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

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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

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).

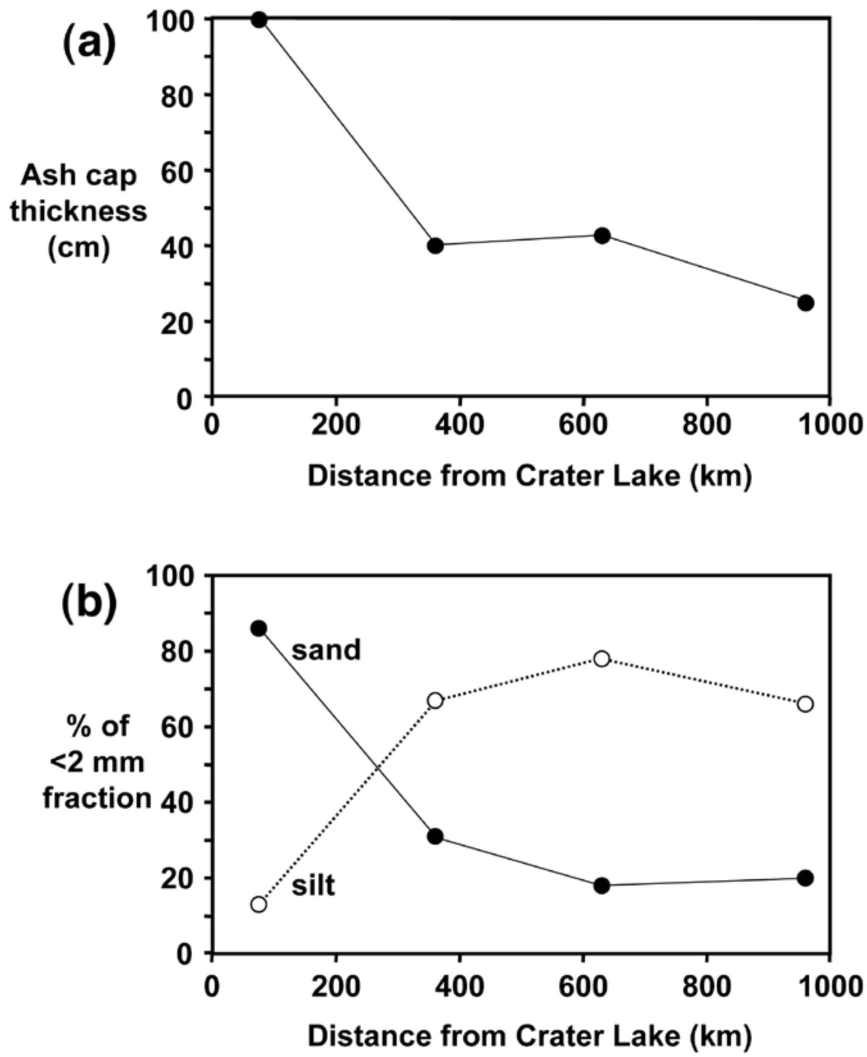

Figure 1—Change in (a) ash-cap thickness and (b) particle-size distribution of Mazama tephra as a function of distance from Crater Lake, OR. Particle-size data represent averages for the ash caps of Lapine, Angelpeak, Threebear, and Jimlake soils and are adapted from McDaniel and others (2005).

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}.

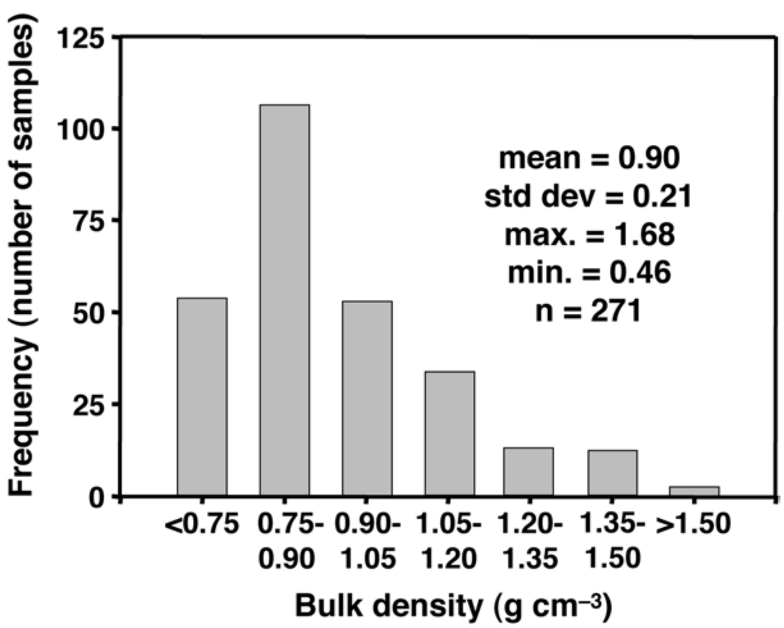

Figure 2—Bulk density data for andic soil horizons of the Pacific Northwest region. Taken from McDaniel and others (2005).

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).

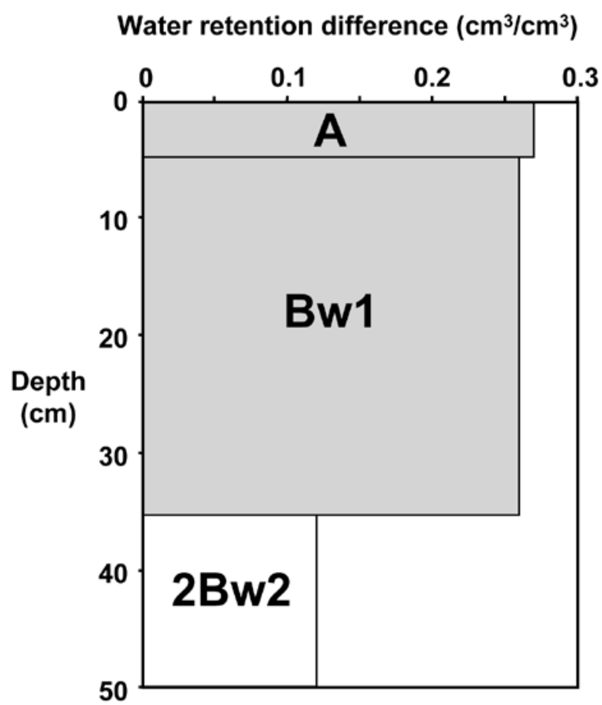

Figure 3—Water retention difference in the top 50 cm of the Bonner series (86ID017002) from north Idaho. Bars represent the difference in water content between –1,500 and –33 kPa, expressed on a volume basis and corrected for rock fragment content. Shaded bars are for andic materials.

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.

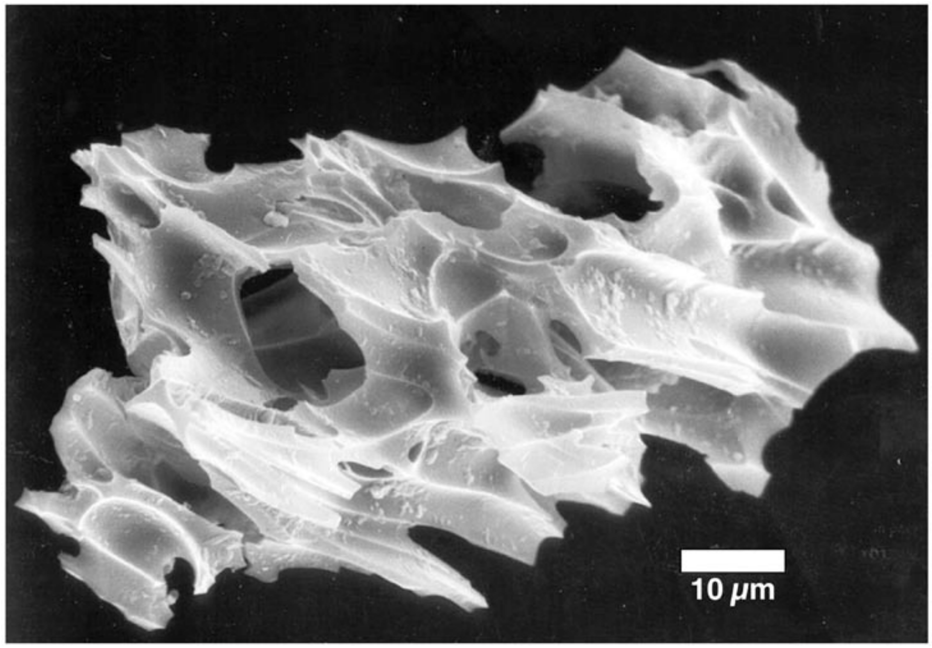

Figure 4—Volcanic glass shard from north Idaho soil. Glass is from the Mazama eruption and measures ~0.1 mm across. Photo from University of Idaho.

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

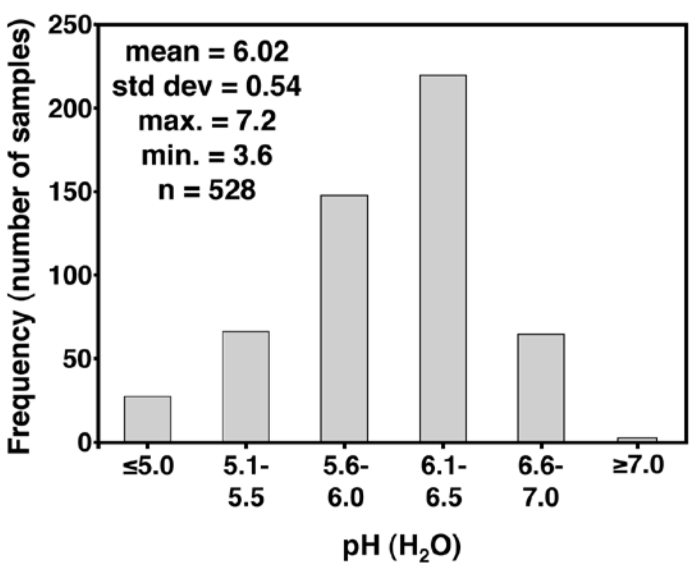

Figure 5—Soil pH data for ash-cap soil horizons from the Inland Pacific Northwest region.

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.

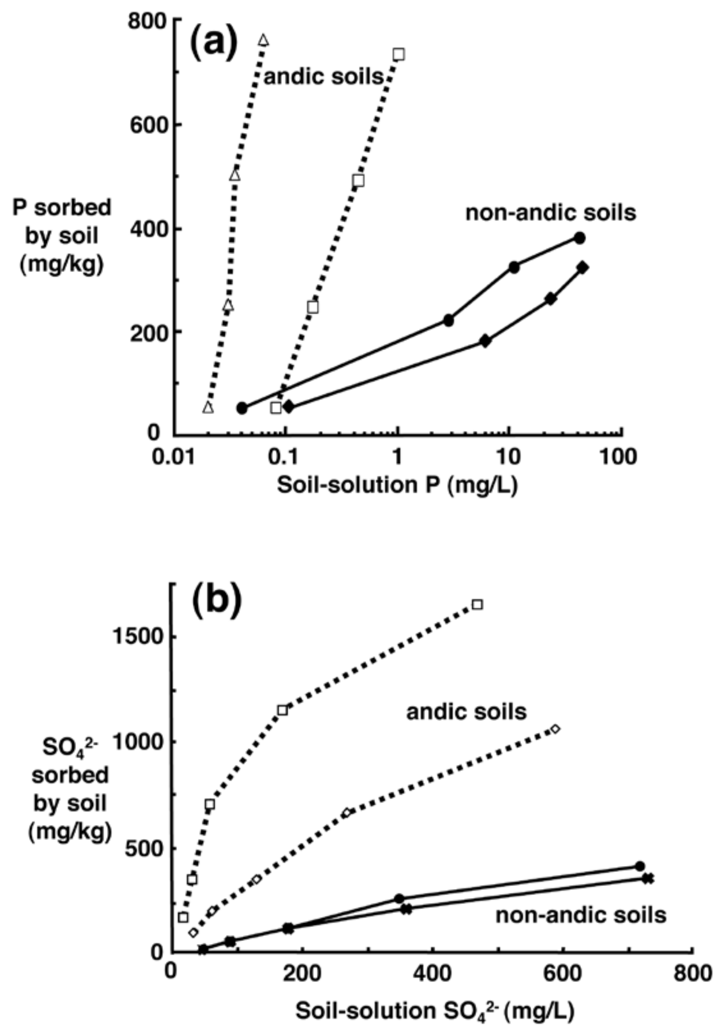

Figure 6—Sorption isotherms for (a) phosphorus additions (adapted from Jones and others 1979), and (b) sulfate additions (adapted from Kimsey and others 2005). Data points represent the proportions of sorbed (plant unavailable) and soluble (plant available) forms with additions of increasing quantities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

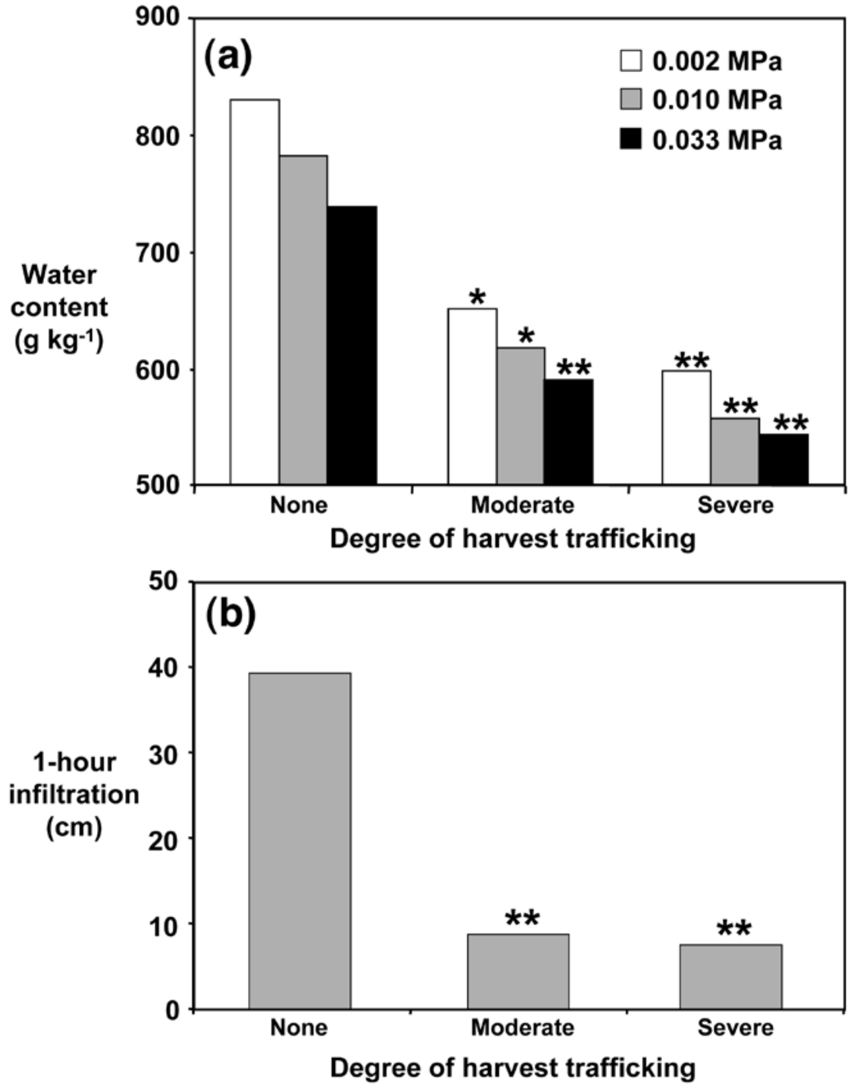

Figure 7—Changes in (a) water content of ash-cap soils due to timber harvest trafficking, and (b) 1-hour infiltration in ash-cap soils due to timber harvest trafficking. *, ** indicate values that differ from the untrafficked controls at the 0.01 and 0.05 significance levels, respectively. Data are adapted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