United States Forest Service (USFS) in some of its policy for the Pacific Northwest (i.e., 15% at 10 J/kg water tension referred to in Boyer 1979). Regardless of the severity of disturbance, aeration porosities were less than 15% (fig. 1). Effects on saturated hydraulic conductivity (i.e., water relations) were similar (fig. 2). Bulk density increased in a similar but opposite trend to the aeration porosity and saturated conductivity, as would be expected. The concern about these effects is how extensive the machine traffic disturbance is on fully mechanized harvesting. On the three sites studied, the combined total of the light ruts, 5-cm ruts, and main trail disturbance ranged from 52 to 64% of the entire cutblock area, with lighter machine disturbance covering from about 30 to over 45% (fig. 3).

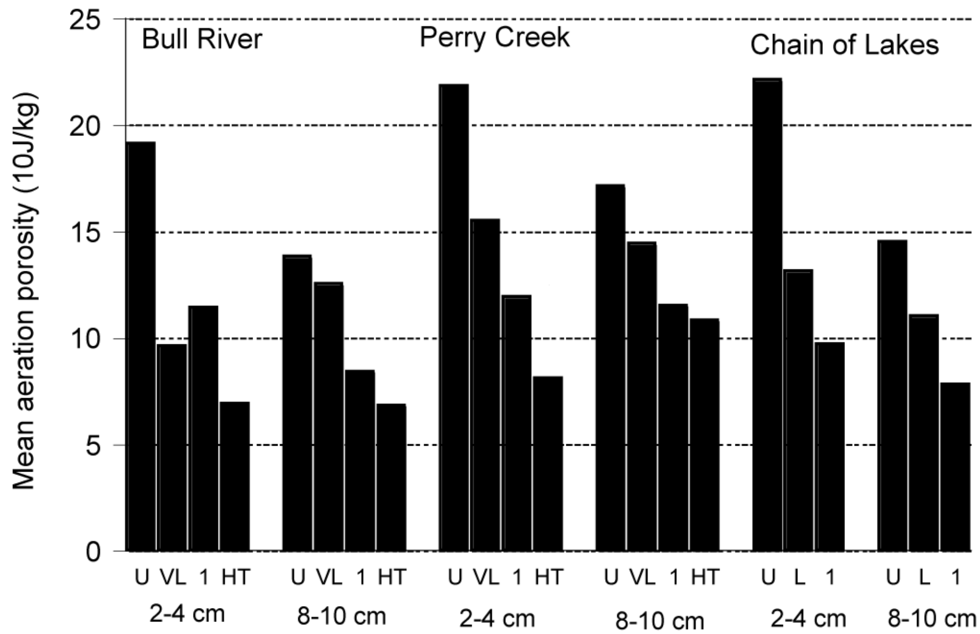


Figure 1—Aeration porosity at 10 J/kg tension for two sample depths at three sites in the southern Rocky Mountain Trench near Cranbrook, BC (Utzig and others 1992). U (undisturbed), VL (very light ruts, <5 cm deep), 1 (ruts 5 cm or deeper), HT (heavy [main] trails).

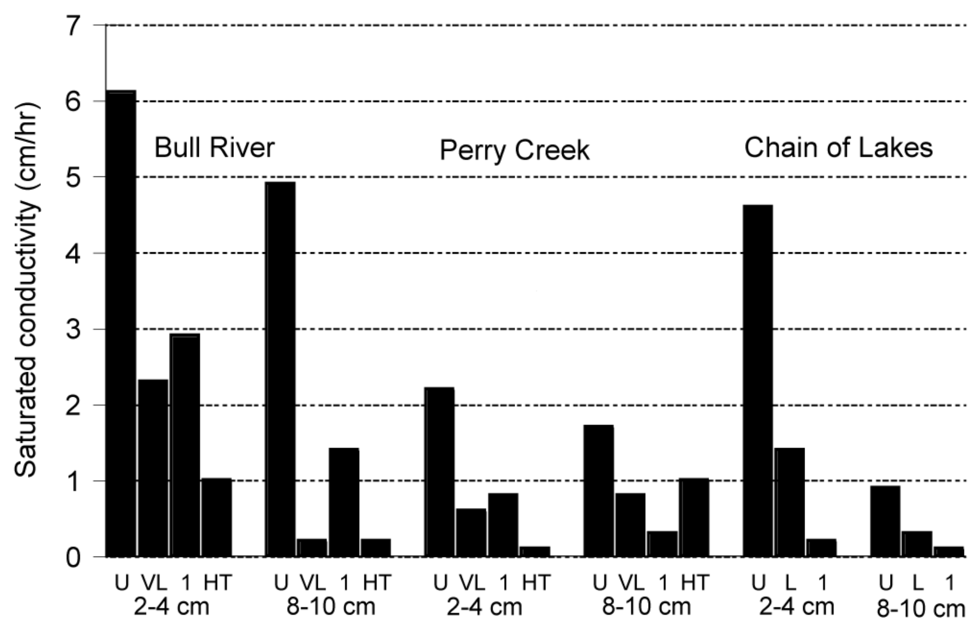


Figure 2—Saturated hydraulic conductivity for two sample depths at three sites in the southern Rocky Mountain Trench near Cranbrook, BC (Utzig and others 1992). U (undisturbed), VL (very light ruts, <5 cm deep), 1 (ruts 5 cm or deeper), HT (heavy [main] trails), from Curran (1999).

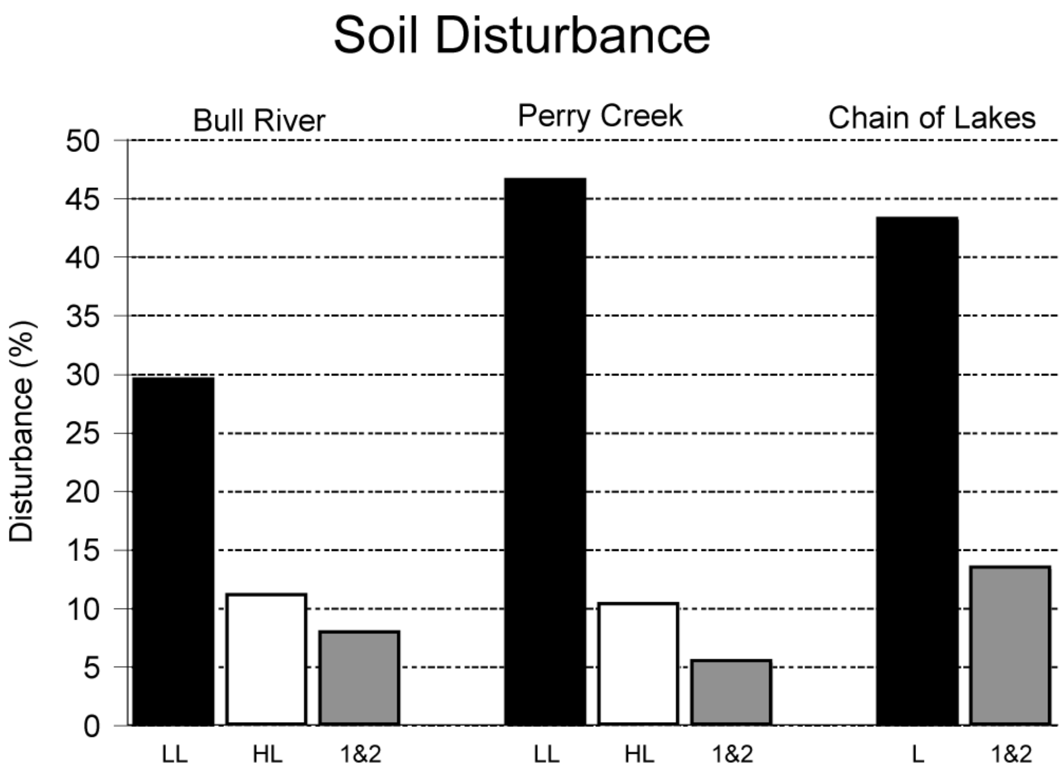


Figure 3—Aerial extent of soil disturbance at three sites in the southern Rocky Mountain Trench near Cranbrook, BC (Utzig and others 1992). LL (very light ruts, <5 cm deep), HL (heavy [main] trails), 1&2 (ruts 5 cm or deeper), and L (very light and heavy, combined) from Curran (1999).

These results are consistent with monitoring studies of nearby sites in northern Washington, Idaho, and Montana (Kuennen and others 1979; Laing and Howes 1988, Svalberg 1979). In the Washington study, based on the literature at the time, Laing and Howes (1988) predicted a "conservative estimate of 35% volume reductions over the next rotation" for detrimentally compacted areas (42% of the cutblock area in their study). On similar sites in Northern Idaho and Montana, Kuennen and others (1979) suggested that changes in soil physical properties resulting from compaction can decrease the ability of trees to compete with pine grass. It is not clear whether these type of effects would be realized on our soils; however, in the absence of long-term data to the contrary, we need to continue to monitor tree growth on these sites. Light compaction is also being studied as part of the North American Long-term Soil Productivity Study (LTSP).

In summary, the implications for site water storage, runoff, and tree growth are of concern when random skidding causes these types of disturbances. It is therefore inferred that, under certain soil conditions (e.g., harvesting under wetter than optimum soil conditions), detrimental compaction can occur before soil disturbance criteria for ruts or trails are reached. Harvesting strategies recommending dispersed skidding traffic need to recognize this risk and "tread lightly." Compaction is a long-lived phenomenon; natural freeze-thaw and wet-dry cycles have not been observed to ameliorate machine-induced compaction at depth. In the ash-cap soil locations, where summer drought is one of the factors most limiting to tree growth, and in the absence of long-term data to the contrary, prevention of widespread "below the FRPA depth limit" compaction is probably the best bet and can be achieved economically.

Soil Displacement Hazard

Soil displacement is the mechanical movement of soil materials by equipment and movement of logs. It involves excavation, scalping, exposure of underlying materials, and burial of fertile surface soils. Three aspects of displacement can produce soil degradation:

- Exposure of unfavourable subsoils, such as dense parent material, gravelly subsoil, and calcareous (high pH) soils.
- Redistribution and loss of nutrients.
- Alteration of slope hydrology, which can lead to hydrologic effects (discussed under compaction, above).

Soil development is often shallow and many of the nutrients that are limiting to tree growth are often biocycled and concentrated in the upper soil horizons throughout the British Columbia Interior. A similar affect occurs on shallow ash-cap soils that overlay less fertile subsoils. Most of the soil nutrients are often concentrated in the forest floor and top 20 cm of mineral soil (table 1). Therefore, we don't want to displace this fertile topsoil away from seedlings, or reduce the rooting volume of these vital topsoil layers.

Table 1—Typical nutrient distribution in British Columbia Interior soils.

	Nutrients in kg ha^{-1} (% of total)		
Soil layer	**Nitrogen**	**Phosphorus**	**Potassium**
Forest floor	1450 (44%)	112 (82%)	224 (73%)
0-20 cm	1050	13	56
20-40 cm	820	8	25
Total	3320	133	305

Forest Floor Displacement Hazard

Forest floor displacement is the mechanical movement of the upper organic materials by equipment and movement of logs. It involves excavation, scalping, mineral soil exposure, and burial of the forest floor. The effects of forest floor displacement range from beneficial to detrimental, depending on site factors (e.g. mineral soil characteristics) and how far the forest floor is displaced from the seedlings.

Forest floors typically represent a major component of the nutrient capital on a forest site. In the British Columbia Interior, it is not uncommon for the forest floor to contain over 50% of the soil nitrogen and 80% of the phosphorus (table 1). Given that many Interior sites are considered nitrogen deficient, conservation of the forest floor is important. On deeper ash-cap or older, richer soils, much of the nutrient capital occurs in the mineral topsoil and forest floor displacement may be of less concern.

Two aspects of forest floor displacement can produce soil degradation:

- Redistribution and loss of nutrients (e.g. chemically bound and unavailable in the mineral soil, and accelerated decomposition of organic matter).
- Exposure of unfavourable rooting medium.

A review of forest floor displacement and implications for tree growth in the Southern British Columbia Interior found that while there were a few trends in soil nutrient levels, it was difficult to relate displacement to any negative effects on tree growth (Hickling 1997). In cooperation with Pope and Talbot Ltd., we installed long-term monitoring plots on various disturbance types including some associated with stumping (Hickling 1998).

Most forest operations were well below the forest floor displacement limits originally set in the FPC, so determining the forest floor displacement hazard is no longer officially required for harvest planning and permitting. However, use of this hazard interpretation is supported and recommended for planning dispersed skidding on steeper slopes, rehabilitation of soil disturbance, and root rot treatments. Forest floor displacement is also more of a concern on calcareous soils due to the higher pH of the mineral soil

Surface Soil Erosion Hazard

Surface soil erosion is the wearing away of the earth's surface by water and includes splash, rill, and gully erosion. It has on-site impacts (soil loss, nutrient loss, lower productivity) and off-site impacts (water quality, sedimentation, habitat impacts). The surface soil erosion hazard key focuses on on-site erosion and conservation of the fertile topsoil layers near developing seedlings. The science and rationale for the British Columbia key were laid out in Carr and others (1991), and the rating weightings tested in the Nelson Forest Region by Commandeur (1994), resulting in modifications to the final key currently in use. Other assessments may be used for haul road erosion and sediment delivery to streams. Haul roads and landings are of concern because erosion and drainage diversions can lead to sedimentation and stability problems. They require careful layout and attention to erosion hazard on haul roads and minimizing erosion and sedimentation during construction and maintenance.

Defining Soil Disturbance

A technical definition of soil disturbance is any disturbance that changes the physical, chemical, or biological properties of the soil (Lewis and others 1991). It is not always negative. Foresters commonly prescribe purposeful soil disturbance as site preparation for seedling planting and establishment; these disturbance types are often not counted in standards (e.g., under FRPA in British Columbia). By controlling how we harvest a site, we can create more "site preparation" type disturbance and keep most of the potentially detrimental disturbance confined to travel corridors; these main trails may then be rehabilitated after harvesting, as appropriate. Whenever planning soil disturbance, the preservation and restoration of natural drainage patterns should be the primary goal (necessary repetition).

The strategies described in this document strike a balance between "favourable" and "detrimental" disturbance by limiting the amount of "counted" soil disturbance. Regionally applicable soil disturbance standards recognize that some level of disturbance is necessary to permit access to timber. Counted disturbance usually includes main trails and ruts/impressions of certain dimensions, and under some schemes (e.g., FRPA in British Columbia) also include wide or deep gouges into the soil. Those developing and implementing a harvesting strategy need to recognize that on more sensitive sites, disturbance types that "count" may be created more easily and may be counted sooner (e.g., in Interior British Columbia 5-cm ruts and impressions on High and Very High Compaction hazard, as opposed to 15 cm on other soils; when Erosion, Displacement, or Compaction hazards are Very High). On sites with lower hazard ratings, less disturbance categories may be counted.

The actual effect of a given soil disturbance on tree growth will depend on the most growth-limiting factors on a given site and how these factors change over the course of a rotation. In the British Columbia Interior, common growth-limiting factors include: competing vegetation, soil moisture (drought or excess), soil temperature, summer frost, rooting substrate (volume), soil nutritional problems (e.g., calcareous soils), and root rot. The net effect on growth will also depend on whether soil disturbance has introduced a new limitation, such as reduced soil aeration from compaction. Long-term effects could include increased susceptibility to blowdown because of poor rooting in detrimentally disturbed soil.

Regional ecology guides often summarize common growth-limiting factors for various ecosystems (Braumandl and Curran 1992), and a model has been developed for comparing disturbance effects on growth-limiting factors when deciding on site preparation prescriptions (Curran and Johnston 1992; Sachs and others 2004).

Regardless of the actual tree growth effects, a number of soil disturbance types are also of concern because of potential effects on site and slope hydrology and the potential for downslope impacts. On-site hydrology changes are difficult to study but we need to err on the conservative side considering that much of British Columbia is not flat and summer drought is often one of the most growth-limiting factors on many sites (effects on hydrology may confound tree growth on apparently "undisturbed" microsites in tree growth studies). Similar hydrologic concerns have been voiced by other researchers in the local area (Kuennen and others 1979).

Synthesis of Above Knowledge and Principles in Our Forest Practices

Machine-Based Practices

Forest harvest, site preparation, and fuel management treatments are most commonly accomplished through the use of machinery. In the case of timber harvest or fuels, this may occur through aerial, cable, or ground-based equipment. Because ground-based harvesting typically creates the most disturbance, it is discussed below but the principles remain the same for the other methods.

Based on the environmental framework described in the preceding section, a given harvesting strategy should meet the following four requirements:

1. Be site specific and responsive to the soil sensitivities on site and downslope.
2. Offer a reasonable amount of independence from climatic interruptions,.
3. Incorporate rehabilitation, if necessary, to lower disturbance below guidelines.
4. It must instill enough confidence at all levels of approval and operations.

In the 1990s we worked on a number of trials with Industry and District staff, to address concerns about managing harvesting soil disturbance. Trials have addressed tree growth on rehabilitated skid roads (Dykstra and Curran 1999), haul roads (Curran, unpublished data), and landings (Bulmer and Curran 1999a). Memos were circulated and a special publication (Curran 1999) summarized simple field tests developed during operational trials of seasonal harvesting constraints (i.e., "how wet is too wet?" and "how much frost is enough frost?"). Other research trials have been successful in demonstrating the feasibility of rehabilitating soil disturbance (Bulmer and Curran 1999b). Combined, these trials were designed to test tree growth on rehabilitated disturbance and develop strategies to reduce the dependency on weather conditions and reduce shutdown of operations during wetter conditions. Research and practical innovation are still ongoing, and further field guides will be produced as warranted (e.g., we are developing a simpler soil texture key at this time).

Based on industry innovation, practical experience, and research trials, we have identified four key strategies that we feel meet the above criteria:

a) close trail spacing with rehabilitation,
b) closely spaced temporary spur (haul) roads with rehabilitation,
c) combination designated and dispersed (random) skidding, and
d) hoe-chucking, Interior style (i.e., forwarding to wider spaced trails).

These strategies may or may not include fully mechanized harvesting, either with cut-to-length feller-processors and forwarders, or with feller-bunchers and grapple skidders. The strategies also may offer the opportunity to reduce site preparation costs by creating disturbance during the harvesting or rehabilitation phases. Each strategy is described in more detail in Curran (1999). Other harvesting strategies have been described for meeting soil disturbance standards under site conditions in western Washington and Oregon by Heninger and others (1997). Again, the objective is to match equipment capabilities to site sensitivity to disturbance. Ground-based equipment may be restricted to designated trails or allowed to travel overland depending on the soil and climatic conditions.

Studies on ash-cap influenced and similar soils in southern Interior British Columbia have shown that large amounts of soil disturbance can occur during mechanical root removal for root disease management (Quesnel and Curran 2000; Curran, unpublished data). Tree growth responses to these disturbances vary with site growth limiting factors and over time. On two sites on similar climate in southern British Columbia, stump removal treatments had differing effects (fig. 4). On an ash-cap influenced soil at Phoenix, soil disturbance either increased or did not negatively affect tree growth; whereas on a soil on the Gates Creek site that had more clay (12% versus 4%), there was a clear negative trend with tree growth and disturbance severity. The long-term growth trend at the Gates Creek site is interesting as it clearly demonstrates the need for long-term tree growth response data (fig. 5).

Insect and Disease

Some forest insects and pathogens are opportunistic organisms that cause primary damage to stressed host trees. Stress may occur due to soil disturbance effects on tree growing environment, climate change resulting in temperature or moisture stress, other biotic or abiotic environmental factors, or multiple interacting factors. Interacting factors that contribute to pest outbreak are complex. For

Figure 4—Fifteen-year volume of Douglas-fir seedlings growing in different disturbance types on the Canadian Forest Service Gates Creek and Phoenix stumping trial sites in southern British Columbia, which are gravelly sandy loam textured with 12% clay at Gates Creek and 4% clay at Phoenix (Curran and others 2005a adapted from Wass and Senyk 1999).

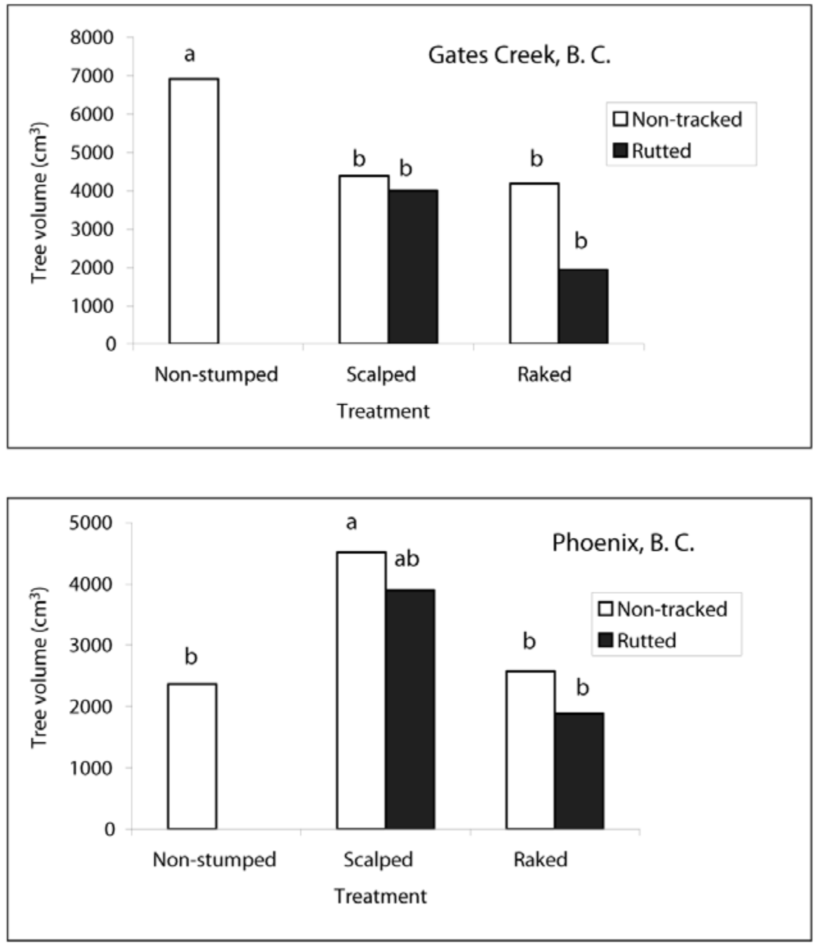
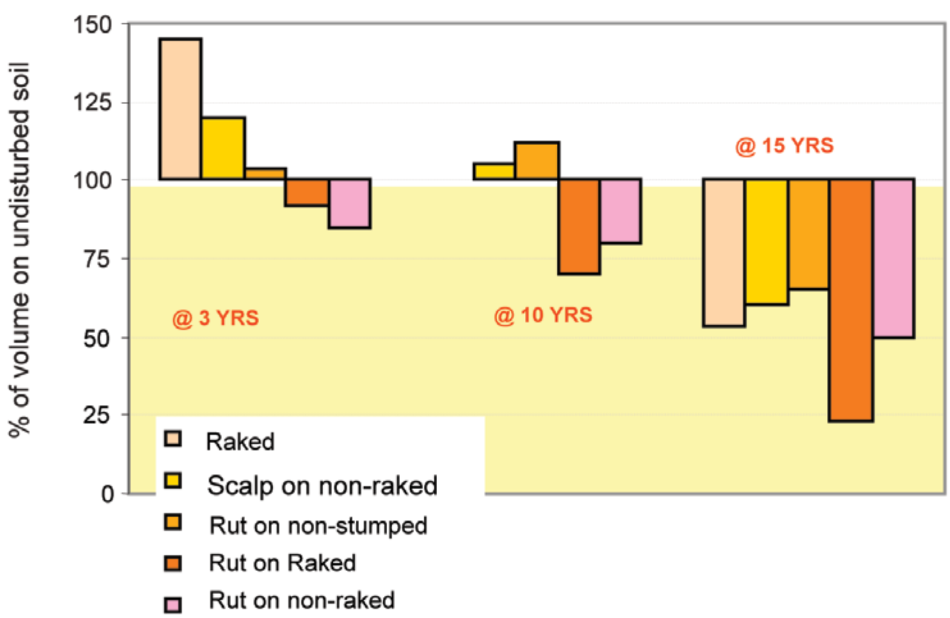


Figure 5—Comparison of relative growth of Douglas-fir on a stump removal trial in southern British Columbia at 3, 10 and 15 years since treatment. All data is relative to the undisturbed condition (Curran and others 2005a adapted from Wass and Senyk 1999).



example, large areas of bark beetle infestations are sometimes attributed to climate change and/or root disease interactions (Partridge and Miller 1972). However, insect attack is also dependent upon inherent dynamics of insect behavior. The following text focuses on root disease organisms in Inland Northwest.

Environmental Factors Affecting the Distribution and Activity of Root Diseases

Biophysical Setting—Armillaria root disease (primarily caused by *Armillaria ostoyae*) and Annosus root disease (caused by *Heterobasidion annonsum*) are widely distributed in western conifer forests. Off-site plantings, wounded trees, and trees growing on compacted soils or in areas with drainage problems are particularly likely to be affected by Armillaria root disease (Goheen and Otrosina 1998; Wiensczyk and others 1997). Douglas-fir dominated stands in northern and central Idaho and northeastern Washington experience substantial mortality from Annosus root disease, especially on dry sites (Schmitt and others 2000). However, in southern interior BC, Morrison and others (2000), found significantly higher rates of *Armillaria* sp. infection on dry sites than moist or wet sites; and once infected, trees on drier sites were less able to resist infection and were more likely to show aboveground symptoms.

Laminated root rot, (caused by *Phellinus weirii*), occurs mainly in hemlock, western red cedar and grand fir habitat types on the Lolo National Forest, but infrequently in Douglas-fir and subalpine fir habitat types, while Armillaria and Annosum root disease are distributed more widely (Byler and others, 1990). Hagle and others (1994) similarly found root disease most severe in grand fir habitat types, and low severity disease ratings occurred most often on Douglas-fir habitat types. Declines in disease severity were noted after 160 years as the more susceptible species died out of the stand. They suggest that grand fir habitat types are most likely to support grand fir and Douglas-fir as seral and climax species, and these are the most susceptible species.

On the Lolo National Forest, Byler and others (1990), found higher probabilities of Armillaria root disease on Douglas-fir habitat types on southerly aspects. Moderate slopes had a higher incidence than either flat or very steep slopes.

Soil Physical Properties—In another study, *Armillaria* spp. infection levels decreased with increasing clay content, which is correlated with moisture-holding ability (Wiensczyk and others, 1997). This is consistent with the hazard rating system of Froelich and others (1977). In the Wiensczyk study, sandy soils were more highly correlated with *Armillaria* spp. activity in black spruce than were silty soils, and as moisture regime increased (based on mottles and gleying), *Armillaria* spp. frequency decreased. This may be due to reduced growth of *Armillaria* rhizomorphs in finer textured and moister soils, or to improved tree vigor. Sand, large soil pores, and high bulk density were also positively correlated with Annosum root disease in loblolly pine plantations (Alexander and others, 1975). It is thought that rapid infiltration in sandy soils allowed easy translocation of root rot spores. Baker and others (1993) also found that low silt in the A horizon was an important predictor of *H. annosum* infection. Blenis and others (1989) also found clay loam to be least favorable for Armillaria root disease and sandy loam the most favorable. The pathogen is known to be sensitive to low levels of oxygen and high levels of carbon dioxide.

Soil Chemical Properties—*Armillaria ostoyae* infection levels were found to increase with increasing phosphorous in the A horizon (Wiensczyk and others 1997). However, phosphorous in ash-cap surface soils is often held in unavailable form and may not locally contribute to infection. Reduced phosphorous may limit tree root elongation, which could reduce the likelihood of underground contact with *A. ostoyae*.

Rishbeth (1951) found *H. annosum* infection rates from stumps to be lower in acid than alkaline soils. He attributes this to competing fungi in more acid soils. Baker and others (1993) found *H. annosum* infection incidence to be lower in acid soils, as did Blenis and others (1989).

Soil Microbiology—Root microflora, such as Actinomycetes and fungi (e.g., *Trichoderma* spp., *Phlebiopsis* spp., *Bjerkandera* spp., *Hypholoma* sp., etc.), can have fungistatic effects on root pathogens (Hagle and Shaw 1991; Holdenreider and Greig 1998; Nelson 1964, 1973;Nelson and Thies 1985, 1986; Raziq 2000). It has been suggested that mixed stands with fewer potential host species, and interruption of succession with shrub and other non-susceptible species reduce *H. annosum* inoculum (Johansson and Marklund, 1980) by supporting enhanced populations of Actinomycetes. Chapman and Xiao (2000) confirmed the ability of a saprophytic fungus, *Hypholoma fasciculare*, to out-compete *A. ostoyae* on a variety of nonliving substrates, such as stumps. Veech and Boyce (1964) also found higher levels of soil fungi, Actinomycetes, and bacteria than in areas of higher *H. annosum* infection. Greig (1962) also found development of *Annosum* root disease to be lower in plantations established on areas formerly occupied by hardwoods than on second-rotation conifer plantations. This "diversity of soil microflora" is hypothesized to be more typical of natural disturbance regimes than stands affected by fire suppression and emphasis on one or two susceptible crop species, like grand fir and Douglas-fir.

Ectomycorrhizal fungi associated with tree roots are known to be important for moisture and nutrient relationships of the host tree (Harvey and others 1986, 1987). Decayed soil wood promotes this association. Root pathogens may interact directly with mycorrhizae so that biomass and energy reserves of all parties are reduced (Graham 2001; Sharma and others 1992), but sometimes pathogen effects on the host tree are reduced (Morin and others 1999). This complex interaction suggests we need to sustain a continuous supply of the organic materials that support healthy mycorrhizal populations.

Relation to Properties of Volcanic Ash—Surface soils formed in volcanic ash tend to be silty in texture, have high porosity, and low bulk density, and low inherent nutrient status, and low nutrient-holding capacity (McDaniel and others 2005). They may adsorb phosphorus and hold it in an unavailable form. Acidity is typically slightly acid to neutral. Tree roots are often concentrated in the volcanic ash layer, suggesting that root contact could be common and distance from stump inoculation point to live root would be short. This would make it easier for infections to spread. High moisture-holding capacity suggests that drought-induced stress during summers would be somewhat mitigated, but that this capacity would be reduced by compaction or displacement. Volcanic ash is highly correlated with grand fir, cedar, hemlock, and subalpine fir habitat series, and to a lesser extent with Douglas-fir.

Management Effects—Fire exclusion, harvest of less susceptible pine and larch, and declines in white pine due to exotic blister rust (*Cronartium ribicola*) have all contributed to the increase in more susceptible Douglas-fir and grand fir, and moisture and nutrient stress, increasing the prevalence of root disease in the range of volcanic ash soils. More studes are needed to determine the effects of partial harvest and soil compaction/displacement on root disease in managed stands.

Climate Change, Root Disease, and Management on Volcanic Ash-cap Soils

Climate change can result in mature trees that are maladapted to their environment, which can increase vulnerability to pathogens (Ayres and Lombardero, 2000), as well as other disturbances like fire or insects. In the Interior Northwest, increasing temperatures and reduced summer moisture (McKenzie and others 2004; Mote and others 2003) increase stress on trees in marginal sites (thin ash-cap, compacted soils), which may make them more susceptible to root diseases. Physiological models to predict how tree defenses would alter with climate change are lacking. Effects of climate change on root disease and competing organisms are not known.

Fire suppression and subsequently more severe fires may increase the rate of root disease by providing more fire-scarred tree wounds as entrance points (Otrosina and Garbelotto 1997). Fire exclusion leading to dominance of susceptible true firs and high levels of root disease would also lead to increased susceptibility to fire and large insect outbreaks. Higher density stands due to fire exclusion could increase the likelihood of belowground spread of the pathogen from tree to tree. Longer periods of high heat and drought could suppress spore germination and stump colonization for longer periods in the summer, although Bendz-Hellgren and Stenlid (1998) found no effect of temperature on stump colonization by *H. annosum*.

Management Opportunities:

- Limit management induced stress by confining soil compaction and displacement to limited areas and rehabilitating them after use.
- Provide connections for species to move in response to changed climatic context (maintaining continuity of species in space, while allowing for movement).
- Use species and density management to allow forest species to use disturbance as stepping stones for migration.
- Introduce and sustain species resistant to root disease.
- Root removal has been proposed to control *Armillaria* root disease (Roth and others 2000), but some studies have concluded that inoculum removal cannot be complete enough to change the dynamics of root disease development (Reaves and others 1993). The associated soil disturbance, particularly in ash-cap soils, is likely to have deleterious physical effects.

The issue of soil restoration to recover suitable moisture and air relationships is complicated by other factors. Soil disturbance associated with roads, skid trails, and precommercial thinning (Hessburg and others 2001) was correlated with incidence of black stain root disease (caused by *Leptographium wageneri*) in southwest Oregon. Alternatively, subsoiling to alleviate soil compaction may result in root damage and dieback of any residual trees, attracting root feeding beetles that carry black stain root disease. Kliejunas and Otrosina (1997) and

Otrosina and others (1996) found higher levels of ergosterol in subsoiled areas, which indicated higher levels of fungal decomposer activity. This was attributed to soil displacement and root severing. This suggests managers should limit the extent of compacted areas as much as possible and avoid subsoiling near trees to avoid both above and below ground damage. Stump removal could have similar effects in adjacent live trees.

Analysis of North Idaho Root Disease Trends in Relation to Soil and Site Factors

Sue Hagle (Pathologist, USDA Forest Service, Region 1) rated stands within randomly selected subcompartments for root disease activity using photo interpretation on a scale of 0 to 9 (Hagle and others 2000). On the three Idaho National Forests (Idaho Panhandle, Clearwater, and Nez Perce) analyzed here, 1,204 plots were available, but 11 of these did not have geologic information and 29 did not have soil survey information. The stand polygons were interacted with geospatial layers including soil survey map units, lithology, mean annual precipitation, elevation, aspect, latitude, longitude, and slope.

Soil survey map units were classified into four classes based on volcanic ash depth:

1: No described volcanic ash influence
2: Thin or mixed ash
3: Andic subgroups
4: Thick ash (Andosols)

Where soil type varied by aspect, aspect was used to refine the ash depth factor.

Geologic groups were developed based on literature describing associations between root disease and rock type (Garrison and Moore 1998; Moore and others 2004). This process was complicated by different scales, notation, and depth of description of available geologic maps. We tried to identify potential strong associations by spatial exploration of root disease activity and geologic formation. Patterns that appeared strong in one area were not consistent in other areas. The resulting groups used are:

2 = Granitics, predominantly Cretaceous, but also Jurassic (292 samples).
3 = Recent metamorphics (younger than Belt Age) (21 samples).
4 = Belt age metamorphics, but not including Belt quartzites described under 11. (666 samples). These were expected to have higher inherent fertility.
5 = Tertiary and more recent sediments (3 samples).
6 = Seven Devils volcanics of Triassic and Permian age (20 samples). These sites were omitted from this analysis because they are thought to be anomalous. They had very high root disease activity ratings. Trends and significance were similar with and without these samples.
7 = Undifferentiated, such as glacial deposits or alluvium (65 samples).
8 = Other volcanics (2 samples).
9 = Limestone no samples.
10 = Belt age sediments no samples.
11 = Belt quartzites (Middle Wallace quartzites, Striped Peak formation, Revett quartzite, and Prichard quartzite (94 samples). These were expected to have the lowest inherent fertility.

Each stand was additionally assigned to a moisture and temperature gradient class after McDonald and others (2000) using the habitat type information associated with each stand polygon:

Understory: Moisture Regime	
No data	0
Dry grass	1
Dry shrub	2
Dry herb	3
Moist herb	4
Wet herb	5
Wet fern	6
Wet shrub	7

Overstory: Temperature Regime	
No data	0
Cold fir	1
Cool fir	2
Cedar hemlock	3
Douglas-fir	4
Ponderosa pine	5
Pinyon juniper	6

The following tables and plots display exploratory analysis of the association of root disease activity (using an 8 class ranking system) and categorical environmental variables. Shown are the median, interquartile range, extremes, and possible outliers. No pattern is apparent for aspect class and root disease ranking,

Root Disease and Ash Depth

Thin or mixed ash is associated with higher incidence of root disease (table 2). Low root disease activity associated with areas of no volcanic ash are usually in very dry steep slopes or poorly drained areas where soils are formed in mixed alluvium.

Soils with no ash influence have significantly lower root disease activity, but Andic soils and Andosols do not differ significantly.

Table 2—Ash-cap depth as related to root disease ranking.

Ash Depth	N	Mean Root Disease Ranking*	95% C.I.
1 – None	25	2.2	1.5-2.9
2 – Thin or mixed	198	3.6	3.3-3.9
3 – Andic	247	3.2	2.9-3.4
4 – Andosol	638	3.0	2.9-3.2

*See Hagle and others (2000) for detailed root disease activity scale.

Geologic Group

No strong trends were noted, however there were some differences among lithologic groups.

Recent metamorphics showed greater root disease activity than in undifferentiated deposits (table 3). The great variability in recent sediments (group 5) suggests a need for further refinement of this class. Belt age metamorphics (group 4) showed relatively low root disease activity, with numerous samples, and were significantly less than granitics, recent metamorphics, and Belt quartzites. Undifferentiated rock types (recent deposits) also showed low root disease activity. The Belt Age quartzites, anticipated to be naturally low in potassium and with high levels of root disease activity, were significantly higher than other Belt metamorphics and undifferentiated rock types, but did not differ from granitics, recent sediments, or recent metamorphics.

Table 3—Influence of geologic group on disease incidence.

Geologic Group	N	Mean Root Disease Ranking*	95% C.I.
2 – Granitics	292	3.5	3.3-3.7
3 – Metamorphics (not Belt Age)	21	3.9	2.8-4.9
4 – Belt Age Metamorphics/not quartzites	666	2.9	2.8-3.0
5 – Tertiary and more recent sediments	3	4.3	.5-8.1
7 – Undifferentiated (recent glacial deposits or alluvium)	65	2.9	2.5-3.3
8 – Other volcanics	2	3.5	NA
11 – Belt quartzites	94	3.5	3.1-3.9

*See Hagle and others (2000) for detailed root disease activity scale.

Root Disease and Forest

The Idaho Panhandle National Forest had the lowest disease ranking, followed by the Clearwater National Forest, and then Nez Perce National Forest (table 4). These differences could be caused by drier soils, changes in geology, soil nutrition, or other inherent site physical, chemical, or biological properties.

Table 4—National Forest and incidence of disease.

National Forest	N	Mean Root Disease Ranking*	95% C.I.
4 – Idaho Panhandle	639	2.7	2.6-2.9
5 – Clearwater	331	3.4	3.2-3.6
17 – Nez Perce	173	4.0	3.7-4.3

*See Hagle and others (2000) for detailed root disease activity scale.

Root Disease and Potential Vegetation (Habitat Type Group)

Potential Vegetation is an indicator of soil moisture and temperature regimes and constrains whether susceptible species are likely to occur as seral or climax on the site. When habitat types (Cooper and others 1991) are grouped according to Jones (2004), it is evident that those habitat types most likely to support susceptible grand fir or Douglas-fir and show higher levels of root disease activity (data not shown). The occurrence and severity of root disease depends strongly on the abundance of a susceptible host. Sites with a longer history of dominance by suitable host species will likely have accrued higher levels of fungal biomass. Drier grand fir and Douglas-fir habitat types, which are more likely to support more ponderosa pine, show lower levels of root disease activity. It is interesting to note that some extremely high values of root disease activity are associated with more moist cedar or western hemlock habitat type groups. It is possible that these sites are capable of very high levels of inoculum where seral white pine has been eliminated for long periods.

Moisture and Temperature Regime

Using the moisture and temperature indices defined by McDonald and others (2000), we compared disease ranking against moisture indicator (understory association) and temperature indicator (overstory series).

Sites with moderately dry moisture regimes (dry shrub) had the highest root disease activity, and differed from dry grass and dry shrub, but not moist herb (table 5). This may be due to the high incidence of susceptible Douglas-fir on these moisture settings.

Sites with moderately warm temperature regimes (Douglas-fir) had the highest root disease activity, and differed significantly from cold fir and ponderosa pine. Cool fir temperature regimes had higher root disease than cold fir, cedar hemlock, and ponderosa pine (table 6). Again, the presence of susceptible host species is highly correlated with these temperature regimes.

Table 5—Root disease ranking as related to understory moisture indicator.

Moisture Regime	N	Mean Root Disease Ranking*	95% C.I.
1 – Dry grass	12	2.2	1.1-3.2
2 – Dry shrub	89	3.4	2.9-3.8
3 – Dry herb	303	2.9	2.7-3.1
4 – Moist herb	734	3.2	3.1-3.3
5 – Wet herb	1	3	NA
6 – Wet fern	1	0	NA
7 – Wet shrub	1	1	NA

*See Hagle and others (2000) for detailed root disease activity scale.

Table 6—Root disease ranking as related to temperature regime.

Temperature Regime	N	Mean Root Disease Ranking*	95% C.I.
1 – Cold fir	366	3.0	2.8-3.2
2 – Cool fir	153	3.6	3.3-3.9
3 – Cedar hemlock	528	3.1	2.9-3.2
4 – Douglas-fir	90	3.5	3.0-3.9
5 – Ponderosa pine	3	1.3	0-4.2

*See Hagle and others (2000) for detailed root disease activity scale.

Association of Root Disease Ranking with Numeric Variables

The most ecologically significant correlations appear to be that root disease activity is positively associated with steep slopes, southerly latitude, westerly longitude, potential for host species (based on habitat type cover tables), and decreasing annual precipitation.

Conclusions

Ash-cap soils are susceptible to disturbance; schemes to predict compaction, displacement, and erosion hazards are useful in forest management application. Whether more or less disturbance should be permitted on ash-cap soils is a controversial topic and it is likely more important to focus on the individual site hazards because ash-cap soils can vary considerably in their state of weathering, texture, depth and inter-mixing with other soil materials. Machine traffic can be managed and as demonstrated in Bulmer and others (this proceedings), and mitigated through rehabilitation in a set of harvest (machine-traffic) strategies that consider site.

Regarding root disease on ash-cap soils, this preliminary coarse-scale investigation suggests some potential relationships among root disease (primarily *Armillaria* in Idaho) and soil and site factors. The strong relationship between presence of susceptible host and development of fungal biomass may be the strongest causal agent, and the soil and site factors promote the presence of the susceptible host.

Thicker ash soils of more northerly areas are related to habitat types that historically supported white pine and a higher diversity of less susceptible species. These more mesic environments also fill in with other species rapidly after root disease mortality occurs, so higher levels of root disease activity are more difficult to discern (Hagle, personal communication, 2006).

Recommendations

Sustainable soil management on ash-cap soils needs to follow protocols developed for all sites whereby an adaptive management / continuous improvement process needs to be supported by research, best management practices, and strategies that include all types of monitoring (compliance, effectiveness and validation).

Development of a common approach to describing soil disturbance and soil disturbance hazards will go a long way toward more effective sharing of management experiences on ash-cap soils.

More work is needed on the long-term effects of cumulative aerial extent of soil disturbance and on soil disturbance categories to refine these and hazard rating systems.

For the root disease work, more site-specific evaluation of soil properties, stand history, and geologic parent materials, both mineralogical composition and weathering state, would help to sort out these relationships.

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Restoring and Enhancing Productivity of Degraded Tephra-Derived Soils

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Abstract

Soil restoration (sometimes termed enhancement) is an important strategy for sustaining the productivity of managed forest landscapes. Tephra-derived soils have unique physical and chemical characteristics that affect their response to disturbance and restoration. A variety of factors reduce forest productivity on degraded soils. Site-specific information on soil physical conditions, organic matter, and nutrient status is required for efficient soil restoration, but only limited research is available to help interpret such information and guide efforts to restore tephra-derived soils. Based on site-specific conditions, reclamation treatments can be identified to control water, till compacted soils, restore organic matter, and revegetate disturbed areas. Successful reclamation investments will often involve simple treatments focusing on low cost options such as decompaction, topsoil replacement, fertilization, and tree planting. Avoiding difficult sites such those in high elevation environments, wet areas or fine textured soils is recommended where possible, as treatments to overcome such problems are likely to be expensive and have uncertain outcomes. Restoration efforts in volcanic terrain likely need to be accompanied by programs to monitor the beneficial effects of treatments on forest productivity, in relation to their costs.

Introduction

Soil restoration (sometimes termed enhancement) is an important strategy for sustaining the productivity of managed forested landscapes (Richardson and others 1999), and ecosystems (Cairns 1999). Restoration techniques play a role as (a) planned activities for improving the efficiency of accessing and harvesting timber while meeting soil conservation goals, or (b) a means to repair unanticipated damage to soils caused by harvesting, or where previous management approaches have been superseded by strategies that reduce the need for soil disturbance, and allow restoration of previously disturbed areas.

Tephra-derived soils have unique physical and chemical characteristics that affect their response to disturbance and restoration. Volcanic materials have undeveloped crystalline structure and weather rapidly in humid environments, producing soils that are characterized by high water holding capacity (Moldrup and others 2003) and cation exchange capacity, the ability to stabilize soil organic matter, and high reactivity towards phosphate. In the Pacific Northwest, mountainous topography leads to strong redistribution of ash fall materials that were likely deposited in fairly uniform layers throughout these landscapes. Strong environmental gradients also create diverse weathering and pedogenic environments in Pacific Northwest forest soils. For these reasons, the expression of andic soil characteristics shows great variation within landscapes, creating a wide range of conditions in tephra-affected soils, and a similar range of responses to soil disturbance and subsequent restoration or enhancement efforts.

In general, the goal of forest soil restoration is to recreate pre-disturbance growing conditions, so that tree growth rates on the reclaimed soil will approximate those of trees on undisturbed soils on similar sites. Effective soil restoration employs techniques that alleviate growth-limiting conditions on sites that have suffered degrading soil disturbance. Degraded soils are defined here as soils that have experienced disturbance leading to a loss in productivity. Forest productivity on degraded soils can be reduced by compaction that causes plant roots to experience limiting conditions of soil mechanical resistance, water availability, and aeration. Removal of surface soil layers may cause similar effects because organic matter may be depleted from the site, or because unproductive subsoil materials may be exposed. Degraded soils may also be more susceptible to erosion which can cause further loss of nutrients and organic matter that are essential for maintaining site productivity. Erosion can also cause serious off-site consequences for aquatic and terrestrial systems.

Site-specific information on soil physical conditions, organic matter, and nutrient status is required for efficient soil restoration, but only limited research is available to help interpret such information and guide efforts to restore degraded soils derived from tephra.

Restoration techniques aimed at controlling erosion include (a) those aimed at stabilizing soils such as slope recontouring, (b) those aimed at managing water such as ditching or outsloping and (c) those aimed at preventing soil detachment such as revegetation. For compacted soils, tillage is often required to restore conditions conducive for productive root growth. Restoration of organic matter, where appropriate, may be accomplished through replacing displaced topsoil materials, by mulching with organic materials such as logging debris, or through the soil building action of seeded cover crops.

This manuscript outlines the role of soil restoration in maintaining the productivity of managed forest landscapes, reviews the principles that govern how the unique characteristics of tephra-derived soils affect restoration planning in volcanic terrain, discusses how information available from elsewhere applies to reclamation techniques in volcanic terrain of the Pacific Northwest, and provides management recommendations to guide restoration and enhancement efforts.

Soil Restoration to Conserve and Enhance Productivity in Forested Landscapes

Minimizing degrading soil disturbance (Page-Dumroese and others 2000) is an important first step to ensure that soils are maintained in a productive condition, and that forest management is sustainable. Throughout North America, regulatory systems are in place for preventing soil degradation during forest harvesting, access development, and other management activities (Powers and others 1998; USDA Forest Service Standards and Guidelines 2521.1 and 2521.2; CCFM 2002; BC Ministry of Forests 2001). These systems generally specify site specific limits for defined forms of degrading soil disturbance, and may also provide incentives for restoring soils that have been degraded by forest management activities.

In British Columbia, soil conservation policy allows more soil disturbance on sites with low sensitivity to soil-degrading processes (BC Ministry of Forests 2001). In the northwestern United States, higher intensity of soil compaction (i.e. 20% increase in bulk density) is considered acceptable on volcanic-ash derived soils (Powers and others 1998), compared to those developed on other parent materials (maximum 15% increase). These differences recognize that many undisturbed tephra-derived soils have low bulk density, but may also imply that they are less sensitive than other soils to modest changes in density. Tephra-derived soils may also respond differently than others to reclamation treatments.

Restoring degraded soils improves forest productivity. On access structures that are no longer needed, restoration and reforestation increases the land base available for growing trees, and can thereby increase future timber supplies. On areas that have suffered degrading soil disturbance, restoration can improve establishment success and productivity of planted trees compared to areas where soils are left in a degraded state. Achieving full benefit from soil restoration practices depends on the development of cost-effective reclamation techniques, and their application to sites where the cost of reclamation will be offset by improved productivity from the reclaimed lands (Richardson and others 1999).

Reclamation work should be subjected to cost benefit analysis the same as any other management activity. Such an approach avoids wrongly thinking of rehabilitation as an intrinsically good activity, where the true costs of reclamation work can be discounted or ignored. Costs of restoration work include dollar costs, diversion of scarce resources from other activities, consumption of fossil fuels, and risk to workers or property, along with potential negative consequences which may not be anticipated such as water diversion, erosion, slope failure, and weed infestation. At the same time, the potential benefits of reclamation work may also be understated if the analysis is restricted traditional economic measures (dollar costs only), or if inappropriate discount rates are applied to timber production. The social and environmental benefits of carrying out reclamation activities may have been neglected in the past, but recent evaluations have shown the important role that healthy ecosystems play in maintaining economies and societies (Hillel 1991). Such considerations are likely to become even more important as globalization and population growth exert increased pressure on natural environments all over the world.

In general, given the almost universal scarcity of resources, the uncertainty of cost benefit analyses, and the risks associated with undertaking any activity that imposes significant disturbance to a natural system, a prudent approach would focus reclamation efforts on sites where simple techniques have been shown to have success. Treatment of high risk sites and use of expensive or exotic treatments are likely best left to special situations where potential values are high, social factors warrant, or where such efforts are treated as an operational trial or where detailed monitoring will improve our overall understanding of rehabilitation and its role in forest management.

Characteristics of Tephra-Derived Soils as They Affect Growth-Limiting Conditions and Restoration Efforts

Variation in soil properties and growth-limiting factors in tephra-derived soils arise from (a) ecological characteristics of the site associated with climate, topography, parent materials, and vegetation, (b) chemical and physical characteristics of the tephra as it was deposited, and (c) redistribution and alteration of tephra in the landscape in response to topography, moisture etc.

Strategies for reclaiming soils without tephra influence have been developed in the Pacific Northwest and elsewhere, and specify different approaches for a range of soils in diverse geographic settings. The applicability of these to tephra-derived soils depends on the differences in soil properties brought about by the presence of tephra. Some questions to consider include:

- Have natural depositions of tephra led to improved soil fertility by providing a supply of readily available inorganic nutrients?
- What is the weathering state of the tephra? Tephra materials weather rapidly in humid surface environments, but in the Pacific Northwest there are many examples of relatively unweathered materials either because of dry climates or short duration of weathering since deposition.
- What is the particle size of the tephra materials? In the Pacific Northwest, variation in physical and chemical properties as they affect plant growth primarily results from particle size effects (including distance from the source) and post depositional alteration including organic matter retention and weathering.
- For a given particle size, tephra-derived soils tend to have physical characteristics (i.e. water holding capacity; specific surface; organic matter retention) that reflect those of other soil materials with finer texture (i.e. sandy tephra materials may behave more like loams derived from other parent materials).

Morphological Characteristics of Tephra-Derived Soils

Tephra-derived soils include those where minor amounts of tephra were deposited to soil, but are no longer discernable as a distinct layer. In other soils, a distinct layer of tephra is present as an "ash-cap' of varying depth (fig. 1). Finally, some soils may be exclusively derived from volcanic materials to the depth of rooting, with little or no influence from other parent materials on the vegetation. Many soils will display intermediate characteristics to these idealized categories, especially where tephra layers become intermixed with subsoils during construction and use of access structures. Depending on the proportion of tephra, and characteristics such as particle size, special considerations may or may not be needed when developing reclamation strategies.

Physical Characteristics of Tephra-Derived Soils

The presence of weathering products with highly reactive surfaces lead to the common characteristics noted for weathered volcanic materials, including high water retention, organic matter stabilization, and well developed aggregate structure. The characteristics are inter-related as organic matter is partly stabilized because of the surface reactivity, while the presence of organic matter results in

Figure 1—Ash cap overlying ultramafic soil material in the Shulaps Range: interior British Columbia.

additional reactive surfaces. The expression of Andic characteristics depends on the degree of weathering of the material.

A key characteristic affecting reclamation is the low bulk density observed in many tephra-derived soils, owing in part to their low particle density but also to the tendency to develop well aggregated structures. Miller and others (1996) found that even after a substantial increase in bulk density of ash derived soils in central Washington, the bulk density was still less than 1000 kg m^{-3}. For this reason, threshold values for growth-limiting conditions need to be determined specifically for ash derived soils, rather than using values derived for other soils.

Relationships between soil texture and management impacts reflect the variable effects of ash characteristics and soil environments. For example, poorly crystalline weathering products act as a cement to create very stable aggregates in Andisols that occupy wet sites. Also, the weathering products of volcanic parent materials have high surface area compared to the clay minerals found in most other soils (Moldrup and others 2003). In addition, tephra particles often consist of porous and fragile materials, so coarse-grained tephra soils are often less resistant to fracture compared to non-tephra soils, and particle size distribution may shift towards finer size fractions following mechanical disturbance (Sahaphol and Miura 2005).

Tephra-derived soils retain large amounts of water compared to soils derived from other parent materials. Conversely, they are also subject to changes upon drying, which can include the development of water repellency (Poulenard and others 2004) and irreversible structural collapse (Poulenard and others 2003) which is most likely for soils formed in wet environments (Shoji and others 1996). In considering the impact of this characteristic on disturbance and reclamation, the high water retention may lead to a soil with low bearing strength, and high susceptibility to rutting when wet. It may also make tillage operations difficult when soils are moist. Despite this, the materials are expected to provide a good growing medium for plant roots, especially on mesic sites.

Unweathered tephra materials are often non-cohesive and prone to erosion by wind and water (Basher and Painter 1997; Arnalds and Kimble 2001), and this susceptibility may last for some time in unvegetated areas. For this reason, planning should consider measures for rapid revegetation of exposed tephra materials resulting from disturbance and reclamation. Tephra-derived materials with coarse particle sizes have also been used as a water conserving mulch (Tejedor and others 2002, 2003). This characteristic may also present challenges when considering the seedbed characteristics of coarse-textured tephra soils.

The unique physical conditions provide both challenges and opportunities, and both need to be considered when planning restoration treatments for tephra-derived soils.

Chemical Characteristics of Tephra-Derived Soils

The chemical characteristics of tephra vary depending on the geologic environment, and these characteristics are inherited by the soils derived from volcanic materials. In general, the composition of tephra materials in the Pacific Northwest are similar to those of rhyolite, which is expected to provide adequate supplies of mineral-bound plant available nutrients in unweathered or moderately weathered soils. The weathering products of volcanic ash have a high affinity for organic matter, and this characteristic accounts for many of the unique properties, including high cation exchange capacity, and high availability of organically bound plant nutrients. Anion exchange capacity derives from the creation of poorly crystalline oxides of Fe and Al, and also from short range order aluminosilicates like allophane. The anion exchange capacity accounts for the high reactivity of tephra-derived soils to phosphate. Despite these features, recent tephra deposits which characterize much of the Pacific Northwest may have similar fertility to other parent materials (McDaniel, this proceedings).

The presence of large amounts of organic matter in weathered ash deposits is expected to lead to soil materials that are resilient to disturbance, but unweathered materials in cold or dry environments, may have low levels of organic matter.

Reclamation planning should consider the need for organic matter and nutrient additions in consideration of soil conditions and forest productivity in undisturbed soils on similar site types in the area.

Planning Considerations for Restoring and Enhancing Productivity of Tephra-Derived Soils

The unique chemical and physical characteristics of soils derived from tephra play an important role in determining what treatments should be considered for rehabilitating or enhancing a degraded soil. To develop the most appropriate restoration approach, the following general questions need to be answered by collecting field information:

1. Is the soil degraded to the point that forest productivity or other values are likely to be significantly affected?
2. What growth-limiting conditions (e.g. compaction, organic matter loss) or other issues such as erosion, sediment delivery to streams, or visual concerns are present that require amelioration?
3. Are there site conditions or other factors (e.g. cultural resources) that preclude or favor the use of one rehabilitation technique or combination of treatments over another for addressing the growth limiting factor(s)?
4. Are proven treatments likely to increase site productivity to an extent where the associated costs will be returned?

Several research efforts in northwestern North America and elsewhere have recently focused on evaluating the effectiveness of commonly used soil rehabilitation techniques. Although research specifically addressing degraded tephra-derived soils in the Pacific Northwest is limited, the principles governing the success or failure of such work are expected to be similar to those from elsewhere, and on different soil types.

For tephra-influenced soils in coastal Washington, Miller and others (1996) observed that trees on compacted skid trails were growing at the same rate as trees in undisturbed soils and trails where soils were decompacted. They concluded that site specific factors determined the response to soil disturbance and rehabilitation. Where climatic factors were favorable, and soil properties of compacted soils remained within thresholds for growth limiting factors, productive forests could develop on disturbed soils. For the tephra-influenced soils studied by Miller and others (1996), despite a 50 percent increase in bulk density after harvest and values of bulk density that were 20 percent higher after 8 years, the disturbed soils still had bulk density below 1000 kg m^{-3}. Partly because of the results, the authors concluded that the relationship between pre-disturbance and post-disturbance bulk density, which has been used as an indicator of soil degradation in the United States, was not a good predictor of productivity effects.

The complex processes affecting seedling response to disturbance and rehabilitation were further illustrated by results from Priest River, Idaho, where soil compaction effects on tree root growth were studied on a soil derived from Mazama tephra. Douglas-fir and western white pine seedlings growing in compacted soils for one year had fewer nonmycorrhizal root tips compared to soils without compaction (Amaranthus and others 1996). Ectomycorrhizal root tip abundance and diversity was reduced by compaction for Douglas-fir, but not western white pine. Despite these results, seedling growth response was not significantly affected. Thus the initial response to compaction, and the need for rehabilitation treatments, not only varies for different soil and disturbance types, but also may depend on the tree species under management.

Recent results in British Columbia on a range of soil types and climatic conditions have shown that relatively simple rehabilitation treatments such as subsoiling followed by planting with lodgepole pine often produce well-stocked new forests (Plotnikoff and others 2002; Bulmer and Krzic 2003), but on wet sites, fine-textured soils, or where topsoil retrieval and replacement were not carried out, growth rates may lag those of undisturbed areas of adjacent plantations. Lodgepole pine is often planted on rehabilitated sites in British Columbia owing to high survival rates and rapid early growth. In contrast to the previous results, soil decompaction without tree planting led to unsatisfactory stocking on 100 sites in BC's southern interior (Bulmer and Staffeldt 2004), indicating that natural regeneration should only be relied on as a reforestation strategy after carefully evaluating the availability of a seed source.

These research studies show that it is difficult to generalize when predicting the response to disturbance and rehabilitation. Site-specific information is essential for determining which research efforts and conclusions apply to a particular site, and therefore which course of action is likely to be most successful and cost-effective. The following critical site factors can affect the response to soil disturbance and rehabilitation on a particular site:

- ***Climatic conditions*** such as temperature and annual water deficit affect the rooting characteristics of trees, and the extent to which they are limited by moisture availability, cold temperatures, short growing season, or other factors.
- ***Slope characteristics and surface drainage patterns*** affect the potential for erosion or slope failure that could affect resources on and off the site.
- ***Soil texture and tephra influence*** affect the response of the soil to the disturbance and subsequent rehabilitation treatments because fine textured materials have low strength when wet and are highly susceptible to compaction, while the pore system in coarse-textured materials is generally resistant to compaction, and less likely to suffer soil degradation associated with machine traffic.
- ***Moisture regime*** strongly affects the tree growth limiting factors, and the likelihood of realizing suitable conditions for tillage equipment. Wet sites in particular often suffer increased soil disturbance because of low soil strength, and restoration efforts face challenges because of poor soil structure resulting from tillage of wet soils.
- ***Presence of unfavorable subsoils*** and the extent to which surface soil displacement has exposed them or may force plant roots to grow in them.
- ***Rooting depth*** in undisturbed soils, potential rooting depth on the disturbed site, and the depth of soil disturbance affect the response of trees.

The expected loss of forest productivity if the site was left alone needs to be balanced against the benefits of intervention to improve conditions on the site. In cases where the expected benefits are small, no treatment would be indicated, and planted trees could simply be monitored to evaluate the need for fertilizer inputs or other activities to maintain growth rates at desirable levels. In such cases, site productivity may be slightly lower than if soil disturbance had not occurred, but the loss in productivity may be small compared to cost of restoration treatments.

In summary, reclamation treatments will likely deliver the most benefit when:

- Climatic and other site conditions favour productive tree growth
- Severe soil disturbance will likely prevent seedling establishment and significantly reduce growth without intervention
- Proven and relatively inexpensive treatments such as decompaction, topsoil replacement, and revegetation are applied to mesic sites with medium and coarse textured soils
- Difficult sites, wet areas and fine-textured soils are avoided, as treatments to overcome these challenges are expensive and benefits unproven.

Restoration Treatments and Unique Aspects of Their Application to Tephra-Derived Soil

Where soil disturbance is likely to reduce tree growth to an unsatisfactory degree, and treatments are indicated, a basic approach to rehabilitation would involve attempting to create site conditions approximating those of undisturbed soils on similar sites in the area, even though this may not always be possible (e.g. where surface soils have been displaced and their retrieval is not feasible). The conditions on undisturbed sites likely reflect what is conducive to productive forest growth in the area. To develop a cost effective plan for implementing reclamation treatments, there is a need to consider:

- The extent to which conditions on the site are expected to exceed thresholds of growth limiting factors such as aeration porosity, soil mechanical resistance, water availability, and nutrient content.
- Availability of displaced surface soil that could be retrieved and nature of surface soils in nearby undisturbed soils on similar sites
- Stones, stumps or other factors that may affect the operation of equipment
- Presence of existing vegetation, and likely seed sources for preferred crop trees and other species to be re-established on the site
- Expected wildlife or cattle use that may affect the success of reforestation or revegetation efforts

Based on site-specific conditions, reclamation treatments can be identified to address each of four objectives.

Managing Water and Preventing Erosion

Water management and erosion control is the first step in reclamation planning. Without a stable substrate that is free of erosion, the beneficial effects of restoration treatments could be destroyed by removal of organic rich surface soil layers, or by exposure of less fertile subsoils. In addition, the high costs of potential off-site effects on water quality, fish, and property require that water and erosion control is given highest priority. Site water management is also essential for correcting detrimental effects of soil disturbance on the soil drainage class and moisture regime.

Water management may be as simple as building a ditch to divert surface water away from a road or landing, or could involve more expensive options such as slope recontouring designed with internal drainage to restore the flow of subsurface water.

Erodibility may be related to poor cohesion of recently deposited tephra materials, high water retention, and low internal strength of deposits. These factors may be offset by high porosity. The characteristics of the subsoils and other site attributes need to be considered before selecting treatments.

Localized erosion was observed in Diamond Lake District, Umpqua National Forest, when surface water flow patterns were disturbed by compaction of deep pumice soils, routing water to the edge of the unit. Routed water affected residual topsoil left post-harvest, and, where compaction endures for long periods, water routing and erosion would continue into the future without tillage.

Treatments to control erosion include:

- outsloping decompaction
- slope recontouring
- diverting / managing surface water
- revegetation

Where water management, erosion, slope stability issues do not pose severe restrictions, the next step is to proceed with efforts to restore site productivity.

Tillage to Restore Soil Physical Conditions

For compacted soils with high soil strength or those that have suffered deterioration of the pore system, restoring soil physical conditions is an essential part of reclamation. Compaction affects the pore system mostly by reducing the number of large pores. This leads to increased water retention and reduced infiltration, and may lead to soils with insufficient air for plant roots.

There are reasons to believe that trees growing in some soils rich in volcanic ash may respond differently to compaction than for other parent materials. The highly developed aggregate structure of weathered and developed soils derived from volcanic materials in other areas has been well documented, suggesting that stable aggregates in such soils may survive the compaction process, and provide stability for large pores. For the Pacific Northwest, recent tephra deposits likely have relatively stable macrostructure where particle strength is high enough to resist particle breakage. On mesic and dry sites, these characteristics may lead to a soil that is able to withstand compaction and still provide a productive environment for plant roots, and/or one that is able to naturally regenerate soil conditions suitable for productive forest growth following disturbance. Despite this, some specific challenges could include:

- **Water retention**: On wetter sites, the high water retentivity of tephra soils may lead to similar problems as identified for fine-textured soils, and could be especially problematic in low-lying landscape positions. The major problems would include excessive soil water, and lack of aeration.
- **Particle breakage**: Some volcanic materials are susceptible to particle breakage when disturbed, which increases the proportion of fines in the particle size distribution. Particle breakage may be a factor in poor performance of regeneration on some sites in Oregon.
- **Irreversible drying**: Cementation may lead to massive structure with high soil strengths that plant roots are incapable of penetrating. Although this phenomenon is not expected to be widespread in the Pacific Northwest, it

could affect results in low lying landscape positions with weathered soils and where soil structure has been destroyed (puddling) by repeated machine traffic, and where sites are subject to occasional drying in summer.

Where tillage is required, a variety of implements are available, including winged subsoilers, rock ripper, excavators with brush rakes, mulching heads, or custom attachments such as the subsoiling grapple rake and subsoiling excavating bucket. The best implement for the job likely depends on factors such as required depth, soil strength, water status, and logistics (e.g. availability of prime movers).

An example of an implement that was purpose-built for decompacting soils in volcanic terrain is the subsoiling grapple rake, which was developed and used in the Diamond Lake Ranger District, Umpqua National Forest (Archuleta and Karr 2004). This implement is a grapple rake fitted with subsoiling shanks and wings. It was designed to mitigate either legacy compaction or newly created harvest impacts, and is best employed when used in concert with an ongoing activity, such as post-harvest slash reduction. At Diamond Lake, the combination of these activities reduced the overall cost of individual projects with a minor increase to either slash piling or subsoiling costs. The subsoiling excavator bucket is another implement that is also equipped with shanks, and allows cost-effective decommissioning of roads. This implement also reduces the subsoiling rate on small tillage projects and makes additional equipment (i.e. dozer and tillage implement) redundant.

Tillage is aimed at alleviating the effects of detrimental compaction, which include increases in soil strength, reduced aeration, and excessive water retention. Although the effectiveness of tillage has been questioned on fine-textured soils in central Alberta where subsoils stayed wet and soft for long periods during the year (McNabb 1994), such issues may be less of a concern in fine-textured tephra-derived soils in the Pacific Northwest because of (a) the strong aggregation expected in fine-textured soils derived from volcanic materials, and (b) dryer climates. For relatively fresh volcanic parent materials, particle sizes may be coarse and water infiltration and aeration may not be limiting.

In summary, for successful tillage, consider:

- tillage is used to reduce soil strength and restore the pore system,
- a variety of implements are available,
- use the rooting depth in natural forests on similar sites as a guide to tillage depth
- for dispersed disturbance, and to reduce costs, consider spot tillage
- the effects of tilling wet volcanic soils, which may be subject to irreversible drying or consolidation, need to be evaluated through monitoring

Restoring Organic Matter and Nutrients

In general, the most effective means of restoring surface soil organic matter is to retrieve and replace displaced topsoil. In situations where recovery of displaced surface soil is not practical, other potential strategies include distributing green logging slash from harvesting operations over the reclaimed area. In central BC, chipped waste logs enhanced soil properties and contributed to successful establishment and early growth of white spruce seedlings (Sanborn and others 2004). Despite their benefits, organic amendments are generally only suitable if they are locally available, as they are expensive to transport.

Since tephra derived materials are known to have a high affinity for soil organic matter, a cost-effective alternative could involve revegetation with grasses and legumes that can build soil organic matter through decomposition of their root systems. In one study (not an ash soil), Bendfeldt and others (2001) showed that vegetation inputs of C were an important source of surface soil organic matter levels after sixteen years on reclaimed mine soil that also received an initial amendment with wood waste.

In summary, to restore organic matter and nutrients, consider:

- Organic matter is an essential component of productive soil, but forest ecosystems vary in the amount present in surface soils.
- Retrieval of displaced topsoil is a cost effective approach for restoring suitable growing conditions.
- Use the characteristics of surface soils on similar sites as a guide to what surface soil organic matter levels are appropriate, and its distribution as a surface layer or incorporated into surface soils.
- Revegetation with agronomic grasses and legumes can contribute significant quantities of organic matter over time.
- Organic amendments can effectively restore soil conditions, but are expensive to transport.

Revegetation

Successful revegetation and reforestation of disturbed areas is an important final step in reclamation efforts. In many cases, the objective for the reclamation is defined by the type of vegetation cover desired. For example, grass and legume cover may be prescribed to prevent erosion, forest restoration provides for timber, or other values may have priority such as wildlife, watershed values, and aesthetics. Tree planting is the most common and effective means to establish a new forest, but natural regeneration could be effective if a seed source and suitable seedbed conditions were present.

For successful and cost-effective revegetation, consider

- **Revegetation** is essential for erosion control in sloping terrain.
- **Seeding agronomic grasses** and legumes are proven means to prevent erosion.
- **Seedbed characteristics** are often best immediately after tillage operations are complete.
- **Droughtiness**; may hamper revegetation efforts in coarse-textured tephras where low water retention results in a lack of seedbed moisture. Seeding treatments in such soils would have to be considered carefully, and consider the timing in relation to expected precipitation, along with the possible need for mulches to conserve moisture.
- **Ingress of native vegetation** may occur without intervention where disturbances are small (e.g. roads and trails).
- **Natural regeneration** of tree seedlings may be a low cost alternative to planting where a seed source is available and slightly longer regen delay is acceptable.

Information and Research Needs

The published information base is limited and provides few specific examples of the effects of soil disturbance, enhancement and restoration on forest site productivity in volcanic terrain in western North America. The lack of information partly reflects the difficulty and expense in designing and implementing studies that are relevant to the wide range of site types, soil conditions, and tree species that occur in the region. Despite this, there is considerable information on soil disturbance and restoration effects for other soil types in similar climates and much of this information can likely be extrapolated to volcanic soils in the Northwest. In addition, soil scientists and forest managers in the region have considerable experience with how the soils respond to management.

To address the lack of specific published information, a useful approach would be to combine existing research from elsewhere with local knowledge of the soils response to management through retrospective study, monitoring, and operational trials. Although these approaches have their limitations for resolving detailed questions, they are extremely useful for answering the broad questions that arise during the initial stages of a detailed research program. Specific questions to be addressed (and suggested approach to study) include:

- Identifying sites most susceptible to degradation, and those where restoration or enhancement provide the greatest benefit (*monitoring and retrospective study*)
- Evaluating a range of treatment options for restoring and enhancing productivity (*monitoring results and operational trials*)
- Characterizing the effect of typical operations on soil properties such as bulk density, penetration resistance, and organic matter (*research*)
- Determining thresholds for unacceptable productivity decline on the most common site types (*research*)

Management Recommendations

1. Evaluate costs and benefits: Soil restoration and enhancement should be considered investments where the expected benefits, costs and risks are carefully evaluated. In general, it is best to focus efforts on sites with the best expected return on restoration dollars, and use low cost, reliable methods for restoration. The benefits of restoration and enhancement efforts typically include:

- increased timber supply,
- reduced environmental liability associated with roads,
- improved watershed, wildlife, and aesthetic values.

2. Have a site-specific plan: Evaluate limitations to productivity, risk of erosion, and other site specific factors, and then set realistic objectives for the work. Where legacy impacts are present, combination machines such as the subsoiling grapple rake and subsoiling excavator bucket may allow restoration to be blended into other work such as brush piling or road decommissioning.

3. Start simple (and cheap): Try the simple solution first. Consider treatments in the following order:

- do nothing (i.e. rely on natural regeneration to recolonize lightly disturbed areas)

- tree planting
- fertilization
- decompaction / tillage plus topsoil recovery
- organic amendments
- re-establishing native species by planting

4. Keep learning: Monitor the results of your efforts and those of others.

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Ash Cap Influences on Site Productivity and Fertilizer Response in Forests of the Inland Northwest

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Abstract

Data from 139 research sites throughout the Inland Northwest were analyzed for effects of ash cap on site productivity, nutrient availability and fertilization response. Stand productivity and nitrogen (N) fertilizer response were greater on sites with ash cap than on sites without. Where ash was present, depth of ash had no effect on site productivity or N fertilizer response. Site productivity increased with increasing potentially available soil water. Potentially available soil water, in turn, increased with increasing ash depth. Decreasing availability of magnesium (Mg) and calcium (Ca) in the upper 12 inches of soil may have constrained site productivity with increasing ash depth. Soil mineralizable N and ammonium N were unaffected by ash presence or depth but did vary by underlying parent material. Site productivity and N fertilizer response varied by underlying parent material even after accounting for ash presence. Stand volume response to sulfur (S) fertilization decreased with increasing ash depth, suggesting possible S adsorption by ash cap. No growth response or change in foliar K status was discerned following K fertilization. Management recommendations by parent material are provided.

Background

Availability to plants of most nutrients besides nitrogen (N) is related primarily to mineral weathering rates and soil physical and chemical properties. Common parent materials of soils in the Inland Northwest include the Columbia River basalt flows, Belt Series metasedimentary rocks, granites, and various glacial deposits. Characteristics that these materials impart to forest soils significantly affect forest nutrition, productivity and response to fertilization (Moore and Mika 1997; Moore and others 2004). However, surficially deposited parent materials are often neglected during analyses of parent rock effects on forest nutrition. This is particularly true for widespread volcanic ash resulting from the eruption of Mount Mazama (now Crater Lake) in southwestern Oregon. The effects of surficially deposited parent materials on forest nutrition, productivity and response to fertilization are poorly understood.

Ash-cap soils common to the Inland Northwest are known for their capability to hold ample available moisture, which in turn is thought to enhance site productivity (Brown and Lowenstein 1978; Mital 1995). Because of the improved soil moisture status, forest stands growing on ash-cap soils are generally expected to show greater growth response to nitrogen (N) fertilization than stands on soils without ash cap, at least so long as some other factor is not more limiting than moisture and/or N. In a study of 90 Douglas-fir fertilization trial stands across the Inland Northwest, Mital (1995) found a positive correlation between Douglas-fir growth response to N fertilization and ash depth at an application rate of 400 lb ac^{-1}, while the relationship was less strong when the application rate was 200 lb ac^{-1}. In another study, Geist (1976) reported that forage production on volcanic ash soils showed strong fertilization response on forested range sites in eastern Oregon and Washington.

Without fertilizers or blending with organic matter, unweathered ash-cap soils are not particularly fertile, being comprised largely of poorly crystalline aluminosilicates and iron (Fe) and aluminum (Al) oxides. Their nutrient cation storage capacity is low, suggesting that supply of the nutrient cations potassium (K), calcium (Ca) and magnesium (Mg) may be poor (McDaniel and others 2005). Furthermore, strong anion adsorption capacity by volcanic ash may impede tree fertilization response. In a study of sulfur (S) adsorption properties of andic soils in the Inland Northwest, Kimsey and others (2005) suggest that applied S fertilizers may be ineffective in increasing S-availability to trees unless a threshold sorption capacity of the ash cap is exceeded. Similar interactions may be expected for the anionic forms of other elements, including N, phosphorus (P) and boron (B). Such a phenomenon may explain, in part, the variable relationship between ash cap depth and N-fertilization rates described by Mital (1995), if some threshold sorption capacity had to be met (such as at the 400 lb rate) before the applied N became available to the forest vegetation. The ash cap may take on nutritional characteristics of underlying residual soils, though this perception has not been scientifically tested.

A statistical analysis of data from nutritional research conducted by the Intermountain Forest Tree Nutrition Cooperative (IFTNC) from 1980 to the present was undertaken to determine whether ash deposits affected tree and soil nutrition, forest productivity and fertilization response. We hypothesized that site productivity and fertilizer response would be greater on ash sites than non-ash sites and that productivity and response would increase with increasing ash depth.

Methodology

Data Compilation

Data from 139 IFTNC research sites were compiled. The data set included 94 sites from the 1980-1982 Douglas-fir Study, 8 sites each from the 1991 and 1993 Mixed Conifer Studies, and 29 sites from the 1994-1996 Forest Health and Nutrition Study (table 1). Soil profile descriptions were used to estimate organic horizon depth, surficial deposit depth and residual soil depth to 36 inches. Surficial deposits were categorized as ash, loess, glacial deposits, other modern (quarternary era) deposits, and tertiary deposits. Residual soils were those derived from the base geology. The division between surficial deposits and base geology

Table 1—List of selected fertilization studies established by the Intermountain Forest Tree Nutrition Cooperative between 1980 and 2000. Regions refer to northeastern Oregon (NE OR), central Washington (C WA), northeastern Washington (NE WA), central Idaho (C ID), northern Idaho (N ID) and western Montana (W MT).

Trial name	No. of sites	Year(s) established	Stand composition	Region	Treatments and rates[a]
Douglas-fir trials	94	1980-1982	Douglas-fir	C ID, C WA, NE WA, NE OR, N ID, W MT	control; 200 lb N; 400 lb N
Umatilla mixed conifer	8	1991	Mixed conifer	NE OR	control; 200 lb N; 200 lb N + 100 lb S
Okanogan mixed conifer	8	1993	Mixed conifer	C WA	control; 200 lb N; 200 lb N + 170 lb K
Forest health and nutrition	29	1994-1996	Mixed conifer	C ID, C WA, NE WA, NE OR, N ID	1994 (12 sites): control; 300 lb N; 170 lb K; 300 lb N + 170 lb K 1995 (12 sites): control; 300 lb N; 170 lb K; 300 lb N + 170 lb K; 300 lb N + 170 lb K + 100 lb S 1996 (7 sites): control; 300 lb N; 170 lb K; 300 lb N + 170 lb K; 300 lb N + 170 lb K + 100 lb S + 5 lb B + 10 lb Cu +10 lb Zn + 0.1 lb Mo All years: Additional N+K combinations ranging from 0 lb N and 0 lb K to 600 lb N and 512 lb K, per experimental design

[a] Rates in lb ac^{-1} as broadcast application

was not always clear. Because the soil depth parameter for this study was limited to 36 inches, deep surficial deposits were often the only parent material noted. Therefore, the base geologic parent material categories for this paper included basalt, granite, sedimentary rock, metasedimentary rock, glacial deposit, tertiary sediments and modern sediments. Ash was considered present if it was continuous and measurable to a depth of 1 inch or greater. Admixtures of ash and other materials were also counted as ash cap if the ash was a predominant and identifiable component of the mix.

Soil water-holding capacity was determined for the upper 24 inches of the soil profile on 110 sites. Potential plant-available water was calculated as the difference in moisture-holding capacity between 1/3 and 15 bars for those sites. Conventional laboratory soil tests were performed on the upper 12 inches of soil for all 139 sites, though some tests were performed on only a subset of the sites. Available P and K were tested using sodium acetate extraction, while NH_4^+ and NO_3^- were analyzed using 2M KCl extraction with analysis by colorimetry (Case and Thyssen 1996a; Case and Thyssen 1996d). Sulfate-sulfur was analyzed by calcium phosphate extraction and ion chromatography, and B was analyzed by calcium chloride extraction and spectrophotometric determination (Case 1996; Case and Thyssen 1996c). Extractable Ca, Mg, K and Na were analyzed by 1N ammonium acetate extraction and ICP, and micronutrients Cu, Zn, Mn and Fe by DTPA (Case and Thyssen 1996b; Case and Thyssen 2000).

Two different approaches were used to estimate site productivity. The first approach utilized Douglas-fir site index (SI, Monserud 1984), available for 110 of the 139 sites. We also selected control plot growth rate (CGR) as an easily calculated productivity estimate available for all sites included in the study. Control plot growth rate was estimated as the average growth rate in $ft^3\ ac^{-1}\ yr^{-1}$ over the first 6 years of each study. Fertilization response was based on 6-year cubic foot volume response ($ft^3\ ac^{-1}\ yr^{-1}$) to N fertilizers applied at 200 to 300 lb N ac^{-1}. Limited data were available for examination of volume response to S fertilizers applied at 100 lb S ac^{-1} and K fertilizers applied at 170 lb K ac^{-1}.

Tree nutrition was assessed by chemical analysis of foliage collected one year after fertilization from the upper third of the crown on dominant or co-dominant trees. Because foliage chemistry differs for different tree species, Douglas-fir was selected for inclusion in this analysis as the species most commonly occurring across the selected test sites. Nutrient deficiencies were identified by the critical levels method, defined as the point on a yield curve where an increase in nutrient concentration no longer results in increased yield. Thus, the "critical level" is the optimum nutrient concentration at which maximum yield is obtained with minimum nutrient input. Currently accepted critical levels for Inland Northwest Douglas-fir foliage are shown in table 2.

Data Analysis

Sites were arrayed in a matrix by geographic region, rock type, vegetation series and ash cap presence or absence to evaluate sample sizes in each category. Analysis of variance was used to detect the effects of region, rock type, vegetation series and ash presence on site productivity, soil and foliage characteristics and fertilization response. The basic statistical model used for this analysis was:

$$Y_{ijk} = \mu + \alpha_j + \beta_k + (\alpha\beta)_{jk} + \varepsilon_{ijk} \qquad (1)$$

Table 2—Nutritional critical levels for Douglas-fir foliage. Adapted from Webster and Dobkowski (1983).

Nutrient	Unit of concentration	Critical level
Nitrogen (N)	%	1.40
Phosphorus (P)	%	0.12
Potassium (K)	%	0.60
Sulfur (S)	%	0.11
Calcium (Ca)	%	0.15
Magnesium (Mg)	%	0.08
Manganese (Mn)	ppm	15
Iron (Fe)	ppm	25
Zinc (Zn)	ppm	10
Copper (Cu)	ppm	2
Boron (B)	ppm	10

Where:

Y_{ijk} = the productivity, soil or foliage characteristic measured at each site
μ = population grand mean for productivity, soil or foliage characteristic
α_j = effect of region, parent material or vegetation series
β_k = effect of ash presence or absence (dummy variable)
$(\alpha\beta)_{jk}$ = effect of region, parent material or vegetation series by ash cap interaction
ε_{ijk} = the error term ~ NID $(0, \sigma^2)$

Because CGR was a function of initial volume, analyses of CGR included initial volume as a covariate in the above model. Similarly, because fertilization response depended on starting volume and stand growth rate, those variables were used as covariates for that analysis. Ash depth as a continuous variable was also incorporated into the above model to perform regression analysis of the effects of ash depth on all variables examined in this study. Results were considered significant at the 90% confidence level (p=0.10).

Results

Ash Distribution

Sites in north Idaho, northeast Washington and northeast Oregon were more likely to have ash than sites in central Washington, Montana and central Idaho (table 3). Sites on tertiary deposits, metasedimentary rocks and glacial deposits were more likely to have ash than those on basalt, granite, modern sedimentary deposits and sedimentary rocks. Almost all western red cedar and western hemlock vegetation series occurred on sites with ash, while only about half the grand fir series and a quarter of the Douglas-fir series occurred on sites with ash cap. The statistical term for this pattern whereby ash occurs in conjunction with certain characteristics and not others is known as "confounding." Confounding between ash presence and other site characteristics make statistical analysis difficult because we cannot determine whether productivity or response differences between sites are due to the ash presence/absence or the other site characteristic (vegetation series, parent rock or geographic region). The occurrence of ash in conjunction with certain parent rocks

Table 3—Number of research sites with and without ash cap by region, underlying geology and vegetation series.

Region	Ash cap present? no	Ash cap present? yes	Total	Percent sites with ash cap
North Idaho	5	26	31	84%
Northeast Washington	6	17	23	74%
Northeast Oregon	7	10	17	59%
Central Washington	23	11	34	32%
Montana	14	2	16	13%
Central Idaho	17	1	18	6%
Underlying geology				
Tertiary deposits	1	6	7	86%
Metasedimentary rocks	8	20	28	71%
Glacial deposits	8	17	25	68%
Basalt	25	13	38	34%
Granite	18	9	27	33%
Modern deposits	7	2	9	22%
Sedimentary rocks	5	0	5	0%
Vegetation series				
Western red cedar	1	22	23	96%
Western hemlock	1	5	6	83%
Grand fir	29	24	53	45%
Subalpine fir	3	2	5	40%
Douglas-fir	38	14	52	27%
Total sites with and without ash cap:	*72*	*67*	*139*	*48%*

or geographic regions is likely coincidental, while the occurrence of ash in conjunction with certain vegetation series is more suggestive of a causal relationship.

Site Productivity

Douglas-fir SI was analyzed for 110 sites (SI information was not available for the Forest Health and Nutrition Study sites). Overall, SI was 10.6% greater on sites with ash cap than sites without. Base parent material explained a significant amount of SI variation (R^2=0.18), and the addition of ash presence to this model explained some additional variation in SI (R^2=0.28; fig. 1a). On all parent material types except basalt, the presence of ash cap somewhat increased site productivity compared to the non-ash sites. However, given ash presence, a subsequent regression analysis revealed no significant influence of ash depth on SI (fig. 1b). Average SI did vary by geographic region (fig. 1c); however, ash presence or absence did not further explain variation in SI once the geographic region was known. Similarly, while a significant amount of variation in SI was explained by vegetation series alone (fig. 1d), ash presence did not explain any further variation.

Control plot growth rate was available for all 139 sites included in the analysis, and was highly correlated with SI (R^2=0.59). Overall, CGR was 29.0% greater on ash versus non-ash sites. Ash depth did not affect CGR (fig. 2a). Control plot growth rate was significantly affected by geographic region (R^2=0.58; fig. 2b),

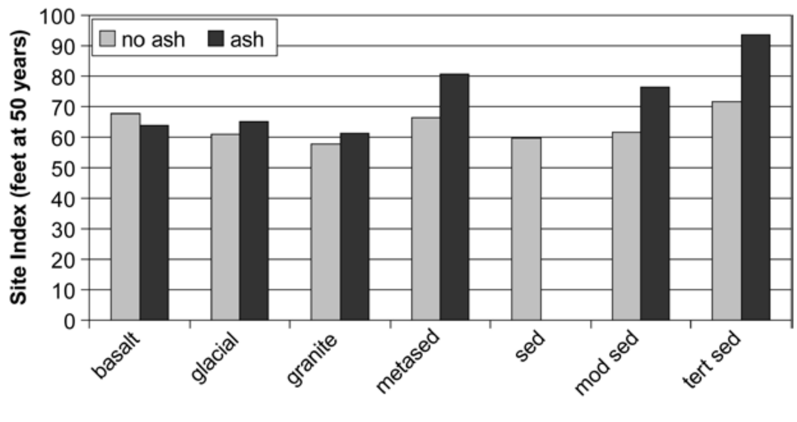

Figure 1a—Douglas-fir site index by base parent material and ash cap presence. Parent materials include basalt, glacial deposit (glacial), granite, metasedimentary (metased), sedimentary (sed), modern sedimentary deposits (mod sed) and tertiary sedimentary deposits (tert sed).

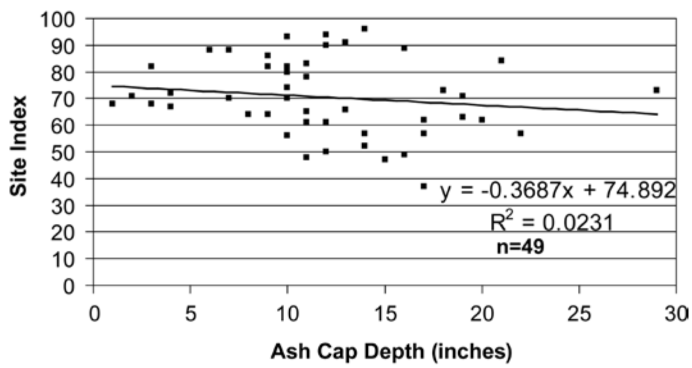

Figure 1b—Douglas-fir site index (ft at 50 years) by ash cap depth for sites with ash cap.

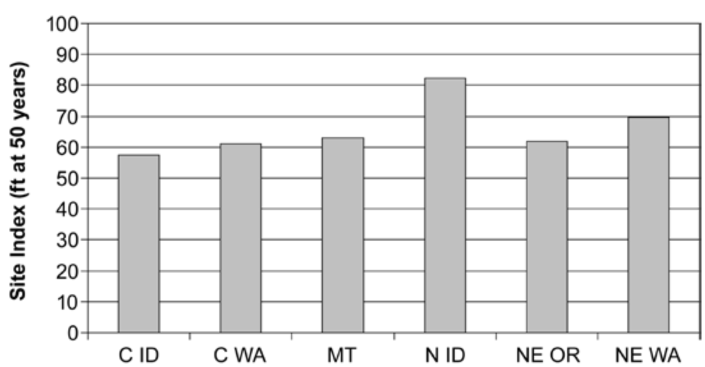

Figure 1c—Douglas-fir site index by geographic region. Regions include central Idaho (C ID), central Washington (C WA), Montana (MT), north Idaho (N ID), northeast Oregon (NE OR) and northeast Washington (NE WA).

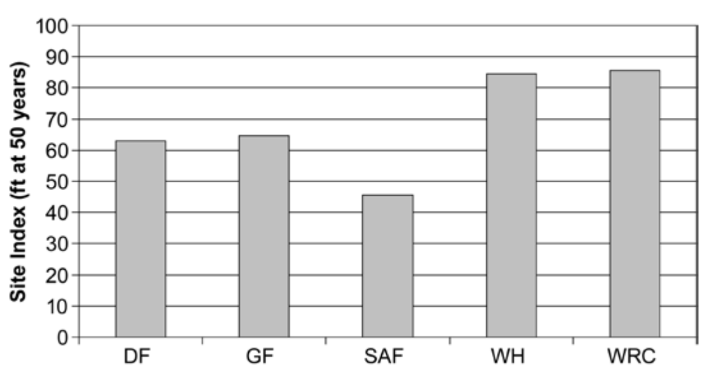

Figure 1d—Douglas-fir site index by vegetation series. Vegetation series include Douglas-fir (DF), grand fir (GF), subalpine fir (SAF), western hemlock (WH) and western red cedar (WRC).

vegetation series (R^2=0.59; fig. 2c) and dominant parent material (R^2=0.46; fig. 2d). Ash presence did not explain any additional variation for the geographic region or the vegetation series models. However, ash presence did explain some additional variation in CGR in the parent material model (R^2=0.57; fig. 2e). The results were similar to those for SI, with ash presence somewhat increasing CGR for most parent materials. Also similar to SI, once ash was present CGR did not change with ash depth.

Site Fertility

Soil moisture—Site productivity increased with increasing potentially available water (fig. 3a). Potentially available water, in turn, increased with increasing ash depth. When arrayed by vegetation series, potentially available water was greater

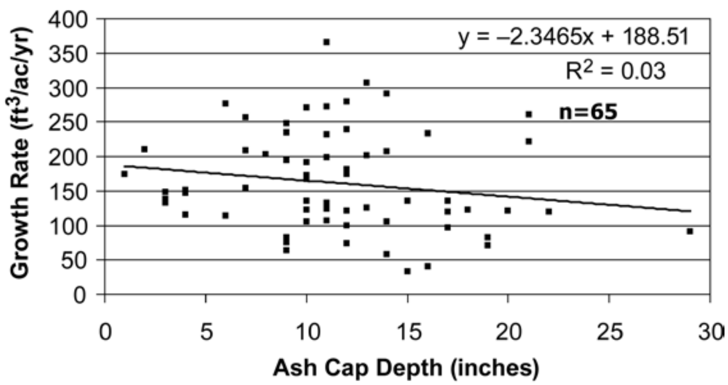

Figure 2a—Control plot growth rate by ash cap depth for sites with ash cap.

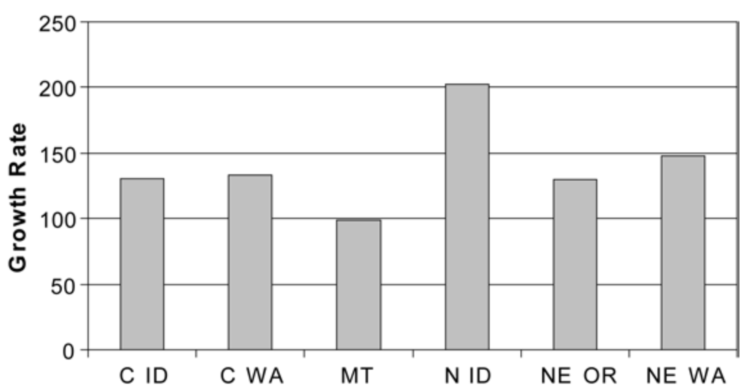

Figure 2b—Control plot growth rate ($ft^3ac^{-1}yr^{-1}$) by geographic region. Regions include central Idaho (C ID), central Washington (C WA),Montana (MT), north Idaho (N ID), northeast Oregon (NE OR) and northeast Washington (NE WA).

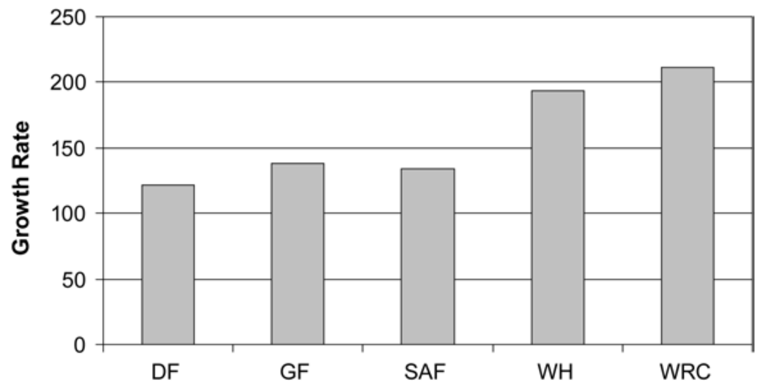

Figure 2c—Control plot growth rate ($ft^3 ac^{-1} yr^{-1}$) by vegetation series. Vegetation series include Douglas-fir (DF), grand fir (GF), subalpine fir (SAF), western hemlock (WH) and western red cedar (WRC).

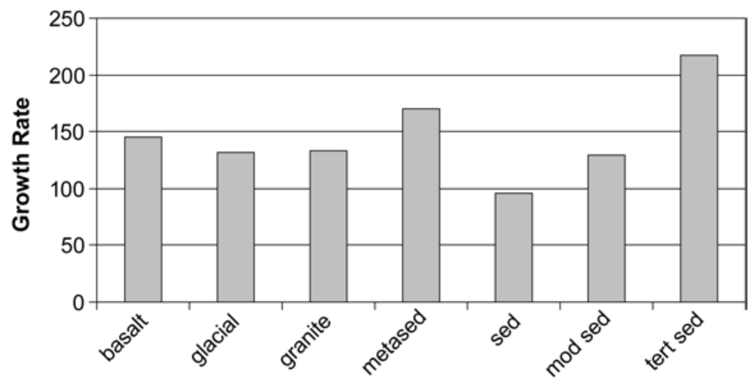

Figure 2d—Control plot growth rate $ft^3 ac^{-1} yr^{-1}$) by base parent material. Parent materials include basalt, glacial deposit (glacial), granite, metasedimentary (metased), sedimentary (sed), modern sedimentary deposits (mod sed) and tertiary sedimentary deposits (tert sed).

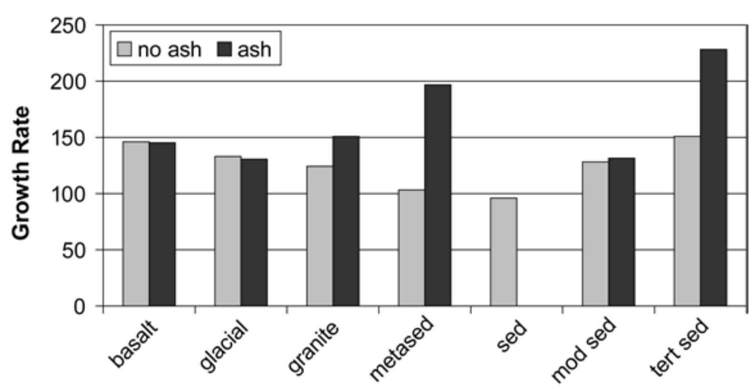

Figure 2e—Control plot growth rate $ft^3 ac^{-1} yr^{-1}$) by base parent material and ash cap presence. Parent materials include basalt, glacial deposit (glacial), granite, metasedimentary (metased), sedimentary (sed), modern sedimentary deposits (mod sed) and tertiary sedimentary deposits (tert sed).

on sites on western red cedar series compared to sites on Douglas-fir and grand fir series (fig. 3b). When arrayed by parent material (fig. 3c), sites with ash caps on basalt and metasedimentary parent materials averaged higher potential water availability than those on granite and glacial till parent materials. However, when ash was absent, sites on glacial till parent materials had higher potentially available water than sites on metasedimentary or granitic rocks.

Soil Acidity—Soil pH data were available for 135 sites. Overall, pH increased with increasing ash depth. Vegetation series had a significant effect on pH, with sites on subalpine fir series less acid than those on grand fir or Douglas-fir series, which in turn were less acid than sites on western red cedar or western hemlock series (fig. 4a). Parent material also affected soil pH, but interacted with ash

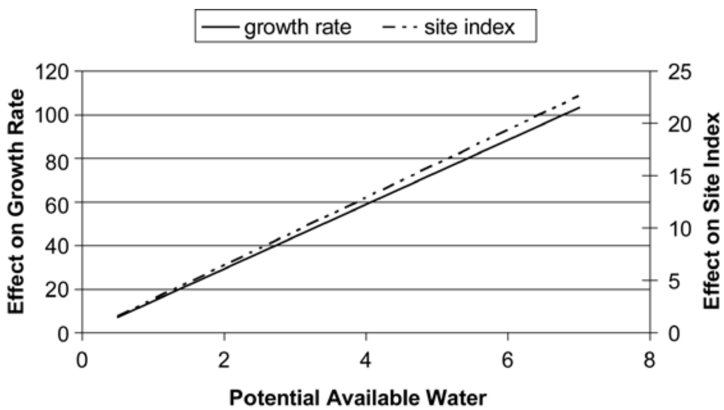

Figure 3a—Control plot growth rate ft^{3}ac^{-1}yr^{-1}) and Douglas-fir site index (ft at 50 years) as a function of potential available water (inches) in the upper 24 inches of soil.

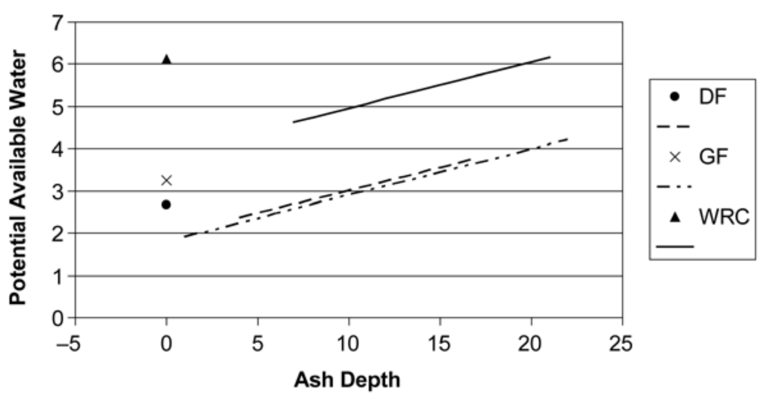

Figure 3b—Potential available water (inches) in the upper 24 inches of soil as a function of ash depth (inches), by vegetation series. Vegetation series include Douglas-fir (DF), grand fir (GF) and western red cedar (WRC).

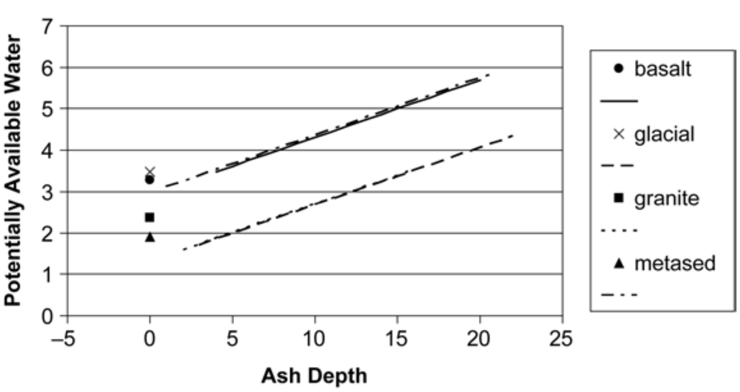

Figure 3c—Potentially available water (inches) in the upper 24 inches of soil as a function of ash depth (inches), by base parent material. Parent materials include basalt, glacial deposit (glacial), granite and metasedimentary (metased).

depth (fig. 4b). Soil acidity decreased with increasing ash depth on granite and perhaps basalt parent materials, and increased with increasing ash depth on tertiary sediments, but showed little variation with ash depth on other underlying parent materials. In the absence of ash, soil acidity was about the same for all underlying parent materials.

Nitrogen—Soil mineralizable N data were available for 119 sites, while ammonium-N data were available for 45 sites and nitrate-N data for 44 sites. None of these three measures of soil-available N varied with ash presence or depth. However, two of the variables, soil mineralizable N and ammonium-N, varied by parent material (fig. 5a and 5b). Both measures showed higher values on metasedimentary and tertiary deposit parent materials, and lower values on

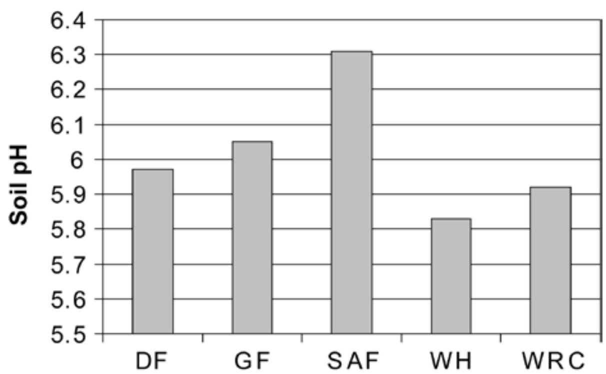

Figure 4a—Soil pH by vegetation series. Vegetation series include Douglas-fir (DF), grand fir (GF), subalpine fir (SAF), western hemlock (WH) and western red cedar (WRC).

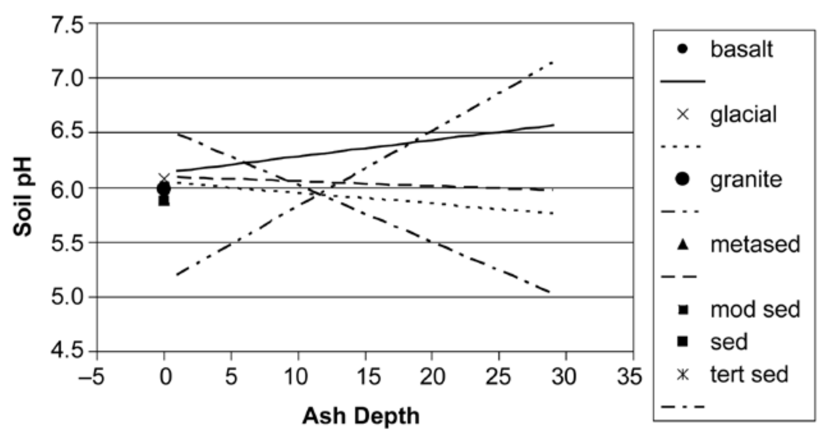

Figure 4b—Soil pH as a function of ash depth (inches) and base parent material. Parent materials include basalt, glacial deposit (glacial), granite, metasedimentary (metased), sedimentary (sed), modern sedimentary deposits (mod sed) and tertiary sedimentary deposits (tert sed).

granitic and basaltic materials. In an effort to determine why parent material would affect soil mineralizable N, several additional statistical analyses were performed using data on percent organic matter (29 sites) and percent carbon (90 sites). Mineralizable N was strongly and positively correlated with both soil organic matter (R^2=0.69) and soil carbon (R^2=0.68), suggesting that parent material could affect soil mineralizable N by affecting soil organic matter and/or carbon content.

Foliar N concentrations of unfertilized Douglas-fir trees were below the critical level of 1.4% for most sites, and were generally unaffected by ash presence or depth. However, foliar N was affected by underlying parent material, with trees on basalt parent materials showing higher foliar N concentrations than trees on other parent material types (fig. 5c). Examination of SI as a function of foliar N showed a positive relationship (R^2=0.28; fig. 5d). The slope of the relationship did not vary by underlying parent material, but SI was higher on tertiary sediments and metasedimentary rocks. Foliage N concentrations were also analyzed as a function of soil-available (mineralizable) N, with the expectation that foliage N levels would increase with increasing soil mineralizable N levels. However, the correlation was very weak (R^2=0.05). A model combining the effects of rock type, mineralizable N and elevation better described variation in foliage N (R^2=0.27), with foliage N positively related to mineralizable N and negatively related to elevation. Interestingly, this model showed that trees on basalt, sedimentary rock or modern sediments had higher foliar N concentrations than those on glacial tills or metasedimentary rocks. Other site factors including soil fertility, soil water potential, aspect and slope were not related to foliage N, and foliage N did not vary by vegetation type or geographic region. This suggested that underlying rock did somehow influence foliage N nutrition.

Cations—Extractable cation data from soil samples from 119 sites indicated that extractable K was not affected by ash cap presence or depth, but was affected by underlying parent material (fig. 6a). Extractable Ca and Mg both decreased with increasing ash depth (Ca: R^2=0.30, fig. 6b and Mg: R^2=0.33, fig. 6c). Given the same depth of ash, Ca and Mg were lowest on sites with granitic parent materials and highest on basalt and metasedimentary parent materials. In contrast to

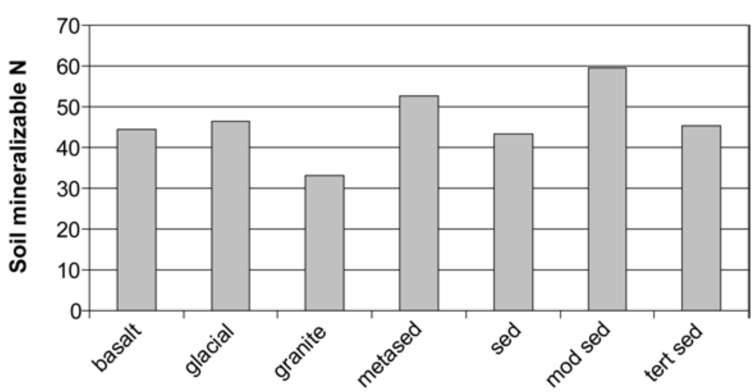

Figure 5a—Soil mineralizable nitrogen (N, ppm) by base parent material. Parent materials include basalt, glacial deposit (glacial), granite, metasedimentary (metased), sedimentary (sed), modern sedimentary deposits (mod sed) and tertiary sedimentary deposits (tert sed).

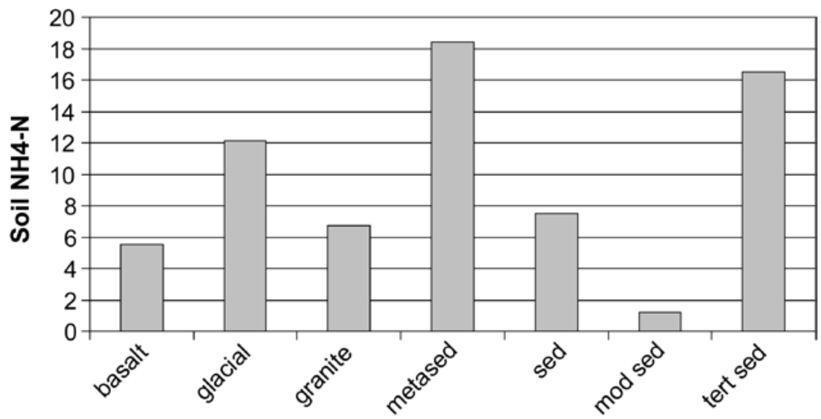

Figure 5b—Soil ammonium-nitrogen (NH4-N, ppm) by base parent material. Parent materials include basalt, glacial deposit (glacial), granite, metasedimentary (metased), sedimentary (sed), modern sedimentary deposits (mod sed) and tertiary sedimentary deposits (tert sed).

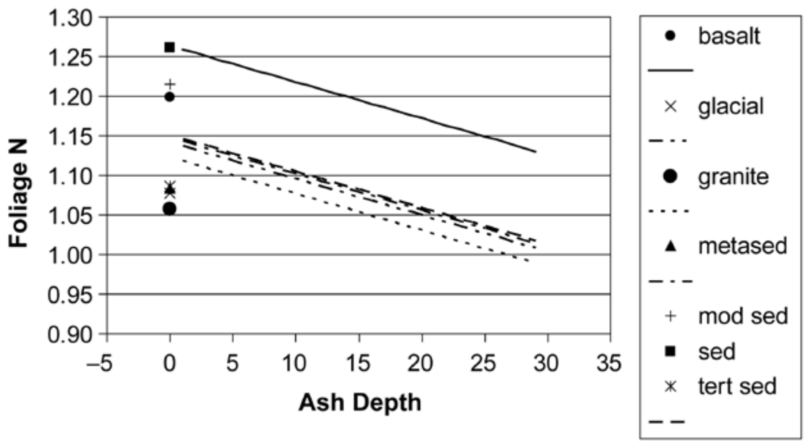

Figure 5c—Douglas-fir foliar nitrogen (N) concentration (percent) as a function of ash depth (inches), by base parent material. Parent materials include basalt, glacial deposit (glacial), granite, metasedimentary (metased), sedimentary (sed), modern sedimentary deposits (mod sed) and tertiary sedimentary deposits (tert sed).

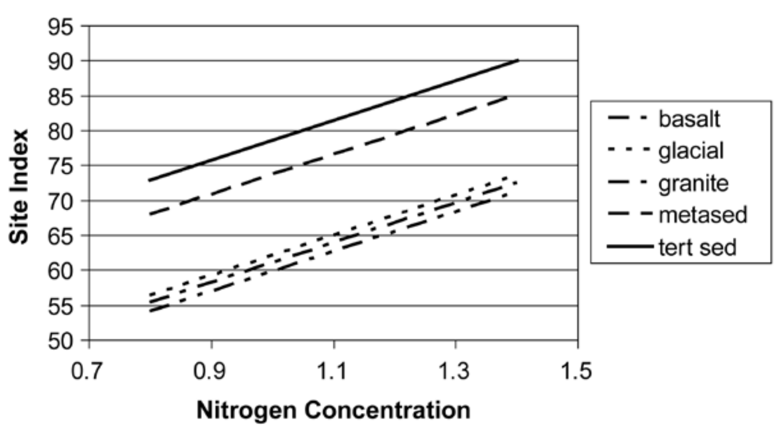

Figure 5d—Site index ($ft^3ac^{-1}yr^{-1}$) as a function of ash depth (inches), by base parent material. Parent materials include basalt, glacial deposit (glacial), granite, metasedimentary (metased), sedimentary (sed), modern sedimentary deposits (mod sed) and tertiary sedimentary deposits (tert sed).

soil K, Douglas-fir foliar K was unaffected by underlying parent rock, but was consistently higher in the presence of ash (fig. 6d). Once ash was present, ash depth had no effect on foliar K. Douglas-fir foliar Ca (fig. 6d) and Mg (fig. 6e) concentrations behaved similarly to soil availability in that both decreased with increasing ash depth. Underlying parent material did not affect foliar Ca or Mg values. Foliar K, Ca and Mg concentrations were generally above nutritional critical levels (table 2).

Phosphorus—Soil-available P data were available for only 45 sites. Soil-available P was not affected by ash presence or depth, but was affected by parent material (fig. 7a), with glacial deposits showing the highest P availability and metasedimentary rocks the lowest. Douglas-fir foliar P values were generally above critical levels (table 2), and were also unaffected by ash presence or depth. Foliar P concentrations differed by parent material, and were highest on glacial deposits

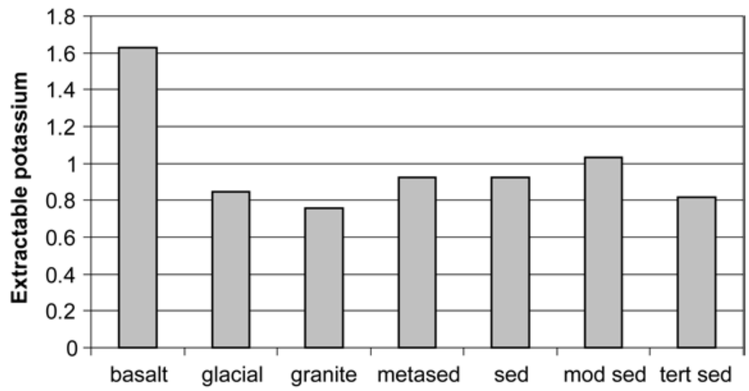

Figure 6a—Extractable potassium (K, cmol kg^{-1}) by base parent material. Parent materials include basalt, glacial deposit (glacial), granite, metasedimentary (metased), sedimentary (sed), modern sedimentary deposits (mod sed) and tertiary sedimentary deposits (tert sed).

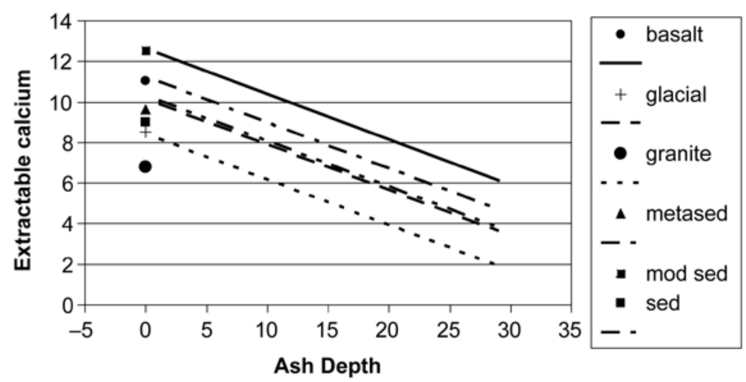

Figure 6b—Extractable calcium (Ca, cmol kg^{-1}) as a function of ash depth (inches), by base parent material. Parent materials include basalt, glacial deposit (glacial), granite, metasedimentary (metased), sedimentary (sed), modern sedimentary deposits (mod sed) and tertiary sedimentary deposits (tert sed).

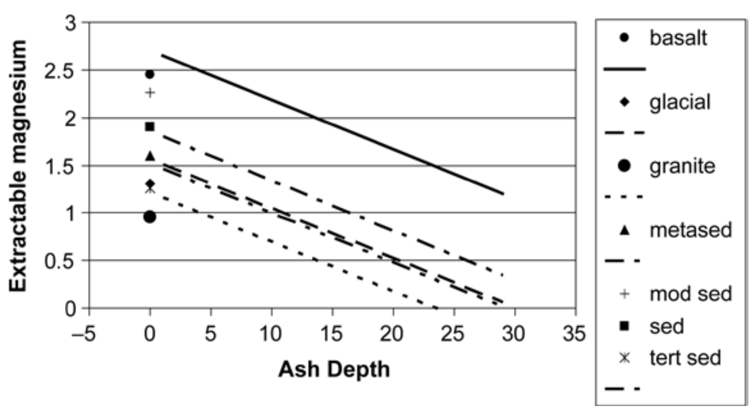

Figure 6c—Extractable magnesium (Mg, cmol kg^{-1}) as a function of ash depth (inches), by base parent material. Parent materials include basalt, glacial deposit (glacial), granite, metasedimentary (metased), sedimentary (sed), modern sedimentary deposits (mod sed) and tertiary sedimentary deposits (tert sed).

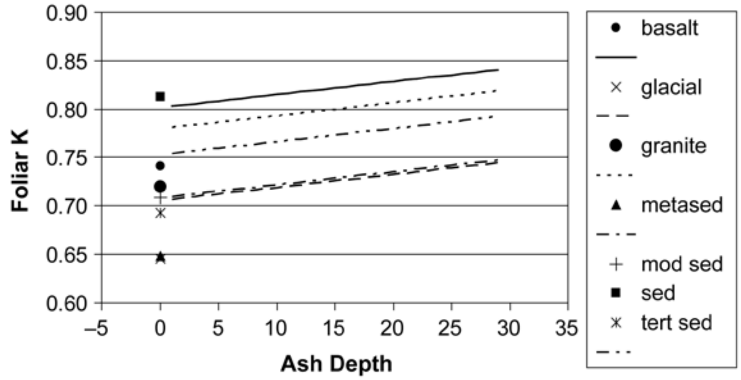

Figure 6d—Douglas-fir foliar potassium (K) concentration (percent) as a function of ash depth (inches), by base parent material. Parent materials include basalt, glacial deposit (glacial), granite, metasedimentary (metased), sedimentary (sed), modern sedimentary deposits (mod sed) and tertiary sedimentary deposits (tert sed).

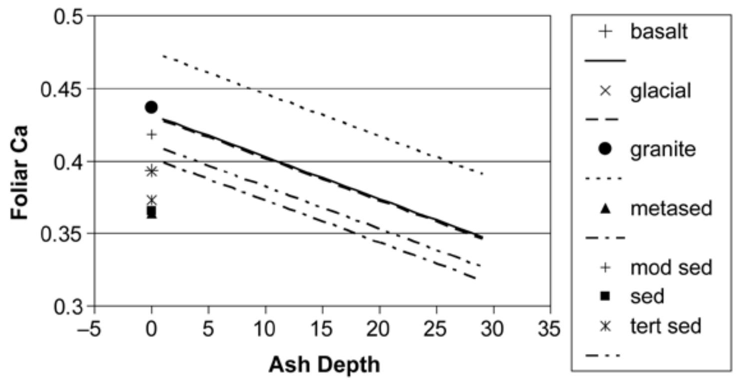

Figure 6e—Douglas-fir foliar calcium (Ca) concentration (percent) as a function of ash depth (inches), by base parent material. Parent materials include basalt, glacial deposit (glacial), granite, metasedimentary (metased), sedimentary (sed), modern sedimentary deposits (mod sed) and tertiary sedimentary deposits (tert sed).

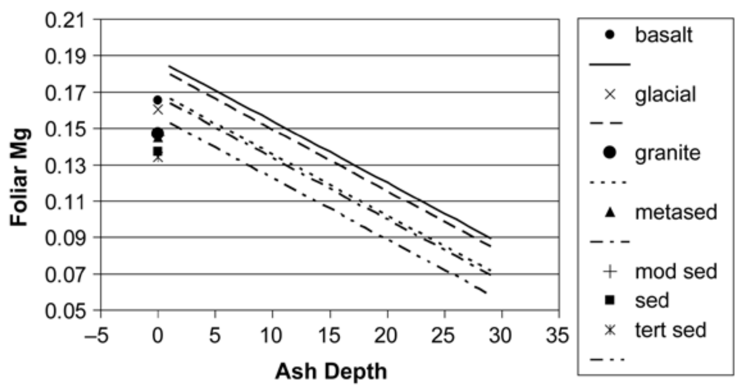

Figure 6f—Douglas-fir foliar magnesium (Mg) concentration (percent) as a function of ash depth (inches), by base parent material. Parent materials include basalt, glacial deposit (glacial), granite, metasedimentary (metased), sedimentary (sed), modern sedimentary deposits (mod sed) and tertiary sedimentary deposits (tert sed).

and lowest on metasedimentary rocks (fig. 7b). Neither foliar P concentrations nor soil P tests suggested any effect of ash on P availability during this study.

Sulfur, B and Cu—Sufficient data were available to perform statistical analyses for available B and S (45 sites) and Cu (29 sites). Given ash presence, available B increased with increasing ash depth (fig. 8a). There was no evidence that parent material or vegetation series affected soil B availability. In contrast, available Cu was not affected by ash presence or depth, but did vary by parent material, ranging from 0.46 ppm on granitic sites to 1.03 ppm on modern sedimentary

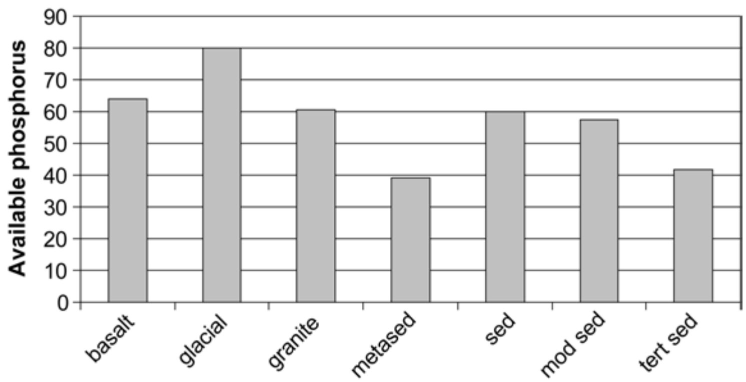

Figure 7a—Available phosphorus (P, ppm) by base parent material. Parent materials include basalt, glacial deposit (glacial), granite, metasedimentary (metased), sedimentary (sed), modern sedimentary deposits (mod sed) and tertiary sedimentary deposits (tert sed).

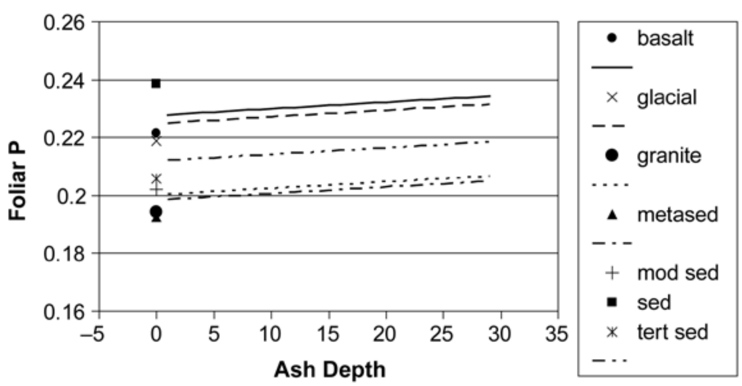

Figure 7b—Douglas-fir foliar phosphorus (P) concentration (percent) as a function of ash depth (inches), by base parent material. Parent materials include basalt, glacial deposit (glacial), granite, metasedimentary (metased), sedimentary (sed), modern sedimentary deposits (mod sed) and tertiary sedimentary deposits (tert sed).

deposits (fig. 8b). Sulfate-S availability was not affected by ash, parent material or vegetation series.

Douglas-fir foliar B values increased with increasing ash depth, showing good agreement with soil-available B tests (fig. 8c). Foliar B was also affected by parent material, ranging from about 23 ppm on granitic rocks to about 29 ppm on tertiary sediments in the absence of ash. Foliar Cu values, in contrast, were not affected by parent material or ash presence or depth. Foliar B and Cu values were generally above nutritional critical levels (table 2). While foliar S concentrations were at or above critical level most of the time, S was the next most likely element, after N, to show deficiency levels.

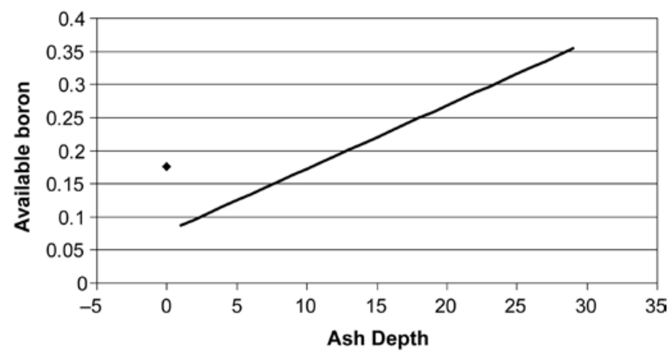

Figure 8a—Soil available boron (B, ppm) as a function of ash depth (inches).

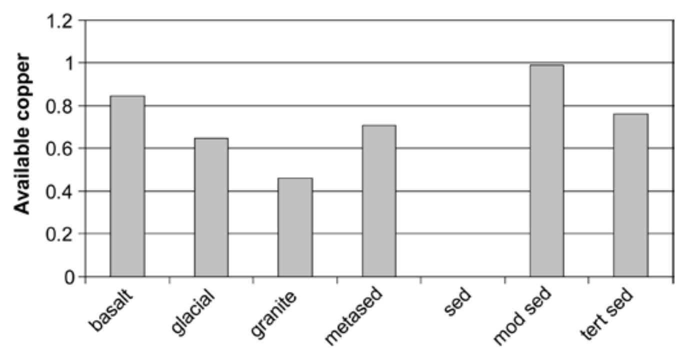

Figure 8b—Available copper (Cu, ppm) by base parent material. Parent materials include basalt, glacial deposit (glacial), granite, metasedimentary (metased), sedimentary (sed), modern sedimentary deposits (mod sed) and tertiary sedimentary deposits (tert sed).

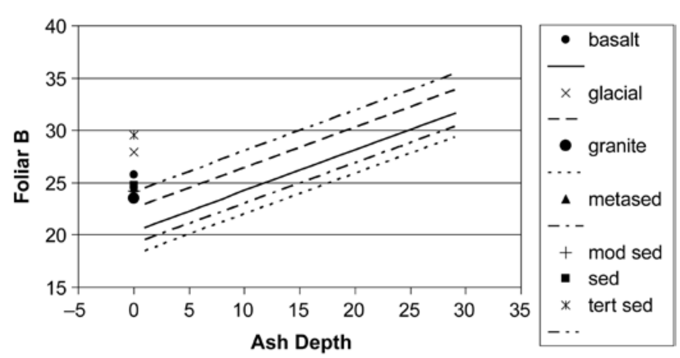

Figure 8c—Douglas-fir foliar boron (B) concentration (ppm) as a function of ash depth (inches), by base parent material. Parent materials include basalt, glacial deposit (glacial), granite, metasedimentary (metased), sedimentary (sed), modern sedimentary deposits (mod sed) and tertiary sedimentary deposits (tert sed).

Fertilization Response

Nitrogen Fertilizer Response—Across all geographic regions, base parent materials and vegetation series, 6-year gross volume response to N fertilizer of stands on ash-cap sites was 49.6% greater on average than fertilizer response of stands on non-ash sites. However, once ash was present, ash depth had no effect. The combined effect of parent material and ash presence more effectively described variation in response than ash cap alone. Ash presence increased volume response by 87% on glacial deposits, 76% on tertiary sediments, 48% on modern sediments and 34% on basalts (fig. 9a). Ash presence did not affect volume response on metasedimentary or granitic parent materials. Vegetation series did not describe any additional fertilization response once ash presence was accounted for. A model combining parent material and vegetation series was more effective at explaining variation in response (fig. 9b) than the parent material and ash model. Sites on western red cedar vegetation series and basalt or glacial till parent materials showed the highest N fertilizer response, while sites on Douglas-fir vegetation series and metasedimentary parent materials showed the lowest response, with other sites falling in between. Even though this relationship between response and vegetation series suggested that soil moisture may affect response, the relationship between volume response to N fertilization and potentially available water in the upper 24 inches of soil was statistically nonsignificant.

Volume response to N fertilizer decreased with increasing soil mineralizable N (R^2=0.34; fig. 9c) and ammonium-N. However, volume response to N fertilizer showed no relationship to unfertilized foliar N levels. Changes in foliar N concentration caused by N fertilization were inversely related to unfertilized foliar N concentrations (fig. 9d). In other words, the lower the untreated foliar N levels, the greater the change in foliar N resulting from N fertilization. Neither ash presence nor depth influenced this change, thus the presence of ash did not appear to affect the availability of applied N to trees. Furthermore, neither vegetation series nor rock type affected the fertilization-induced change in foliar N concentration.

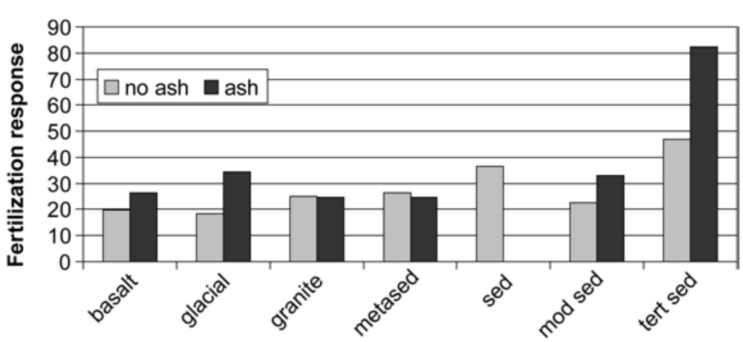

Figure 9a—Six-year nitrogen (N) fertilization response ($ft^3ac^{-1}yr^{-1}$) by base parent material and ash cap presence. Parent materials include basalt, glacial deposit (glacial), granite, metasedimentary (metased), sedimentary (sed), modern sedimentary deposits (mod sed) and tertiary sedimentary deposits (tert sed).

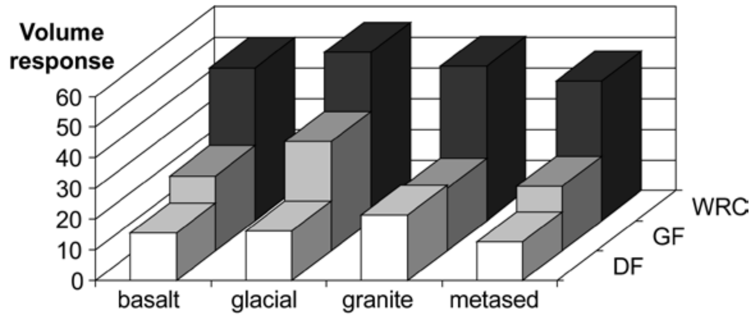

Figure 9b—Six-year nitrogen (N) fertilization response (ft^{3}ac^{-1}yr^{-1}) by base parent material and vegetation series. Parent materials include basalt, glacial deposit (glacial), granite and metasedimentary (metased). Vegetation series include Douglas-fir (DF), grand fir (GF) and western red cedar (WRC).

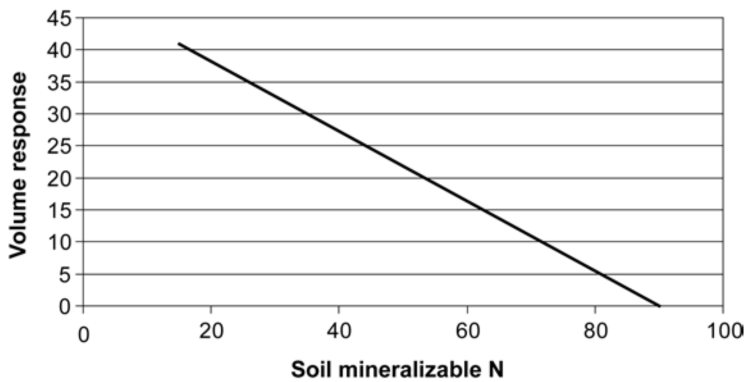

Figure 9c—Six-year nitrogen (N) fertilization response (ft^{3}ac^{-1}yr^{-1}) as a function of soil mineralizable nitrogen (N, ppm).

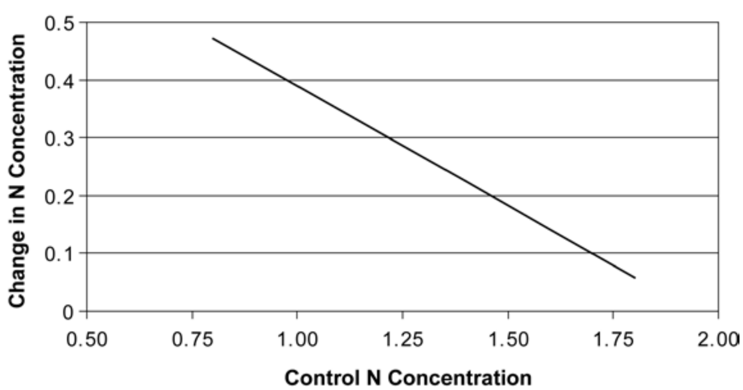

Figure 9d—Change in Douglas-fir foliar nitrogen (N) concentration (percent) following N fertilization as a function of control plot (unfertilized) foliar N concentration (percent).

Discussion

Ash distribution

Ash presence generally explained the same variation as geographic region, parent material and vegetation series. The confounding with vegetation series was not unexpected. It has long been known, for example, that western red cedar habitat types are highly likely to have ash cap. It is also known that ash cap is more widely distributed in north Idaho, northeast Washington and northeast Oregon and less commonly found in central Washington and central Idaho. The confounding of ash presence with underlying parent material type is perhaps less intuitive, but is likely related to the geographic distribution of those parent materials. Sites located on tertiary sedimentary deposits, metasedimentary rocks and glacial deposits are more likely to occur in north Idaho and northeast Washington, while sites located on basalts, granites, modern deposits and sedimentary rocks are more likely to occur in central Washington and central Idaho.

Site Productivity

While SI was available for only 110 sites and CGR for all 139 sites, the two variables were highly correlated ($R^2=0.59$), suggesting that both variables behaved similarly as descriptors of site productivity. For both variables, ash presence at a depth of 1 inch or greater significantly increased site productivity relative to non-ash sites. The increase was greater for CGR, suggesting that this variable was a more sensitive indicator of the effect of ash presence on site productivity. However, additional ash depth had no effect on either of the site productivity variables. Thus, once ash was present, it did not appear to matter how deep the ash was in terms of predicting site productivity.

Even though potentially available water was positively correlated with ash depth and site productivity, site productivity was unaffected by increasing ash depth. This meant that something about the ash besides potentially available water was affecting site productivity. Decreased nutrient availability was one possible factor limiting site productivity. Foliage and soil-available Mg and Ca generally decreased with increasing ash depth. Decreased availability of these elements on sites with deeper ash caps could help explain the lack of a corresponding increase in site productivity even though potentially available water was higher on such sites. Positive relationships between ash and nutrient availability of B, P and K suggested that these elements were not likely growth-limiting in the presence of ash.

Site Fertility

Soil Moisture—Potential available water is a descriptor of the capability of a site to retain and supply moisture to the plants growing on that site. Potentially available water increased with increasing ash depth, as seemed reasonable based on our experience with ash-cap soils. The finding that potentially available water was greater on western red cedar series than on grand fir or Douglas-fir series also seemed reasonable, given that most western red cedar sites occurred in conjunction with ash-cap soils. However, variation in potentially available water by vegetation series and ash depth (fig. 3b) suggested that sites on western red cedar vegetation series still had higher available water than sites on grand fir or Douglas-fir series even after accounting for ash. Thus, something besides ash presence and depth affected potentially available water and the resulting vegetation series. Factors besides ash likely to affect soil moisture and vegetation series are climate, soil temperature regime, soil depth, soil texture, parent material and topographic position (slope, aspect, and elevation).

Some of the variation in potentially available water among parent materials in the presence of ash likely reflected differences in underlying soil texture as well as ash depth. Basalt and metasedimentary rocks weather to finer size-class soils with inherently higher potential moisture availability compared to the coarser-grained and more permeable soils derived from granitic rocks and glacial deposits. However, the interaction between ash presence and parent material was less easily explained. Sites on granitic rocks and glacial deposits showed higher moisture availability in the absence of ash than in the presence of a shallow ash layer (fig. 3c). Sites on granitic rocks needed about 7 inches of ash and glacial sites about 16 inches of ash to achieve the same potentially available moisture as the non-ash sites on these same rock types. After meeting these threshold levels, potentially available moisture continued to increase with increasing ash depth on both rock types. Perhaps some degree of soil mixing occurred between ash and the underlying residual soils that negatively impacted moisture-holding capacity at the shallower ash depths.

Soil Acidity—Soil pH tended to increase with increasing ash depth. However, a complex relationship between parent material and ash depth suggests that this increase was driven primarily by data from sites on granitic and basaltic substrates, where increasing ash depth led to increased pH. On all other parent materials, which were sedimentary in origin, ash depth had no effect on soil pH. The reasons for this behavior are not entirely clear. Soil pH levels of the research sites included in this study were within a range where nutrient availability and uptake of applied fertilizer elements should not be adversely affected.

Nitrogen—Foliar and soil measures of N availability suggested that N was affected by parent material, but unaffected by ash presence or depth. Soil mineralizable N and available ammonium-N were consistently higher on metasedimentary and tertiary deposit sites and lower on granitic and basaltic sites. In contrast, foliar analyses suggested that N uptake was greatest on sites with basalt parent materials. This suggests that trees growing on basalt parent materials were better able to take advantage of soil-available N than trees on other rock types, or conversely that trees on metasedimentary and tertiary sedimentary deposits were less able to utilize soil-available N.

Reasons for the contrasting effects of parent material on soil-available N pools were not clear from this analysis. Parent material could positively affect N supply by imparting soil textural or chemical conditions that are conducive to increased N-mineralization rates. Conversely, parent material may negatively affect plant uptake of N through introduction of a more significant growth-limiting factor, such as low moisture availability (affected by soil texture) or low nutrient availability (affected by parent material mineralogy). Either scenario could contribute to an increase in the soil mineralizable N pool. Mineralizable N was strongly correlated with soil organic matter and soil carbon, suggesting that N-mineralization rates were also governed by organic matter availability. Climatic conditions may affect organic matter production by affecting productivity and/or by affecting conditions conducive to N mineralization. While foliar N was only weakly correlated with mineralizable N, it was negatively correlated with elevation, suggesting greater N availability on warmer, lower elevation sites. Other site factors including site fertility, soil water potential and topographic factors had no effect on foliage N concentrations.

Cations—Like N, cations were also affected by base parent materials, though in a more predictable fashion. In the absence of ash, soil-extractable Ca and Mg concentrations in the upper 12 inches of soil were higher on basalt parent materials and lower on granites. Because basalts are higher in Ca- and Mg-bearing minerals than granites, this finding is plausible. However, once ash was present, available Ca and Mg decreased with increasing ash depth on both basalts and granites. This suggests that Ca and Mg storage in ash is poor even in the presence of Ca- and Mg-rich underlying parent materials, and that soil Ca and Mg availability may be lower on sites with deeper ash caps. This may reflect the dilution of residual soils with increasing ash presence, and a resulting dilution of Ca and Mg pools in the upper 12 inches of soil. Foliar chemistry also suggested that plant uptake of both elements decreased at increasing ash depths.

In contrast to Ca and Mg, soil-extractable K was unaffected by ash presence or depth, and was only affected by parent material. The parent material effect was driven by basalt, which showed higher extractable K than other rock types. However, foliar K was unrelated to parent material, and was positively affected by ash presence (but not affected by depth). The lack of a relationship between soil-extractable K and foliar K could indicate that either the soil or foliar test for K was inadequate. These results could also suggest that ash presence somehow facilitated tree uptake of K, even though soil-extractable K appeared unaffected by ash presence. This may also be an indicator of low cation retention by ash soils and the high mobility of the K^+ ion.

Phosphorus—Despite concerns of possible P adsorption by ash soils, soil and foliar tests suggested that P availability and uptake were unaffected by ash presence or depth. On all sites, foliar P concentrations were at or above nutritional critical levels, suggesting that sufficient P was available for tree growth and function.

Boron, Cu and S—Boron showed increasing soil availability and foliar concentration with increasing ash depth. This positive relationship suggests that ash may provide efficient storage for B, and also that ash does not adsorb B to an extent that makes the B unavailable for plant uptake. Ash did not affect soil or foliar Cu values. Soil-available Cu showed some variation by parent material that was likely related to trace minerals in the various parent materials. However, there was poor agreement between soil-available and foliar Cu concentrations in that foliar Cu showed no corresponding parent material effect. Soil-available S was unaffected by ash presence or depth, or by parent material.

Fertilization Response

Nitrogen—Overall, volume growth response to N fertilization was much better on sites with ash than on sites without. Including base parent material in the model with ash contributed an additional degree of predictability of volume response to N fertilization. Ash was particularly valuable in increasing fertilization response on the sedimentary deposits (including glacial deposits) and somewhat less so on the basalt, granite and metasedimentary rocks.

The relationship of fertilization response to soil mineralizable N suggested that the lower the mineralizable N, the higher the fertilization response. This supports the idea that N-deficient sites should show a higher degree of response to N fertilization. Similarly, the change in foliar N concentration following fertilization should indicate the effectiveness of the fertilization treatment in changing the amount of N available to the trees for growth. However, unfertilized foliar N concentrations, while inversely proportional to the change in foliar N concentration following N application, did not show any relationship to fertilization response. Thus, while lower foliar N levels were predictive of a greater increase in foliar N after fertilization, they were not necessarily predictive of a greater N fertilization response. Increases in foliar biomass following N fertilization have been shown to be more predictive of future volume response than changes in N concentration alone (Weetman and Fournier 1986; Hasse and Rose 1995; Brockley 2000).

Sulfur and K—Sites with ash generally responded better to S fertilization than those without. However, once ash was present, the trend was decreasing response with increasing ash depth, suggesting possible S adsorption by ash-cap soils. No evidence was found to suggest that ash presence affected growth response or foliar K status following K fertilization.

Nutritional Characteristics of Ash

Anion adsorption may be an issue of concern in ash soils due to the characteristic variable charge of ash (McDaniel and others 2005; Kimsey and others 2005). The decrease in tree growth response to S fertilization with increasing ash depth suggests possible sulfate retention by ash soils. However no evidence of nitrate retention appeared following N application as urea or ammonium. Foliar tests suggested that applied N was taken up by the trees, and 6-year growth response suggests that N-fertilization did increase biomass and volume production. Phosphorus and B were not applied during these fertilization trials because foliage tests indicated that these elements were not deficient. Our results also suggested that ash did not have any effect on soil-available or foliar P, implying that P is not likely a growth-limiting element on ash-cap soils. Boron availability appeared to increase with increasing ash depth according to both soil-available and foliage tests. While insufficient data were available to test for the fate of B following application, B adsorption did not seem to be a growth-limiting characteristic of ash soils during this analysis.

The inability of pure, unweathered ash to store and supply cations may also be an issue of concern in andic soils (McDaniel and others 2005). Despite the degree of mixing and weathering exhibited by the ash-cap soils in our study, storage and supply may still have been an issue for Mg^{2+} and Ca^{2+}. Both elements showed decreased soil availability and foliar concentration with increasing ash depth. This occurred even when the underlying parent materials were high in Ca and Mg, suggesting possible dilution of residual soil nutrient pools by ash. In contrast, soil-extractable K was unaffected by ash presence or depth, and was only affected by parent material. Thus, ash soils appeared capable of taking on the K characteristic of underlying parent material, but not the Ca or Mg characteristic. This could occur because K^+ is a more mobile ion and is likely to be taken up by plants and deposited on the soil surface. Also, foliar K was positively affected by ash presence, suggesting that ash soils were better able to supply K, though not necessarily store it, compared to non-ash soils. Thus, cation storage and supply or nutrient pool dilution of the divalent cations appeared potentially problematic in ash soils, while the monovalent K ion was less affected by ash retention and dilution issues.

Management Recommendations

Site Nutrition and Nutrient Management

"Nutrient management" refers to silvicultural activities as they affect the nutrient capital of a forest stand. It can include fertilization treatments and activities that retain nutrients on site during silvicultural activities. Because most nutrients are held in limbs and foliage (Cole and others 1967; Pang and others 1987; Miller and others 1993; Moller 2000), a conservative nutrient management strategy would be to leave the tops and limbs of harvested trees on-site through a variety of bole-only harvesting techniques. Whole-tree operations in late fall and winter, when breakage is more likely, should also be effective at retaining some nutrients on the site. Species differ in nutrient demand (Gordon 1983; Gower and others 1993; Miller and others 1993; Moore and others 2004). Therefore, planting nutritionally challenged sites with less-demanding species and favoring less-demanding species during silvicultural operations are also conservative nutrient management strategies.

Tests of foliage and soil chemistry may be performed as site specific indicators of productivity and potential fertilization response. Foliar N was a better predictor of site productivity, while soil mineralizable N was a better predictor of fertilizer response. If satisfactory information on site productivity is available and the parent material/ash combination suggests that the site may be responsive to fertilization, managers should consider focusing on tests of soil mineralizable N. If mineralizable N is below 70 ppm, the site should show a 6-year volume response of 10% or more, with the potential response increasing as mineralizable N decreases. Foliar N may be tested as an indicator of overall site productivity; however, the effort and expense of this test make it less desirable than performing simple site height/age measurements.

Nutrient Management Recommendations by Parent Material and Ash Presence

Basalts, Glacial and Modern Deposits—Sites on basalts, glacial deposits and modern sedimentary deposits showed no change in site productivity in terms of CGR in the presence of ash. However these sites did show moderate (basalt and modern sedimentary) to high (glacial deposit) increases in volume growth responses to N fertilization when ash was present. This suggests that sites on these parent materials should respond reasonably well to N fertilization without ash, and respond even better when ash is present. There was weak evidence that on basalt parent materials, the presence of ash inhibited volume response to S fertilization. However, other IFTNC studies have shown that S is sometimes necessary to stimulate a growth response to N fertilization on basalt parent materials (Garrison and others 2000). While all parent materials in this category should respond well to fertilization with N only, stronger growth responses might be induced by multi-nutrient fertilization that includes S. Conservative nutrient management strategies should be evaluated, but may be less crucial on these parent materials compared to other parent materials.

Metasedimentary and Granite—Metasedimentary parent materials showed relatively lower site productivity and granites showed moderate productivity compared to other parent materials. Site productivity increased in the presence of ash on both parent material types, with metasedimentary productivity doubling in terms of CGR. However, N-fertilizer response was unaffected by ash presence for either parent material. This suggests that (1) trees grow better on metasedimentary and granitic rocks when ash is present, and (2) fertilization with N alone will not increase productivity on ash sites over that of non-ash sites on metasedimentary or granitic rocks. There was weak evidence that metasedimentary and granitic sites with ash may respond positively to S fertilization. Preliminary results of recent fertilization screening trials on both parent material types showed generally poor growth response to fertilization with N alone, and stronger response to a combined treatment of N, K, S, and B when ash was present (Garrison-Johnston and others 2005, unpublished data). Thus, multinutrient fertilization is more likely to stimulate growth response on ash soils on metasedimentary and granitic parent materials. General nutritional challenges of these sites suggest use of conservative nutrient management strategies.

Tertiary Sedimentary Deposits—Tertiary sedimentary parent materials behaved somewhat differently than the other parent materials in that both site productivity and N fertilization response were enhanced in the presence of ash. Because the available data for tertiary sedimentary sites was sparse, these results for this deposit type should be viewed cautiously. However, this suggests that if stands on tertiary sediments are growing well, they should respond well to N fertilization in the absence of ash, and even better when ash is present. Some caution should be exercised in applying fertilizer, however, as field experience has also shown that tertiary sedimentary deposits can inherently be quite variable in composition. Pending further investigation, use of conservative nutrient management strategies is also recommended.

Conclusions

Stand productivity was greater on sites with ash cap than on sites without; however once ash was present, changes in ash depth did not affect site productivity. Because ash presence or absence tended to coincide with particular vegetation series and geographic regions, ash presence did not further explain variation in site productivity beyond that described by those variables. While ash presence also tended to coincide with particular parent material types, ash presence still explained some variation in site productivity beyond that explained by parent material. Ash presence was most likely to increase site productivity on metasedimentary rocks, granites and perhaps tertiary sediments.

Although site productivity was positively correlated with potentially available water and potentially available water was positively correlated with ash depth, there was no correlation between site productivity and ash depth. This suggests that something else about the ash, such as poor nutrition, affected productivity. Soil-available and foliar Mg and Ca decreased with increasing ash depth. Thus, while increasing ash depth may have a positive effect on soil moisture potential, it may have a negative effect on nutrient availability, particularly for Mg and Ca, and therefore on site productivity.

Soil N availability (mineralizable and ammonium) and foliage N concentrations were not affected by ash presence or depth, but were affected by parent material. Reasons for the parent material effect were not entirely clear, however the site productivity and soil textural and chemical conditions associated with particular underlying parent materials likely affected organic matter production and cycling. Soil organic matter and carbon content were highly correlated with soil N availability. Climate and elevation likely interacted with parent materials to have an effect on N availability, as well.

Possible nutrient adsorption and supply by ash were also considered. Adsorption of applied N did not appear to occur in ash-cap soils in this study. In contrast, decreasing growth response to S-fertilization at greater ash depths suggested that adsorption of applied S may have occurred. Foliage and soil-availability of P and B either showed no change (P) or increased availability (B) with increasing ash depth, suggesting that availability of these elements may not be an issue of concern in ash-cap soils. Lack of soil Mg and Ca storage and supply at greater ash depths, or perhaps dilution of Mg and Ca supply by increasing quantities of ash, did appear to occur. Soil K was unaffected by ash presence or depth, while foliar K concentrations increased when ash was present, suggesting that K supply was perhaps enhanced by ash presence.

Average volume response to N fertilization was almost 50% greater on ash compared to non-ash sites. However changes in ash depth did not further affect volume response. Ash presence increased volume response to N fertilization on glacial deposits, tertiary sediments, modern sediments and basalts, but not on granite or metasedimentary parent materials. Volume response was greatest on western red cedar vegetation series, followed by grand fir and then Douglas-fir vegetation series. However ash presence or depth did not further affect volume response once vegetation series was known. Parent material combined with vegetation series best described volume response to N-fertilization.

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Economics of Soil Disturbance

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Abstract

Economic implications of soil disturbance are discussed in four categories: planning and layout, selection of harvesting systems and equipment, long-term site productivity loss, and rehabilitation treatments. Preventive measures are more effective in minimizing impacts on soils than rehabilitation treatments because of the remedial expenses, loss of productivity until mitigation occurs, and the possibility that original soil conditions may not be restored. Alternative harvesting practices that are designed to minimize impacts on soils, such as use of designated skid trails and wide trail-spacing, increase overall harvesting costs. Sites with high risk for soil disturbance may require use of expensive wood extraction methods (e.g., skyline yarding), as opposed to lower cost options (e.g. ground skidding). Tillage treatments in severely compacted areas appear to be cost effective if properly implemented. An accurate estimation of economic consequences from long-term site productivity losses is difficult, although there is a general consensus that soil disturbance at some locations can reduce tree growth.

Introduction

Questions on the economics of soil disturbance are often raised regarding long-term productivity losses, efforts to minimize soil impacts, and rehabilitation of damaged soils. What are potential financial impacts from site productivity losses? Should we require every ground-skidding machine on high-risk sites to use designated skid trails and how does this affect logging costs? Would it be cost-effective to ameliorate compacted soils? Are we financially getting a significant benefit from soil rehabilitation treatments? These questions have not been extensively answered because of the difficulty in obtaining appropriate data about tree responses to site disturbance across an entire rotation, the value of offsite impacts, and other pertinent information such as preventive and remediation measures (Lousier 1990; Miller and others 2004).

Lack of information on the economics of soil disturbance limits forest practioners from attempting to develop harvesting plans and timber sales. A harvesting plan needs to account for soil disturbance risks, previous impacts on soils, and preventive measures that minimize further damage to soils. Preventive measures may require cable logging systems on gentle slopes (<30 percent) or wider spacing of designated skid trails, but these often result in higher logging costs. Lack of compelling evidence to justify these high logging options often causes disagreements among forest managers, although there is a general consensus that soil disturbance may reduce tree growth at some locations (Miller and others 2004). One would also wonder if these preventive measures would financially benefit landowners in the long run.

This paper summarizes economic information related to soil impacts in four categories: planning and layout, selection of harvesting systems and equipment, long-term site productivity loss, and rehabilitation treatments. In this paper, soil disturbances include soil compaction, scalping, puddling, and soil displacement.

Planning and Layout: Measures to Prevent Soil Disturbance

Soil disturbance from timber harvesting may not be avoidable, but can be minimized through careful planning and operations. Preventive measures are more effective in minimizing impacts on soils than remedial mitigation because of the remedial expenses, loss of productivity until mitigation occurs, and the possibility that original soil conditions may not be restored (Miller and others 2004). Existing guidelines and requirements for soil protection should always be observed when the harvesting plan is developed. A good harvest plan can minimize soil disturbance by recognizing and identifying the risk of soil disturbance. Some important factors determining "risk rating" include soil texture, moisture content, slope, and organic materials at the top soil.

Planning and layout components for timber harvesting include locations for roads and landings, marking trees to cut or leave, and flagging skid trails or skyline corridors. These vary with different harvesting systems. For example, skyline yarding requires locating anchors for rigging and ground-profile analysis for available deflection, causing higher planning and layout costs for cable logging than ground-based harvesting system. Kellogg and others (1998) compared planning and layout cost for logging contractors in various silvicultural treatments. They found that a CTL system using a mix of random and designated skid trails (60-ft spacing) had the lowest cost, followed by the tractor-based winching system for hand-felled trees that used 130-ft spacing designated skid trails. The skyline systems had the highest cost.

Use of designated skid trails has been recommended in past soil compaction studies because it effectively reduces the skid trail areas in a harvesting unit and facilitates rehabilitation efforts (Andrus and Froehlich 1983). Designated skid trails at a wide spacing increase logging costs. In an earlier study (Bradshaw 1979), the harvest unit with pre-planned skid trails and winching had a 29 percent higher skid cost than the conventionally harvested unit. However, only 4 percent of its area was in skid trails, compared to 22 percent for the conventionally harvested unit.

There are other planning and layout components that increase costs, but are difficult to estimate. These include expenses related to evaluating soil disturbance risks, identifying areas in the field that pose a high risk for soil damage and erosion, and development strategies and guidelines to minimize soil impact. Delaying logging operations to dry seasons or winter season logging and strict requirements for best management practices (BMP) are examples for preventive efforts at a planning stage. These expenses usually occur in the form of overhead or administrative cost and can be estimated based on companies or agencies' indirect cost rates.

Selection of Harvesting Systems and Equipment

Because harvest equipment creates ground pressures and soil disturbance types (e.g., compaction and scalping), choice of harvesting systems and equipment type can greatly affect the degree and extent of soil impacts. Cable systems are often preferred over ground-based systems because cable logging does not require heavy machines moving on harvesting areas. Logs are fully or partially suspended to the skyline and pulled to the landings. Allen (1997) reported that a skyline thinning operation in western Oregon left only 2 percent of soil disturbance while a single entry of cut-to-length (CTL) system caused 25 percent of the harvest area compacted.

However, cable logging is typically more expensive than a ground-based system: cable yarding costs are 65 to 160 percent higher than conventional ground-based logging (Lousier 1990). For example, Keegan and others (1995) surveyed stump-to-truck harvest costs in the Montana and northern Idaho region and found that the cost for ground-based systems was lowest ($87 to $124/thousand board feet (MBF)), followed by cable systems ranging from $13 to $164/MBF. Helicopter systems were most expensive at $233/MBF. Compared to mechanized ground-based systems, cable logging requires more labor to manually handle trees or logs on steep grounds (typically >30 percent slope) as well as to set-up and tear down an entire yarding system, which results in low daily production of timber. Time spent changing skyline roads and rigging also contributes to high costs in cable logging. High logging costs in cable logging becomes more noticeable when handling small-diameter trees. At average 10-inch diameter at breast height (DBH), skyline and helicopter stump-to-truck logging and chipping costs were about 3 and 6 times more expensive, respectively, compared with a mechanized whole-tree harvesting system that showed the lowest cost at $34.23/100 cubic feet (Han and others 2004).

Cable yarding, combined with mechanized felling and processing, has been considered as a way of reducing soil compaction and other types of soil disturbance from the ground skidding or forwarding phase of timber harvesting. Although mechanized felling and in-woods processing using a feller-buncher or a harvester have insignificant impacts on soils, subsequent ground skidding and forwarding cause significant increase in soil bulk density (Allen 1997). The question is how much more expensive it is to use skyline yarding than ground-based skidding. Johnson (1999) reported that cable yarding ($0.51/ft^3) resulted in 113 percent cost increase over forwarding ($0.24/ft^3) of logs felled and processed by a CTL harvester. However, the average forwarding distance (212 ft) for cable yarding was much longer that the one (129 ft) with forwarding. This may lower the road density required for timber harvesting activities and reduce the area of soils disturbed. In eastern Oregon, a skyline yarder was used to extract logs processed by a CTL harvester in an effort to avoid further damage to soil from fuel reduction thinning on slopes that averaged 12 percent or less on all units, with maximums of 25 percent (Drews and others 2000). They reported that the harvester-yarder system averaged much higher ($80/green ton) stump-to-mill costs than the harvester-forwarder system ($46/green ton).

Low ground-pressure machines, such as log loaders and wide-tired skidders, for wood extraction from stump to landing are also often considered to minimize soil compaction. Shovel logging uses a hydraulic log loader to repeatedly swing the logs to reach the road or landing area, and has been used as an alternative to a cable system on moderate grounds (20 to 40 percent slope) or a ground-based system on gentle slopes (<20 percent). The average unit production cost for shovel logging in western Washington was 40 percent less than the one with cable logging at an average external yarding distance of 600 feet (Fisher 1999). Use of a skidder equipped with wide tires to reduce ground pressure has been used by machinery manufacturers as machines have increased in size and weight (Brinker and others 1996). Past studies indicated that wider tires resulted in 13 to 23 percent increase (Meek 1994) or no significant difference (Klepac and others 2001) in skidding cost. Klepac and others (2001) also noted that loggers are reluctant to use wide tires because of additional overhang during machine transport from one site to another, and requirement for a higher torque, heavy-duty rear axle in the skidder.

When selecting a mechanized, ground-based system for timber harvesting, a CTL system is often compared with a whole tree system consisting of a feller-buncher, skidder, a processor, and a loader for its harvesting productivity and cost. While production rates and costs for these two systems are comparable (Hartsough and others 1997; Lanford and Stokes 1996; Gingras 1994), impacts on sites can differ significantly (Lanford and Stokes 1995; Gingras 1994). A CTL system is often favored over a whole-tree harvesting system because a harvester processes trees to log length at the stump, leaving all branches and tree tops on site. A forwarder drives over the slash mat, and this helps to minimize impacts on soils.

Long-term Site Productivity Losses

A concern for site productivity losses after soil disturbance from timber harvesting activities is a primary reason for imposing strict requirements for soil protection in the context of sustainable forestry. Some studies have shown that soil compaction adversely impact tree growth. However, estimation of actual or possible productivity losses resulting from soil disturbance is a complicated issue because of difficulties of accurate estimation of soil disturbances consequences on tree growth (Miller and others 2004; Heninger and others 2002; Lousier 1990; Helms and others 1986). Miller and others (2004) suggested that forecasts of reduced timber yield from degraded soils are uncertain because tree response to soil disturbance is greatly affected by other site-specific, growth-determining factors.

In addition to tree's biological and physical responses to soil disturbances, discount rates also have significant impact on the overall economic analysis of soil disturbances; the analysis performs over the entire tree rotation period and discount rates are greatly sensitive to time. Stewart and others (1988) developed an economic model that addressed financial impacts of soil compaction on a long-term basis. The model used a stand-growth simulator and included various scenarios of management options. At a 4 percent discount rate, net-present value analysis showed positive values, thus encouraging preventive efforts (wide trail spacing) and indicating higher affordability for careful logging. Under an assumption that tree yield was reduced on 100 percent of skid trail areas, the net present value (NPV) with 4 percent was $504/ac while it was $144/ac with 8 percent discount rate. One could afford to spend an extra $144/ac to avoid these yield reductions.

Rehabilitation

Soil rehabilitation involves mechanical measures (e.g. tillage) to break up severely compacted soils. It helps promote water and air movement (Andrus and Froehlich 1983) and increase nutrient availability (Miller and others 2004) in a compacted soil. The efficacy of tillage in loosening compacted soils depends on equipment types used and soil properties (Unger and Cassel 1991; Andrus and Froehlich 1983), number of machine passes (Andrus and Froehlich 1983), and tillage depth (McNabb and Hobbs 1989). The overall cost of tilling is directly influenced by these factors.

Andrus and Froehlich (1983) studied production rates and costs for skid-trail tillage at selected sites in Oregon and Washington. Four types of tillage equipment were evaluated in the study: disk harrow, rock ripper, brush blade, and winged subsoiler. Production rates were highest when tilling with one pass of the machine. Uphill tilling on steep grounds required a large crawler tractor at a higher machine cost. The winged subsoiler lossened more than 80 percent of the compacted soil in a single pass and was the most cost-effective tillage method (fig. 1). The authors indicated that tillage results for these sites would have improved if the tillage improvement had made additional passes along the skid trails, but additional passes would increase the cost of tilling.

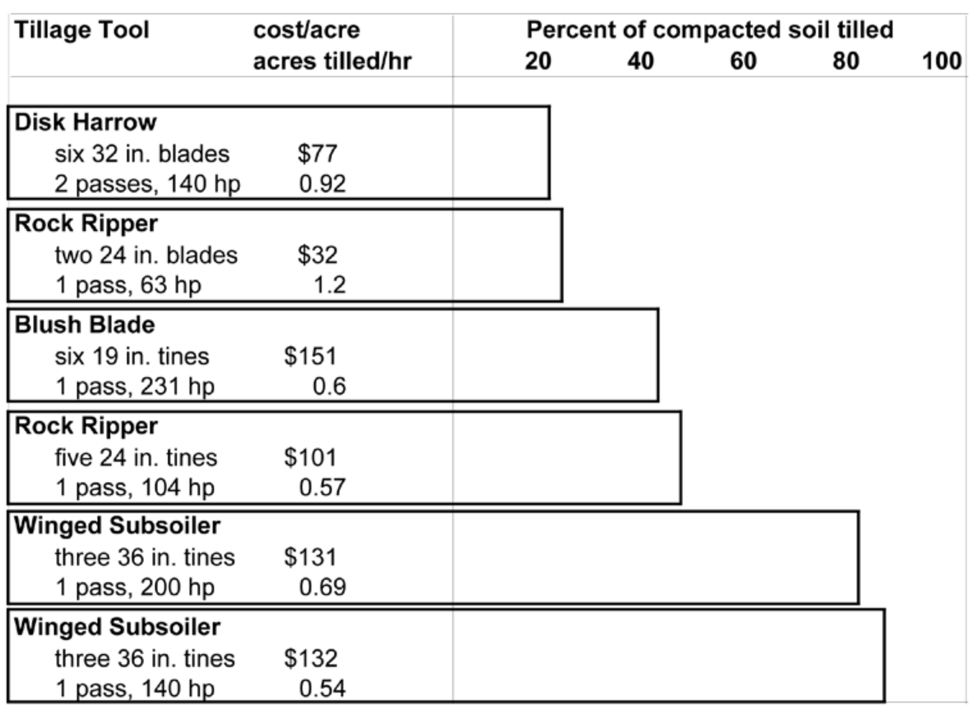

Figure 1—Tillage costs and rates for various type of tillage equipment (Andrus and Froehlich 1983)

If properly implemented, tillage may be cost-effective under the most extreme compaction situations, such as landing areas and heavily traveled skid trails. Stewart and others (1988) estimated the justifiable increased cost for high-cost logging or rehabilitation per harvest entry with 125-ft skid trail spacing. The net financial benefit from tillage was notably affected by discount rates and site index and ranged from $86/ac to $284/ac. This range of justifiable costs is far more than a cost estimate ($20/ac or $176/mile) for skid trail restoration with a winged subsoiler mounted behind Cat D6C crawler tractor (Froehlich and Miles 1984).

Conclusion

Economics of soil disturbance is complicated and requires measuring economic consequences from long-term site productivity losses and expenses for preventive and rehabilitation measures. An accurate estimation of soil disturbances consequences on tree growth is difficult because the tree's response to soil disturbance is affected by other site-specific, growth-determining factors. Many assumptions are needed to estimate future growth and yield and these greatly affect overall financial analyses. Although direct costs for prevention and rehabilitation can be estimated, direct and indirect financial benefits from these practices are not well documented. Major uncertainties originate from the requirement for long-term economic analysis of unknown biological impacts from soil disturbance and inconsistent discount rates used in the analysis.

Preventive measures are more effective in minimizing impacts on soils than rehabilitation treatments because of remedial expenses, loss of productivity until mitigation occurs, and the possibility that original soil conditions may not be restored. Careful planning and layout and selection of harvesting systems and equipment often increase overall harvesting costs. Alternative harvesting practices that are designed to minimize impacts on soils, such as use of designated skid trails and wide trail spacing, increase overall harvesting costs. Rehabilitation expenses are additional to these increased costs. However, these initial expenses can be justified when preventive and rehabilitation measures are focused on high risk sites and severely disturbed areas. Expenses for careful planning and layout, alternative logging practices and rehabilitation measures should be recognized as part of overall logging cost estimation to support the idea of minimizing impacts on soils.

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Special Topic—Grand Fir Mosaic

The Grand Fir Mosaic Ecosystem—History and Management Impacts

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Abstract

The Grand Fir Mosaic (GFM) ecosystem is found on ash-cap soils in some mid-elevation forests of northern Idaho and northeastern Oregon. Harvesting on GFM sites results in successional plant communities that are dominated by bracken fern (*Pteridium aquilinum*) and western coneflower (*Rudbeckia occidentalis*), and have large populations of pocket gophers (*Thomomys talpoides*). Succession to trees and shrubs is very slow on disturbed GFM sites. Four factors contribute to the protracted stages of bracken fern plant communities and the slow rate of succession to woody plants: (1) competition among plants for site resources, (2) allelopathy from bracken fern and western coneflower, (3) pocket gopher activity, and (4) a nonallophanic soil forming process. Nonallophanic soils occur under the bracken fern successional plant communities — they are dominated by Al-humus complexes, have strongly acid pH, have high KCl-extractable Al, and may cause Al toxicity to plants. Allophanic soils occur under forested conditions — they are dominated by allophane and imogolite, have weakly to moderately acid pH, and have low Al availability. Allophanic and nonallophanic soils exist side-by-side in the GFM, with mineralogy being dependent upon the dominant vegetation. Bracken fern and western coneflower, with below-ground carbon inputs from their well-developed root systems, provide a mechanism that promotes the shift from allophanic to nonallophanic soils. Recommendations for reforesting GFM sites are provided.

Introduction

Imagine a moist forest environment in the northern Rocky Mountains where supposedly seral plant communities dominated by bracken fern (*Pteridium aquilinum*) and western coneflower (*Rudbeckia occidentalis*) are really climax plant communities that persist within a matrix of overmature grand fir (*Abies grandis*) and western redcedar (*Thuja plicata*) forests. There are few wildfires here, so natural succession has reduced the occurrence of seral conifers such as lodgepole pine (*Pinus contorta*), Douglas-fir (*Pseudotsuga menziesii*), western white pine (*Pinus monticola*), and western larch (*Larix occidentalis*). Late successional, shade-tolerant species like grand fir, western redcedar, Pacific yew (*Taxus brevifolia*), and sometimes mountain hemlock (*Tsuga mertensiana*) and subalpine fir (*Abies lasiocarpa*), are common along with mid-successional Engelmann spruce (*Picea engelmannii*). Regeneration of conifers in forest canopy openings is a slow and unreliable process in these low pH volcanic ash-cap soils that have abundant populations of pocket gophers (*Thomomys talpoides*). Disjunct and rare plant species occur in and near these forests, including evergreen synthyris (*Synthyris platycarpa*), Oregon bluebell (*Mertensia bella*), Dasynotus (*Dasynotus daubenmirei*), and Case's corydalis (*Corydalis caseana*). These moist forests are collectively called the Grand Fir Mosaic (GFM) ecosystem.

Grand Fir Mosaic forests occur on productive volcanic ash-cap soils in and near the Clearwater, Nez Perce, and southern St. Joe National Forests in northern Idaho, and the Umatilla National Forest in northeastern Oregon. The name for the GFM comes from the dominant conifer (grand fir) and the variety of sizes and shapes of natural openings in the forest canopy. The GFM encompasses approximately 500,000 acres at elevations primarily between 4,500 and 5,500 ft, but is found as low as 4,200 ft and as high as 6,000 ft (Ferguson and Johnson 1996). The most common habitat type is *Abies grandis/Asarum caudatum* (grand fir/wild ginger), a cool, moist habitat defined by Cooper and others (1991).

Successional plant communities in the GFM are dominated by bracken fern and western coneflower. Bracken fern is usually present in low densities under forest canopies, but rapidly expands following disturbance, and can reach heights of 6 ft and densities of 116,000 fronds per acre (Znerold 1979). Below-ground bracken biomass, primarily rhizomes and fine roots, may be as much as 27,280 lbs per acre (Jimenez 2005).

Bracken fern glades are plant communities dominated by bracken fern and western coneflower that appear to persist for millennia. Charcoal samples found at or near the lower boundary of GFM ash-caps were found to be 1,335±75 and 7,755±75 cal. yrs BP using radiocarbon dating (Jimenez 2005). These charcoal samples suggest that woody vegetation has been absent for thousands of years, perhaps dating back to the time of ash deposition during the eruption of Mt. Mazama (Crater Lake, OR) ~7,600 yrs BP (Zdanowicz and others 1999).

Pocket gophers also alter the course of secondary succession in the GFM, particularly for planted conifers. Entire plantations of seedlings can be killed by pocket gophers. Small seedlings are usually pulled from below ground into tunnels where the whole tree is eaten. Gophers may eat all or most of the root system of larger seedlings and saplings.

Our investigations on the GFM were initiated because of difficulty in regenerating harvested areas in the GFM. The first task was to define key ecological processes that might account for the lack of regeneration and the absence of other woody species. Research was planned and implemented to study competition and allelopathy from bracken fern and western coneflower, effects of pocket gophers, environmental characteristics of the GFM relative to adjacent forests, and soil development.

Bracken Fern, Western Coneflower, Pocket Gopher, and Environmental Research

There is abundant research on bracken fern from around the world dealing with allelopathy, competition, encroachment rates, and harm to crops, livestock, and humans. The allelopathic potential of bracken fern has been demonstrated by several researchers, including Stewart (1975) and Gliessman (1976). The allelopathic potential of bracken fern in the GFM was demonstrated by Ferguson and Boyd (1988), who found that most of the seeds that germinated on soil dominated by bracken fern died before the seedcoat was shed. Ferguson (1991) demonstrated allelopathic potential for western coneflower in laboratory tests. Volatile compounds (vapors) from western coneflower reduced or delayed seed germination, and water extracts reduced growth of the seedling radicle.

Growth and mortality of planted conifers at GFM sites was reported by Ferguson and Adams (1994) and Ferguson (1999). Hand weeding of bracken fern and western coneflower from planting sites increased height growth of planted conifer seedlings. Pocket gophers killed from 24 to 59 percent of the seedlings, depending on species. Of the seedlings killed by pocket gophers, 77 percent were killed the first summer (following spring planting) and the first or second winter, but few seedlings were killed the second or third summers.

Environmental conditions were studied by Ferguson and Byrne (2000) to see if they differed between GFM and non-GFM sites in the same vicinity. Remote monitoring stations were used to sample harvested areas at a GFM site and three adjacent habitat types (non-GFM grand fir, subalpine fir, and western redcedar). Variables sampled were wind speed and wind direction at 9 ft above the soil surface; precipitation; solar radiation; relative humidity at 4.5 ft; air temperature at 4.5 ft; soil temperature on the soil surface, 1 inch, and 8 inches depth; soil water potential at 1 inch and 8 inches; and soil pH at 1 inch.

Comparison of the GFM site to non-GFM sites in the same vicinity showed that the GFM site had a shorter growing season, even though one of the sites was a subalpine fir habitat type 140 ft higher in elevation than the GFM site. Snow melted at the GFM site an average of 9 days later than at the subalpine fir habitat type, 24 days later than at the non-GFM grand fir habitat type, and 52 days later than at the western redcedar habitat type.

Average GFM soil temperatures at 1 and 8 inches were cooler than the non-GFM sites in April and May because of late snowpacks at the GFM site. During the rest of the growing season, the GFM site was warmer than the subalpine fir habitat type, but cooler than the grand fir and western redcedar habitat types.

Summer soil moisture at the GFM site did not dry to the permanent wilting point as often as the non-GFM sites. Soils at 8 inches dried to a water potential of –15 bars in only 2 of 6 years of monitoring at the GFM site, while –15 bars was reached during 4 of the 6 monitoring years at the non-GFM grand fir habitat type, 4 of 5 years at the western redcedar habitat type, and 5 of 5 years at the subalpine fir habitat type.

The most insightful variable measured was soil pH at 1-inch depth. The GFM site was different from the other three sites because soil pH cycled from about 6.0 in the spring to 4.0 in the summer and back to 6.0 in the fall (fig. 1). Each year for 7 years, soil pH was lower than 5.0 for several weeks to a few months. A soil pH below 5.0 is a commonly cited threshold where Al toxicity is common to many crops (Shoji and others 1993). A laboratory study has shown that exchangeable Al increases exponentially in GFM soils as pH decreases below 5.0 (Page-Dumroese and others, this proceedings).

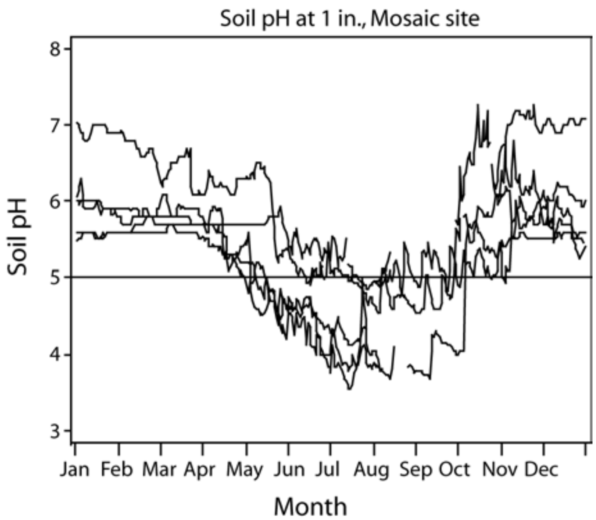

Figure 1—Average daily soil pH at 1 inch for a GFM site, 1989 through 1995 (Ferguson and Byrne 2000). Each line is a different year of data, and discontinuous lines are periods of time when soils were too dry to collect pH measurements. The horizontal line at pH 5 shows a commonly cited threshold where plants start to experience Al toxicity.

Ash-cap Soil Relationships

Allophanic and Nonallophanic Andisols

The Andisol soil order includes soils that are characterized by andic soil properties that arise from the presence of significant amounts of noncrystalline aluminosilicates such as allophane and imogolite, Al-humus complexes, and/or poorly crystalline Fe oxides (Soil Survey Staff 2003). A lack of illuvial B horizons indicates that the process of translocation is not significant within the Andisol order (Ugolini and others 1988; Dahlgren and others 1991) and clearly separates Andisols from other soil orders with similar mineralogical components.

Andisols are commonly described as being allophanic or nonallophanic, depending on the nature of the minerals present. Allophanic Andisols are dominated by allophane, imogolite, and clay minerals; are weakly to moderately acid; and have low KCl-extractable Al and low Al saturation (table 1) (Shoji and others 1985; Nanzyo and others 1993). Nonallophanic Andisols have Al-humus complexes and crystalline clay minerals as their dominant mineralogical components, and contain

Table 1—Comparative characteristics of allophanic and nonallophanic Andisols.

Characteristic	Allophanic	Nonallophanic
Mineralogy	More allophane and imogolite; less Al-humus complexes	Less allophane and imogolite: more Al-humus complexes
Soil acidity	Weakly to moderately acid	Strongly acid
Exchangeable Al	Low	High
Al toxicity	Rare	Common

a substantially smaller proportion of allophane and imogolite as compared to allophanic Andisols. In addition, nonallophanic soils are strongly to very strongly acid, have high KCl-extractable Al, and commonly exhibit Al toxicity (table 1) (Shoji and others 1985; Nanzyo and others 1993). Al-humus complexes and high concentrations of exchangeable Al in nonallophanic Andisols result in rapid dissolution and equilibrium between Al in solid and solution phases. Allophanic Andisols are dominated by allophane and imogolite, which have slower dissolution rates and, therefore, result in slower release of Al into soil solution (Dahlgren and Saigusa 1994; Dahlgren and others 2004). The rapid release rates of Al in nonallophanic Andisols provide a source of Al for plant uptake. Due to the possibility of Al toxicity, the distinction of allophanic and nonallophanic Andisols is important for management purposes.

Because of the impact of Andisol mineralogy on plant productivity (Dahlgren and others 2004), it is important to understand the factors that control mineral formation and weathering within the order. Differences in parent material such as tephra age, geochemistry, hydraulic properties, and additions of exogenous materials such as loess (Inoue and Naruse 1987; Vacca and others 2003) have been reported to influence the development of certain mineralogical components within ash-influenced soils. Other factors that are more influenced by management include organic matter and pH (Shoji and Fugiwara 1984; Johnson-Maynard and others 1997). The formation of allophanic Andisols tends to be favored in environments where pH is greater than 5. In contrast, nonallophanic Andisols are predominately found in more acidic (pH < 5) environments with higher concentrations of organic matter (Shoji and Fujiwara 1984; Shoji and others 1993).

The relationship between organic matter, pH, and Al availability indicates that plant communities may play a role in influencing Andisol properties. Specific examples of the impact of vegetation and vegetation conversion on Andisol morphology and chemistry have been reported. Japanese pampas grass (*Miscanthus sinensis*), for example, is associated with the formation of dark, humus-rich, surface horizons known as melanic epipedons (Shoji and others 1990). Biomass production by Japanese pampas grass was estimated to be 4,840 lbs per acre above ground and 15,500 lbs per acre below ground. With all of the above-ground and one-quarter of the below-ground parts added to the soil each year, Japanese pampas grass creates conditions that promote accumulation and humification of soil organic matter resulting in the formation of melanic epipedons (Shoji and others 1993). Dahlgren and others (1991) reported lowering of soil solution pH with a corresponding increase in Al concentrations in A horizons of Alic Melanudands where Japanese oak (*Quercus serrata*) replaced Japanese pampas grass. The accumulation of organic matter was a distinguishing feature between soils under the two vegetation types. Another example of the effect of plants on Andisols can be found on the North Island of New Zealand where Andisols rarely display thick dark humus horizons except where native podocarp forest has been converted to bracken fern (*Pteridium aquilinum* var. *esculentum*) (Leamy and others 1980).

Andisols in the Grand Fir Mosaic

Sommer (1991) sampled soils and foliage in three GFM plant communities: mature forest, natural bracken fern glade, and bracken-invaded clearcut. Soil pH was lower and exchangeable Al was higher in bracken-dominated plant communities than in the mature forest. Soil and foliar nutrients were adequate for conifer growth, although Al was approaching levels known to be toxic to some plant species. Small sample size and high variability prevented conclusive results, but evidence suggested that disturbed forest sites in the GFM are invaded by bracken fern plant communities and become more like bracken fern glades.

The important documentation of both allophanic and nonallophanic Andisols in the GFM was reported by Johnson-Maynard and others (1997). Soil chemical and mineralogical properties were studied in adjacent mature forest, natural bracken fern glade, and bracken-invaded clearcut. Retrospective comparison of the 30-year-old clearcut to the mature forest and bracken fern glade showed a conversion from allophanic to nonallophanic soils (fig. 2). Soils in the forest were dominated by short-range-order Al-Fe minerals, had low exchangeable Al, and had pH >5, all of which are consistent with characteristics of allophanic soils (table 1). Soils in the bracken-invaded clearcut and bracken fern glade were dominated by Al-humus complexes, had high exchangeable Al, and pH <5, which is consistent with nonallophanic soils. Johnson-Maynard and others (1997) were the first to report nonallophanic Andisols in northern Idaho. Also, they were the first, to our knowledge, to report a conversion from allophanic to nonallophanic mineralogy. Allophanic and nonallophanic soils exist side-by-side in the GFM, their expression being dependent upon the dominant plant community.

The chemistry of soil water moving through soils of the GFM has also been studied in the GFM (Johnson-Maynard and others 1998), using the same study sites as Johnson-Maynard and others (1997). Soil water chemistry was consistent with the preferential formation of Al-humus complexes in bracken-dominated sites that had once been forested. Soil solution was also collected from a weeded area in a bracken fern glade where bracken fern and western coneflower were hand weeded for 6 years prior to sampling (Ferguson 1999). Soil water pH, Al, and dissolved organic carbon in the weeded area were more similar to the forest than to soil water collected from under the bracken fern glade. Weeding appeared to result in soil water with chemical composition more similar to that measured in

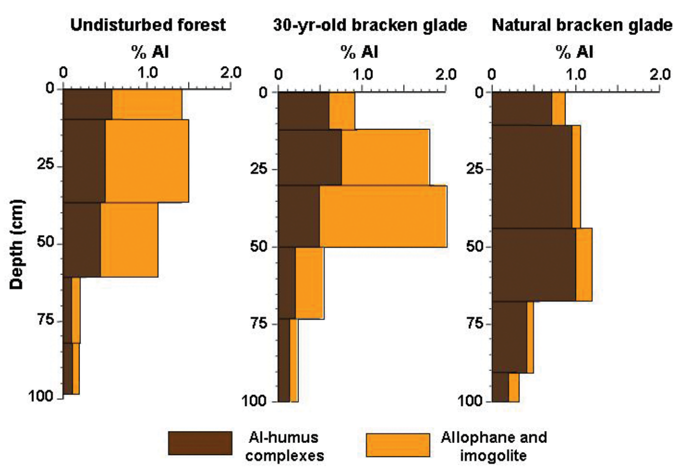

Figure 2—Depth distribution of Al in soil fractions as determined by selective dissolution techniques (adapted from Johnson-Maynard 1995).

the undisturbed forest, suggesting that the growth of bracken fern and western coneflower play an important role in the conversion from allophanic to nonallophanic soils.

Although soil water Al concentrations were highest in bracken-dominated plant communities, they were lower than published toxicity levels for other conifer species. More work is indicated to determine toxic levels for plant species in the GFM and to determine the different forms and toxicity of Al in soil solution.

Discussion

Research on the GFM ecosystem has identified four factors that, individually and collectively, may account for the slow rate of secondary succession to woody vegetation following disturbances that create openings in the forest canopy. The first factor is competition among plants for site resources such as light, water, nutrients, and growing space. Competition can be intense because forb communities dominated by bracken fern and western coneflower expand rapidly into previously forested openings.

The second factor is allelopathy. Direct and indirect effects of phytotoxins released by plants can reduce the successful establishment and growth of other species. The allelopathic potential of bracken fern and western coneflower has been demonstrated (Stewart 1975; Gliessman 1976; Ferguson 1991). The quantification of the individual effects attributable to allelopathy and competition is difficult because removal of a plant from its natural environment simultaneously removes the source of allelopathy and competition. Ecologists use the term "interference" to refer to the combined effects of allelopathy and competition (Muller 1969).

The third factor is large populations of pocket gophers. Gophers can cause a substantial amount of mortality to planted and natural seedlings in the GFM. Most gopher-caused mortality to planted seedlings takes place the first summer after planting and during the first and second winters (Ferguson 1999; Ferguson and others 2005). Partial removal of the overstory canopy allows enough light to reach planted seedlings so they can survive and grow — albeit slower than in full sunlight — and also reduces abundance of pocket gophers, bracken fern, and western coneflower (Ferguson and others 2005).

The fourth factor is a nonallophanic soil forming process. The data collected by Johnson-Maynard and others (1997, 1998) demonstrate the conversion of allophanic to nonallophanic mineralogy based on the criteria summarized in table 1. In the undisturbed forest, the dominant secondary mineralogical component of soils is inorganic, short-range order minerals, which is consistent with allophanic type Andisols. In bracken/coneflower dominated areas, Al-humus complexes are the dominant component of soils, consistent with what has been described in nonallophanic soils.

Allophanic and nonallophanic soils exist side-by-side in the GFM, with mineralogy dependent upon the dominant vegetation (fig. 2). Allophanic conditions occur when vegetation is dominated by coniferous trees, but nonallophanic conditions occur when sites are dominated by bracken fern and western coneflower (Johnson-Maynard and others 1997). When bracken fern and western coneflower are removed, soil water chemistry is similar to that under allophanic GFM soils (Johnson-Maynard and others 1998), indicating that bracken fern and western coneflower are a mechanism in promoting nonallophanic soils. It is likely that bracken fern and western coneflower are not only sources of large annual additions of carbon to the soil, thus favoring the formation of Al-humus complexes, but also sources of organic acids that lower soil pH (Johnson-Maynard and others 1998).

Reforesting GFM Sites

In this section, we discuss management strategies for reforesting GFM sites as they relate to the nonallophanic soil forming process. The most important point to remember is that natural regeneration of woody plant species will be a slow and unreliable process within the GFM. We know of many examples of cutover GFM forests that have little woody vegetation after 20 to 30 years. Seeds that germinate in openings in the GFM forest canopy are subject to competition, allelopathy, pocket gophers, and Al toxicity. These four factors can combine to virtually eliminate the natural establishment of trees and other woody plant species.

Prompt planting following a disturbance will help seedlings become established before the site has abundant bracken fern, western coneflower, and pocket gophers. Planting larger vs. smaller seedlings helps increase survival and growth rates. Planted seedlings in clearcuts need to be protected from pocket gophers until the third spring after they are planted.

Partial cuttings, where only a portion of the overstory trees are removed, retain the shrub component better than clearcuts, and result in less bracken fern, western coneflower, and gopher-caused damage to seedlings (Ferguson and others 2005). Planted trees do not need protection from pocket gophers in partial cuttings; however, they will not grow as fast as in clearcuts. After seedlings are established (5 to 10 years), all or part of the remaining overstory trees can be removed to improve growth of seedlings.

The overall performance of some planted conifer species was better in trial plantings on GFM sites (Ferguson 1999; Ferguson and others 2005). Engelmann spruce and western white pine grew well, had little mortality from non-gopher causes, and had little top damage from snow or senescing bracken fern fronds. Douglas-fir also did quite well, especially if larger seedlings were planted. Lodgepole pine grew rapidly, but this species often suffered severe snow damage to tops, limbs, and stems. Western larch had very high overall mortality, both from gopher and non-gopher causes, but surviving trees grew rapidly. Another concern with western larch is top damage and severe lean caused by snowloads in the GFM.

Research Questions

Much has been learned about ash-cap soils and management options for the GFM, and additional research would help fill the gaps in our knowledge. Research studies show that allophanic and nonallophanic soil forming processes exist side-by-side in the GFM. Allophanic processes occur where conifers dominate the site, and nonallophanic processes occur where bracken fern and western coneflower dominate. It would be helpful to study allophanic vs. nonallophanic mineralogy across a range of overstory densities, and determine how quickly allophanic processes turn into nonallophanic processes following harvest or other activities that reduce the density of the forest canopy.

Another key research topic is to understand why pH is cyclic in GFM sites dominated by bracken/coneflower successional plant communities (fig. 1). Comparisons of seasonal patterns in pH under bracken fern glades to undisturbed grand fir forests may shed light on the mechanisms behind this observation.

Soil pH values cycle below 5.0 during part of the growing season, which could result in Al toxicity (Page-Dumroese and others, this proceedings). However, little is known about Al toxicity thresholds for plant species and their mychorrhizal associations in the GFM. We would expect that Al toxicity varies with Al concentration, the various Al compounds that exist in ash-cap soils, and size/age of plant species. The cyclic nature of soil pH in the GFM may also interfere with nutrient availability (see Page-Dumroese and others, these proceedings). More information is needed on availability of nutrients other than Al, especially nitrogen. Recent work has suggested that additions of lime are effective in raising pH and reducing levels of bioavailable Al in nonallophanic Andisols (Takahashi and others 2006). Liming experiments could therefore be used to provide valuable information about the role of pH and active forms of Al in tree regeneration problems observed in the GFM.

The allelopathic potential of bracken fern has been demonstrated by several researchers around the world, but we only have rudimentary knowledge of allelopathy in western coneflower. Ferguson (1991) demonstrated the allelopathic potential of western coneflower in laboratory tests, but additional research is needed under field conditions.

The answers to these research questions would improve our knowledge of the mechanisms that delay secondary succession to woody plant species in the GFM, thereby helping refine management recommendations for GFM ash-cap soils.

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Chemical Changes Induced by pH Manipulations of Volcanic Ash-Influenced Soils

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Abstract

Data from volcanic ash-influenced soils indicates that soil pH may change by as much as 3 units during a year. The effects of these changes on soil chemical properties are not well understood. Our study examined soil chemical changes after artificially altering soil pH of ash-influenced soils in a laboratory. Soil from the surface (0-5 cm) and subsurface (10-15 cm) mineral horizons were collected from two National Forests in northern Idaho. Soil collections were made from two undisturbed forest stands, a partial cut, a natural bracken fern (*Pteridium aquilinum* [L.] Kuhn) glade, an approximately 30-year-old clearcut invaded with bracken fern, and a 21-year-old clearcut invaded with western coneflower (*Rudbeckia occidentalis* Nutt.). Either elemental sulfur (S) or calcium hydroxide ($Ca(OH)_2$) were added to the soil to manipulate pH. After 90 days of incubation, pH ranged from 3.6 to 6.1 for both National Forests and all stand conditions. Total C, total N, and extractable base cations (Ca, Mg, and K) were generally unaffected by pH change. Available P increased as pH dropped below 4.5 for both depths and all soil types. Nitrate was highest at pH values greater than 5.0 and decreased as pH decreased indicating that nitrification is inhibited at lower pH. Contrary to nitrate, potentially mineralizable N increased as pH declined. Total acidity and exchangeable aluminum increased exponentially as pH decreased, especially in the uncut and partial cut stands. Data from this laboratory study provides information on the role of pH in determining the availability of nutrients in ash-cap soils.

Introduction

In north-central Idaho, some forests are characterized by conifer regeneration problems despite favorable climatic conditions (udic moisture and frigid soil temperature regimes). Forest stands at mid-elevations are most at risk after timber harvest or other disturbance because they are quickly invaded by bracken fern (*Pteridium aquilinum* [L.] Kuhn), western coneflower (*Rudbeckia occidentalis* Nutt.), and pocket gophers (*Thomomys talpoides*). These sites are collectively known as the Grand Fir Mosaic (GFM) and are named for the dominant conifer, grand fir (*Abies grandis* [Dougl. ex D. Don] Lindl.), that occurs in a mosaic pattern with shrub and forb communities (Ferguson 1991a; Ferguson and others, this proceedings).

Timber harvesting began in the GFM in the 1960s and it soon became evident that regeneration problems existed. Woody vegetation is still infrequent on many of these sites 30 years after clearcutting, even with repeated plantings (Ferguson and Adams 1994). Clearcut stands were quickly invaded by forbs (predominately bracken fern and western coneflower) and rodents. The allelopathic potential of both bracken fern and western coneflower has been well documented (Stewart 1975; Ferguson and Boyd 1988; Ferguson 1991b). In addition to invading forbs, pocket gophers also cause substantial seedling mortality (Ferguson and others 2005). Competition for light, moisture, and nutrients within the GFM is high. While the combination of competition, pocket gophers, and allelopathy contribute to the arrested state of secondary succession (Ferguson and Adams 1994), these factors do not appear to entirely explain reforestation failures.

Soils throughout the GFM are strongly influenced by volcanic ash in the surface horizons. The ash was deposited approximately 7,700 years ago when Mt. Mazama erupted (Zdanowicz 1999). Volcanic ash-influenced soils have unique parent materials and secondary mineral assemblages that, in general, are not as well understood as those in other mineral soils. Volcanic ash-influenced soils are classified as either *allophanic* or *nonallophanic*, depending on the relative abundance of organic matter and inorganic short-range-order minerals (Shoji and others 1993). Nonallophanic soils have more organic matter, lower pH, higher levels of KCl-extractable aluminum (Al), and lower levels of calcium (Ca) relative to allophanic soils (Shoji and others 1993). Low soil pH may increase concentrations of extractable (potentially plant available) Al, leading to Al toxicity to woody vegetation (Dahlgren and others 1991). Clearcutting and intensive utilization (whole tree harvesting) of forest biomass may accelerate soil acidification processes (Ulrich and others 1980; Nosko and Kershaw 1992). In addition to acidification from harvest activities, vegetation-induced acidification appears to occur under bracken fern and western coneflower plant communities (Johnson-Maynard and others 1997). These acidified volcanic ash-influenced soils, which are high in exchangeable Al, may release Al into soil solution at levels toxic to woody vegetation (Anderegg and Naylor 1988).

Two soil factors have become a concern in GFM forest openings. First, soil pH drops below 5.0 after harvest operations and the subsequent invasion of bracken fern and western coneflower (figs. 1 and 2). At this pH, Al can reach toxic levels and low soil pH can inhibit growth of some seedling species (Nosko and Kershaw 1992). Second, there are seasonal pH fluctuations of 2-3 pH units that are not typically found in bulk mineral soil unless heavily impacted by acid rain or, occasionally, harvest activities (Mroz and others 1985; Brais and others 1995; Alewell and others 1997). Winter pH values average around 6, but drop below 4 during the growing season. These seasonal pH fluxes could be correlated with inputs of acid litter from bracken fern and western coneflower, increasing root respiration during the growing season, or decreases in soil moisture content. In addition, these two species likely take up high amounts of nutrients from the soil, which may also contribute to acid conditions (Gilliam 1991). Many factors influence forest soil pH (for example, precipitation, nutrient exchange, and soil age), but harvest activity can particularly influence it (Staaf and Olsson 1991). Although forest harvesting can lower pH, subsequent invasion by bracken fern and western coneflower appears to contribute to and maintain low pH relative to undisturbed forest soils.

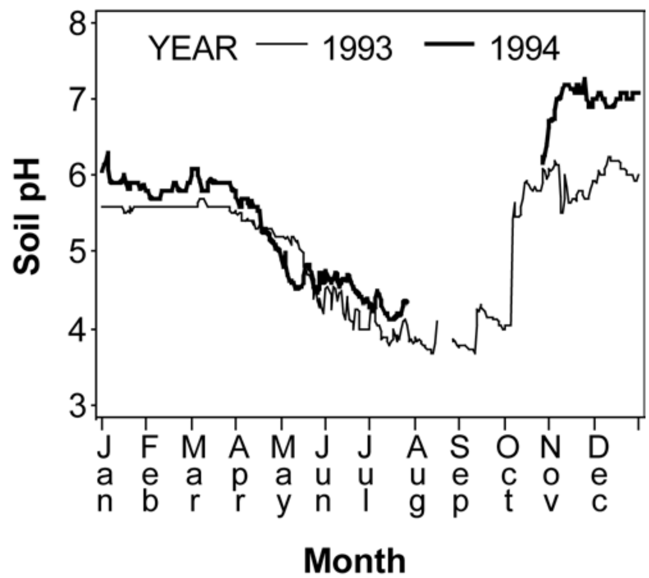

Figure 1—Average soil pH at 2.5 cm for the Nez Perce National Forest coneflower-invaded clearcut (from Ferguson and Byrne 2000). The bold line is 1994, which was a dry growing season. The thin line is 1993, which was a wet growing season. Discontinuous parts of the line are from removal of the pH probe during the driest part of the growing season. Soil pH at this site was assessed *in situ* using pH probes (model 613, IC controls Orangeville, Ontario, Canada) buried 2.5 cm below the mineral soil surface.

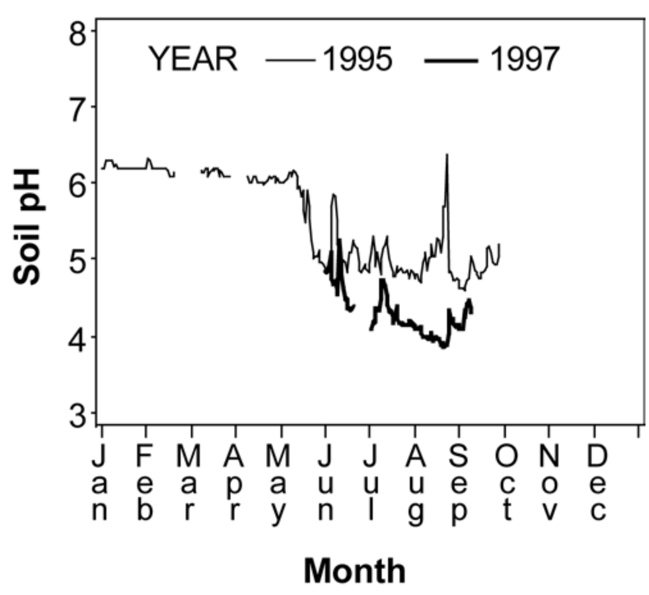

Figure 2—Average soil pH at 2.5 cm for the Clearwater National Forest fern-invaded clearcut (unpublished data collected as described in Ferguson and Byrne 2000). The bold line is 1997 and the thin line is 1995.

The slow forest regeneration process in the GFM has decreased management options for fuel reductions and biomass production, biodiversity of native flora and fauna, and aesthetic values in and near these areas. Low soil pH and its cyclic nature over a growing season may be altering soil chemistry, nutrient cycling processes, and preventing establishment of woody vegetation. Consequently, our objective was to artificially alter pH of ash-influenced forest soils from the GFM by additions of sulfur (S) or calcium hydroxide ($Ca(OH)_2$) to better evaluate potential *in situ* chemical changes within these soils.

Study Site Description

Two study sites, one on the Clearwater National Forest and one on the Nez Perce National Forest of north-central Idaho, were selected to provide a north/south range of plant community cover types for soil collection. There are thicker deposits of volcanic ash in the northern part of the GFM where these soils are classified as Andisols. Inceptisols dominate in the southern part of the GFM where ash deposits are thinner and more highly mixed. Bracken fern dominates forb communities in the northern part of the GFM and western coneflower dominates in the southern part, although both species occur together throughout the GFM. Table 1 lists study site locations, vegetation types, and soil classifications.

Clearwater National Forest soil samples were collected in 1994 near Eagle Point (elevation 1,400 m, eastern aspect, 20 percent slope, T40N, R7E, S35). The dominant soil feature of this study area is approximately 60 cm of Mt. Mazama volcanic ash underlain with colluvium or residuum derived from fine-grained igneous rock. To assess the importance of vegetation community structure, soil samples were collected from adjacent areas with similar slope, aspect, and parent material, but different vegetation cover. Soil samples were collected from the undisturbed forest (46 m^2 ha^{-1} basal area of overstory), a partial cut (approximately 30 m^2 ha^{-1} of overstory remaining), a naturally occurring bracken fern glade (present when the adjacent areas were harvested), and a ~30-year-old bracken fern-invaded clearcut (invaded by bracken fern and western coneflower after harvesting between 1965 and 1968).

Nez Perce National Forest soil samples were collected in 1994 at Dogleg (elevation 1,740 m, southern aspect, 5 percent slope, T31N, R6E, S34). The dominant soil feature is approximately 40 cm of Mt. Mazama volcanic ash underlain with deeply weathered mica schist (Sommer 1991). Vegetation types at this site were undisturbed forest (45 m^2 ha^{-1} basal area of overstory) and a 21-year-old western

Table 1—Location, vegetation type, and soil classification of study sites.

National Forest	Vegetation type	Soil classification‡
Clearwater	Undisturbed forest	Typic Hapludand
Nez Perce	Undisturbed forest	Vitrandic Cryumbrept
Clearwater	Partial cut	Typic Hapludand
Clearwater	Natural bracken fern glade	Alic Fulvudand
Clearwater	30-year-old bracken fern-invaded clearcut	Alic Hapludand
Nez Perce	21-year-old western coneflower-invaded clearcut	Vitrandic Cryumbrept

‡ Clearwater National Forest soil classifications from Johnson-Maynard and others (1997)
Nez Perce National Forest soil classifications from Sommer (1991).

coneflower-invaded clearcut (invaded by western coneflower and bracken fern after harvesting in 1973). Vegetation types were adjacent to each other, having similar slope, aspect, and parent material. There were no natural western coneflower glades dating to pre-harvest activities and no partial cut stands in the vicinity.

Methods

Field Collection Methods

In each forest and vegetation type, mineral soil was collected from the 0-5 cm and 10-15 cm depths. Soil samples were brought to the USDA Forest Service, Moscow Laboratory, air dried, and passed through a 2-mm sieve. Initial pH was measured electrometrically in a 2:1 water:soil suspension.

Laboratory Methods

Depending on initial soil pH, we chose five treatments to raise or lower soil pH in an attempt to establish a range of pH values from 3.5 to 6.0. For each vegetation type and depth, S at rates of 0.45, 0.90, 1.80, 2.70, or 3.6 g kg^{-1} or $Ca(OH)_2$ at rates of 0.45, 0.90, or 1.80 g kg^{-1} were added to provide a range of pH values. In addition, there was a control (no chemical added) for each vegetation type and soil depth. Each S or $Ca(OH)_2$ soil addition rate and the control from each vegetation type was replicated three times. Soil was placed in 655 cm^3 plastic tubes with nylon screen over the bottom openings to prevent soil loss.

Soil water potential was brought to –0.033 MPa by the addition of deionized water. The tubes were randomly located on a greenhouse bench and incubated at a daytime temperature of 25 °C and a nighttime temperature of 18 to 20 °C until the pH stabilized (90 days). When soil water potential dropped below –0.10 MPa, additional deionized water was added until the soil reached field capacity. After pH stabilized (unchanged for 5 days), soil was air dried for chemical analyses. Final pH was measured as described above after the incubation period.

Total carbon (C) and nitrogen (N) were analyzed in a LECO induction furnace operated at 1050 °C (LECO Corp, St. Joseph, MI). Total acidity and exchangeable Al were extracted with 1*N* KCl (Bertsch and Bloom 1986). Exchangeable calcium (Ca), magnesium (Mg), and potassium (K) were extracted using 1*N* NH_4Cl (Palmer and others 2001). Calcium and Mg were analyzed by atomic absorption spectroscopy, and K was analyzed by flame emission. Nitrate-N (NO_3-N) was determined on moist samples using 1*N* KCl extract and an Alpkem Rapid Flow Analyzer (Mulvaney 1996). Potentially mineralizable N (PMN) was estimated using the 7-day anaerobic incubation technique on moist samples (Powers 1980). Extractable phosphorus (P) was determined using either the Bray 1 method (for samples with a pH<6.0) or the Olsen method (for samples with a pH >6.0) (Kuo 1996). Organic matter was determined by weight loss after combustion at 375 °C for 16 h (Ball 1964).

Statistical Analyses

Regression equations were developed using PROC MIXED in SAS (Littell and others 1996), at the 0.05 significance level, and LSMEANS was used to compare vegetation types within soil depths. When analyzing results for Ca, we excluded treatments to raise soil pH because the $Ca(OH)_2$ would have artificially elevated Ca levels. Transformations of variables were explored to achieve homogeneity of error variance, normality and independence of error and block effects, and to obtain additivity of effects (Littell and others 1996).

Results and Discussion

Soil pH Changes

Field studies in the GFM indicate that substantial pH fluxes occur throughout the year (figs. 1 and 2) (Ferguson and others, this proceedings). Results of our controlled study confirm our initial observation that changes in vegetation type influence forest soil pH (table 2). Before treatment with S or $Ca(OH)_2$, the 0-5 cm soil pH was lowest in the natural bracken fern glade (5.0) and fern-invaded clearcut (4.7) on the Clearwater National Forest, intermediate on the Nez Perce National Forest undisturbed area (5.4) and coneflower-invaded clearcut (5.4), and highest on the Clearwater National Forest undisturbed forest (6.3) and partial cut (6.4) (table 2). Soil pH at the 10-15 cm depth followed the same trends. After treatment with S or $Ca(OH)_2$ and 90 days of incubation, final pH values ranged from 3.6 to 6.1 (table 2). Most pH changes occurred within 45 days of starting the incubation period, but the lowest pH values were achieved after 85 days.

Interestingly, untreated soils from the Clearwater National Forest undisturbed and partial cut treatments exhibited a decline in soil pH during incubation in the greenhouse. For example, the initial average pH in the undisturbed forest was 6.3, but at the end of the incubation period, the highest pH value was 5.4. This "natural" decrease in the absence of vegetation and biotic processes is similar to the pH decreases shown in figures 1 and 2. In these two figures, winter pH values average around 6, but drop below 4 during the growing season. These seasonal pH fluxes may be driven by inputs of acid litter from bracken fern and western coneflower. In addition, these two species likely take up high rates of nutrients from

Table 2—Initial and final soil pH ranges after treatment with S or $Ca(OH)_2$.

National Forest	Vegetation type	Initial pH	Final pH range
		------0-5 cm depth--------	
Clearwater	Undisturbed forest	6.3	3.7 - 5.4
Nez Perce	Undisturbed forest	5.4	3.8 - 5.3
Clearwater	Partial cut	6.4	3.6 - 5.0
Clearwater	Natural bracken fern glade	5.0	3.7 - 5.0
Clearwater	30-year-old bracken fern-invaded clearcut	4.7	3.7 - 5.6
Nez Perce	21-year-old coneflower-invaded clearcut	5.4	3.8 - 5.8
		------ 10-15 cm depth ------	
Clearwater	Undisturbed forest	5.8	3.6 - 5.3
Nez Perce	Undisturbed forest	5.3	3.8 - 5.5
Clearwater	Partial cut	6.2	3.8 - 5.2
Clearwater	Natural bracken fern glade	4.9	3.9 - 5.1
Clearwater	30-year-old bracken fern-invaded clearcut	4.3	3.7 - 5.1
Nez Perce	21-year-old coneflower-invaded clearcut	5.6	3.8 - 6.1

the soil, which may also contribute to acid conditions (Gilliam 1991). Although forest harvesting can lower pH, subsequent invasion by bracken fern or western coneflower appears to contribute to and maintain low pH relative to undisturbed forest soils. However, the laboratory data indicates that some pH changes within these soil types are possible even without vegetation facilitating the change.

Carbon and Nitrogen

There were significant differences in total C concentration among the vegetation types (table 3). Soil C concentration was highest under the fern-invaded clearcut at both depths (11.27 percent 0-5 cm depth; 10.00 percent 10-15 cm depth). Total C was lowest at the 10-15 cm depth where conifers were present (both undisturbed forests and partial cut). The soils that support the highest vegetation turnover rates (bracken fern and western coneflower) had similar C concentrations at both depths, while vegetation types with conifers present had about twice as much C in the surface soil compared to the 10-15 cm depth.

The fern-invaded clearcut has approximately 390 g/m^2 of bracken frond biomass added to the soil annually (Znerold 1979). On the Clearwater National Forest, rhizome and fine root biomass in the fern-invaded communities averaged 4000 g/m^2 (Jimenez 2005); in the natural glade, rhizome and fine root biomass averaged 3200 g/m^2. It is not surprising that this vegetation type has higher C concentrations. We expected that the natural bracken fern glade would have as much C as the fern-invaded clearcut, but this was not the case. The natural bracken fern glade soil appears to be at an intermediate point between the undisturbed forest and the fern-invaded clearcut. These results are similar to C and N data collected from nearby sites within the GFM (Johnson-Maynard and others 1997). One explanation may be that the natural bracken fern glade has reached a steady state.

Table 3—Mean C, N, Ca, Mg, and K in the control treatment, by vegetation type and depth. Each mean is an average of three replications.

National Forest	Vegetation type	Carbon	Nitrogen	Calcium	Magnesium	Potassium
		- - - - - - percent - - - - - -			*- - - mg/kg - - -*	
					0-5 cm depth	
Clearwater	Undisturbed forest	6.60 a‡	0.40 a	12.21 d	1.12 b	1.54 b
Nez Perce	Undisturbed forest	7.87 b	0.74 c	14.16 e	1.14 b	0.99 a
Clearwater	Partial cut	6.23 a	0.36 a	7.86 b	0.74 a	0.99 a
Clearwater	Natural bracken fern glade	7.93 b	0.61 b	6.88 a	3.29 d	2.77 c
Clearwater	Bracken fern-invaded clearcut	11.27 c	0.69 bc	6.70 a	2.34 c	2.89 c
Nez Perce	Coneflower-invaded clearcut	6.17 a	0.35 a	9.16 c	0.92 a	1.02 a
					10-15 cm depth	
Clearwater	Undisturbed forest	3.17 a	0.24 a	5.41 c	0.74 d	1.22 c
Nez Perce	Undisturbed forest	3.90 b	0.22 a	5.38 c	0.41 a	0.71 b
Clearwater	Partial cut	3.63 ab	0.25 a	3.79 b	0.49 c	0.71 b
Clearwater	Natural bracken fern glade	5.90 c	0.48 c	4.25 b	1.38 e	2.20 e
Clearwater	Bracken fern-invaded clearcut	10.00 d	0.67 d	2.72 a	0.77 d	1.30 d
Nez Perce	Coneflower-invaded clearcut	6.27 c	0.34 b	5.66 c	0.45 b	0.46 a

‡ Within soil depth, means followed by different letters are significantly different ($p = 0.05$) using LSMEANS.

Because bracken fern produces high levels of allelopathic chemicals (Ferguson and Boyd 1988), it is perhaps becoming autotoxic (Gliessman and Muller 1978), which results in less frond biomass (natural glade 678 g/m^2; fern-invaded clearcut 916 g/m^2 (Jimenez 2005)) and less organic C incorporated into the soil. These two types of bracken fern stands (natural glade and invaded clearcut) may also be at different lifecycle stages (Atkinson 1986).

Higher soil C concentrations in the fern-invaded clearcut are consistent with the development of nonallophanic soil characteristics following invasion (Nanzyo and others 1993; Johnson-Maynard and others 1997; Dahlgren and others 2004). Increased levels of C in the bracken fern sites, as compared to undisturbed soils, may increase the potential for preferential formation of Al-humus complexes (Dahlgren and others 1993).

Forest sites invaded by western coneflower maintained moderate levels of C throughout the sampling depths. At the 10-15 cm depth the coneflower-invaded clearcut had nearly twice as much C as the undisturbed forest soil (table 3). Carbon was distributed deeper in the soil profile in the coneflower-invaded clearcut than on the bracken fern sites. This may be because the coneflower-invaded site had greater surface and subsoil mixing caused by pocket gophers (Ferguson and Adams 1994) or because of slightly less surface volcanic ash deposition (Sommer 1991).

For each vegetation type, there was generally more N in the 0-5 cm depth than in the 10-15 cm depth, with two notable exceptions. Both the fern-invaded clearcut and the coneflower-invaded clearcut soils had as much N in the 10-15 cm depth as the surface soil. This is likely caused by the large annual inputs of forb biomass that usually occur in newly invaded clearcuts (Attiwill and others 1985).

Regression analyses showed that total C and N were unchanged after altering pH. This result was not unexpected since we did not add organic matter.

Base Cation Concentrations

Based on the control samples, vegetation type does influence soil Ca, Mg, and K concentrations in these volcanic ash soils (table 3). For both soil depths, the fern glade and the fern-invaded clearcut had significantly more K and Mg than soils from under the other vegetation types. In contrast, Ca content was greatest in soils under both undisturbed forests.

Regression analysis showed that base cation concentrations (Ca, Mg, and K) did not change as a result of pH changes (data not shown). Our results differ from those of Mohebbi and Mahler (1988) who found a strong correlation between pH and cation concentration after artificially changing pH in a loessal soil. In their study, as pH increased, both K and Mg decreased; however, Ca sharply increased from pH 5 to 7. It also increased after pH dropped below 3.5. It is unusual that soil consisting of volcanic-ash influenced materials, which have a variable charge, did not show a marked reduction in the retention of exchangeable bases with decreasing pH. This indicates there may be enough permanent charge minerals to maintain base concentrations. In the fern glade and the fern-invaded clearcut, soils may be developing properties typical of nonallophanic Andisols (Johnson-Maynard and others 1997).

Lack of pH-driven changes in cation concentration in our study may be related to high organic C content of the ash-influenced soil (Shoji and others 1993). Theoretically, once these sites are harvested, substantial losses of basic cations are possible. Both loss of nutrients from aboveground pools (Boyle and others 1973; Federer and others 1989) and increased leaching losses have been reported after harvesting (Hendrickson and others 1989). However, cations may be redistributed into new, immediate regrowth of bracken fern or western coneflower after harvesting and not lost from the site (Johnson and others 1997).

Available Phosphorus

Phosphorus (P) amounts varied significantly among vegetation types and soil depths. The mean values for P in the control treatment are shown in table 4. The largest P means are in the 0-5 cm depth under the undisturbed forests (Nez Perce National Forest 3.17 μg/g and Clearwater National Forest 3.03 μg/g). The fern glade (2.73 μg/g) and fern-invaded clearcut (2.20 μg/g) were intermediate in P, and the lowest means were in the coneflower-invaded clearcut (1.87 μg/g) and partial cut (1.70 μg/g).

Regression analyses showed that P increased with decreasing pH. Response of soil P was similar at both soil depths; therefore, regression equations are shown only for the 0-5 cm depth (table 5). The vegetation types had similar response

Table 4—Mean P, potentially mineralizable N (PMN), nitrate (NO_3-N), aluminum (Al), and total acidity in the control treatment, by vegetation type and soil depth. Each mean is the average of three replications.

National Forest	Vegetation type	P	PMN	NO_3-N	Al	Total acidity
		μg/g	- - - - - - *mg/kg* - - - - - - -		- - - - -*cmol/kg* - - - - -	
				0-5 cm depth		
Clearwater	Undisturbed forest	3.03 c‡	100.41 b	87.73 a	0.17 a	0.28 a
Nez Perce	Undisturbed forest	3.17 c	60.16 ab	172.01 b	0.22 a	0.41 ab
Clearwater	Partial cut	1.70 a	14.96 a	105.18 a	0.34 ab	0.58 bc
Clearwater	Natural bracken fern glade	2.73 c	7.56 a	230.07 bc	0.54 b	0.78 c
Clearwater	Bracken fern-invaded clearcut	2.20 b	55.32 ab	246.99 c	1.14 c	1.77 d
Nez Perce	Coneflower-invaded clearcut	1.87 ab	2.14 a	97.51 a	0.23 a	0.34 ab
				10-15 cm depth		
Clearwater	Undisturbed forest	1.80 c	6.55 a	24.03 a	0.18 a	0.31 a
Nez Perce	Undisturbed forest	2.10 d	38.85 a	36.51 a	0.81 ab	0.95 ab
Clearwater	Partial cut	1.40 b	28.04 a	51.68 ab	0.50 a	0.61 a
Clearwater	Natural bracken fern glade	1.50 b	3.97 a	136.94 c	1.38 b	1.70 b
Clearwater	Bracken fern-invaded clearcut	2.53 e	192.30 b	127.45 bc	3.55 c	4.22 c
Nez Perce	Coneflower-invaded clearcut	0.93 a	29.31 a	47.61 ab	0.21 a	0.31 a

‡ Within each soil depth, means followed by different letters are significantly different ($p = 0.05$) using LSMEANS.

Table 5—Regression equations for 0-5 cm depth (bold lines on figs. 3, 5, and 6).

$Y = \exp(\beta_o + \beta_1 * pH)$ and Y, β_o, and β_1 take on the following values:

Definition	Dependent (Y)	β_o	β_1
P concentration	PHOS	2.6789	–0.3612
Potentially mineralizable N	PMN	10.4498	–1.4457
NO3-N concentration	NO3-N	–7.1482	2.2212
KCl-extractable Al	ALUM	10.5408	–2.2514
Total acidity	ACID	9.9878	–2.0526

surfaces (fig. 3). Soil from the Clearwater National Forest undisturbed forest had the highest available P when pH dropped below 4.0. Both humus and allophane content in volcanic ash-influenced soils affect P availability and the high level of C in the fern-invaded clearcut soil may be sorbing P (Wada 1985). These results are quite different from the loessal soils that have a strong linear increase in available P as pH increases (Mohebbi and Mahler 1988). For volcanic ash-influenced soils, the pH dependency of phosphate sorption is highest between pH 3 and 4, and generally decreases with increasing pH (Nanzyo 1987). This is especially true for allophanic ash-influenced soils as compared to nonallophanic ash-influenced soils (Nanzyo and others 1993).

In soils consisting of weathered volcanic ash, P sorption is a major soil fertility problem (Andregg and Naylor 1988). In most mineral soils, organic matter is an important reservoir for P. However, in many volcanic ash-influenced soils, organic matter protects P from sorption (Moshi and others 1974). This appears to be the case for these soils as well.

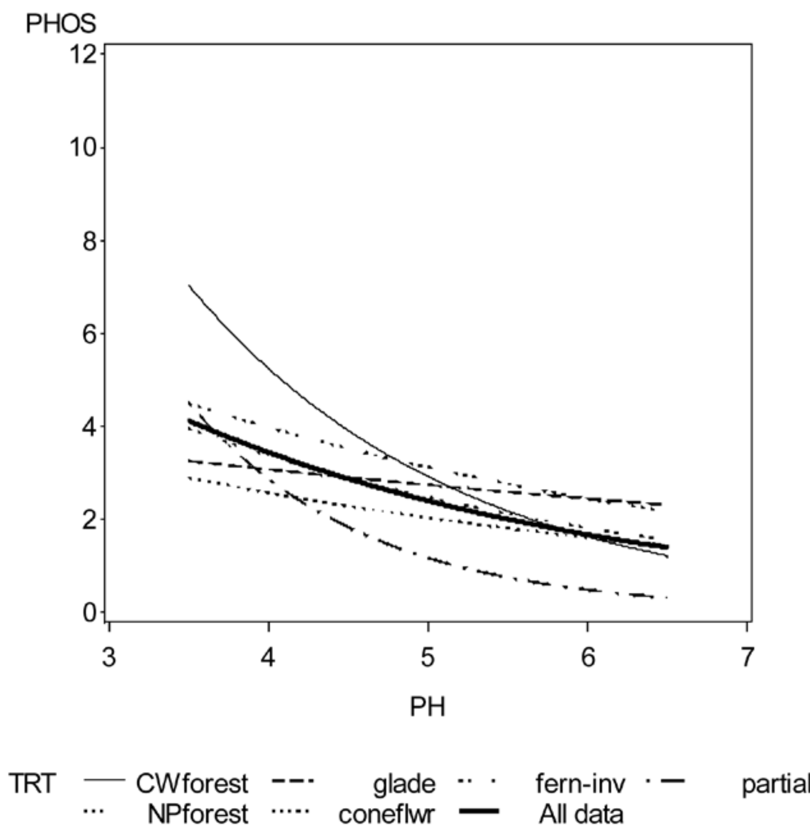

Figure 3—Regression equations for available P concentration (µg/g) of the 0-5 cm depth as affected by pH manipulation by vegetation type. The bold line is the regression for all vegetation types.

Potentially Mineralizable N and Nitrate-N

Potentially mineralizable N (PMN) concentrations varied widely among vegetation types and soil depths (table 4). For example, in the control soil for the 0-5 cm depth, PMN ranged from a low of 2.14 mg/kg in the coneflower-invaded clearcut to 100.41 mg/kg in the undisturbed forest on the Clearwater National Forest. Amounts of PMN at the 0-5 cm soil depth was low in the fern glade, but intermediate in the fern-invaded clearcut.

Nitrate-N (NO_3-N) also varied among vegetation and soil depths. The largest means at the 0-5 cm depth for the control soil (table 4) were in the fern-invaded clearcut (246.99 mg/kg) and fern glade (230.07 mg/kg), and the lowest mean was 87.73 mg/kg in the undisturbed forest soil from the Clearwater National Forest. Means for NO_3-N at the 10-15 cm depth were lower than the 0-5 cm depth, but the trends were similar.

Analyses showed that PMN concentrations declined rapidly as soil pH increased above 5.0 and, in contrast, soil NO_3-N concentration increased rapidly above pH 5.0, except in the fern glade and fern-invaded clearcut where this change in N form occurred below pH 4.5 (fig. 4a-f). While the soils in both undisturbed forests and the partial cut forests exhibited a threshold level of pH 5.0 for substantial changes in the quantity of available N, the two sites with bracken fern vegetation types and the coneflower-invaded clearcut had steady changes in N as pH increased. Both soil depths have similar regression curves for each vegetation type; therefore, only the 0-5 cm soil depth is shown (table 5).

The sharp decline in PMN from these ash-influenced sites is different from the northern Idaho loessal soils, which had a significant increase in PMN as pH increased from 3.0 to 7.0 (Mohebbi and Mahler 1988). This may indicate a difference in organic matter concentration from loess-grassland areas to ash-forested areas, and suggests that organic N in volcanic ash-influenced soils may be fairly resistant to microbial decomposition because of the Al-organic complexes that are formed (Shoji and others 1993).

While soil from most of the vegetation types show a crossover in relative abundance of PMN and NO_3-N around pH 5.0, the bracken-fern dominated vegetation types change below pH 4.5. Increased NO_3 -N and decreased PMN at higher pH values is consistent with results of acid rain and soil nutrition studies (Schier 1986; Marx 1990). Nitrogen mineralization often increases when soil pH is raised (Montes and Christensen 1979), but occasionally has been shown to decrease (Adams and Cornforth 1973). Nitrification is also pH sensitive and generally increases as pH is raised from very acid to moderately acid (Robertson 1982). In this study, the clearcuts invaded with either bracken fern or western coneflower likely exhibit this N change each year as pH changes (Binkley and Richter 1987).

Aluminum and Total Acidity

KCl-extractable Al (which reflects exchangeable Al) and total acidity varied significantly among vegetation types and soil depths. Mean values in the control treatments are shown in table 4. Aluminum and total acidity are significantly higher in the fern glade and fern-invaded clearcut, for both depths. Mean Al and acid values are generally higher in the 10-15 cm depth soil as compared to the 0-5 cm depth.

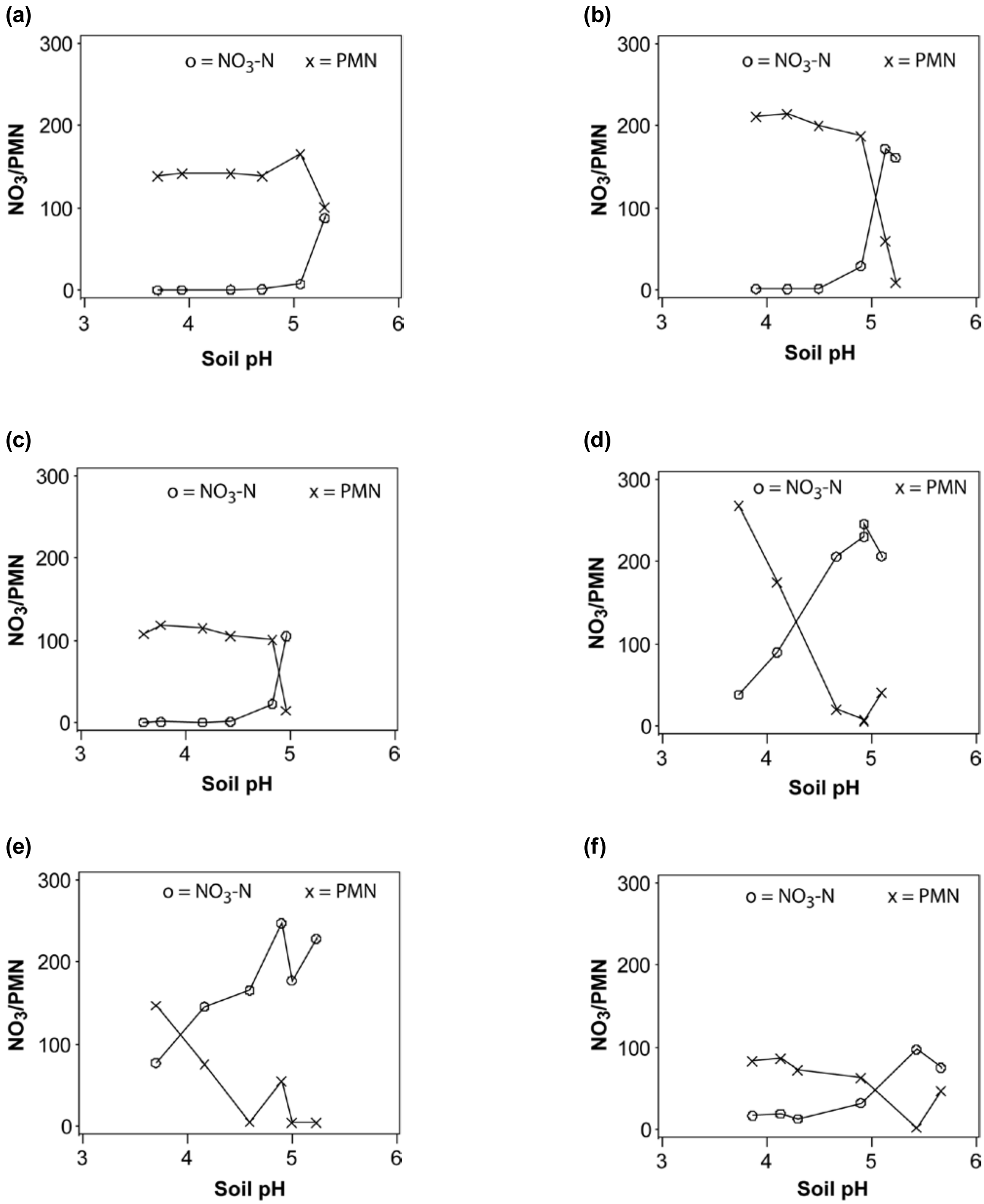

Figure 4—Soil NO_3-N and PMN concentration (mg/kg) in the 0-5 cm depth as affected by pH manipulation, by vegetation type (a) Clearwater National Forest, undisturbed, (b) Nez Perce National Forest, undisturbed, (c) Clearwater National Forest, partial cut, (d) Clearwater National Forest, bracken fern glade, (e) Clearwater National Forest, bracken fern-invaded clearcut, (f) Nez Perce National Forest, coneflower-invaded clearcut.

Regression analyses showed that Al was highly correlated with changes in pH (table 5) in all vegetation types. Aluminum increased exponentially when the pH decreased below 4.5 (fig. 5). Both 0-5 cm and 10-15 cm depths had similar curves; therefore, only the 0-5 cm soil depth regression lines are shown. Volcanic ash-influenced soils contain high levels of Al-containing materials that can undergo dissolution under acidic (less that pH 5.0) conditions (Tisdale and others 1993). In these soils, very little exchangeable Al was detected above pH 5.0. Based on continuous soil measurements of pH (figs. 1 and 2), soils under bracken fern and coneflower vegetation have a pH below 5.0 each growing season. Soil pH 5.0 is generally considered to be the critical point for Al toxicity to woody vegetation (Wolt 1994).

In general, woody plant species appear to be more tolerant of Al than agriculture crops (McCormick and Steiner 1978; Ryan and others 1986), and there is considerable variation in Al tolerance among tree species (McCormick and Steiner 1978; Steiner and others 1984; Arp and Ouimet 1986; Hutchinson and others 1986; Schaedle and others 1989; Raynal and others 1990). Aluminum toxicity alters tree root anatomy, which first occurs in the roots (Hutchinson and others 1986; Schaedle and others 1989; McQuattie and Schier 1990; Nosko and Kershaw 1992; Schier 1996). The result of Al toxicity is impaired root development, resulting in reduced root length and formation of a shallow root system. At high

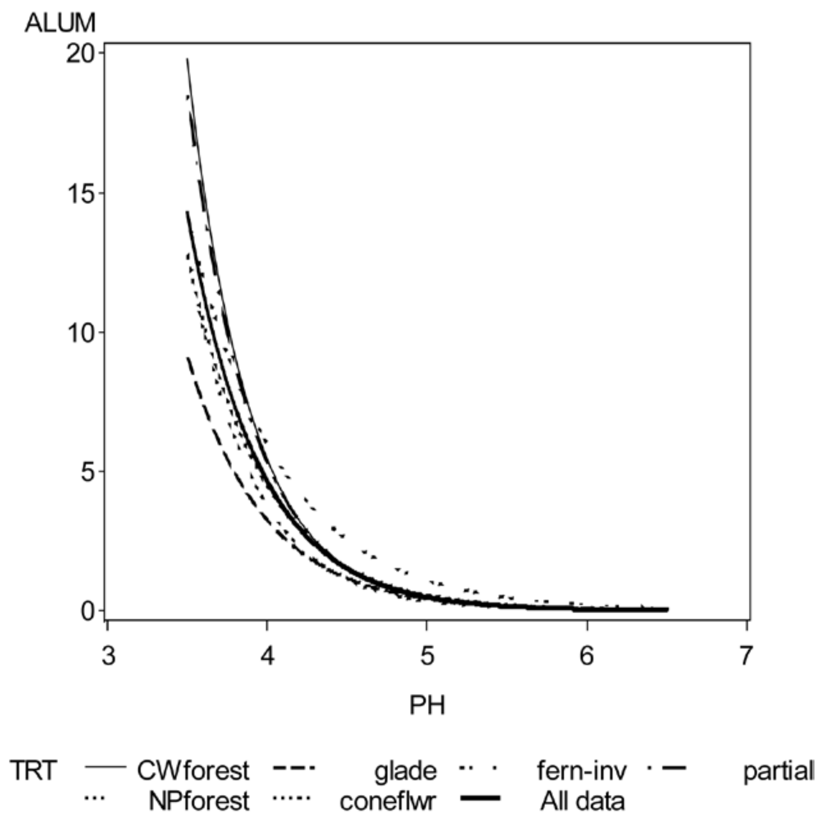

Figure 5—Exchangeable Al concentration (cmol/ kg) in the 0-5 cm depth as affected by pH, by vegetation type. The bold line is the regression for all vegetation types.

Al levels, mitosis is almost completely inhibited. Leamy (1988) noted that in volcanic ash-influenced soils, Al toxicity may occur at concentrations of 2 cmol/kg soil, and this value is used as a threshold in Soil Taxonomy for identifying those Andisols in which Al phytotoxicity may occur (Soil Survey Staff 2003). Aluminum levels found in this laboratory study are much higher than 2 cmol/kg when pH decreased below 5.0 and indicates a strong potential for Al toxicity in these ash-influenced soils as pH values decline.

The various studies on Al toxicity in tree species are difficult to compare because of different study methods, units of measure, growth media, length of experiments, and age of trees (Schaedle and others 1989; Nosko and Kershaw 1992). However, one important finding is that young seedlings are more sensitive to Al toxicity than older seedlings. For example, Schier (1996) found that Al concentrations of 0.32 mM/l inhibited root biomass in newly germinated red spruce (*Picea rubens)* seedlings, while the threshold was 2.1 mM/l in 1-year-old seedlings. It seems reasonable to assume that conifer seed germinating on GFM sites could be impacted by low concentrations of Al. Aluminum toxicity, allelopathic compounds, and competition could combine to eliminate the natural establishment of trees and other woody plant species on these sites.

Regression analyses for total acidity followed the same trend as extractable Al (fig. 6), and only the 0-5 cm soil regression lines are shown. The regression equation for total acidity is shown in table 5. Most of the acidity in these soils

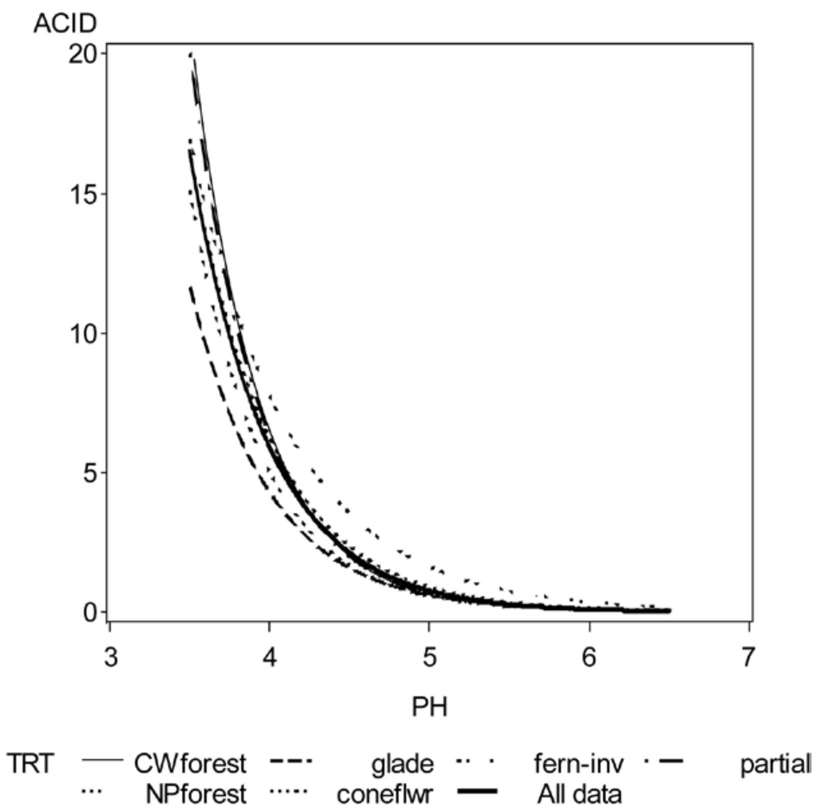

Figure 6—Total acidity (cmol/kg) in the 0-5 cm depth as affected by pH manipulation by, vegetation type. The bold line is the regression for all vegetation types.

occurs as Al. The relationship between exchangeable Al and total acidity is not unusual since most of the exchangeable acidity is derived from Al and H on the exchange sites (Binkley and Richter 1987). Changes in exchangeable acidity generally occur over a long period of time and are due to acidification through weathering, leaching, cation uptake, or atmospheric deposition (Richter 1986). Rapid changes in acidity occur occasionally by other H-ion inputs. In the GFM, both bracken fern and western coneflower vegetation have the potential to input H-ions via organic acid production or additions of high amounts of organic C through yearly vegetation cycles.

Summary

Analysis of unaltered soil samples supporting undisturbed grand fir forest and bracken fern/western coneflower plant communities suggests that chemical properties of GFM forest soil are altered through invasion of successional plant species after timber harvest or other disturbance. Changes in soil conditions are similar to a depth of 15 cm. Seasonal decreases in soil pH under bracken fern and western coneflower vegetation types most likely cause a release of exchangeable Al at levels toxic to woody vegetation. High levels of C, exchangeable Al, and total acidity under these two vegetation types may also be facilitating a localized conversion of these ash-influenced soils from allophanic to nonallophanic Andisols. Forested soils in the GFM are capable of exhibiting these same characteristics once disturbed.

Results of this study also provide insights into the chemical changes that may occur in volcanic ash-influenced soils as pH fluctuates. Mechanisms that contribute to forb-dominated secondary successional plant communities have been identified. For example, the apparent change in N between PMN and NO_3-N has implications in determining which species can grow on these sites, as does the exponential increase of Al below pH 5.0. Clearly, this laboratory study points out the potential for Al toxicity that may accompany seasonal pH fluctuations. These laboratory study findings are consistent with *in situ* soil solution data, which indicate that soils invaded by bracken fern and western coneflower undergo conversion from allophonic to nonallophanic properties (Johnson-Maynard and others 1997). However, altering the pH of ash-influenced soils differed from altering loessal soils (Mohebbi and Mahler 1988). These soil-type differences are likely attributable to the unique physical, chemical, and biological properties of ash-influenced soils as compared to those derived from other parent materials (Dahlgren and others 2004).

This laboratory study highlights important characteristics of ash-influenced soils that may contribute to changes in vegetation. This type of study, combined with field work, will help in the development of practical management recommendations.

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Summaries of Poster Papers

WEPP FuME Analysis for a North Idaho Site

William Elliot, Ina Sue Miller, and David Hall

In: Page-Dumroese, Deborah; Miller, Richard; Mital, Jim; McDaniel, Paul; Miller, Dan, tech. eds. 2007. Volcanic-Ash-Derived Forest Soils of the Inland Northwest: Properties and Implications for Management and Restoration. 9-10 November 2005; Coeur d'Alene, ID. Proceedings RMRS-P-44; Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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Introduction

A computer interface has been developed to assist with analyzing soil erosion rates associated with fuel management activities. This interface uses the Water Erosion Prediction Project (WEPP) model to predict sediment yields from hillslopes and road segments to the stream network. The simple interface has a large database of climates, vegetation files and forest soil properties to support this and other interfaces, including Disturbed WEPP for forests and WEPP:Road for road segment analyses. The soil databases for roads and disturbed forested hillslopes are based on rainfall simulation and natural rainfall studies.

The WEPP FuME interface carries out erosion prediction runs for six forest conditions:

1. Undisturbed mature forest
2. Wildfire
3. Prescribed fire
4. Thinning
5. Low traffic roads
6. High traffic roads

The climate, soil texture, topography, road density, wildfire return interval, prescribed fire cycle and thinning cycle are specified by the user.

The WEPP FuME interface can be used anywhere within the United States using the existing climate database. The interface is intended to provide an overview of the sources of sediment on a given fuel management site. Sediment predictions from WEPP FuME are for surface erosion only.

Hillslope Method and Parameters

The example in this paper is an area within the Yellowpine timber sale in northern Idaho (fig. 1). The watershed hillslope boundaries were delineated using GeoWEPP (a geo-spatial interface tool for WEPP) (fig. 2). Each hillslope from the example watershed was examined using the FuME model. Only one hillslope can be run at a time and in this instance, hillslope number 22 is displayed (fig. 2).

FuME was run for an individual hillslope (number 22, fig. 2). The conditions of the model were sandy loam soil texture, hillslope length of 708 feet, hillslope gradient starting with the top of the hill 25, 36, and 20 percent, a 40 ft buffer length and the default road density, fire and thinning cycles.

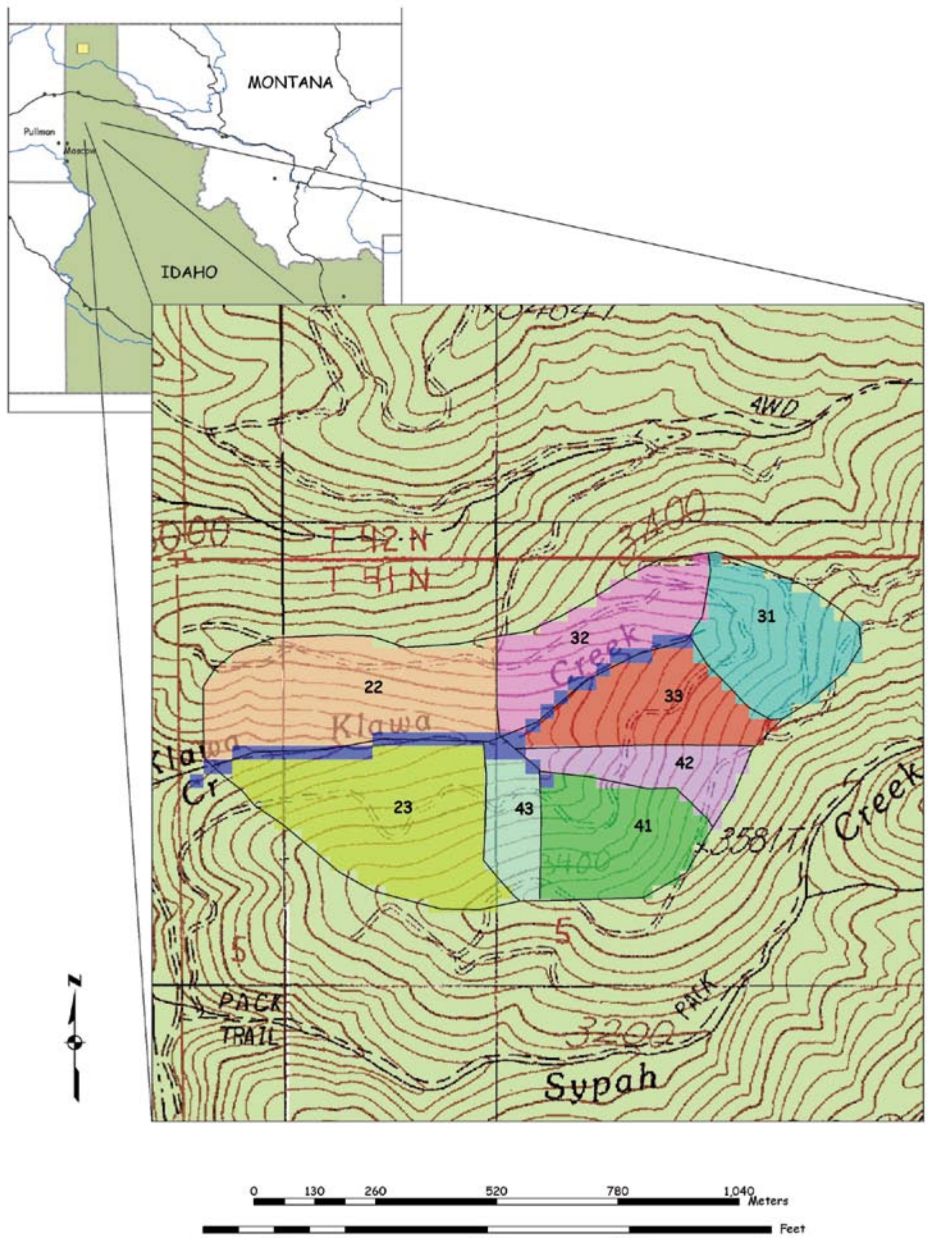

Figure 1—Unit 4 of the Yellowpine timber sale in northern Idaho.

Figure 2—The WEPP-FuME model windows for hillslope 22.

Cumulative Watershed Results

All hillslopes from the example watershed were analyzed with WEPP FuME. The summarized results and weighted averages for the example watershed are displayed in table 1 below.

From the table we can observe that if a moderate fire scenario occurs every 40 years for the watershed, in combination with the prescribed fire and thinning management activities, including erosion from roads, there is a 65 percent decrease of erosion occurring when compared to the background rate. In the event of a high severity fire, in combination with the prescribed fire and thinning management activities including the erosion from roads, the total watershed results in a 6 percent increase of predicted erosion. For both examples, the background rate includes low impact roads and the high severity fire scenario.

Table 1—WEPP FuME summarized results and weighted averages.

Hill slope	Background sedimentation	Thinning effects	Rx Fire effects	Thinning + Rx fire w/high severity fire	Thinning + Rx fire w/moderate severity fire
	- - - - - - - - - - - - -	*(ton/mi^2)*	- - - - - - - - - - -	*(ton/mi^2)**	*(ton/mi^2)***
22	139	141.6	152.1	155.6	52.92
23	97.2	98.2	99.1	100.2	30.52
31	92.2	92.8	93.2	93.8	28.48
32	120.8	122.8	126.6	129.7	55.94
33	118.3	119.6	120.2	121.6	39.46
41	104.1	105.1	105.1	106.2	31.38
42	144.3	145.6	144.3	145.9	48.32
43	93.3	94.3	94.6	106.1	29.02
Weighted averages for the example watershed	113.7	115.2	117.9	120.3	39.9

* The projected background rate in this column assumes fuel management activities did not reduce the fire hazard by removing excess fuel. The estimated background rate for this column was calculated with a high severity fire value.
** The projected background rate in this column assumes fuel management activities reduce the fire hazard by removing excess fuel. Therefore, the estimated background rate for this column was calculated with a moderate severity fire value.

Note: All sedimentation estimates displayed above are calculated from the low end erosion rates of the road network. The high severity fire value was used in the background sedimentation rate calculation unless stated otherwise.

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Erosion Risks in Selected Watersheds for the 2005 School Fire Located Near Pomeroy, Washington on Predominately Ash-Cap Soils

William Elliot, Ina Sue Miller, and Brandon Glaza

In: Page-Dumroese, Deborah; Miller, Richard; Mital, Jim; McDaniel, Paul; Miller, Dan, tech. eds. 2007. Volcanic-Ash-Derived Forest Soils of the Inland Northwest: Properties and Implications for Management and Restoration. 9-10 November 2005; Coeur d'Alene, ID. Proceedings RMRS-P-44; Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

***William Elliot** is Project Leader, **Ina Sue Miller** is Hydrologist, and **Brandon Glaza** is Civil Engineer, Soil and Water Engineering Research Work Unit, Rocky Mountain Research Station, Moscow, ID.*

Geo-WEPP Spatial Analysis

A limited erosion potential analysis was carried out on the 50,000 acre School Fire. Three WEPP interfaces were used for the analysis, a GIS wizard, an online interface and a windows interface. Ten watersheds within the fire area were modeled with the GeoWEPP tool (a geo-spatial interface for WEPP, Water Erosion Predication Project). The watersheds covered 18,823 acres, or about 38 percent of the total burned area. Hillslopes were specified high, moderate or low burn severity by examining the BAER (Burned Area Emergency Response) severity map.

By consulting with the BAER specialists, watersheds of greatest interest were identified. One set included four watersheds discharging into the Tucannon River from the western side, including School Creek, which flowed into the Tucannon River at the Tucannon Guard Station. A second set included three watersheds flowing into the Tucannon River from the east side, south of the Tucannon Guard Station. The third set of watersheds were larger and incorporated Dry Creek (a tributary to Cummings Creek), Cummings Creek and Pataha Creek.

ERMiT Hillslope Analysis – Online Interface

The ERMiT (Erosion Rehabilitation Management Tool; August, 2005 version) results for a single storm erosion prediction are given in table 1 below. Table 2 provides an overall average of all ERMiT runs. Hillslopes were specified high, moderate or low severity from the BAER severity map. An average of about 12 randomly selected hillslopes or 5 percent of the hillslopes on larger watersheds, were run with ERMiT for each watershed, with the exception of upper Pataha. In the upper Pataha watershed, only 10 hillslopes were identified as moderate or severely burned. The mulching treatment assumed an application role of 0.9 tons/acre following the fire. On average, there is a 20 percent chance that the erosion rate in the watershed will be greater than 7 tons per acre if left untreated, and only a 10 percent probability that erosion will exceed 10 tons/ac if left untreated.

Table 1—ERMiT single storm erosion predictions – August-2005 version.

			Untreated		Seeded		Mulched	
			Year		Year		Year	
Drainage	Exceedance		1	2	1	2	1	2
			(tons/ac)					
Tucannon West 3	10%	Mean	12.98	9.00	12.98	4.98	1.34	3.11
		Std Dev	8.00	5.97	8.00	3.32	0.85	2.16
	20%	Mean	8.57	5.78	8.57	2.27	0.00	0.92
		Std Dev	5.56	3.93	5.56	1.76	0.00	0.79
Tucannon West 2	10%	Mean	10.05	7.24	10.05	3.95	0.99	2.43
		Std Dev	8.40	6.30	8.4	4.08	1.02	2.50
	20%	Mean	6.56	4.67	6.56	1.73	0.00	0.70
		Std Dev	6.22	4.71	6.22	2.09	0.00	0.86
Tucannon West 1	10%	Mean	14.14	9.61	14.14	5.27	1.36	3.16
		Std Dev	8.11	5.95	8.11	3.79	1.33	2.51
	20%	Mean	9.23	6.25	9.23	2.21	0.00	0.90
		Std Dev	5.79	4.44	5.79	1.99	0.00	0.87
School Canyon	10%	Mean	6.00	4.15	6.00	2.21	0.53	1.34
		Std Dev	7.00	5.24	7.00	3.33	0.74	2.04
	20%	Mean	3.77	2.51	3.77	0.92	0.00	0.37
		Std Dev	5.13	3.84	5.13	1.64	0.00	0.67
Grub Creek	10%	Mean	10.71	7.70	10.71	4.38	1.10	2.67
		Std Dev	8.31	6.23	8.31	3.87	0.93	2.37
	20%	Mean	7.31	5.18	7.31	1.93	0.00	0.78
		Std Dev	6.02	4.65	6.02	1.95	0.00	0.84
Hixon Creek	10%	Mean	6.71	4.49	6.71	2.06	0.65	1.39
		Std Dev	8.31	5.78	8.31	3.41	1.34	2.41
	20%	Mean	4.10	2.48	4.10	0.95	0.00	0.37
		Std Dev	5.78	4.08	5.78	2.00	0.00	0.75

(continued)

Table 1 (Continued).

Drainage	Exceedance		Untreated Year 1	Untreated Year 2	Seeded Year 1	Seeded Year 2	Mulched Year 1	Mulched Year 2
			(tons/ac)					
Tucannon East unnamed	10%	Mean	8.22	5.72	8.22	2.90	0.72	1.82
		Std Dev	8.44	6.24	8.44	3.93	0.89	2.35
	20%	Mean	5.28	3.44	5.28	1.22	0.00	0.51
		Std Dev	5.94	4.49	5.94	1.97	0.00	0.83
Upper Cummings Creek	10%	Mean	10.23	6.94	10.23	3.99	1.04	2.34
		Std Dev	6.08	4.42	6.08	2.62	1.03	1.71
	20%	Mean	6.70	4.73	6.70	1.56	0.00	0.51
		Std Dev	4.16	3.07	4.16	1.25	0.00	0.56
Dry Creek	10%	Mean	11.32	7.77	11.33	5.25	3.08	4.38
		Std Dev	8.59	6.05	8.58	4.28	2.75	3.59
	20%	Mean	6.87	4.61	7.30	2.70	0.73	1.51
		Std Dev	5.78	4.07	5.77	2.71	1.05	1.67
Upper Pataha	10%	Mean	13.88	9.48	13.88	6.54	3.89	5.59
		Std Dev	6.17	4.15	6.17	3.10	1.93	2.75
	20%	Mean	9.02	5.60	9.02	3.40	0.76	1.55
		Std Dev	3.90	2.65	3.90	1.70	0.54	0.81

Table 2—Average of ERMiT runs.

Drainage	Exceedance		Untreated Year 1	Untreated Year 2	Seeded Year 1	Seeded Year 2	Mulched Year 1	Mulched Year 2
			(tons/ac)					
Means of ten sets of ERMiT runs	10%	Mean	10.82	7.53	10.82	4.38	1.51	2.95
		Std Dev	2.50	1.68	2.50	1.24	1.08	1.24
	20%	Mean	7.06	4.80	7.10	1.99	0.15	0.85
		Std Dev	1.68	1.11	1.68	0.72	0.31	0.40

WEPP Windows Analysis

The WEPP windows interface was run for each watershed to estimate return periods for peak runoff rates. These results were combined with other methods to make final runoff predictions.

Conclusions

The GeoWEPP tool allows the user to quickly estimate hillslope parameters for use in the ERMiT program. The results from the ERMiT program show that mulching will have major benefits in reducing erosion, especially on the high severity areas. On the other hand, erosion risks on low severity burned slopes were projected as being minimal.

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Conference Wrap-up

Richard E. Miller

In: Page-Dumroese, Deborah; Miller, Richard; Mital, Jim; McDaniel, Paul; Miller, Dan, tech. eds. 2007. Volcanic-Ash-Derived Forest Soils of the Inland Northwest: Properties and Implications for Management and Restoration. 9-10 November 2005; Coeur d'Alene, ID. Proceedings RMRS-P-44; Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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My purpose is twofold: to review key messages from previous speakers and to offer some concepts that may help you link recently acquired information.

When Mt. Mazama erupted about 7,000 years ago, its airborne ash and pumice fell on a wide variety of existing soils. This Mazama tephra was a new parent material for soil development (fig. 1). At some locations, the original deposition was redistributed by: gravity, wind, water, plants, or animal activities, including those of humans. Soil at any specific location in the Inland West is a result of these soil-forming factors and their many possible interactions.

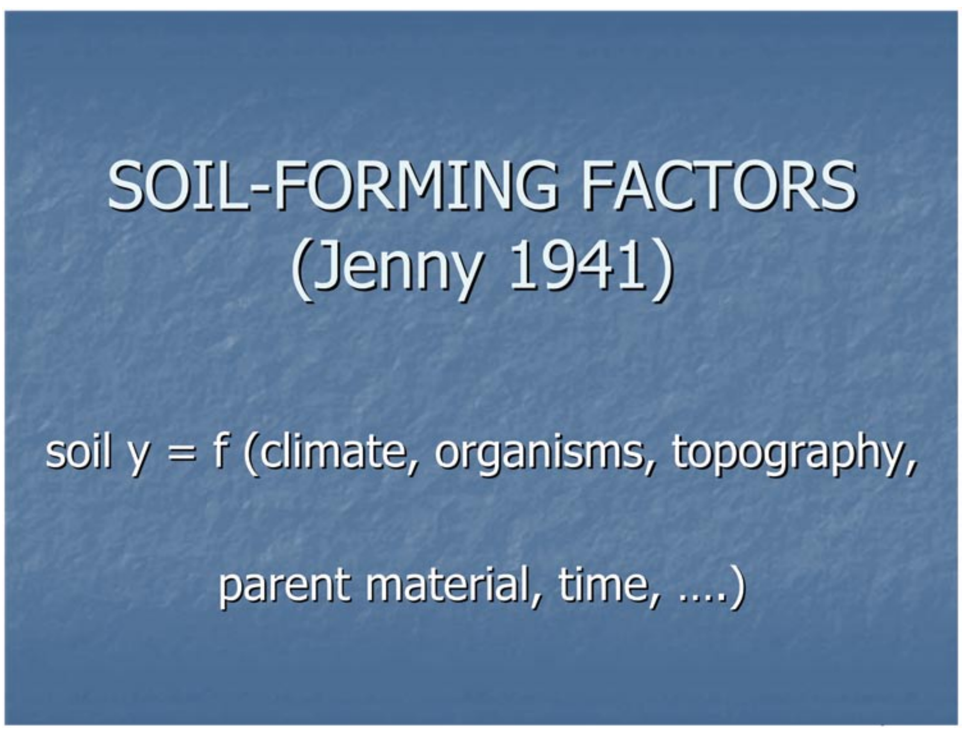

Figure 1—Soil-forming factors (Jenny 1941).

Major Take-Home Messages

1. Ash-derived soils are extensive, variable, and different from soils derived from other parent materials.
2. Activities (equipment, fire) can change soil properties and functions.
3. Consequences of soil changes for vegetative growth or soil erosion are uncertain, because they are seldom quantified.
4. Hence, optimum allocation of preventative or restorative efforts is uncertain.

What is a Forester to do?

Assuming your intent is to protect and manage soil at specific locations, how will you use information gained at this conference? Can you state facts and explain relationships among these facts? Will this new information change or affect your future decisions about prescribing or controlling activities on ash-derived or ash-influenced soils?

Most foresters and land managers are concerned about yield…of wood, forage and protective vegetation. Most recognize that yield at a specific location depends on numerous factors and their interactions (fig. 2). Several speakers reviewed the effects on soil properties of either heavy equipment used in harvesting or of wild and prescribed fire. You should recognize that a change in soil properties is a change in one of several factors that contributes to yield. Despite visually apparent or measured changes in soil characteristics (for example, bulk density, resistance, organic matter) or functions, however, yield may not change. Other factors that also affect yield at a given location can be enhanced by or compensate for the

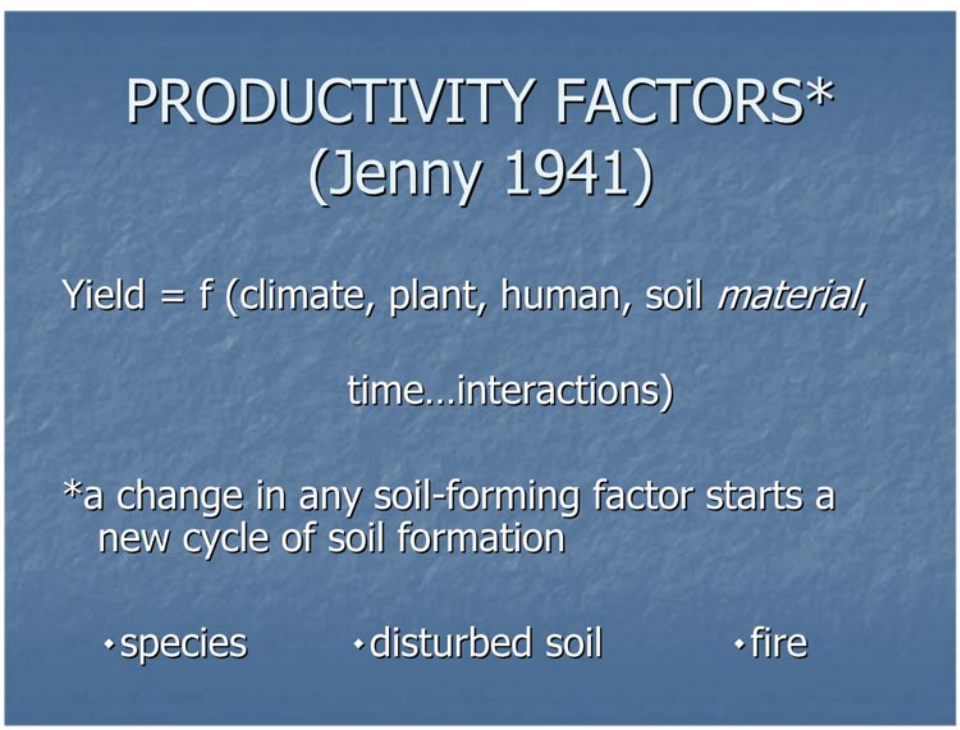

Figure 2—Factors that set productivity or yield (Jenny 1941).

potentially negative effects of soil changes on yield. Factors controlling yield also interact. For example, soil disturbance may reduce vegetative competition for trees. Consequently, this indirect effect of soil disturbance on competing vegetation can enhance tree growth or compensate for direct, potentially negative effects of disturbance on tree growth.

When you propose to harvest trees or prescribe fire, can you predict likely consequences on soil properties and subsequent plant yield? The components of this practical and important question are displayed in figure 3. You, as the agent, propose to use ground based equipment at location Y. Do you recognize that each location has a unique combination of soils, climate, and other factors that determine the severity of soil disturbance and the practical consequences for tree or vegetative growth? Therefore, do not anticipate the same effects on soil or growth at all locations. Refer to current research results and explanations, for example, Gomez and others (2002); Powers and others (2005) for justification of your decisions and remember your A, B, C's (fig. 4).

The concept of ecological stability also applies to soil stability (fig. 5). Soils differ in their initial resistance to heavy equipment traffic. For example, compare visual effects of traffic on a sandy soil containing 70- to 90-percent gravel and cobbles by volume in the top 3 feet with that on a deep silt loam soil that is stone-free. These two soils differ in their weight-bearing capacity and in shear strength, especially when moist or wet. Soils also differ in their resilience or rate of recovery after disturbance. Rate of recovery of soil properties and functions depends largely on interactions among climate, above-and-below ground organisms, and soil properties. For example, recovery is hastened in climates that cause soil to have cycles of thawing and freezing, wetting and drying, or climates that promote rapid growth of plants and other organisms.

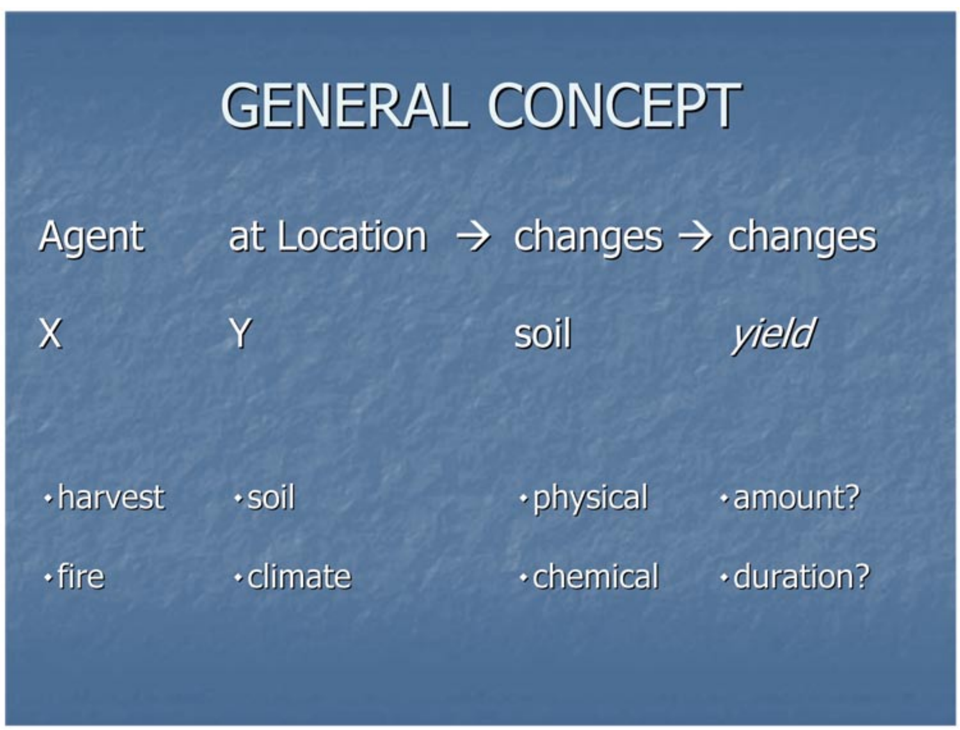

Figure 3—A general concept of actions and consequences.

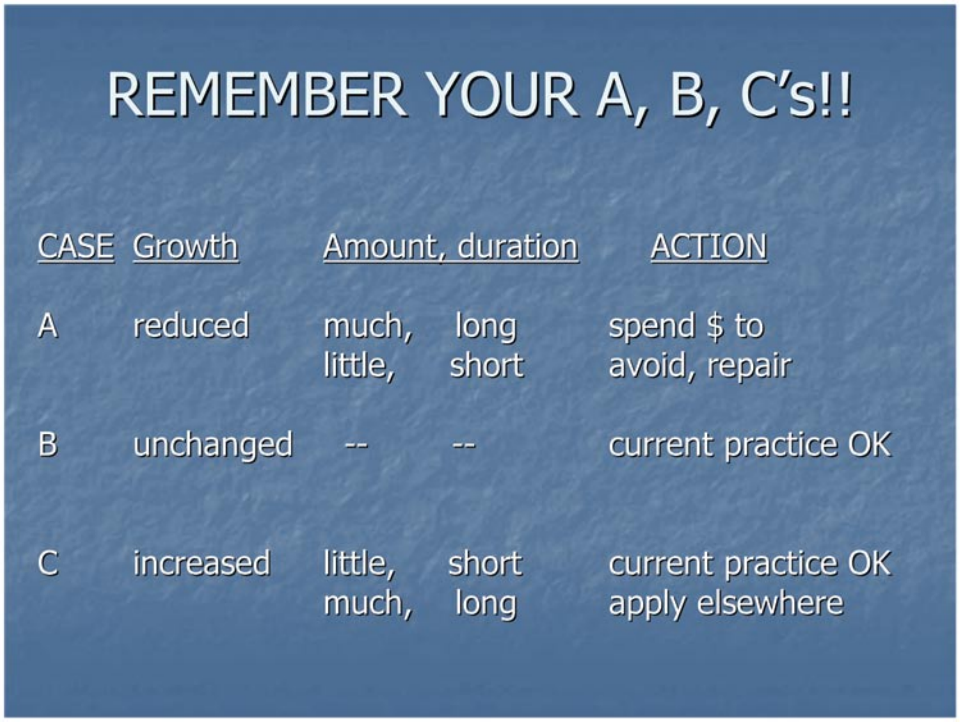

Figure 4—Locations (sites) differ: Remember your A, B, C's.

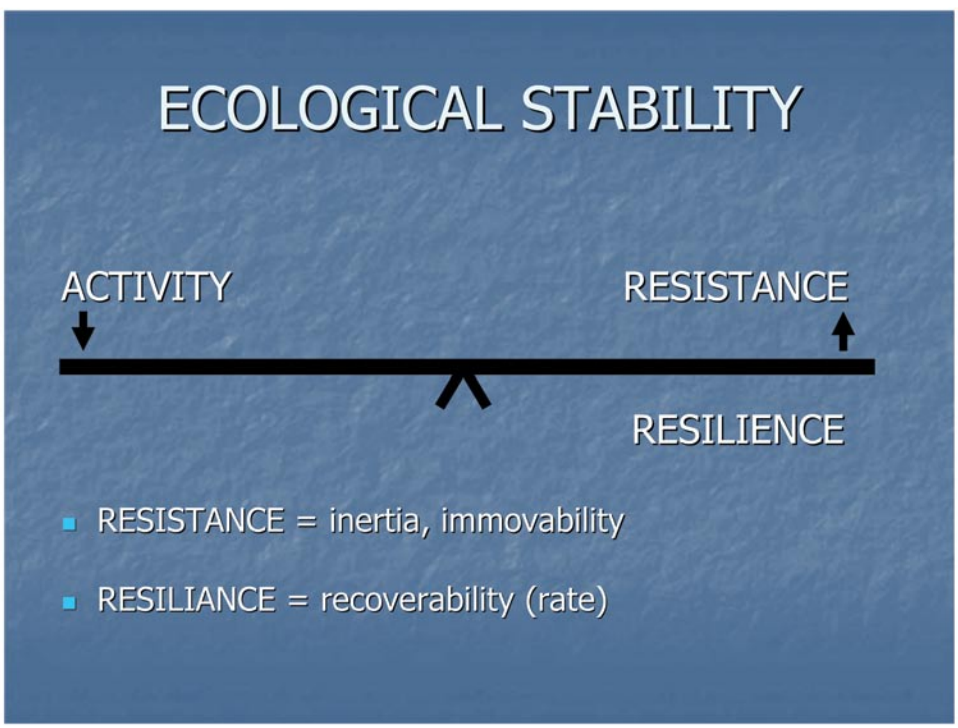

Figure 5—Ecological stability: response depends on resistance; recovery depends on resilience.

Among the many combinations of soils and micro- and macro-climates in the Inland West, we need to identify our A-, B-, C-locations. Recall a similar urging by our after-dinner speaker, Larry Ross: "go forth and stratify forestland;" then fit the practice to the soil.

Soils and climates differ. Soils and climates interact to create varying consequences of soil disturbance or fire for yield (fig. 6). Your considering differences in soil depth like differences in bank accounts will be helpful: Equate shallow soils to a $100 account and deep soils to a $1,000 account. Thus, your prescribing ground-based equipment or fire to reduce fuels will most likely result in reduced growth and subsequent yield on shallow soils or soils with shallow ash caps. Moreover, presence of coarse, non-weathered rock fragments further reduce effective soil depth or the "bank account." Finally, remember interactions: where equipment or fire degrade soil for plant growth, anticipate stronger reductions in plant growth where climate is harsh and less favorable for plant growth.

Final Take-Home Messages

1. Do not assume negative "consequences" for vegetation yield on all soils and locations (soils differ… climates differ…hence, tree response differs).
2. Help others to identify Case A, B, C locations by measuring tree response to disturbance.
3. Know your A-, B-, C-soils/sites.
4. Allocate time and dollars at Case A locations (where activities reduce growth).
5. Save time and dollars at Case B and C locations (where activities have no effect or improve growth).
6. In short, allocate your protective and restorative efforts… to achieve favorable benefit/cost ratios.

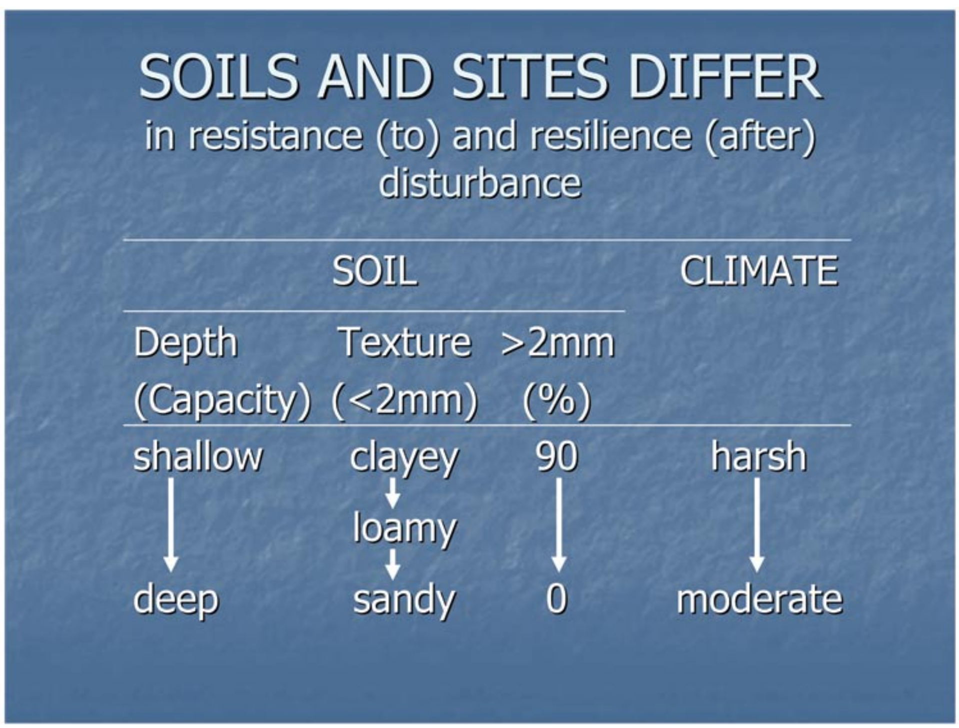

Figure 6—Soils and site differ in resistance and resilience.

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