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Article

Geologic soil parent material influence on forest surface soil chemical characteristics in the Inland Northwest, USA

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Abstract: Successful fertilization treatments targeted to improve stand productivity while reducing operational complexities and cost depend on a clear understanding of soil nutrient availability under varying environmental conditions. Soil nutrient data collected from 154 forest sites throughout the Inland Northwest, USA were analyzed to examine soil nutrient characteristics on different geologic soil parent materials and to rank soil fertility. Results show that soil parent material explains significant differences in soil nutrient availability. Soils developed from volcanic rocks have the highest CEC and are relatively high in P, K, S, Mg, Cu, Ca, and B, but generally poor in N. Forest soils developed from plutonic rocks exhibit the lowest CEC and are low in N, S, K, Mg, Cu, and Ca, but higher in P. Some soils located on mixed glacial till are low only in K, Cu, Mg, and Ca, but many glacial soils are relatively rich in other nutrients, albeit the second lowest CEC. Soils developed from metasedimentary and sedimentary rocks are among those with lowest soil nutrient availability for P and B. Sulfur was found to have the highest concentrations in metasedimentary influenced soils and the least in sedimentary derived soils. Our results should be useful in designing site-specific fertilizer and nutrient management prescriptions for forest stands growing on soils developed from these major geologies within the Inland Northwest region of the United States.

Keywords: Forest nutrition, soil chemistry, geology, cumulative distribution functions

1. Introduction

Soil nutrient availability is closely associated with many aspects of plant nutrition, growth and ecosystem processes, including nutrient uptake and use efficiency [1–3], foliar nutrient concentrations [4], forest net primary productivity [5], decomposition [6] and growth damage and recovery from herbivory [7,8]. Coniferous forests in the Inland Northwest of the United States are generally deficient in many nutrients [9,10]. However, interpreting the results of forest soil chemical tests is difficult since diagnostic "critical" values are lacking. One approach is to compare collected soil samples with probability distributions of soil nutrient concentrations developed from large data sets collected over a wide geographic area. Graphic presentation of soil nutrient concentrations in cumulative distributions allows readers to quickly compare their sample-derived estimates with soil nutrient concentration distributions developed from large population samples.

Inherent soil properties, fertility, species distribution and forest growth are functions of parent material and topography [11–15]. Soil parent materials (SPM) are highly variable mineralogically and chemically [16]. Previous studies have demonstrated that stand growth responses and foliage nutrient status are significantly different among sites overlying various rock types, thus specific nutrient amendments may be required to meet growth demand for trees growing on soils derived from different SPMs[17,18]. A better understanding of soil nutrient status and site nutritional characteristics is central to effective development and implementation of nutrient management prescriptions for maintaining and improving stand productivity.

Sustaining forest and soil productivity continues to be a concern for forest managers and researchers [19–24]. For example, Tiarks and Haywood [25] reported that slash pine (Pinus elliottii Engelm.) plantations averaged 7% and 24% less in height and volume growth, respectively, at age 10 years in the second rotation. Rose and Shiver [26] obtained similar results for slash pine. Long-term agricultural crop productivity monitoring suggests that appropriate forest management practices could sustain forest productivity as well [23]. A better understanding of forest soil physical and chemical properties and potential soil nutrient deficiencies would allow for tailored site-specific forest nutrient management practices that maintains long-term forest soil productivity. Thus, knowledge of soil fertility across broad geographic regions and diverse SPMs is necessary for these site-specific forest management practices.

We studied soil nutrient characteristics for common forest SPMs in the Inland Northwest of the United States. Major tree species such as Douglas-fir (Pseudostuga menziesii var. glauca (Beissn.) Franco), grand fir (Abies grandis (Dougl.) Forbes), ponderosa pine (Pinus ponderosa Dougl.) and lodgepole pine (Pinus contorta var. latifolia Engelm.) commonly grow on these soils. Most forest soils naturally develop from different SPMs in the Inland Northwest and many SPMs exist in this large area [27]. Since SPM has shown to be a good indicator of forest growth rates and carrying capacity [28–31], forest management including nutrient amendments and weed control strategies for these species on different SPMs may vary in order to maintain or enhance forest health and/or to produce maximum growth improvement and economic returns. Understanding soil nutrient availability allows soil fertility ranking that can be a guideline to aid in designing environmentally and economically sound management practices for different forest soils.

2. Materials and Methods

2.1 Data source

Data used in this study came from 154 permanent research plots established by the Intermountain Forestry Cooperative, University of Idaho. These data were collected from early 1980s to the 2000s from throughout the Inland Northwest comprising central and northern Idaho, western Montana, northeast Oregon, central and northeast Washington. We only used soil nutrient data before fertilizer applications. These data reflect natural soil nutrient availability under the existing environmental conditions for the various SPM types in the analyses (Fig. 1). Soil nutrient availability and fertility were examined and grouped by underlying SPM. SPM was classified into five categories: metasedimentary, mixed glacial till (mixed), plutonic, sedimentary, and volcanic. Of the 154 control plots from different study stands, 28 were classified as metasedimentary, 31 as mixed, 32 as plutonic, 9 as sedimentary, and 54 as volcanic.

Five soil samples were collected and composited from each of the 154 permanent plots at the time of establishment. Sample points were dispersed across each plot. Soil samples were collected by a 4-inch bucket auger at the top 25.4 cm of mineral soils. The five collected soil samples were then transported to the laboratory, where all samples were air dried, passed through a 2 mm sieve and stored in a 1-quart ice cream carton for further analyses.

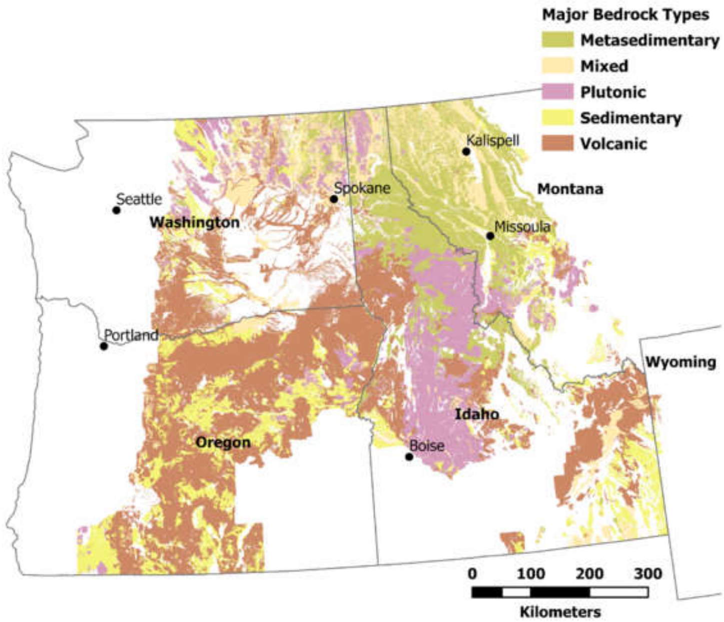

Figure 1. Major bedrock soil parent material distribution across the forested Inland Northwest, USA.

2.2 Chemical analyses

Mineral soil chemical characterization included mineralizable N (ppm), available P, S, B and Cu (ppm), exchangeable K, Mg and Ca (meq 100g-1), cation exchange capacity (cmolc kg-1), and soil pH. Soil samples were processed, and solutions were extracted using the following analytic methods:

Mineralizable N was estimated by placing 5 g of oven-dried soil samples in a container and then incubated at 40°C with 25 ml of distilled water for one week. Soil solutions were then extracted with 25 ml of 2 N KCl and agitated on an orbital shaker for 15 minutes to achieve more accurate and uniform results. An auto analyzer was used to determine the NH4+ concentrations in the solutions [32].

Available soil P was determined by the NaOAc method [33]. About 10 g of dried soil samples was extracted with 50 ml of 0.75 N NaOAc for 30 minutes. The liquid was filtered after solutions were agitated on a mechanical shaker. Phosphorus concentrations were calorimetrically determined on a spectrophotometer with a 660 nm NIR filter.

Exchangeable K, Mg and Ca were determined by the NaOAc method [33]. In brief, 2 g of oven-dried soil samples were extracted in 40 ml of NaOAc adjusted to pH 7 for 30 minutes, and solutions were then agitated on an orbital shaker. Potassium, Mg and Ca concentrations were determined by an ICP. The summation method was then used to estimate cation exchange capacity (CEC) [34].

Soil sulfate S was determined by ion chromatography [35,36]. About 10 g of oven-dried soil samples were extracted by 25 ml of 0.08 M $CaSO_4$. Extracted solutions were agitated on an orbital shaker for 30 minutes, and then filtered into a 125 ml gas bottle. Available soil S was obtained from a calibrated ion chromatograph.

Available soil B was determined by the pouch method [37]. About 20 g of dried soil samples were placed in a Ziploc bag and 40 ml of 0.01 M $CaCl_2$ was added. The plastic

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bag was sealed to contain as little air as possible. About 9 to 15 sample bags were placed into the boiling bath. After bags started to boil and float for 7 minutes, they were removed from the bath and allowed to cool for 20 minutes. Then, a ½ teaspoon Darco was added into each bag. Soil solutions were then filtered into plastic vials and soil B was determined by a spectrophotometer at 430 nm using a VIS filter.

Available soil Cu was determined by the DTPA (diethylenetriamine pentaascetic acid) method [38]. About 20 g of dried soil samples were extracted by 40 ml of DTPA extractant in a 250 ml Wheaton bottle. Soil solutions were agitated on a shaker for 2 hours and then filtered into a 50 ml Erlenmeyer flask. Soil Cu was determined by an ICP. In addition, soil pH values were determined by glass electrode in a 1:1 paste [39].

2.3 Statistical analyses

Analysis of variance (ANOVA) was used to test whether soil nutrient availability significantly differed by SPM. The one-way ANOVA model extends the independent samples t-test problem to the situation with a > 2 groups. One way ANOVA's treatment effects model takes the following form:

$$y_{ij} = \mu + \tau_j + \epsilon_{ij} \quad (1)$$

where μ is the overall mean that is common to all observations, τ_i is the *j*-th group's treatment effect, which satisfies $\sum_{j=1}^{a} \tau_j = o$ and the error terms are iid normal variables with mean zero and homogeneous variance. Significance was evaluated at $p < 0.1$.

Multiple comparison of means for each nutrient variable were conducted among SPMs through the method of the least significant difference (LSD) [40]. The LSD test declares the difference between means $\bar{Y}_j$ and $\bar{Y}_k$ of treatments τ_j and τ_k to be significant when:

$$\bar{Y}_j - \bar{Y}_k \mid > \text{LSD, where} \quad (2)$$

$$LSD = T_{\frac{a}{2}, df_{MSE}} \sqrt{MSE\left(\frac{1}{r_1} + \frac{1}{r_2}\right)} \quad (3)$$

A significant difference between means was declared at a probability value of 0.1.

The relative cumulative distribution of sites for each of the soil nutrient variables was calculated for each SPM to visually aid in understanding general distribution and variability. The data were aggregated into easily interpreted smooth curves for each soil nutrient by SPM by fitting a three-parameter Weibull distribution of the following form [41]:

$$f(x) = 1 - exp\left[-\left(\frac{x-\theta}{\beta}\right)^{\alpha}\right] \quad (4)$$

where: $f(x)$ is the percentage cumulative distribution for SPM x, *exp* the exponential term, θ the location parameter indicating the shift in the distribution on the horizontal axis, β the scale parameter for stretching or compressing the distribution on the vertical axis, and α the shape parameter allowing Weibull distributions flexible to take on a variety of shapes. Kolmogorov-Smirnov (K-S) tests [42,43] were used to test for significant differences in nutrient distributions between SPMs. The agricolae R package [44] was used to perform ANOVA and mean comparisons. The fitdistrplus [45] and FAdist [46] R packages were used to derive the Weibull cumulative distribution function, and the cumulative distribution plots were drawn using the ggplot2 R package [47].

3. Results

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3.1 Soil nutrient concentrations by soil parent materials

All soil nutrient characteristics except for available P, S and B were significantly different as a function of SPM at the 90% confidence level (Tables 1 and 2). Soil pH was not significantly different among SPMs. Forest sites on igneous plutonic and volcanic SPM averaged 32.7 and 39.3 ppm of mineralizable N, respectively, greatly lower than those on alluvially or glacially deposited SPM (metasedimentary, mixed, sedimentary) (Table 2).

Table 1. Summary of analyses of variance results for testing effects of soil parent material on soil chemical characteristics.

Variable	df	Sum of square	Mean square	F value	Pr(>F)
pH	4	0.168	0.04211	0.591	0.670
CEC	4	2273	568.3	17.44	<0.001
Mineralizable N	4	7911	1977.7	7.267	<0.001
Available P	4	116.7	29.18	1.946	0.115
Exchangeable K	4	9.18	2.2961	8.429	<0.001
Exchangeable Mg	4	27.33	6.832	7.125	<0.001
Exchangeable Ca	4	228.6	57.15	5.824	<0.0019
Available S	4	17.98	4.495	0.9	0.471
Available B	4	0.0348	0.008689	1.153	0.342
Available Cu	4	0.755	0.18876	3.779	0.012

Sites on plutonic and volcanic SPM were most abundant in available P. Exchangeable soil K was significantly higher on volcanic SPM compared to all other SPMs. Available S concentrations showed higher levels in metasedimentary SPM relative to plutonic and sedimentary but were insignificantly higher than mixed and volcanic. Concentrations of Mg were higher on sites developed from volcanic and sedimentary SPM. Soil Cu concentrations along with calcium concentration and cation exchange capacity (CEC) were significantly lower for plutonic SPM compared to all other SPMs (Table 2).

Table 2. Comparison of mean soil chemical characteristics among soil parent material types. Means followed by the same letters are not significantly different at the 90% confidence level.

SPM[1]	N	P	S	B	Cu	K	Mg	Ca	CEC	pH
	----------------ppm---------------------------					--------------meq 100 g-1----------				
MS	51.73a	2.13c	6.61a	0.14a	0.92a	0.93b	1.4b	9.22ab	20.43b	6.02a
MX	51.08a	3.97bc	5.32ab	0.2a	0.67bc	0.84b	1.14bc	8.2b	17.48c	5.97a
PLU	32.68b	6.8a	4.69b	0.16a	0.53c	0.74b	0.81c	6.51c	12.54d	5.96a
SED	51.2a	3.02bc	3.73b	0.15a	0.73abc	0.94b	2.1a	10.89a	23.65ab	5.97a
VOL	39.31b	5.57ab	5.45ab	0.21a	0.8ab	1.38a	1.93a	9.76a	25.52a	6.04a

[1] SPM – Soil parent material: MS = Metasedimentary; MX = Mixed; PLU = Plutonic; SED = Sedimentary; VOL = Volcanic.

3.2 Soil fertility ranking for major soil parent material types

All sample data in the cumulative distributions for select soil nutrients generated from the fitted Weibull function are provided for different SPM types in Figures 2 through 6. Other soil chemical property distributions not graphically displayed are presented in Table 3. The vertical axes of Figures 2 through 6 are the percentages of all sites on a given SPM type with soil nutrient concentrations less than or equal to a particular value on the horizontal axis. Therefore, curves representing SPM types on the left (low) side of the figures are usually poor in soil nutrient concentrations compared to SPM types on the right side of the figure.

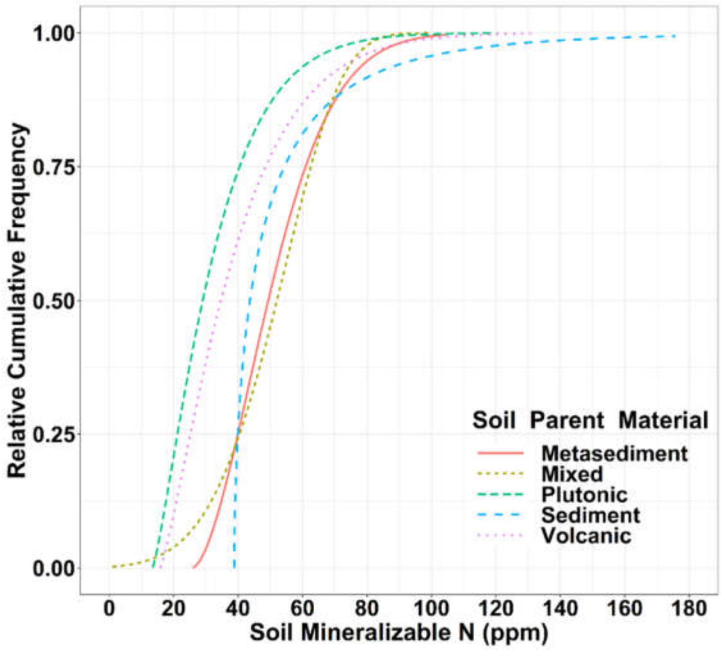

Figure 2. Soil mineralizable nitrogen cumulative distributions for different bedrock soil parent materials in the Inland Northwest, USA.

Soils developed on metasedimentary, mixed glacial till, and sedimentary SPM had similar soil mineralizable N, and each was significantly higher (K-S test; $\alpha = 0.1$) than those on plutonic and volcanic SPM (Figure 2). Soil exchangeable K was significantly higher (K-S test; $\alpha = 0.1$) on volcanic (mostly basalts) SPM, compared to sites on metasedimentary, mixed, plutonic, and sedimentary, which were lower and similar to each other in exchangeable K (Figure 3). Almost all sites located on these last 4 SPMs showed K concentrations below 1.4 meq 100g-1. This result compares to about 65% of volcanic SPM sites with concentrations above 1.4% (Figure 3).

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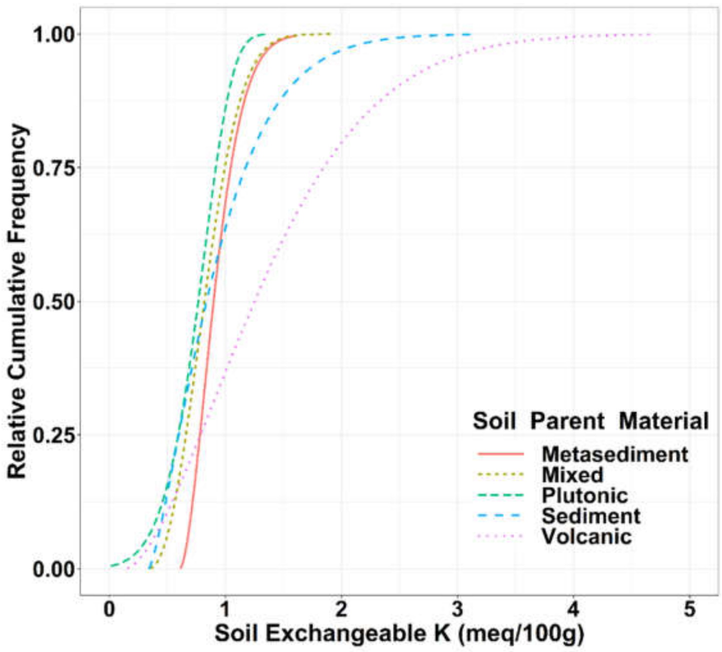

Figure 3. Soil exchangeable potassium cumulative distributions for different bedrock soil parent materials in the Inland Northwest, USA.

Sites located on plutonic SPM were significantly lower (K-S test; $\alpha = 0.1$) in soil Mg relative to those on other SPMs. Soils on plutonic SPM were so low in Mg that its population cumulative distribution (CDF) did not overlap those of soils on sedimentary and volcanic SPM. Metasedimentary and mixed CDFs were intermediate in soil Mg concentrations compared to the other SPMs (Figure 4). Soil Ca concentrations on plutonic SPM were also significantly lower (K-S test; $\alpha = 0.1$) in Ca concentrations compared to the other four SPMs (Figure 5). Soil CEC on plutonic SPM was significantly lower (K-S test; $\alpha = 0.1$) than all other SPMs and showed relatively low variation in the collected samples, as did most SPMs except volcanic (Figure 6). The plutonic CEC cumulative distribution curve did not overlap any other CDF.

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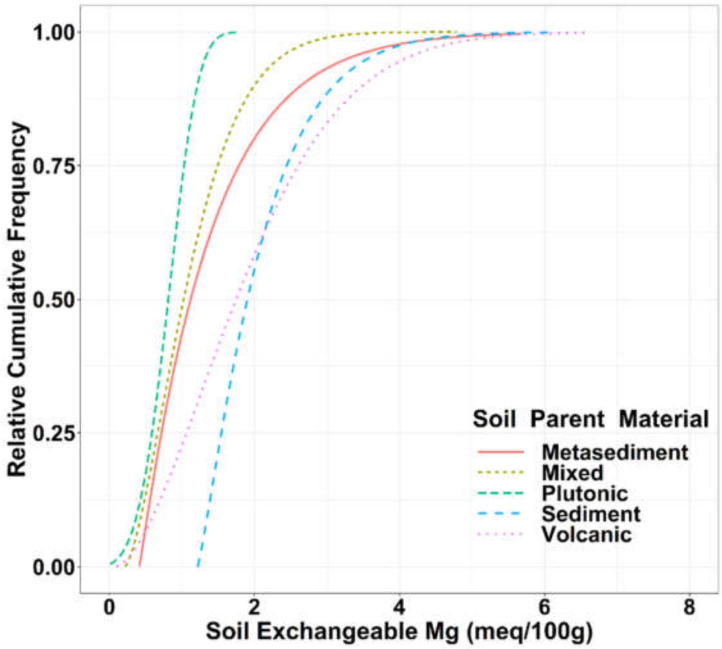

Figure 4. Soil exchangeable magnesium cumulative distributions for different bedrock soil parent materials in the Inland Northwest, USA.

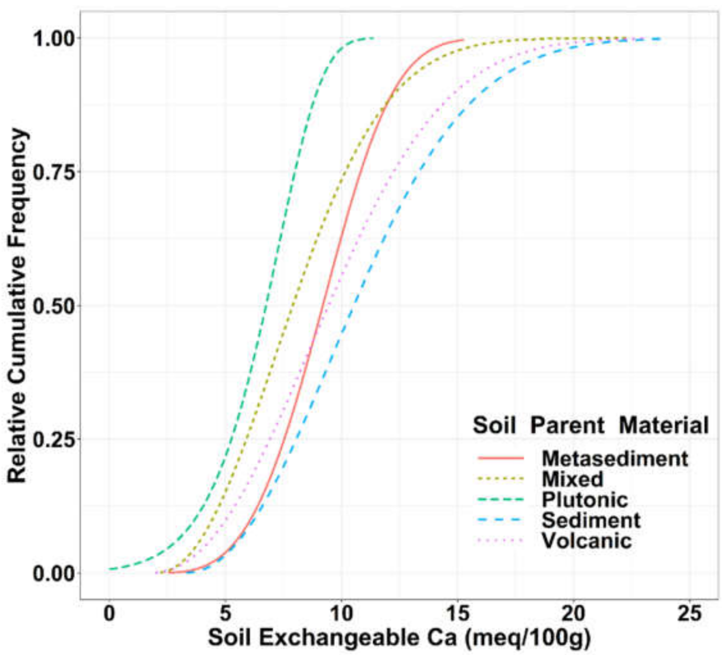

Figure 5. Soil exchangeable calcium cumulative distributions for different bedrock soil parent materials in the Inland Northwest, USA.

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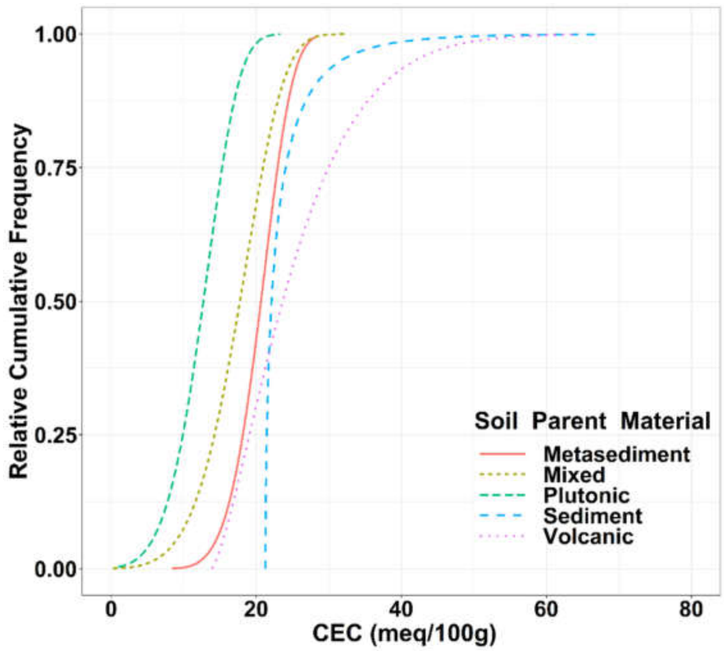

Figure 6. Soil cation exchange capacity cumulative distributions for different bedrock soil parent materials in the Inland Northwest, USA.

Soil available P on plutonic SPM was significantly higher than those located on metasedimentary types (K-S test; $\alpha = 0.1$); whereas, soils located on volcanic and mixed glacial till bedrocks were intermediate in available P (Table 3). Soil available S was variable among different SPMs with metasedimentary and mixed SPM relatively higher than soils on plutonic and volcanic SPM.

Table 3. Soil chemical characteristic percentiles among sites on different soil parent materials. Gray shaded region reflects inadequate sample size for CDF percentiles.

SPM[1]	%tile	N	P	S	B	Cu	K	Mg	Ca	CEC	pH
MS	5	30.00	1.18	5.12	0.09	0.67	0.69	0.62	6.71	14.14	5.82
	10	32.66	1.24	5.24	0.10	0.69	0.72	0.69	7.22	14.98	5.87
	20	37.38	1.35	5.48	0.12	0.72	0.76	0.85	7.87	17.32	5.92
	30	44.23	1.44	5.67	0.13	0.74	0.78	0.90	8.48	18.88	5.97
	40	45.58	1.52	5.81	0.14	0.75	0.87	0.95	8.63	19.88	5.99
	50	48.15	1.60	5.95	0.14	0.76	0.91	1.10	8.73	20.50	6.04
	60	54.76	1.72	6.73	0.15	0.82	0.95	1.13	8.98	21.30	6.10
	70	61.80	1.84	7.51	0.16	0.88	0.99	1.27	9.92	22.46	6.12
	80	65.60	2.44	8.04	0.17	1.04	1.03	1.36	10.05	23.42	6.15
	90	71.34	3.52	8.32	0.18	1.29	1.16	2.07	11.61	24.80	6.19
	95	75.55	4.06	8.46	0.18	1.42	1.35	2.81	13.46	25.17	6.27
MX	5	26.47	0.90	2.55	0.10	0.39	0.48	0.39	3.91	8.64	5.61
	10	32.32	0.90	3.07	0.12	0.47	0.50	0.54	5.22	12.39	5.64
	20	41.46	0.90	3.76	0.13	0.55	0.62	0.67	6.05	14.72	5.88
	30	44.65	0.96	4.06	0.16	0.59	0.70	0.79	6.43	15.30	5.89
	40	47.20	2.30	4.35	0.17	0.64	0.77	0.84	7.66	15.96	5.92
	50	51.10	4.15	4.94	0.19	0.70	0.82	0.92	8.02	17.70	5.98
	60	53.48	4.55	6.02	0.20	0.70	0.92	1.05	8.22	18.88	6.00
	70	58.34	5.08	6.57	0.21	0.71	0.99	1.31	8.74	19.53	6.05
	80	61.64	6.24	6.60	0.23	0.78	1.06	1.58	9.87	20.60	6.08

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	90	70.84	7.13	8.13	0.24	0.90	1.13	2.07	11.49	22.14	6.13
	95	76.98	8.91	8.66	0.36	0.97	1.23	2.49	13.97	25.01	6.44
PLU	5	18.10	1.36	2.80	0.08	0.27	0.31	0.26	2.54	8.51	5.64
	10	18.95	1.76	3.00	0.10	0.29	0.43	0.43	4.36	9.56	5.73
	20	20.70	2.68	3.10	0.12	0.36	0.56	0.57	5.57	10.32	5.80
	30	23.10	4.52	3.54	0.14	0.43	0.64	0.64	5.88	10.54	5.80
	40	24.30	5.32	3.78	0.16	0.45	0.68	0.74	6.15	11.70	5.88
	50	26.20	5.90	4.20	0.18	0.51	0.75	0.82	6.34	11.90	5.93
	60	28.60	7.46	4.48	0.19	0.57	0.77	0.95	6.90	12.48	5.97
	70	32.20	8.39	5.20	0.19	0.59	0.89	0.99	7.57	14.26	6.02
	80	48.00	10.64	5.36	0.20	0.66	1.00	1.02	8.00	14.98	6.17
	90	61.70	11.96	7.28	0.22	0.76	1.05	1.11	9.14	16.44	6.30
	95	62.90	13.89	9.34	0.22	0.85	1.08	1.33	9.74	19.52	6.50
SED	5	38.87					0.45	1.33	6.14	21.35	5.60
	10	38.93					0.48	1.34	6.89	21.39	5.61
	20	39.71					0.54	1.50	7.53	21.48	5.71
	30	40.85					0.61	1.74	7.76	21.57	5.87
	40	41.20					0.77	1.74	9.27	21.88	5.99
	50	46.80					0.91	1.78	10.59	22.30	6.06
	60	52.54					1.00	1.98	11.88	22.72	6.11
	70	53.38					1.02	2.59	13.27	23.57	6.13
	80	62.02					1.25	2.70	14.03	25.28	6.17
	90	70.25					1.51	2.92	15.37	26.99	6.21
	95	73.23					1.65	3.17	16.50	27.85	6.22
VOL	5	17.46	1.09	3.08	0.09	0.62	0.48	0.74	4.14	15.34	5.65
	10	19.81	1.64	3.82	0.11	0.65	0.58	0.78	5.20	16.66	5.72
	20	22.44	2.22	4.00	0.14	0.67	0.80	0.93	7.25	17.26	5.82
	30	27.76	3.24	4.12	0.15	0.69	0.92	1.04	7.66	18.62	5.90
	40	31.89	3.73	4.55	0.17	0.70	1.00	1.29	8.36	22.12	5.93
	50	36.70	4.90	5.00	0.18	0.75	1.06	1.66	8.80	25.10	5.99
	60	40.28	5.42	5.05	0.19	0.80	1.25	2.02	9.46	27.58	6.00
	70	46.26	6.60	5.82	0.23	0.88	1.61	2.33	10.82	29.52	6.07
	80	55.56	7.98	6.36	0.27	0.91	1.95	2.81	13.54	32.30	6.19
	90	60.38	9.90	7.18	0.34	0.98	2.64	3.76	15.72	37.10	6.50
	95	70.78	13.50	8.01	0.39	1.10	3.08	3.91	16.49	38.12	6.63

[1] SPM – Soil parent material: MS = Metasedimentary; MX = Mixed; PLU = Plutonic; SED = Sedimentary; VOL = Volcanic.

4. Discussion

Differences in soil nutrient availability are associated with different soil parent materials and consequent forest stand productivity. Therefore, our results should provide a better understanding of the forest soil nutrient environment and facilitate the design and implementation of forest nutrient management activities, including operational fertilization plans. Inherent differences in soil available nutrients developed from different geologies, show noticeable differences that can produce substantially varied forest stem wood growth and leaf nutrient response to forest management practices [28,29,48–52]. In addition, SPM can be directly related to tree mortality rates [53,54], environmental niches of plant species [55], and regional plant species and community distributions [11,56]. Soil parent materials that provide the soil nutrients required for plant growth, especially cations, is of critical importance for forest growth and health. Results from our study show that SPM explains substantial differences in available soil nutrients in the Inland Northwest, USA.

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Littke et al [57] studied glacial, igneous, and sedimentary SPM in the Pacific Northwest and found such a categorization to be useful in understanding differences in forest soil nutrition and site productivity. Our study includes these same SPM category names, plus others, but the rocks contained therein are unlikely to be the same lithologies as in their study. However, the concept of using SPM to differentiate soil nutrient environments is similar in both studies.

James et al. [58] suggested that leaching with dissolved organic matter was an important factor determining exchangeable Ca and Mg concentrations in forest soil profiles of the Pacific Northwest. Conversely, plant uptake was more important in determining the distribution of exchangeable K in the soil profile. We realize that leaching, uptake and weathering determine nutrient concentrations vertically in forest soils and that these processes can produce nutrient pools deeper in the soil profile. In our study, we sampled the upper 25.4 cm of the soil and these samples showed nutrient concentration differences between SPMs. These observations can be attributed to decades and centuries of natural soil mixing processes across our study sites, allowing for differential geochemical expression by SPM in the upper soil profile. Similar findings were suggested by Kimsey et al. [59] who found distinct subsurface geologic soil parent material influence in overlying eolian volcanic ash deposits.

Johnston et al. [16] modified Reiche's [60] classic Weathering Potential Index (WPI) for use with geologic parent materials commonly found in the Inland Northwest of the United States. Specifically, they studied metasedimentary, plutonic, and volcanic parent materials. Johnston et al. [16] collected, sampled and analyzed the bed rocks from 31 of the 154 research sites used in our current study. Their study sites were nearly evenly distributed across 3 of the SPM categories used in our current study. The volcanic SPM, which included basalts and andesites, showed the highest average WPI of 22.8. The plutonic SPM, which included granites, granodiorites, diorites, quartz diorites, and tonalities, produced an average WPI of 13.7. Their metasedimentary SPM, that included several lithologies, had the lowest average WPI of 10.7, but also showed high variation, probably due to within category differences in geologic lithologies. This high variation makes their metasedimentary results difficult to interpret in the context of our study. Importantly, the differences in WPI demonstrated by Johnston et al [16] for volcanic and plutonic SPMs likely explains some of our study results. Volcanic SPM typically weather more rapidly into fine textured soils while plutonic SPM weather more slowly forming coarse textured soils. These weathering outcomes are evident in the much lower CEC values for plutonic SPMs compared to volcanic SPMs provided in Table 2 and illustrated in Figure 6.

5. Conclusions

Our study demonstrates and quantifies the relationships between SPM and soil nutrient availability for forest soils across a large geographic area. Specifically, forest soils occurring on volcanic and sedimentary SPM are generally higher in soil K, Mg, and Ca, whereas those located on plutonic and metasedimentary SPM are generally lower in these cations. Soil CEC was much lower on plutonic SPM compared to other SPMs. Our study provides new information on the forest nutrient environment in the Inland Northwest, USA that can help inform forest nutrient management decisions in the region, and supports similar approaches used across other US regions.

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