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:

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

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 $\sim$ 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?		Total	Percent sites with ash cap
	no	yes		
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),
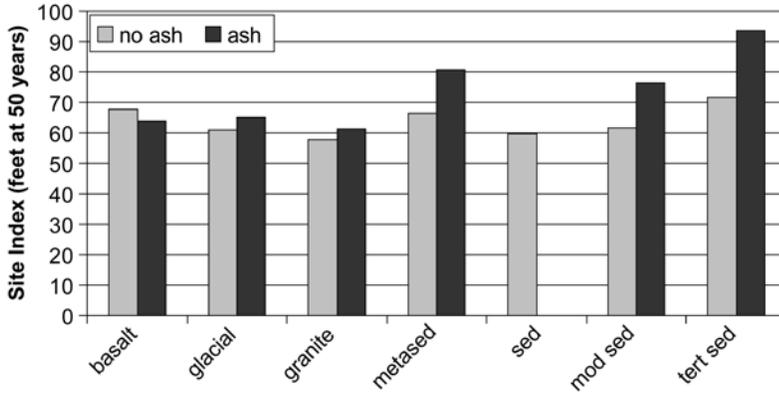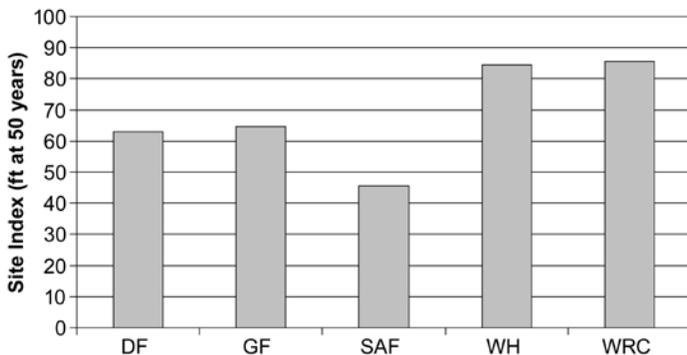
Figure 1a—Douglas-fir site index by base parent material and ash cap presence. Parent materials include basalt, glacial deposit (glacial), granite, metasedimentary (metased), sedimentary (sed), modern sedimentary deposits (mod sed) and tertiary sedimentary deposits (tert sed).
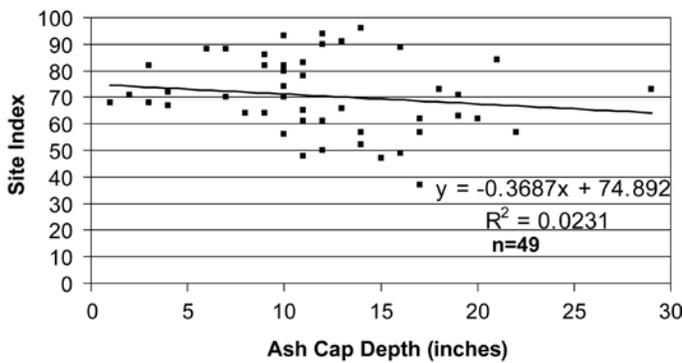
Figure 1b—Douglas-fir site index (ft at 50 years) by ash cap depth for sites with ash cap.
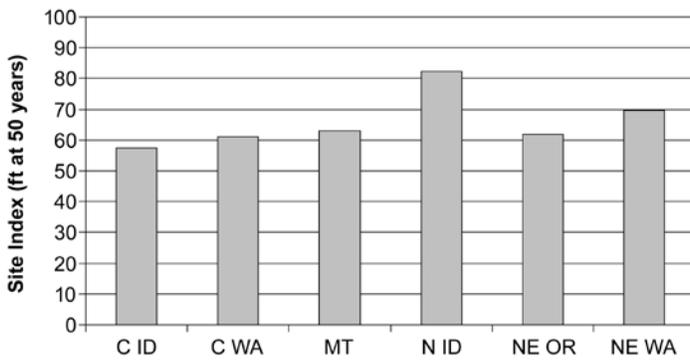
Figure 1c—Douglas-fir site index by geographic region. Regions include central Idaho (C ID), central Washington (C WA), Montana (MT), north Idaho (N ID), northeast Oregon (NE OR) and northeast Washington (NE WA).

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
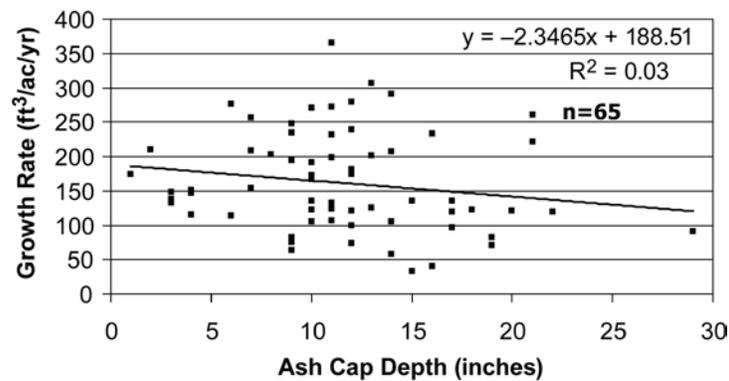

Figure 2a—Control plot growth rate by ash cap depth for sites with ash cap.
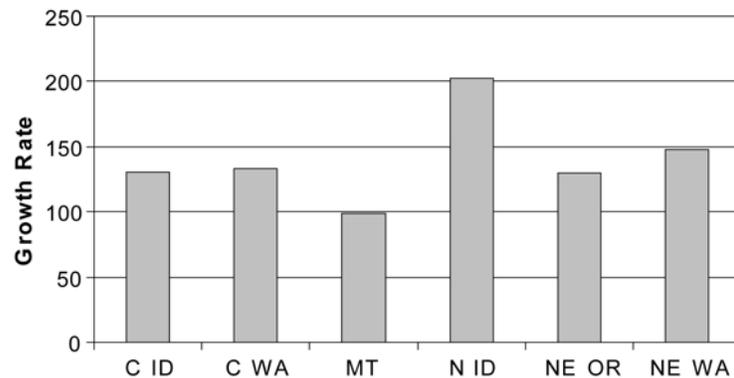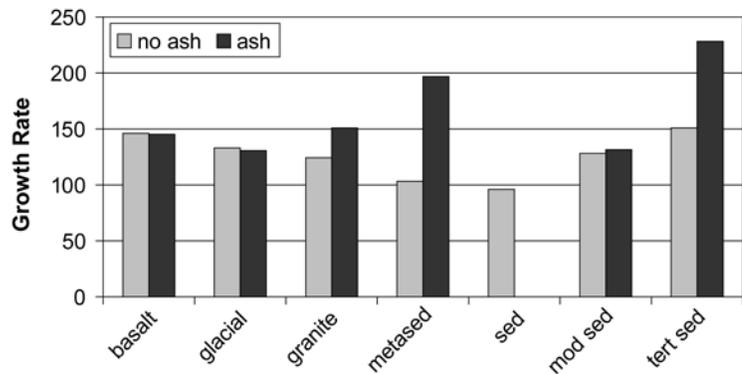

Figure 2b—Control plot growth rate (ft^{3}ac^{-1}yr^{-1}) by geographic region. Regions include central Idaho (C ID), central Washington (C WA),Montana (MT), north Idaho (N ID), northeast Oregon (NE OR) and northeast Washington (NE WA).
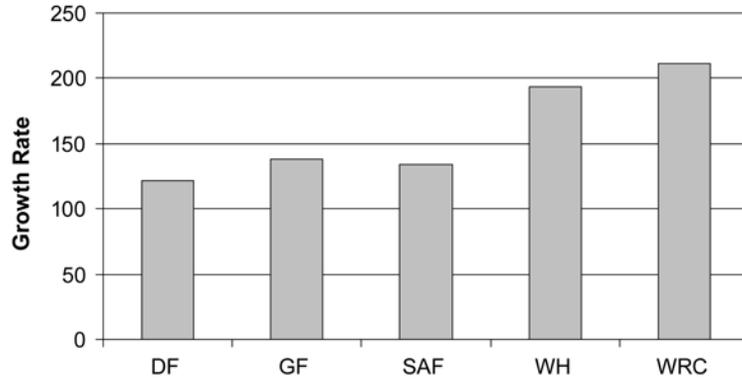
Figure 2c—Control plot growth rate (ft^{3}ac^{-1}yr^{-1}) by vegetation series. Vegetation series include Douglas-fir (DF), grand fir (GF), subalpine fir (SAF), western hemlock (WH) and western red cedar (WRC).
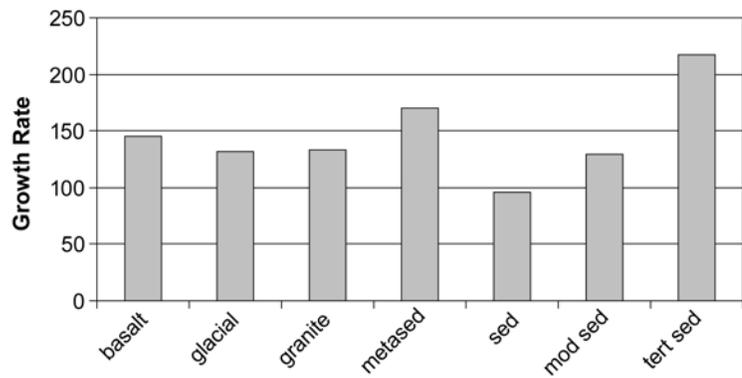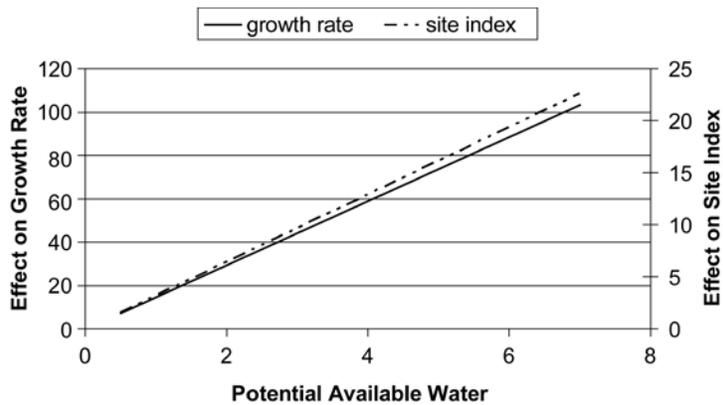

Figure 2d—Control plot growth rate ft^{3}ac^{-1}yr^{-1}) by base parent material. Parent materials include basalt, glacial deposit (glacial), granite, metasedimentary (metased), sedimentary (sed), modern sedimentary deposits (mod sed) and tertiary sedimentary deposits (tert sed).

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 ft³ac⁻¹yr⁻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.
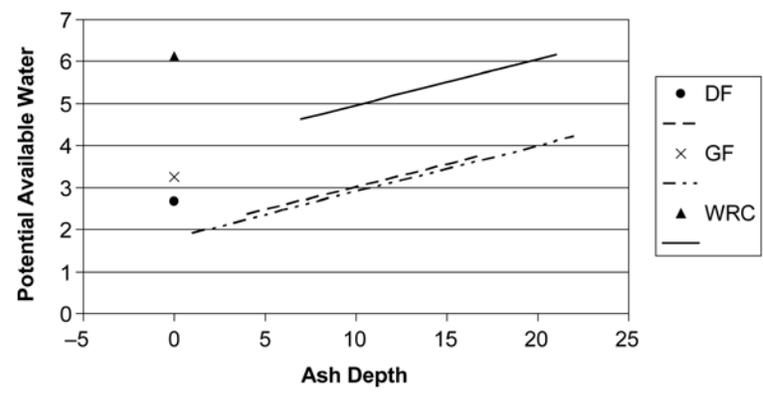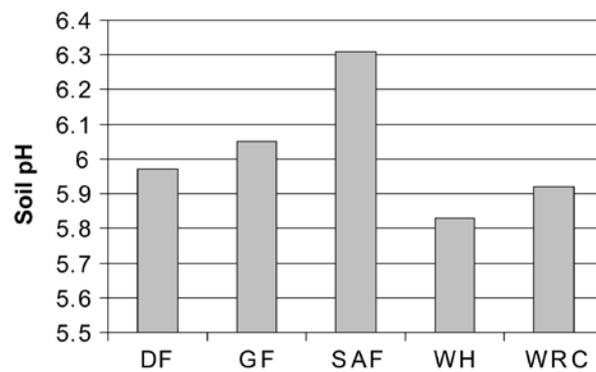

Figure 3b—Potential available water (inches) in the upper 24 inches of soil as a function of ash depth (inches), by vegetation series. Vegetation series include Douglas-fir (DF), grand fir (GF) and western red cedar (WRC).
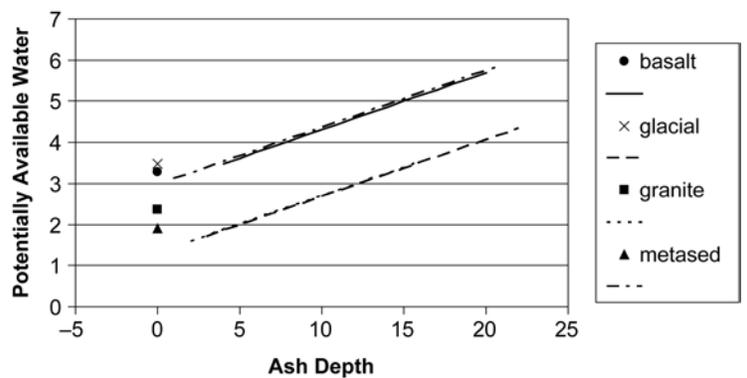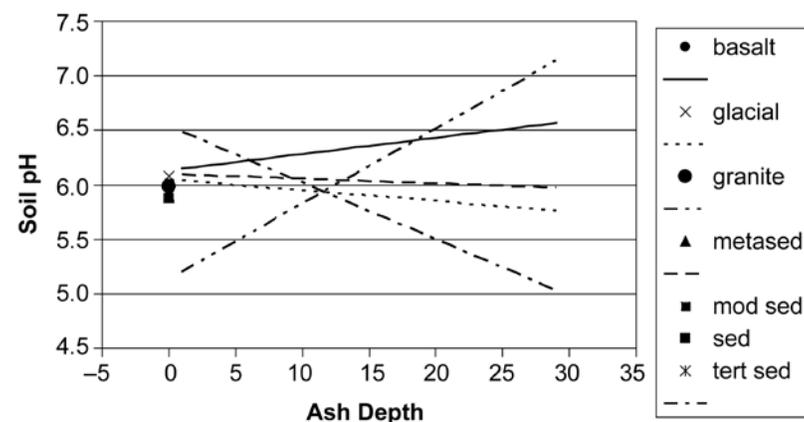

Figure 3c—Potentially available water (inches) in the upper 24 inches of soil as a function of ash depth (inches), by base parent material. Parent materials include basalt, glacial deposit (glacial), granite and metasedimentary (metased).

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).
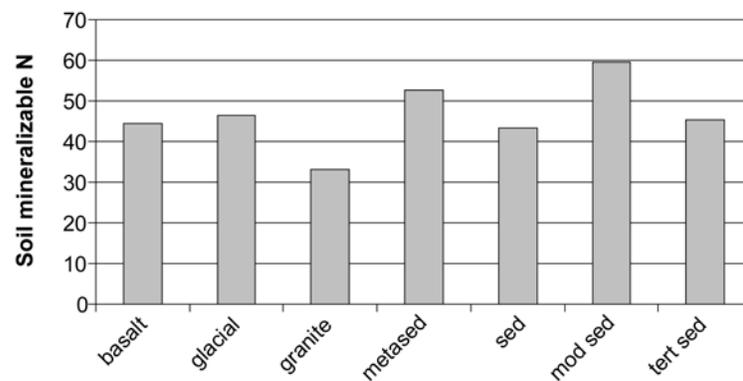

Figure 4b—Soil pH as a function of ash depth (inches) and base parent material. Parent materials include basalt, glacial deposit (glacial), granite, metasedimentary (metased), sedimentary (sed), modern sedimentary deposits (mod sed) and tertiary sedimentary deposits (tert sed).

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
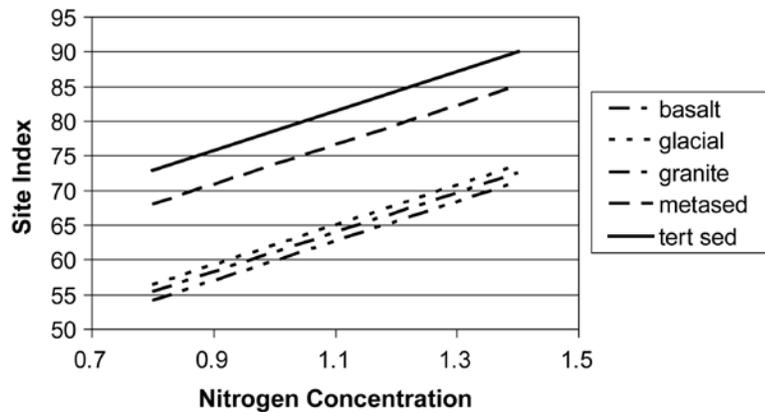

Figure 5a—Soil mineralizable nitrogen (N, ppm) by base parent material. Parent materials include basalt, glacial deposit (glacial), granite, metasedimentary (metased), sedimentary (sed), modern sedimentary deposits (mod sed) and tertiary sedimentary deposits (tert sed).
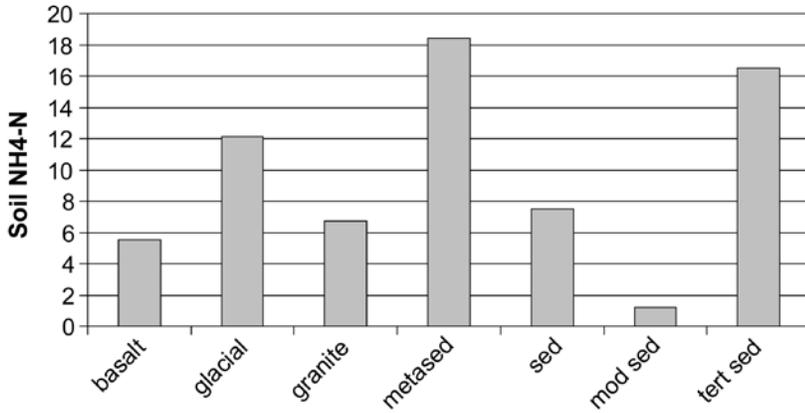
Figure 5b—Soil ammonium-nitrogen (NH4-N, ppm) by base parent material. Parent materials include basalt, glacial deposit (glacial), granite, metasedimentary (metased), sedimentary (sed), modern sedimentary deposits (mod sed) and tertiary sedimentary deposits (tert sed).
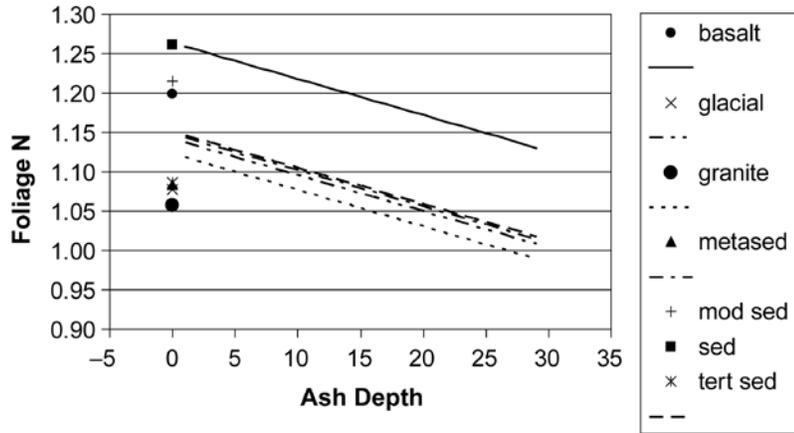
Figure 5c—Douglas-fir foliar nitrogen (N) concentration (percent) as a function of ash depth (inches), by base parent material. Parent materials include basalt, glacial deposit (glacial), granite, metasedimentary (metased), sedimentary (sed), modern sedimentary deposits (mod sed) and tertiary sedimentary deposits (tert sed).

Figure 5d—Site index (ft^{3}ac^{-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).
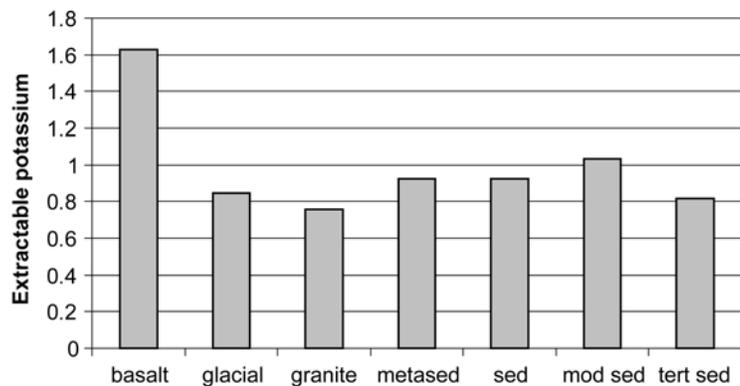
Figure 6b—Extractable calcium (Ca, cmol kg^{-1}) as a function of ash depth (inches), by base parent material. Parent materials include basalt, glacial deposit (glacial), granite, metasedimentary (metased), sedimentary (sed), modern sedimentary deposits (mod sed) and tertiary sedimentary deposits (tert sed).
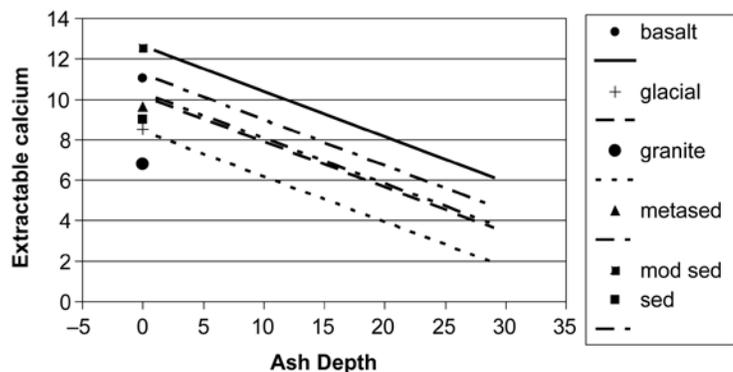
Figure 6c—Extractable magnesium (Mg, cmol kg^{-1}) as a function of ash depth (inches), by base parent material. Parent materials include basalt, glacial deposit (glacial), granite, metasedimentary (metased), sedimentary (sed), modern sedimentary deposits (mod sed) and tertiary sedimentary deposits (tert sed).
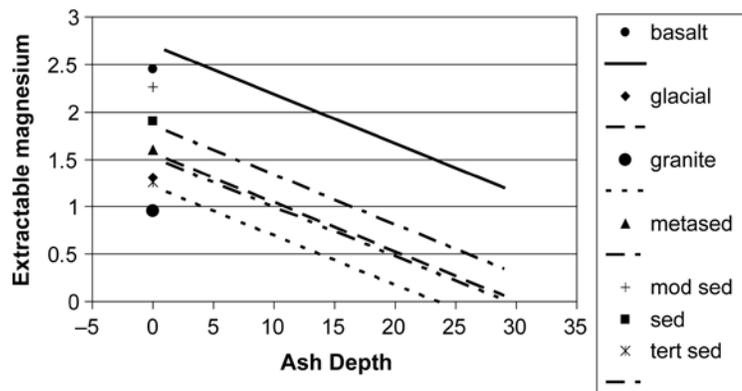
Figure 6d—Douglas-fir foliar potassium (K) concentration (percent) as a function of ash depth (inches), by base parent material. Parent materials include basalt, glacial deposit (glacial), granite, metasedimentary (metased), sedimentary (sed), modern sedimentary deposits (mod sed) and tertiary sedimentary deposits (tert sed).
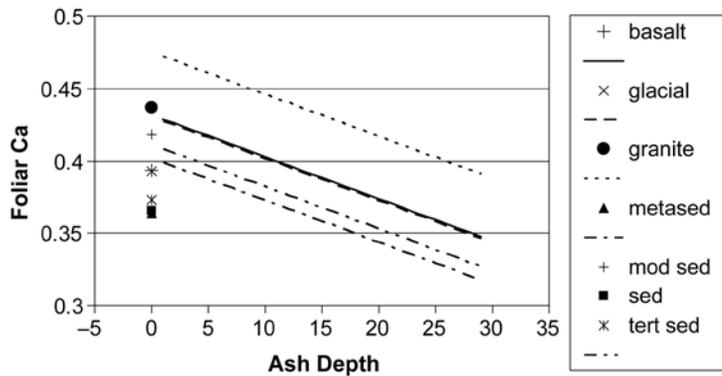
Figure 6e—Douglas-fir foliar calcium (Ca) concentration (percent) as a function of ash depth (inches), by base parent material. Parent materials include basalt, glacial deposit (glacial), granite, metasedimentary (metased), sedimentary (sed), modern sedimentary deposits (mod sed) and tertiary sedimentary deposits (tert sed).
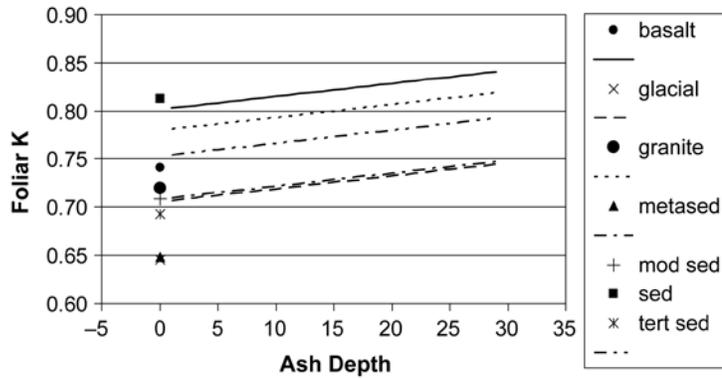

Figure 6f—Douglas-fir foliar magnesium (Mg) concentration (percent) as a function of ash depth (inches), by base parent material. Parent materials include basalt, glacial deposit (glacial), granite, metasedimentary (metased), sedimentary (sed), modern sedimentary deposits (mod sed) and tertiary sedimentary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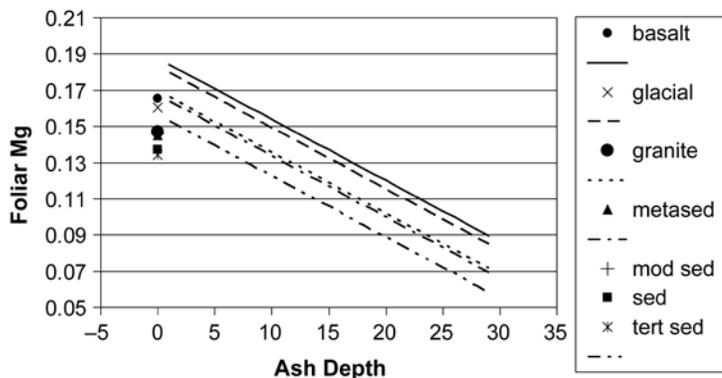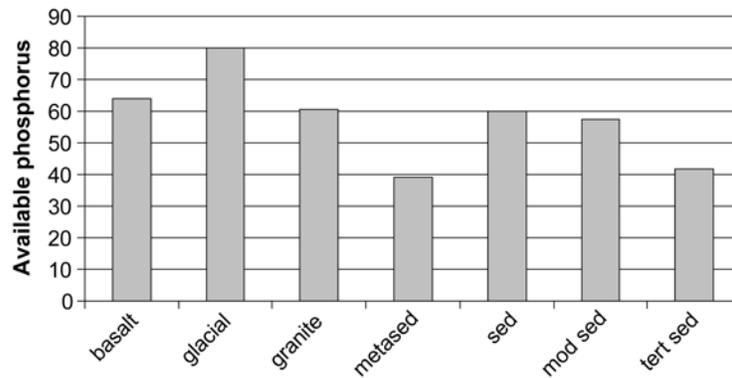

Figure 7b—Douglas-fir foliar phosphorus (P) concentration (percent) as a function of ash depth (inches), by base parent material. Parent materials include basalt, glacial deposit (glacial), granite, metasedimentary (metased), sedimentary (sed), modern sedimentary deposits (mod sed) and tertiary sedimentary deposits (tert sed).
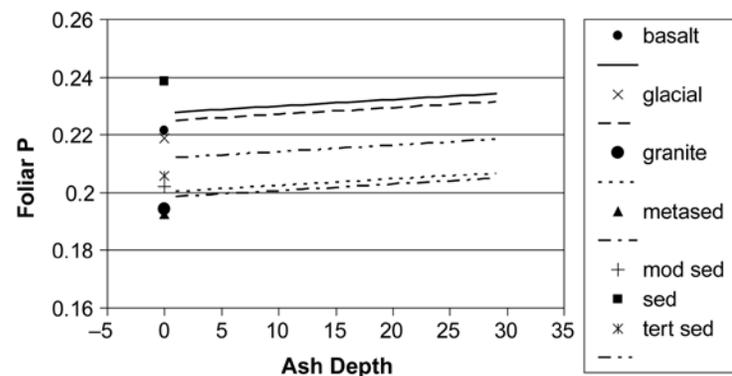
deposits (fig. 8b). Sulfate-S availability was not affected by ash, parent material or vegetation series.

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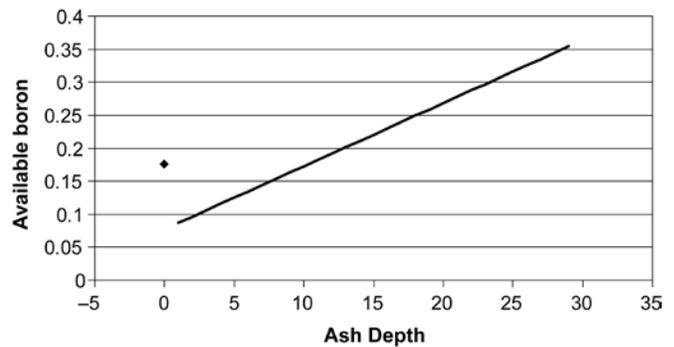
Figure 8b—Available copper (Cu, ppm) by base parent material. Parent materials include basalt, glacial deposit (glacial), granite, metasedimentary (metased), sedimentary (sed), modern sedimentary deposits (mod sed) and tertiary sedimentary deposits (tert sed).

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).
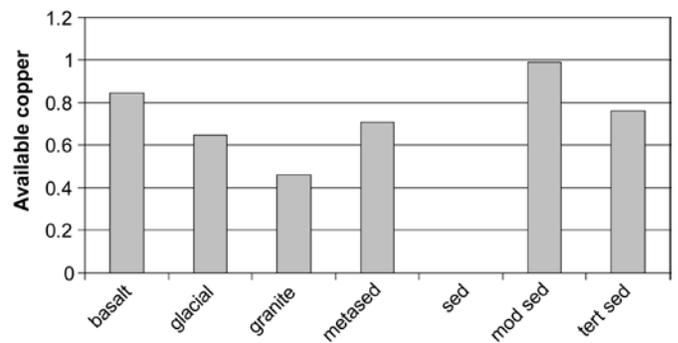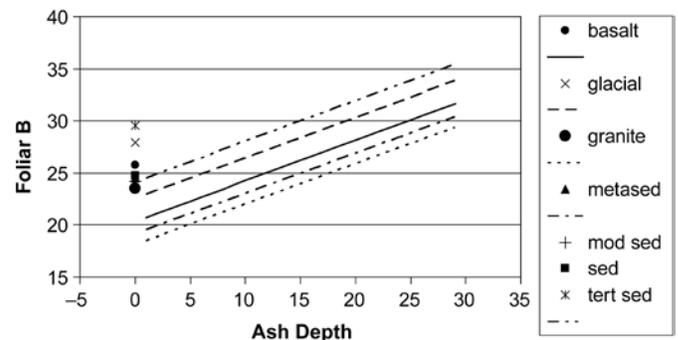
Fertilization Response

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.
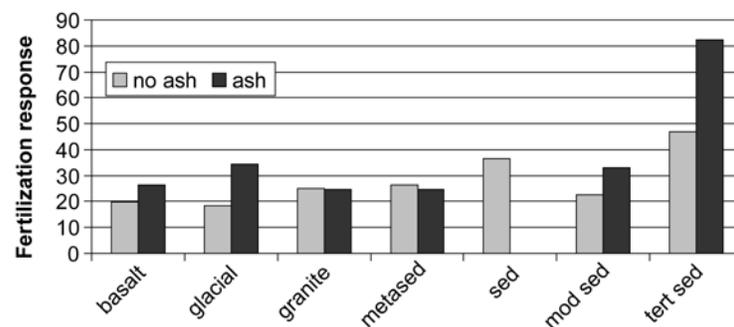
Figure 9a—Six-year nitrogen (N) fertilization response (ft^{3}ac^{-1}yr^{-1}) by base parent material and ash cap presence. Parent materials include basalt, glacial deposit (glacial), granite, metasedimentary (metased), sedimentary (sed), modern sedimentary deposits (mod sed) and tertiary sedimentary deposits (tert sed).
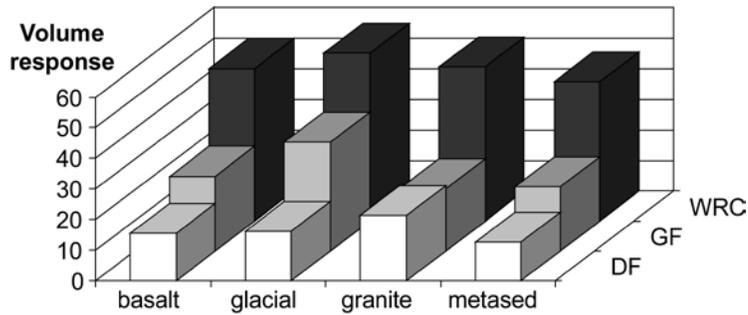
Figure 9b—Six-year nitrogen (N) fertilization response (ft^{3}ac^{-1}yr^{-1}) by base parent material and vegetation series. Parent materials include basalt, glacial deposit (glacial), granite and metasedimentary (metased). Vegetation series include Douglas-fir (DF), grand fir (GF) and western red cedar (WRC).
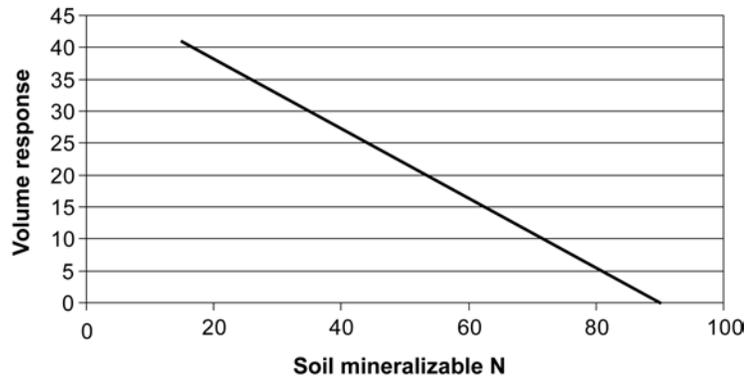
Figure 9c—Six-year nitrogen (N) fertilization response (ft^{3}ac^{-1}yr^{-1}) as a function of soil mineralizable nitrogen (N, ppm).
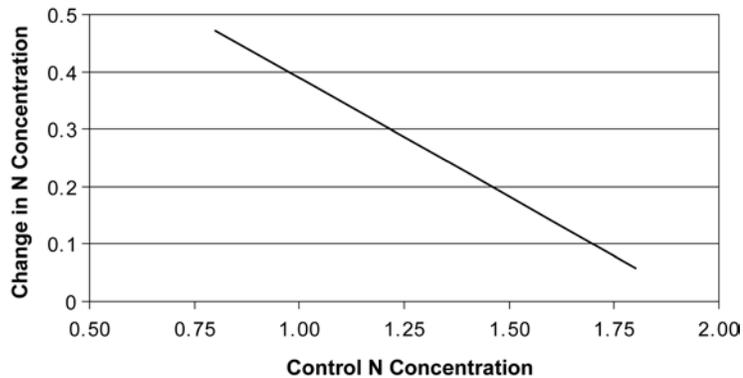
Figure 9d—Change in Douglas-fir foliar nitrogen (N) concentration (percent) following N fertilization as a function of control plot (unfertilized) foliar N concentration (percent).

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.

References

Brockley, R. P. 2000. Using foliar variables to predict the response of lodgepole pine to nitrogen and sulphur fertilization. Canadian Journal of Forest Research. 30: 1389-1399.

Brown, H. G.; Lowenstein, H. 1978. Predicting site productivity of mixed conifer stands in northern Idaho from soil and topographic variables. Soil Science Society of America Journal. 48: 910-913.

Case, T. E. 1996. Sulfate-sulfur in soils. Analytical Sciences Laboratory Standard Methods SMM.85.090.03. Moscow, ID: University of Idaho. 4 p.

Case, T. E.; Thyssen, B. C. 1996a. Available phosphorus and potassium in soils sodium acetate method. Analytical Sciences Laboratory Standard Methods SMM.85.050.04. Moscow, ID: University of Idaho. 6 p.

Case, T. E.; Thyssen, B. C. 1996b. Extractable and exchangeable cations. Analytical Sciences Laboratory Standard Methods SMM.85.100.03. Moscow, ID: University of Idaho. 4 p.

Case, T. E.; Thyssen, B. C. 1996c. Soil boron, pouch method. Analytical Sciences Laboratory Standard Methods SMM.85.060.02. Moscow, ID: University of Idaho. 5 p.

Case, T. E.; Thyssen, B. C. 1996d. Soil nitrate and ammonium nitrogen extraction method. Analytical Sciences Laboratory Standard Methods SMM.85.080.03. Moscow, ID: University of Idaho. 6 p.

Case, T. E.; Thyssen, B. C. 2000. Zn, Mn, Cu, Fe, Pb, Cd, Ni and As in soils — DTPA Method. Analytical Sciences Laboratory Standard Methods SMM.85.110.04. Moscow, ID: University of Idaho. 4 p.

Cole, D. W.; Gessel, S. P.; Dice, S. F. 1967. Distribution and cycling of nitrogen, phosphorus, potassium and calcium in a second-growth Douglas-fir ecosystem. In: Symposium on the primary productivity and mineral cycling in natural ecosystems: proceedings: 1967; Ecological Society of America, American Association for the Advancement of Science Annual Meeting: 197-232.

Garrison, M. T.; Moore, J. A.; Shaw, T. M.; Mika, P. G. 2000. Foliar nutrient and tree growth response of mixed-conifer stands to three fertilization treatments in northeast Oregon and north central Washington. Forest Ecology and Management. 132: 183-198.

Geist, J. M. 1976. Forested range fertilization in eastern Oregon and Washington. Rangeman's Journal. 3: 116-118.

Gordon, A. G. 1983. Nutrient cycling dynamics in differing spruce and mixed wood ecosystems in Ontario and the effects of nutrient removals through harvesting. In: Wein, R. W.; Riewe, R. R.; Methven, I. R. Resources and Dynamics of the Boreal Zone: proceedings; 1982 August; Thunder Bay, Ontario. Ottawa, Canada: Association of Canadian Universities for Northern Studies: 97-118.

Gower, S. T.; Reich, P. B.; Son, Y. 1993. Canopy dynamics and aboveground production of five tree species with different leaf longevities. Tree Physiology. 12: 327-345.

Hasse, D. L.; Rose, R. 1995. Vector analysis and its use for interpreting plant nutrient shifts in response to silvicultural treatments. Forest Science. 41: 54-66.

Kimsey, M.; McDaniel, P.; Strawn, D.; Moore, J. 2005. Fate of applied sulfate in volcanic ash-influenced forest soils. Soil Science Society of America Journal. 69: 1507-1515.

McDaniel, P. A.; Wilson, M. A.; Burt, R.; Lammers, D.; Thorson, T. D.; McGrath, C. L.; Peterson, N. 2005. Andic soils of the Inland Pacific Northwest, USA: properties and ecological significance. Soil Science. 170(4): 300-311.

Miller, J. D.; Cooper, J. M.; Miller, H. G. 1993. A comparison of above-ground component weights and element amounts in four forest species at Kirkton Glen. Journal of Hydrology. 145: 419-438.

Mital, J. M. 1995. Relating soil, vegetation, and site characteristics to Douglas-fir response to nitrogen fertilization in the Inland Northwest. Moscow, ID: University of Idaho. PhD Dissertation.

Moller, I. S. 2000. Calculation of biomass and nutrient removal for different harvesting intensities. New Zealand Journal of Forest Science. 30(1/2): 29-45.

Monserud, R .A. 1984. Height growth and site index curves for inland Douglas-fir based on stem analysis data and habitat type. Forest Science. 30: 943-965.

Moore, J. A.; Mika, P. G. 1997. Influence of soil parent material on the nutrition and health of established conifer stands in the Inland Northwest. In: Haase, D. L.; Rose, R. Forest Seedling Nutrition From the Nursery to the Field: proceedings; Corvallis, Oregon: Nursery Technology Cooperative, Oregon State University: 144-153.

Moore, J. A.; Mika, P. G.; Shaw, T. M.; Garrison-Johnston, M. T. 2004. Foliar nutrient characteristics of four conifer species in theInterior Northwest United States. Western Journal of Applied Forestry. 19(1): 13-24.

Pang, P. C.; Barclay, H. J.; McCullough, K. 1987. Aboveground nutrient distribution within trees and stands in thinned and fertilized Douglas-fir. Canadian Journal of Forest Research. 17: 1379-1384.

Webster, S. R.; Dobkowski, A. 1983. Concentrations of foliar nutrients for trees and the dosage frequency of fertilizer trials. Weyerhaeuser Research Report No. 1; Project 050-3920/3. 25 p.

Weetman, G. F.; Fournier, R. M. 1986. Construction and interpretation of foliar graphical diagnostic technique. In: Interior forest fertilization workshop: proceedings; Kamloops, British Columbia: 55-76.