Foliar Nutrient Characteristics of Four Conifer Species in the Interior Northwest United States

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ABSTRACT: *This article provides foliar nutrient concentration distributions and sample size calculations for Douglas-fir, grand fir, ponderosa pine, and lodgepole pine. Managers can obtain foliar nutrient values from their own lands and use this information to make judgments on the relative nutrient status of forest stands. Foliage was collected from unfertilized trees at 160 different research sites of the Intermountain Forest Tree Nutrition Cooperative spanning a 16 yr period from 1982 to 1997. Douglas-fir showed the lowest variation in foliar nutrient concentrations, while grand fir was the most variable of the species sampled. Nitrogen was the least variable and Mn and Mo generally the most variable elements for all species. Grand fir had much higher foliar concentrations of K and Ca than the other species. Ponderosa pine had the highest foliar N concentrations. The pines generally have lower nutrient concentrations than the firs, with the exception of Zn. Western hemlock habitat types showed lower Douglas-fir foliar Ca, Mg, and B concentrations, but higher K concentrations than other habitat type series. Douglas-fir growing on soils derived from meta-sedimentary rocks generally had lower foliar nutrient concentrations than those growing on other rock types. West. J. Appl. For. 19(1):13–24.*

Key Words: *Pseudotsuga menziesii, Abies grandis, Pinus ponderosa, P. contorta.*

The need for site-specific assessment of forest nutrient status in the inland Northwest is increasing. Such information is potentially useful in guiding forest management decisions ranging from forest health concerns to designing operational fertilization programs. Various techniques have been developed to assay forest nutrient status; the most effective involve foliage sampling and analysis (Van den Driessche 1974, Timmer and Stone 1978, Ingestad 1979, Weetman and Fournier 1982, Powers 1983, Brockley and Sherman 1994). Diagnostics based on foliar assays include comparing samples with established critical levels (Powers 1983, Powers et al. 1985, Webster and Dobkowski 1983, Ballard and Carter 1986), or with critical foliar nutrient concentration ratios (Ingestad 1979) and more sophisticated techniques such as graphical vector analysis (Timmer and Stone 1978, Prescott et al. 1992, Weetman et al. 1993, Haase and Rose 1995). Another approach is to compare samples with probability distributions of foliar nutrient concentrations developed from large data sets collected over a wide geographic area (Zinke and Stangenberger 1979). We used the latter approach in this article. Presentation of foliar nutrient concentration data in a cumulative distribution allows readers to quickly compare sample-derived estimates with nutrient concentration distributions developed from large population samples.

The primary objective of this article is to provide foliar nutrient concentration distributions for Douglas-fir (*Pseudostuga menziesii* var. *glauca*), grand fir (*Abies grandis*), ponderosa pine (*Pinus ponderosa*), and lodgepole pine (*P. contorta* var. *latifolia*) within the inland Northwest of the United States. We compare foliar nutrient characteristics among species and make ecological interpretations regarding observed species differences. Published foliar nutrient concentration critical values (Table 1) are also contrasted with the empirical distributions presented in this article. Information on the number of foliage samples needed to produce reliable statistical results for foliar nutrient concentrations are provided. Finally, Douglas-fir foliar nutrient distributions are compared by rock type and habitat type series.

Methods

The Data

Foliage was collected during a 16 yr period from 1982 to 1997 from unfertilized trees on 160 different research sites established by the Intermountain Forest Tree Nutrition Cooperative (IFTNC) in eastern Oregon and Washington, western Montana, and Idaho. A stratified random sampling design was used to select study sites. Strata were geographic

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Table 1. Critical foliar nutrient concentrations (%) and percent (%) of sites sampled less than the critical value for several conifer species in the inland northwest.

Foliar conc.	Douglas-fir[a]	True fir[b]	Lodgepole[c]	Ponderosa[d]
N (%)	1.40* (97)	1.15[††] (82)	1.20* (80)	1.10[††] (15)
K (%)	0.60* (22)	0.58[†] (0)	0.50* (20)	0.48[†] (0)
S (%)	0.11[†] (95)	0.08[§] (60)	0.09[§] (99)	0.08[§] (50)
Ca (%)	0.15* (0)	0.12[†] (0)	0.08* (5)	0.05[†] (0)
Fe (ppm)	25* (5)	50* (95)	58* (99)	50[††] (85)
Zn (ppm)	10* (5)	10* (8)	52* (70)	30[††] (5)
B (ppm)	10* (0)	10[‖] (0)	4.3* (0)	20[††] (42)

Values obtained by:

* Best estimate by cited author based on literature review and personal experience

[†] Derived by cited author using optimal proportions

[††] Derived by cited author experimentally

[§] Critical S values derived for this paper using an N:S ratio of 14.7 in conjunction with the given critical N values (Blake et al. 1990, Turner and Lambert 1979)

[‖] General value established for all conifer species, not yet species-specific (Ballard and Carter 1986)

[a] From Webster and Dobkowski (1983), these values are considered inadequate for growth, critical values would be somewhat higher.

[b] All values except S from Powers (1983). S value calculated as noted above.

[c] All values except S from Ballard and Carter (1986), based on Everard (1973) and Swan (1972). S value calculated as noted above. Micronutrient values from Van den Driessche (1979).

[d] Value for N from Powers et al. (1985), values for K and Ca from Powers (1983). S value calculated as noted above. Micronutrients from Boyer (1984, unpublished).

area, habitat type, and stand density. These were the design variables in the region-wide fertilization experiments for each species. Rock type was added as a stratum for study sites established after 1993. Cooperating land management organizations submitted stand lists that fit within the strata, and potential study sites were randomly selected from these lists. Stands were selected without regard to nutrient status prior to establishment of the fertilization experiments. An observation is the average of 4 to 20 individual dominant or codominant sample trees/site. Douglas-fir distributions are based on foliage collections from 130 sites, ponderosa pine from 37 sites, grand fir from 14, and lodgepole pine from 9 sites. The study sites occurred on western hemlock (*Tsuga heterophylla*), western redcedar (*Thuja plicata*), subalpine fir (*Abies lasiocarpa*), grand fir, and Douglas-fir habitat series (Daubenmire and Daubenmire 1968) in second-growth managed stands ranging from 10 to 100 yr breast height age. Some study sites provided foliar samples for more than one tree species.

Because the experimental designs used to select sites for the four species were similar, the resultant distributions of site and stand conditions for each species are similar (Figure 1). Douglas-fir and ponderosa pine each occurred on five rock types; grand fir was sampled on four rock types; lodgepole pine occurred on three rock types, reflecting the relatively small number of lodgepole study sites. All rock types sampled, with the exception of sedimentary rocks, are common in the inland Northwest. Grand fir was sampled only on moist habitat types since, by definition, it does not occur on drier habitat types. Ponderosa pine was sampled only on two habitat type series, where it is commonly managed. Ponderosa pine habitat types drier than Douglas-fir and grand fir are not part of the population sampled. Quadratic mean stand diameter ranged between 1 and 15 in.; a few stands were larger, for these second-growth stands. We believe that differences in foliar nutrient characteristics reflect species rather than sample site distribution differences.

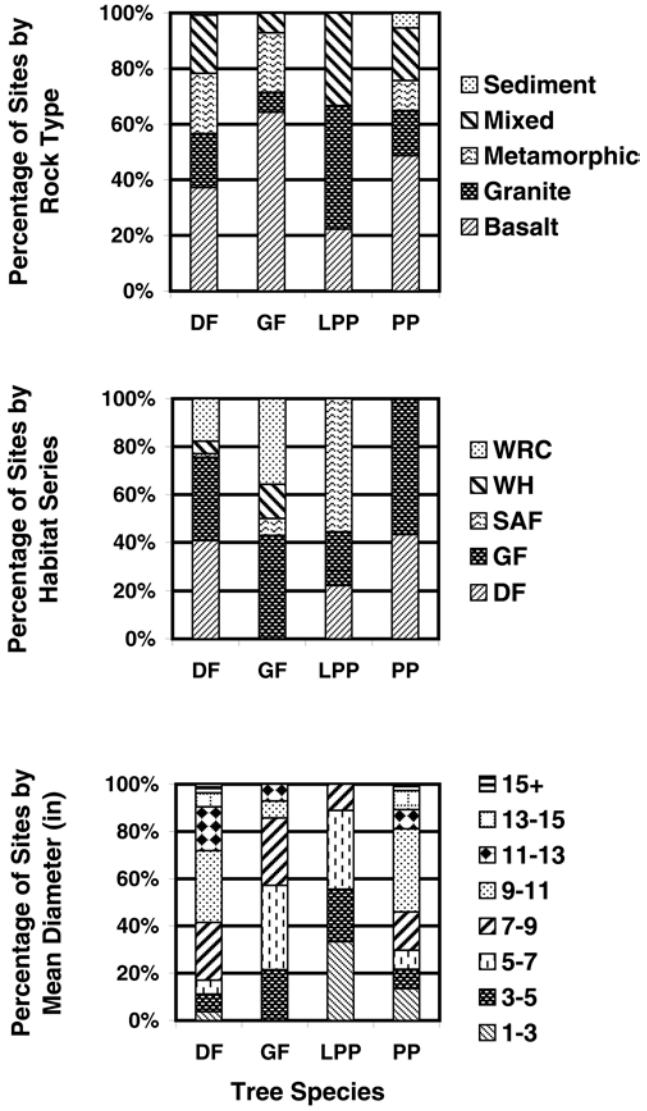

Figure 1. Distribution of foliage sample sites by rock type, habitat series, and quadratic mean stand diameter for Douglas-fir (DF), grand fir (GF), ponderosa pine (PP), and lodgepole pine (LPP) trees in the inland Northwest.

Foliage Collection and Analysis

Foliage was collected in late Fall following bud set from dominant or codominant Douglas-fir, grand fir, lodgepole pine, and ponderosa pine trees. All sample trees were free from any sign of stress, disease, or insect infestation. Various combinations of species were sampled from each site, depending on the particular experiment. A branch containing current-year foliage was collected at the third whorl from the top of each sample tree, placed in a plastic bag, stored in an ice-cooled container, and expeditiously transported to the laboratory for deep-freeze storage. Samples were held in the freezer for 1 to 4 months prior to processing. In the laboratory, current-year needles were stripped from each sample branch. Three repetitions of 30 or 50 needles (depending on the specific study) were counted and weighed for calculation of needle weights. The separated needles were then dried at 70°C for 24 hr and ground to a fine consistency in a coffee grinder in preparation for chemical analysis.

Foliar nutrient concentrations analyzed were: nitrogen (N), phosphorus (P), potassium (K), sulfur (S), calcium (Ca), magnesium (Mg), zinc (Zn), copper (Cu), boron (B), iron (Fe), manganese (Mn), and molybdenum (Mo). Foliar analyses were performed at several laboratories, depending on the specific study and year. Collections included in this report spanned a 16 yr time interval from 1982 to 1997. For all elements except N and in some cases P, laboratory protocols included either wet ash or dry ash preparation of the samples (Miller 1998a, 1998b, Anderson 1996, Huang and Schulte 1985, Blanchar et al. 1965). Wet ash methods typically employed a predigestion in nitric acid, followed by digestion in hydrogen peroxide, and dilution by either mild hydrochloric acid or deionized water. Dry ash methods included high-temperature ashing followed by digestion in nitric acid and dilution with deionized water. Digestrate was analyzed using either DC-argon plasma emission spectrometry or inductively coupled plasma spectrometry. All laboratories employed the micro-Kjeldahl method of N analysis (Horneck and Miller 1998, Bremner 1996, Bremner 1965). Foliar samples from collections made in the early 1980s used a sulfuric acid digest for N and P, and concentrations were determined using Technicon AutoAnalyzer II instrumentation (US EPA 1979, Technicon Instruments Corporation 1977, Sommers and Nelson 1972, Bremner 1965, Olsen and Dean 1965).

Data Analysis

Individual tree nutrient concentration levels were used to calculate means and coefficients of variation for each species present at each study site. The coefficients of variation thus obtained were further summarized, yielding an average coefficient of variation for each nutrient-tree species combination. Using this latter figure, we then performed sample size calculations for each of twelve nutrients/species using the following equation (Harris et al. 1948):

$$n = \frac{CV^2 \times F_{1-\alpha}(1, n-1) \times F_{1-\beta}(n-1, m)}{PE^2} \qquad (1)$$

where n is the sample size, PE is the desired percent error, CV is the average coefficient of variation calculated as stated above, α is the confidence coefficient for the confidence interval, β is the probablity that the length of the confidence interval will not exceed that specified by the chosen percent error, m is the degrees of freedom associated with the coefficient of variation estimate, and $F_{1-\alpha}(1, n-1)$ and $F_{1-\beta}(n-1, m)$ are $1-\alpha$ and $1-\beta$ critical levels for the variance ratio with their respective degrees of freedom. Sample sizes were calculated for Douglas-fir, grand fir, ponderosa pine, and lodgepole pine using percent error rates of 5, 10, and 20%, α levels of 95, 90, and 75%, and β levels of 95, 90, and 50%. Variance estimates for lodgepole pine and grand fir (five grand fir sites had insuffient samples to calculate within stand variation) were based on only nine and eight observations, respectively. However, Marshall and Jahraus (1987) analyzed only 10 sites to good effect in estimating sample size for foliar nutrient analyses of coastal Douglas-fir.

Kolmogorov-Smirnov tests (Lehmann 1975, Kim and Jennrich 1970) were used to test for significant differences in nutrient distributions between tree species. We also compared critical foliar nutrient concentrations compiled from the various published sources provided in Table 1 with the cumulative distributions developed for each species. A three-parameter Weibull distribution (Bailey and Dell 1973) was fit to the foliar nutrient distributions for each species to aggregate the data into easily interpreted smooth curves. An iterative procedure using numerical derivatives was used to fit the Weibull cumulative distribution function (SAS Inst. Inc. 1989). Starting values for parameter estimates were obtained by first fitting a two-parameter Weibull distribution to the data shifted relative to the observed minimum value. Even for lodgepole pine where we had observations from only nine sites, the parameter estimation procedure converged and we obtained a good fit of the data.

Unlike ponderosa pine, grand fir, and lodgepole pine, sufficient Douglas-fir observations were available to allow development of empirical foliar nutrient distributions by rock type and habitat type series. For comparisons, we simply calculated Douglas-fir foliar concentration descriptive statistics for the rock and habitat type strata.

Results

Sample Size Calculations

A statistically reliable sample from a forest stand enables meaningful comparisons of collected samples with data presented in this article. The average coefficients of variation of foliar elemental concentrations we found for Douglas-fir, grand fir, lodgepole pine, and ponderosa pine are given in Table 2. The resulting samples sizes needed for estimatation with various levels of α, β, and percent error rates calculated using Equation (1) are also given in Table 2. For example, four sample trees are required to obtain a Douglas-fir foliar N concentration confidence interval estimate that 90% of the time will be of length < or = to ± 20% of the mean, and that will include the true population mean 90% of the time. Our estimates of Douglas-

Table 2. Required number of Douglas-fir or grand fir for estimating foliar elemental concentration at varying levels of percent error (PE), probability that the confidence interval includes the true mean (α), and probability that the interval will be less than or equal to the desired width (β). Calculations are based on the average coefficient of variation (CV) with its associated degrees of freedom (df) as listed below.

			α = 0.95, β = 0.95			α = 0.90, β = 0.90			α = 0.90, β = 0.50			α = 0.75, β = 0.50		
Nutrient	df	CV (%)	PE: ±5%	PE: ±10%	PE: ±20%	PE: ±5%	PE: ±10%	PE: ±20%	PE: ±5%	PE: ±10%	PE: ±20%	PE: ±5%	PE: ±10%	PE: ±20%
Douglas-fir														
N	197	10.8	30	11	6	21	8	4	14	5	3	7	3	3
K	197	16.4	61	20	8	42	14	6	31	9	4	15	5	3
P	197	18.9	78	25	9	53	17	7	41	12	4	20	6	3
Ca	197	22.8	108	33	12	74	23	8	58	16	5	29	8	3
Mg	197	15.7	56	19	8	39	13	6	29	8	3	14	4	3
Mn	197	23.9	118	36	13	81	25	9	64	17	6	31	9	3
Fe	197	21.4	96	30	11	66	21	8	51	14	5	25	7	3
Zn	112	30.0	352	99	18	187	53	12	113	31	8	57	17	4
B	197	23.9	117	36	13	80	24	9	64	17	6	31	9	3
Cu	197	21.0	93	29	11	64	20	7	50	14	5	25	7	3
Mo	12	23.9	207	56	17	122	33	11	67	18	6	33	9	3
S	15	21.5	152	42	14	92	26	9	54	15	5	27	7	3
Grand fir														
N	7	11.6	72	21	8	40	12	5	18	6	3	9	3	3
K	7	25.4	324	84	24	176	46	14	79	21	6	39	10	3
P	7	16.9	145	39	13	79	22	8	36	10	4	18	5	3
Ca	7	20.5	212	56	17	115	31	10	52	14	5	25	7	3
Mg	7	18.2	169	45	14	92	26	8	41	12	4	20	6	3
Mn	7	38.6	744	189	50	402	103	28	180	46	13	88	23	6
Fe	7	23.4	275	72	21	149	40	12	67	18	6	33	9	3
Zn	7	28.9	419	108	30	227	59	17	101	27	8	50	13	4
B	7	15.6	370	97	11	125	34	7	46	13	3	23	7	3
Cu	7	14.2	104	29	10	57	17	6	26	8	3	13	4	3
Mo	7	31.9	510	131	36	276	72	20	123	32	9	61	16	5
S	7	21.3	230	61	18	125	34	11	56	15	5	28	8	3
Lodgepole pine														
N	8	13.4	85	24	9	48	14	5	23	7	3	11	4	3
K	8	27.5	344	89	25	191	50	15	91	24	7	44	12	4
P	8	25.4	294	77	22	163	43	13	78	21	6	38	10	3
Ca	8	29.5	395	102	29	219	57	17	104	27	8	51	14	4
Mg	8	17.3	140	38	13	78	22	8	37	11	4	18	5	3
Mn	8	31.6	455	117	32	252	66	19	120	31	9	59	15	5
Fe	8	29.7	401	104	29	222	58	17	106	28	8	52	14	4
Zn	8	18.5	158	43	14	88	25	8	42	12	4	21	6	3
B	8	26.6	324	84	24	180	48	14	85	23	7	42	11	4
Cu	8	18.3	156	42	14	87	24	8	41	12	4	20	6	3
Mo	8	24.7	279	73	21	155	41	13	74	20	6	36	10	3
S	2	19.6	1,148	289	74	395	100	27	61	17	5	30	8	3
Ponderosa pine														
N	28	12.7	48	16	7	31	11	5	20	6	3	10	3	3
K	28	16.3	74	23	9	48	15	6	31	9	4	15	5	3
P	28	15.9	71	22	8	46	15	6	30	9	3	15	4	3
Ca	28	22.9	141	40	14	90	26	9	60	16	5	30	8	3
Mg	28	16.1	72	22	8	47	15	6	30	9	3	15	5	3
Mn	28	27.8	204	56	18	130	36	12	88	23	7	43	12	4
Fe	28	18.7	96	28	11	62	19	7	41	12	4	20	6	3
Zn	28	17.7	86	26	9	55	17	6	36	10	4	18	5	3
B	28	19.9	107	31	11	69	21	7	46	13	4	22	6	3
Cu	28	23.5	148	42	14	94	27	9	63	17	6	31	9	3
Mo	13	27.4	260	69	21	154	42	13	87	23	7	43	12	4
S	10	19.3	150	41	13	87	24	8	45	13	4	22	6	3

fir foliar nutrient variation and resultant sample size calculations are similar to those reported for coastal Douglas-fir by Marshall and Jahraus (1987). Douglas-fir showed the least foliar nutrient concentration variation, while grand fir was the most variable of the four species sampled (Table 2). Nitrogen was the least variable, while Mn and Mo were generally the most variable elements for all four species.

Spatial variation should also be considered when designing a foliage-sampling scheme. Sample trees should be apportioned into relatively homogeneous soil or site strata within a stand. Avila (1997), working with a subset of the data

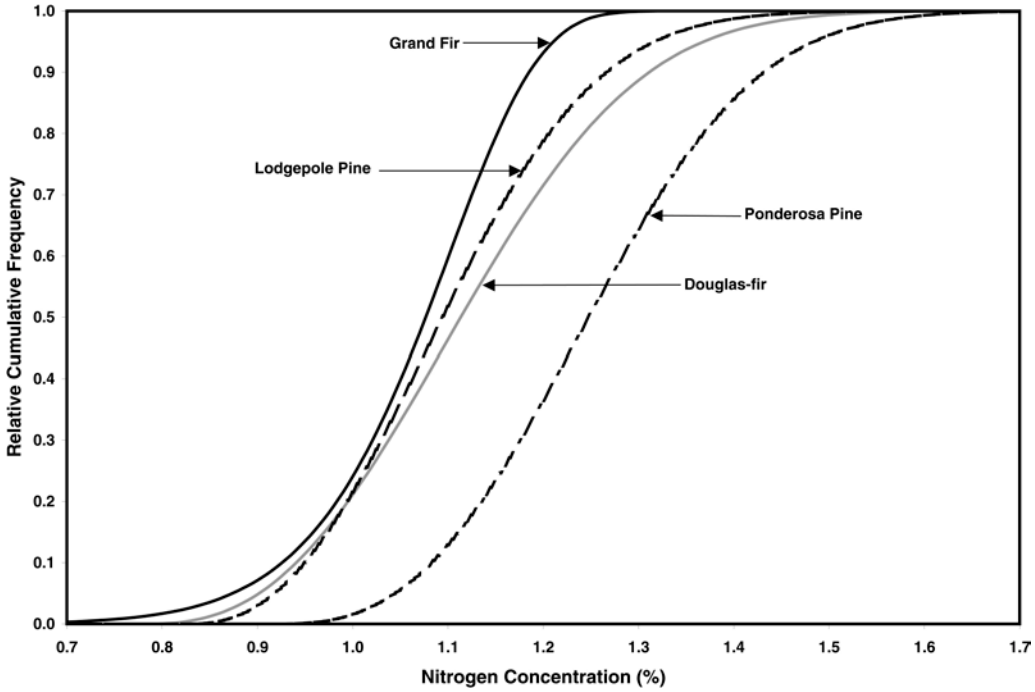

Figure 2. Foliar nitrogen concentration cumulative distributions for Douglas-fir, grand fir, ponderosa pine, and lodgepole pine in the inland Northwest.

presented in this article, estimated that individual Douglas-fir sample trees should be spaced about 91 m apart for the most statistically efficient sample for foliar nutrients, with about 10% greater spacing for grand fir.

Foliar Nutrient Concentrations

The Weibull cumulative distribution function fits of the site means of foliar nutrient concentrations for N, K, and Ca are presented in graphical form for Douglas-fir, grand fir, ponderosa pine, and lodgepole pine in Figures 2–4. The vertical axis of these graphs is the proportion of all sites with foliar concentrations less than or equal to a particular value on the horizontal axis. Ponderosa pine foliar N concentrations were significantly higher than the other three species (Figure 2). Foliar N concentration distributions were similar for Douglas-fir, grand fir, and lodgepole pine. Trees on about 97% of the Douglas-fir sites were below the critical foliar N concentration of 1.4% (see Table 1). Most of the lodgepole pine and grand fir were also below their respective published

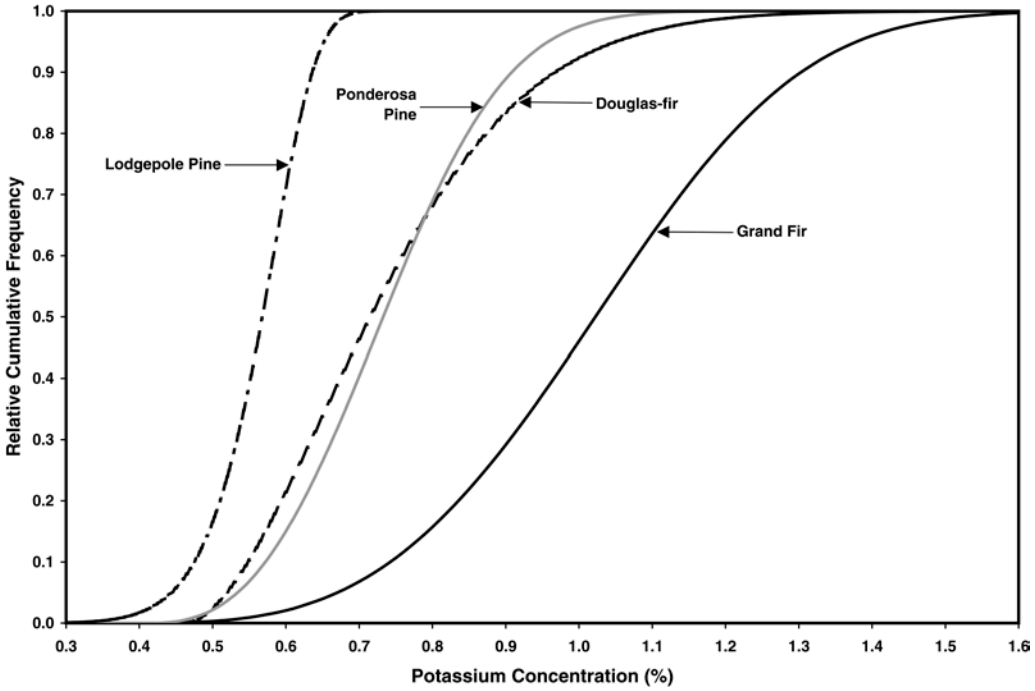

Figure 3. Foliar potassium concentration cumulative distributions for Douglas-fir, grand fir, ponderosa pine, and lodgepole pine in the inland Northwest.

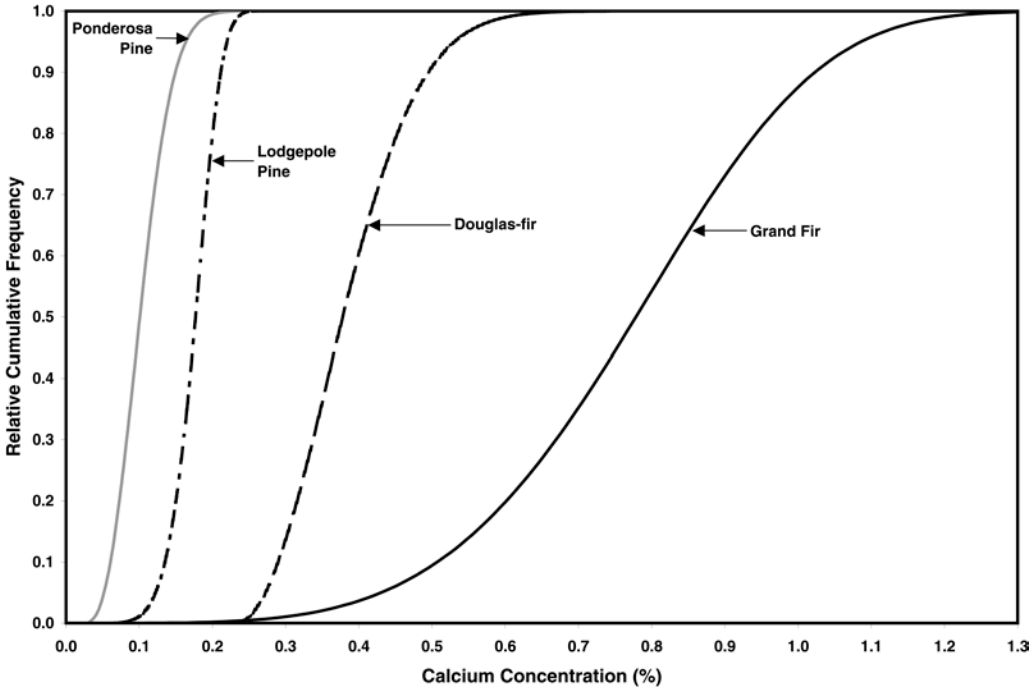

Figure 4. Foliar calcium concentration cumulative distributions for Douglas-fir, grand fir, ponderosa pine, and lodgepole pine in the inland Northwest.

critical levels (1.2 and 1.15%, respectively). However, only about 15% of ponderosa pine N concentrations were below its suggested critical level of 1.1%.

Species differences are clear for foliar K concentrations (Figure 3), particularly for grand fir, which was much higher than the other species. The grand fir distribution did not overlap that of lodgepole pine since the minimum sample value for grand fir (0.74%) was greater than the maximum K concentration for lodgepole pine (0.68%). Foliar K concentrations were similar for Douglas-fir and ponderosa pine and were intermediate between grand fir and lodgepole pine. All of the grand fir and ponderosa pine sites were greater than their published critical levels (0.58 and 0.48%, respectively), while about 20% of the Douglas-fir and lodgepole pine sites were below critical K levels (0.6 and 0.5%, respectively) (Table 1). Foliar Ca concentrations for grand fir were also much higher than the other species (Figure 4). Douglas-fir Ca concentrations were intermediate and the pines were lowest. All sites and species were above published critical levels for Ca (Table 1).

All other foliar nutrient concentration distributions are presented in tabular form (Tables 3–5). Foliar S concentration distributions were similar for the three species analyzed for S. Nearly all of the Douglas-fir sites showed foliar S concentrations below critical level (0.11%) while about one-half of the grand fir and ponderosa pine sites were below their respective critical levels. Grand fir foliar B concentrations were highest, followed by Douglas-fir and then the pines (Tables 3–6). None of the Douglas-fir, grand fir, or lodgepole pine sites were below the suggested B critical levels for those species, while about 40% of the ponderosa pine sites were below the 20 ppm critical level (Table 1).

Douglas-fir foliar Fe concentrations were substantially higher than the other three species (Tables 3–6), and nearly all of the Douglas-fir sites were above the published critical level of 25 ppm (Table 1). Conversely, the suggested

Table 3. Foliage weight and nutrient concentration percentiles for Douglas-fir.

Percentile	Weight[a] (g)	N	P	K	S	Ca	Mg	Mn	Fe	Zn	B	Cu	Mo
		(%)						(ppm)					
5	0.446	0.902	0.152	0.519	0.042	0.272	0.085	68	24.7	19.3	16.7	1.83	0.17
10	0.479	0.941	0.164	0.548	0.052	0.290	0.092	101	30.4	21.0	18.0	2.08	0.22
20	0.523	0.995	0.179	0.594	0.064	0.316	0.103	151	38.8	23.4	20.0	2.46	0.30
30	0.557	1.038	0.191	0.635	0.073	0.337	0.114	195	45.9	25.3	21.7	2.78	0.36
40	0.587	1.076	0.201	0.674	0.080	0.358	0.124	237	52.5	27.0	23.2	3.09	0.42
50	0.615	1.113	0.210	0.715	0.087	0.378	0.135	280	59.1	28.7	24.8	3.39	0.47
60	0.644	1.152	0.220	0.759	0.094	0.399	0.148	325	66.0	30.5	26.4	3.72	0.53
70	0.675	1.193	0.230	0.810	0.102	0.423	0.162	377	73.8	32.5	28.3	4.08	0.59
80	0.712	1.242	0.241	0.873	0.110	0.453	0.181	441	83.2	34.8	30.6	4.53	0.66
90	0.763	1.311	0.257	0.968	0.122	0.495	0.210	536	96.9	38.1	33.8	5.18	0.76
95	0.804	1.368	0.269	1.051	0.131	0.531	0.235	618	108.5	40.9	36.6	5.74	0.84

[a] Foliage weight for 100 needles.

Table 4. Foliage weight and nutrient concentration percentiles for grand fir.

Percentile	Weight[a] (g)	N	P	K	S	Ca	Mg	Mn	Fe	Zn	B	Cu	Mo
		(%)						(ppm)					
5	0.61	0.874	0.125	0.670	0.051	0.431	0.079	63	29.0	16.0	20.0	1.48	0.42
10	0.74	0.926	0.136	0.742	0.058	0.507	0.084	78	32.2	17.7	21.6	1.63	0.52
20	0.93	0.983	0.150	0.836	0.066	0.602	0.092	98	35.9	20.0	23.8	1.81	0.64
30	1.11	1.021	0.159	0.905	0.071	0.669	0.099	112	38.5	21.7	25.5	1.92	0.73
40	1.29	1.051	0.167	0.966	0.076	0.726	0.104	125	40.5	23.3	27.1	2.02	0.81
50	1.47	1.077	0.174	1.022	0.080	0.779	0.110	136	42.4	24.8	28.6	2.10	0.89
60	1.66	1.101	0.181	1.079	0.084	0.830	0.116	148	44.1	26.3	30.2	2.18	0.96
70	1.89	1.125	0.188	1.139	0.088	0.883	0.123	161	45.9	27.9	31.9	2.26	1.04
80	2.17	1.152	0.196	1.209	0.092	0.943	0.131	175	47.9	29.9	33.9	2.35	1.13
90	2.60	1.185	0.207	1.303	0.098	1.023	0.142	194	50.5	32.5	36.8	2.47	1.25
95	2.98	1.210	0.215	1.379	0.103	1.086	0.152	210	52.5	34.7	39.2	2.56	1.34

[a] Foliage weight for 100 needles.

Table 5. Foliage weight and nutrient concentration percentiles for ponderosa pine.

Percentile	Weight[a] (g)	N	P	K	S	Ca	Mg	Mn	Fe	Zn	B	Cu	Mo
		(%)						(ppm)					
5	10.2	1.045	0.135	0.534	0.037	0.052	0.068	39	22.1	36.3	12.8	1.64	0.21
10	12.5	1.083	0.148	0.572	0.046	0.061	0.072	45	25.3	37.5	14.7	1.88	0.26
20	15.4	1.135	0.165	0.624	0.056	0.073	0.077	55	29.7	39.7	16.8	2.21	0.32
30	17.5	1.176	0.176	0.663	0.064	0.083	0.081	64	33.0	41.6	18.4	2.48	0.37
40	19.4	1.213	0.186	0.699	0.071	0.092	0.085	72	35.9	43.5	19.6	2.72	0.42
50	21.1	1.248	0.194	0.733	0.078	0.101	0.088	81	38.7	45.5	20.7	2.96	0.46
60	22.8	1.283	0.202	0.767	0.084	0.110	0.092	90	41.5	47.8	21.8	3.20	0.50
70	24.6	1.322	0.210	0.804	0.091	0.120	0.096	100	44.5	50.3	23.0	3.47	0.54
80	26.7	1.368	0.220	0.848	0.099	0.132	0.101	113	48.0	53.6	24.2	3.78	0.60
90	29.5	1.432	0.232	0.908	0.109	0.149	0.108	133	52.8	58.6	25.9	4.23	0.67
95	31.8	1.484	0.241	0.958	0.118	0.164	0.114	149	56.7	63.1	27.2	4.60	0.73

[a] Foliage weight for 100 needle fascicles and sheaths.

Table 6. Foliage weight and nutrient concentration percentiles for lodgepole pine.

Percentile	Weight[a] (g)	N	P	K	Ca	Mg	Mn	Fe	Zn	B	Cu	Mo
		(%)					(ppm)					
5	1.96	0.918	0.111	0.444	0.122	0.080	57	16.9	37.4	12.2	2.22	0.54
10	2.00	0.950	0.113	0.475	0.135	0.084	59	19.1	38.3	14.1	2.33	0.55
20	2.10	0.994	0.117	0.510	0.150	0.090	64	22.1	40.0	16.5	2.47	0.56
30	2.22	1.030	0.121	0.533	0.161	0.093	69	24.3	41.8	18.2	2.56	0.58
40	2.37	1.063	0.125	0.552	0.169	0.096	75	26.3	43.8	19.7	2.65	0.61
50	2.54	1.094	0.129	0.568	0.177	0.099	82	28.1	46.0	21.0	2.72	0.64
60	2.76	1.127	0.134	0.583	0.184	0.101	90	30.0	48.7	22.2	2.80	0.69
70	3.05	1.163	0.140	0.598	0.192	0.103	101	32.0	52.0	23.5	2.88	0.75
80	3.46	1.206	0.149	0.615	0.200	0.106	115	34.3	56.4	25.0	2.97	0.85
90	4.19	1.267	0.162	0.636	0.211	0.109	139	37.5	63.7	26.9	3.09	1.05
95	4.94	1.317	0.174	0.652	0.220	0.111	163	40.1	70.7	28.4	3.18	1.26

[a] Foliage weight for 100 needle fascicles and sheaths.

critical levels for grand fir, ponderosa pine, and lodgepole pine are substantially higher than for Douglas-fir, and nearly all sites for those three species were below critical concentrations (Table 1). In contrast to other elements, foliar Zn concentrations were higher for the pines than for the firs (Tables 3–6). Most Douglas-fir, grand fir, and ponderosa pine sites were above their respective published critical levels (Table 1). However, the suggested Zn critical level for lodgepole pine (52 ppm) is much higher than for the other species, and most of the lodgepole pine sites sampled were below that level.

Douglas-Fir Foliar Nutrient Concentrations by Habitat Type Series

Douglas-fir stands growing on Douglas-fir habitat types typically had lower foliar N and K concentrations than Douglas-fir growing on the other habitat type series (Figure 5). Douglas-fir stands growing on western hemlock habitat types had higher foliar K concentrations than other habitat type series, with a median concentration of 0.79%. However, the same stands on western hemlock habitat types showed generally lower foliar Ca, Mg, and B concentrations than on other habitat type series, with a median B concentration of

only 18.4 ppm. For Ca and Mg, foliar concentrations tend to decline from drier to wetter habitat type series.

Douglas-Fir Foliar Nutrient Concentrations by Rock Type

Douglas-fir growing on soils derived from basalt or sedimentary rocks had higher foliar N concentrations than other rock types, while trees on granite sites were lowest (Figure 6). The median foliar N concentration for granite rocks (1.045%) ranks only at about the 20th percentile of the basalt foliar N concentration distribution. Douglas-fir foliar K concentrations were lowest on meta-sedimentary rocks (median = 0.66%), and highest on basalts (median = 0.76%). The median foliar K concentration for meta-sedimentary rocks ranks at about the 20th percentile of the basalt foliar K concentration distribution. Foliar P, B, and Mg concentrations all tended to be higher on basalt sites, while Ca concentrations were highest for Douglas-fir growing on soils derived from granite rocks. A bit more than 25% of Douglas-fir stands growing on granite or meta-sedimentary derived soils have foliar K and B concentrations below 0.6% and 20 ppm, respectively.

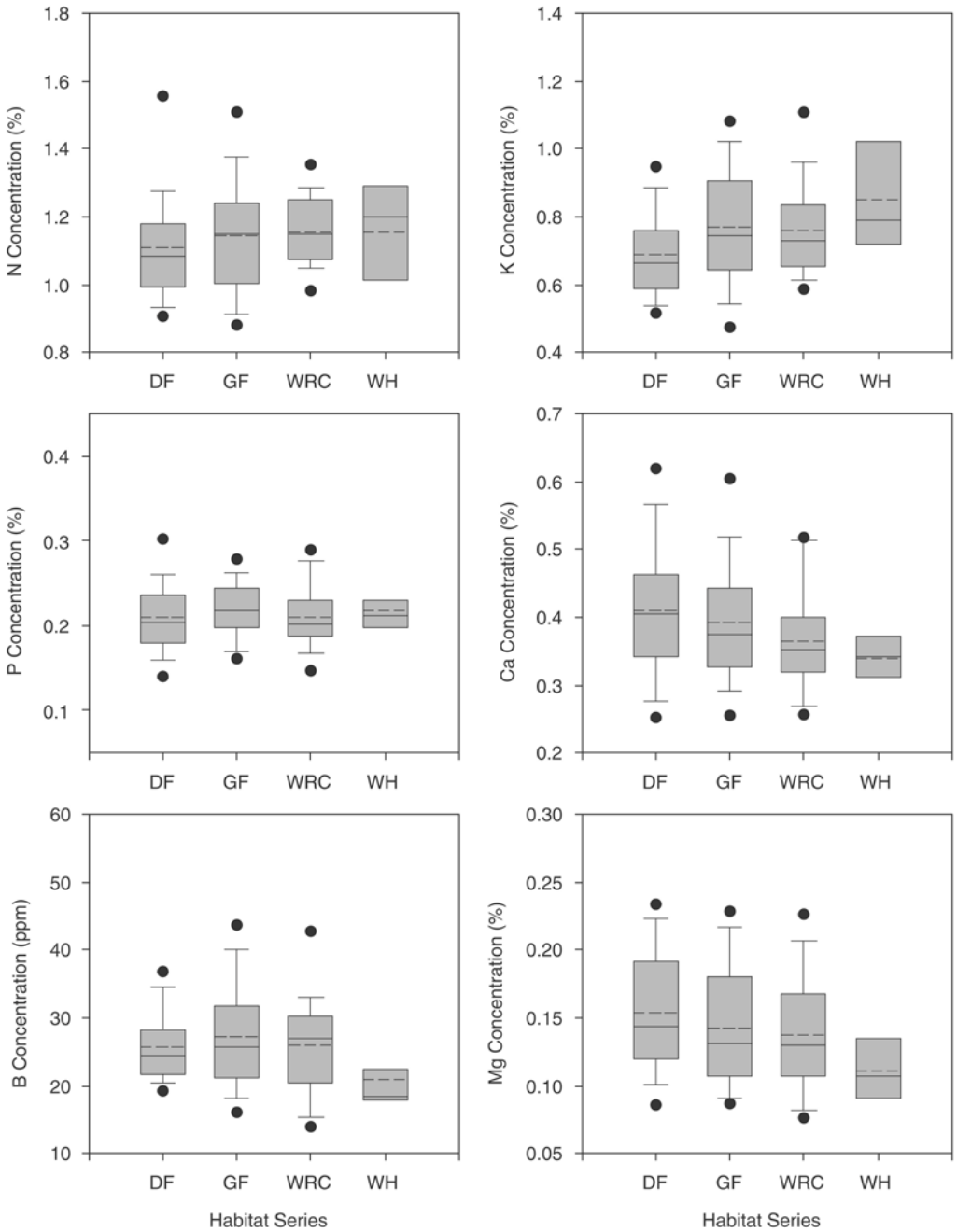

Figure 5. Box plots of Douglas-fir foliar nutrient concentration levels by different habitat series. The solid line within the box represents the median, the dashed line is the mean, the upper and lower ends of the box are the 75th and 25th percentiles, the end of the whiskers are the 90th and 10th percentiles and the points are the 95th and 5th percentiles of the distribution, respectively. The vegetation series are Douglas-fir (DF), grand fir (GF), western redcedar (WRC), and western hemlock (WH). For the latter series, insufficient data was available to calculate the 5th, 10th, 90th, and 95th percentiles.

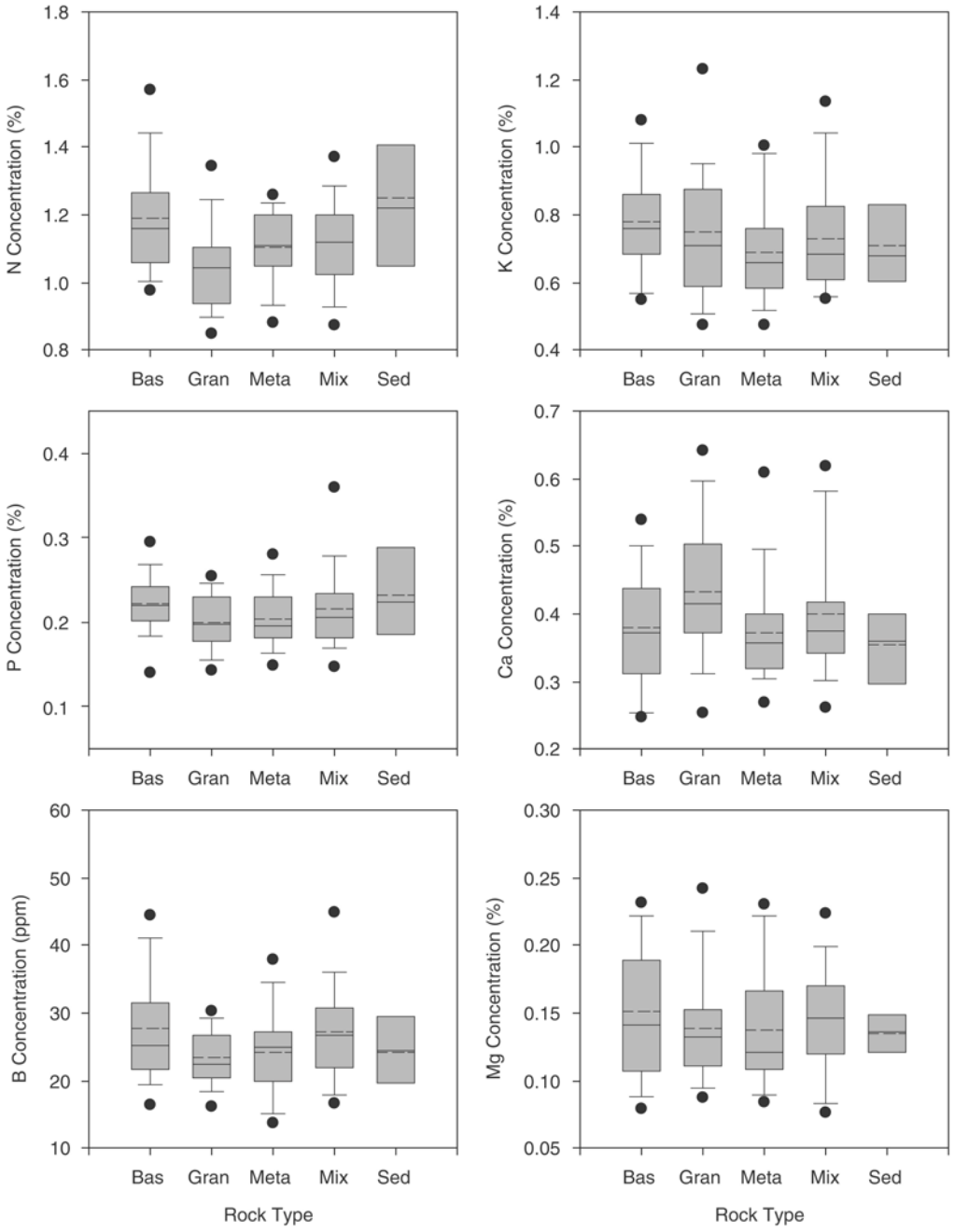

Figure 6. Box plots of Douglas-fir foliar nutrient concentration levels by different rock types. The solid line within the box represents the median, the dashed line is the mean, the upper and lower ends of the box are the 75th and 25th percentiles, the end of the whiskers are the 90th and 10th percentiles and the points are the 95th and 5th percentiles of the distribution, respectively. The rock types are basalt (Bas), granite (Gran), meta-sedimentary (Meta), mixed (Mix) and sedimentary (Sed). For the latter rock type, insufficient data was available to calculate the 5th, 10th, 90th, and 95th percentiles.

Discussion

Assessing Site Nutrient Status

For all four species, a sample of five trees/stand should at least produce an N concentration confidence interval estimate that 90% of the time will be within 20% of the mean, and will include the true population mean 90% of the time (Table 2). However, the same sample size will produce less precise estimates for all other nutrients. It may be impractical to collect sufficient samples to produce very precise foliar concentration estimates for the micronutrients, especially Mn and Mo. For most situations, we recommend basing the sample size on the macronutrients of interest and accepting the less precise estimates for the micronutrients as quantified in Table 2.

The foliar nutrient distributions provided in Tables 3–6 allow a direct assessment of a site's nutrient status. For example, a foliage sample collected from a Douglas-fir stand with an N concentration of 1.0% would rank at the 20th percentile in the distribution (Table 3). Such a stand might have a higher priority for N fertilization than another Douglas-

fir stand with foliar N concentration greater than average (the 50th percentile is an N concentration of 1.11%). The same logic and process can be used for any of the species and nutrients provided in Tables 3–6. The information thus obtained should allow managers to make relative rankings of forest stands' nutrient status. Readers can also develop nutrient "profiles" for sites by ranking all or several nutrients obtained from chemical analyses of foliage samples.

Foliar Critical Levels vs. Foliar Nutrient Distributions

Different authors, using various methods, developed the estimates for foliar critical levels for the nutrients and species provided in Table 1. Good estimates of nutrient critical levels provide biological interpretations that are not possible from distributions such as those provided in Tables 3–6. Based on substantial IFTNC empirical and experimental experience, the values for N critical levels (Table 1) seem useable given the almost universally positive initial (i.e., during the first 2 yr) growth response to N fertilization in the inland Northwest (Shafii et al. 1989, Moore et al. 1991, Moore et al. 1998, Garrison et al. 2000). Furthermore, fertilization response results support the idea portrayed in Figure 1 that ponderosa pine generally has better N status than the other species. Ponderosa pine N fertilization response is usually of lower magnitude and shows more variation than Douglas-fir, grand fir, or lodgepole pine on the same or similar sites (Moore et al. 1998, Garrison et al. 2000). We suggest that the N foliar critical level of 1.1% for ponderosa pine is a bit low; perhaps 1.2% (~ the 35th percentile in our foliar N distribution) is closer to the critical level for inland Northwest ponderosa pine based on positive growth response from ponderosa pine with low foliar N concentrations in N fertilization trials.

The foliar K critical level seems reasonable for Douglas-fir since using 0.6% as an estimate of that value identified different long-term N response patterns within a large set of Douglas-fir fertilization trials (Mika and Moore 1990). We are suspicious of the 0.58% critical level suggested for grand fir since all of our samples were well above that concentration. However, we currently have little experience with grand fir response to K fertilization. The 30th percentile of the grand fir foliar K distribution is about 0.9%, and perhaps this value could serve as a "low" foliar K concentration for grand fir.

Essentially all sites were well above the Ca foliar critical levels for all four species. We have no reason to question the Ca critical values in Table 1, and have observed no Ca deficiencies after fertilization with other nutrients (Hayek 1999, IFTNC unpublished). The Douglas-fir foliar S critical level also seems usable, since most sites showed foliar S concentrations below the critical level. Positive response to S fertilization is common in the inland Northwest (Cochran 1978, Blake et al.1990, Garrison et al. 2000), thus supporting widespread S deficiencies in the region.

We question the foliar B critical levels for Douglas-fir, grand fir, and lodgepole pine since all sites for these species were above critical levels (Table 1). Positive response to B fertilization has been demonstrated for these species in the region (Hayek 1999, IFTNC unpublished). We propose using the 20 ppm critical B concentration suggested for ponderosa pine for the other three species until better species-specific estimates are developed.

Foliar Fe critical levels for grand fir, lodgepole and ponderosa pine seem high since most sample sites for these species were below critical (Table 1). In contrast, Douglas-fir Fe critical level of 25 ppm is only about one-half those of the other species, and as a consequence, most of the Douglas-fir sites are above critical. The Douglas-fir critical concentration is more reasonable, but we have no Fe fertilization response data to support our opinion. Similarly, we believe that the Zn critical value of 52 ppm for lodgepole pine is too high based on comparison with critical values for the other species, coupled with the result that most of the lodgepole pine sites we sampled are below 52 ppm foliar Zn concentration. We don't intend to be "critical" of existing critical values; however, based on experimental and empirical experience, additional work is needed to better estimate foliar critical concentrations for certain nutrients for inland Northwest conifers.

Species Nutrient Ecology

Figures 2–4 illustrate important species differences in foliar nutrient concentrations for four species often growing on the same or at least similar sites. For example, grand fir had substantially higher concentrations of K and Ca than the other species. Ponderosa pine had the highest foliar N concentrations, but, except for Zn, the pines generally had lower nutrient concentrations than the firs. Perhaps lower nutrient concentrations reflect different adaptive strategies for seral, shade-intolerant, pioneer species such as lodgepole and ponderosa pine.

Foresters directly affect the forest nutrient environment during stand establishment, stand development, and harvesting activities. Species nutritional characteristics should be considered in species/site matching just as shade tolerance, cold hardiness, and drought resistance are during the stand establishment phase of silviculture. Controlling stand density and species composition during stand development will greatly influence site nutrient status through a rotation. Controlling tree species composition during all phases of stand development is an important component of forest nutrient management.

Some Douglas-fir foliar nutrient concentration distributions differed by habitat type series, with western hemlock habitat types generally having lower Ca, Mg, and B concentrations but higher K concentrations. Hemlock habitat types have higher annual precipitation than other habitat series in our study and thus may experience higher nutrient leaching. Nelson and Uhland (1995) demonstrated that in areas where water percolation is high, leaching potential is also high. Moist sites also produce faster tree growth rates and higher biomass accumulation (Wykoff 1990) and, consequently, higher soil organic matter. Higher stand nutrient demands, coupled with higher leaching rates, could deplete soil nutrients, while higher soil organic matter would increase CEC, and thus soil nutrient availability. Interactions of these factors, and likely others, probably produced the observed foliar nutrient distribution differences. Whatever the true underlying processes that produced our results, habitat type series influenced some Douglas-fir foliar nutrient distributions in our data.

Douglas-fir growing on soils derived from basalt rocks generally had higher foliar nutrient concentrations than those growing on meta-sedimentary sites. Whole rock geochemical analyses for basalts also show higher mineral nutrient contents than meta-sedimentary rocks (Klein and Hurlbut 1993), except for K and Ca. Rock mineral nutrient content is important, but not the only factor influencing nutrient availability for trees. For example, rock weathering rates and different soil physical properties derived from different rocks also influence nutrient availability. Meta-sedimentary and granite rocks tend to weather to sandy soils, with low cation exchange capacities (CEC) (Buol et al. 1989). Soils derived from basaltic and sedimentary rocks tend to be richer in clay minerals and have a higher CEC. We believe that meta-sedimentary rocks poorly supply trees with nutrients, due to lower rock content for some nutrients and derived soils with lower CEC.

Conclusions

The foliar nutrient concentration probability distributions provided for four conifers allow relative ranking of forest stands' status for 12 nutrients individually and collectively. Douglas-fir showed the least foliar nutrient concentration variation, while grand fir was the most variable of the four species sampled. Nitrogen was the least variable, while Mn and Mo were generally the most variable elements for all four species. Micronutrients were more variable than macronutrients, and it may be impractical to collect sufficient samples to produce very precise foliar concentration estimates for them, especially Mn and Mo. For most situations, we recommend basing the sample size on the macronutrients of interest and accepting the less precise estimates for the micronutrients.

Ponderosa pine showed the highest foliar N and Zn concentrations, and lodgepole pine also had high Zn concentration. The pines generally had the lowest concentrations for all other nutrients. Grand fir foliar K and Ca concentrations were higher than for the other species.

Western hemlock habitat types generally had lower foliar Ca, Mg, and B concentrations but higher K concentrations for Douglas-fir. Douglas-fir growing on soils derived from basalt rocks generally had higher foliar nutrient concentrations than those growing on sites located on meta-sedimentary rocks.

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