Chapter 10

Fertilization Response of Subalpine *Abies* Forests in California

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ABSTRACT. Subalpine forests are a valuable resource for wood production, but productivity often is limited by nutrient availability. Experiments at 15 *Abies concolor* and *A. magnifica* sites in California show that one application of 224 kg N/ha as urea can increase five-year volume growth an average of 35%, but that growth may decline at higher application rates. Stands of saplings and poles responded better than young sawtimber, and increased their growth by as much as 6.5 m³/ha per year. Absolute volume growth sometimes declined following thinning, but growth could be recaptured when thinning was combined with fertilization. Soil and foliar analyses helped to identify stands with high response potential. Stands on soils testing less than 15 ppm mineralizable N responded strongly and consistently, as did stands with foliar nutrient concentrations testing less than 1.15% N and more than 0.15% P. Fertilizing some stands with both nitrogen and phosphorus improved growth more than fertilizing with nitrogen alone, and growth responses lasted for at least ten years. Although fertilization increased nitrate-N concentrations in soil solutions, concentrations below the fine root zone rarely exceeded public health limits.

Increasingly, subalpine forests are seen as a valuable and comparatively untapped resource for wood production. Cold temperatures and low nutrient availability are major factors controlling forest productivity on such sites, and Powers and Edmonds (this volume) conclude that this forest type has an immense potential for responding to nutrient management. One such management technique is fertilization. The paucity of research on nutrition and fertilization in subalpine conifers, and the likelihood that nitrogen (N) is commonly deficient because of slow rates of organic matter decomposition, led Gessel and Klock (1982) to call for further research on the mineral nutrition in forests of the genus *Abies*.

This chapter presents the latest information from a network of fertilization experiments in subalpine *Abies* stands in California. Because subalpine forests share many ecological properties affecting their nutrition, many of the findings reported here may apply much more broadly to the types of western *Abies* forests described by Powers and Edmonds (this volume).

R.F. Powers is Principal Silviculturist, Pacific Southwest Research Station, USDA Forest Service, Redding, California. Broad support for this study was provided by C.B. Goudey, A.A. Leven, J.R. Fisher, and G.A. Anderson. I thank S.R. Miles, G.M. Nakamura, G.D. Jackson, G.R. Chase, R.M. Leonard, J.R. Anstead, R.W. Jones, K.C. Vail, and C.M. Siegel for assisting with many phases of this work.

Past Work

Nutrient deficiencies are not uncommon in cold-dominated forests. Broad surveys of foliar nutrient concentrations in *Abies* forests in the Pacific Northwest (Radwan et al. 1989; Miles and Powers 1988) indicate that many stands probably are deficient in nitrogen and possibly in phosphorus (P). Studies of *Abies balsamea* (balsam fir) in Nova Scotia and Quebec showed that N and N+P fertilization increased volume growth an average of 19 and 23%, respectively (Weetman et al. 1976). Early work in California revealed that poor growth rates in subalpine *Abies* forests often are keyed to low availability of nitrogen and that urea fertilization could improve growth by 30 to 80% (Powers 1981). In southeastern Oregon stands of 50 to 55-year-old *Abies concolor* (white fir), nitrogen fertilization increased five-year volume growth by up to 2 m³/ha per year, and a combined nitrogen, phosphorus, sulfur (S), and potassium (K) fertilizer increased growth by 2.1 to 4.2 m³/ha (Heninger 1982). Cochran et al. (1986), in an operational fertilization study of *Abies amabilis* (Pacific silver fir) in Washington's Cascades, found strong growth response to aerial applications of nitrogen. More recently, Weetman et al. (1988) reported that nitrogen fertilization improved four-year basal area growth by more than 40% for individual trees in some stands of *Pinus contorta* var. *latifolia* (lodgepole pine) in interior British Columbia. Combining nitrogen with phosphorus or potassium at higher rates of nitrogen seemed to boost growth further. Most recently, fertilization increased two-year basal area growth between 19 and 38% in young stands of *A. amabilis* in western Washington and Oregon, and between 29 and 51% in young stands of *A. procera* (noble fir) (Chappell and Bennett, in preparation).

Previously I had described a cooperative program in forest fertilization research between the Pacific Southwest Region and the Pacific Southwest Research Station, both of the USDA Forest Service (Powers 1983). Goals of the program were to develop the means for predicting the growth response potential of California forests to nitrogen fertilization, and to assess the effects of fertilization on the quality of groundwater. Beginning in 1975, the formal program ran ten years and covered four forest types. Results for each study location were summarized by Miles and Powers (1988). For this paper, those data for *A. concolor* and *A. magnifica* (California red fir) have been reexamined and combined with data from new studies not previously reported. The following is a state-of-the-art summary of fertilization research in true fir of California's subalpine forests.

The California Study

Characteristics of Study Sites

Study sites were all on national forest lands in California. They spanned about 4.4 degrees of latitude and 670 m of elevation, from the Sierra National Forest in the central Sierra Nevada to the Klamath National Forest in the Cascades (Table 1). Of these, only the Bonta Original installation predated the main series of formal experiments, in that it was established in 1972 as an administrative study by the Tahoe National Forest. Selection criteria for all other sites were that soils be of a major series and that stands be healthy and of sufficient extent to include a minimum of three replications of control and fertilization treatments. In all, 22 separate experiments encompassed about 200 plots at 15 locations. Soils were predominantly Inceptisols derived from andic or granitic parent materials. Two sites were on Alfisols derived from volcanics, and one on a Psamment formed from granodiorite.

All stands were even-aged and naturally regenerated. Collectively, they covered a broad array of size classes and ages. Site indices varied between 13 and 32 m at 50 years, corresponding to productivity ranges of between 9 and 16 m^3/ha per year at culmination of mean annual increment (Schumacher 1926, 1928). Most sites had received some management in the past. The young-

Table 1—Characteristics of California red fir (RF) and white fir (WF) study sites.

Place Name	National Forest	Elevation (m)	Soil	Species	Site Index (m)	Stand Age (yr)	Mean dbh (cm)	Thinned
Bonta								
Original	Tahoe	2,286	Andic Xerumbrepts	RF	18	4	0.0	N
Re-treat	Tahoe	2,286	Andic Xerumbrepts	RF	18	11	3.6	N
1980	Tahoe	2,316	Andic Xerumbrepts	RF	17	11	1.0	N
Swain Mountain	Lassen	2,042	Typic Dystrandepts	RF	13	16	0.5	N
Pumice Stone Mountain	Klamath	1,890	Dystric Xerorthents	RF	17	40	6.9	Y
Brown Cone	Sierra	2,073	Dystric Xeropsamments	WF	17	60	16.5	Y
Lewis Mill	Tahoe	1,926	Ultic Haploxeralfs	WF	17	70	21.1	Y
Fowler Peak	Plumas	1,646	Andic Xerumbrepts	RF	22	60	24.1	Y
Mule Canyon	Eldorado	1,981	Dystric Xerochrepts	WF	21	60	27.7	N
Fredonyer	Lassen	1,676	Typic Xerumbrepts	WF	15	70	27.9	Y
Franks Valley	Plumas	1,859	Ultic Haploxeralfs	WF	19	65	30.0	Y
Diamond	Lassen	2,042	Pachic Xerumbrepts	WF	14	80	30.5	N
Baxter	Lassen	1,829	Pachic Xerumbrepts	WF	17	75	33.3	Y
Willard	Lassen	1,890	Typic Xerumbrepts	WF	17	55	34.5	N
Sylvester	Stanislaus	1,707	Entic Xerumbrepts	WF	27	50	35.8	N
Haskell Peak	Tahoe	2,134	Andic Xerumbrepts	RF	20	75	40.4	Y
Clavey River	Stanislaus	1,676	Entic Xerumbrepts	WF	32	55	48.3	Y

est stands (Bonta and Swain Mountain, Table 1) had regenerated following clearcutting where logging slash had been piled and burned. Many stands of pole-size and larger trees had been operationally thinned a few years before fertilization. Stand densities were great enough at others (Pumice Stone Mountain, Fowler Peak, Haskell Peak, and Clavey River) that thinning treatments were included in factorial combination with fertilization. Details of each study site are described in Miles and Powers (1988).

Treatments and Measurements

Following preliminary soil identification and stand reconnaissance, plots of 0.04 to 0.16 ha were established. Plots contained an inner measurement plot surrounded by a treated buffer wide enough to contain two or more "rows" of trees, and plot size for each location was set at the minimum area needed to provide at least 30 dominant and codominant trees per measurement plot. Usually, three replications of each treatment were established per location. Soil samples and foliage samples were collected before fertilization to provide baseline information on nutrient status. Soil profiles were described according to National Cooperative Soil Survey standards (Soil Survey Staff 1975), and horizon samples were analyzed for a variety of physical and chemical properties at the National Soil Survey Laboratory. All trees in the measurement plot were tagged and measured for breast-height diameter (dbh), and some or all of the trees were measured for total height and stem volume. Volumes for pole-size and smaller trees were estimated from dbh and height measurements using standard equations (Walters et al. 1985). Volumes for larger trees were estimated from upper stem diameters using an optical dendrometer and the STX program (Grosenbaugh 1974). Porous cup soil water samplers were installed in at least one replication of each treatment for measuring soil solution chemistry at soil depths of 20, 50, and 100 cm.

Plots generally were blocked according to observed site differences or to differences in stand density before treatment. Treatments consisting usually of 0, 224, and 448 kg N/ha as agricultural grade urea were assigned randomly within blocks. In certain instances, other fertilizers were included as well. In one case (Pumice Stone Mountain) the treatment was 300 kg N/ha. If stand densities exceeded 65 m^2/ha basal area, thinning to a basal area of about 45 m^2/ha was combined factorially with fertilization. Fertilizers were applied by hand in the fall following the onset of the wet season. Posttreatment measurements included soil solution samples collected at up to 0.08 MPa suction as often as was practicable for the next three years. Tree growth and foliar samples were collected from the upper third of dominant tree crowns at five-year intervals after treatment. Nutrient concentrations were determined using standard microKjeldahl procedures, colorimetry, and atomic absorption spectrophotometry. In one case (Bonta Retreat, Table 1), a set of new treatments was superimposed eight years after the original treatments. Generally, treatment effects were examined statistically through analysis of variance for each installation. If main effects were judged significant at $p = 0.05$, means were compared using Fisher's protected LSD. Where appropriate, initial differences in stocking were adjusted through regression and analysis of covariance.

Treatment Effects on Tree Growth

Growth Response to Nitrogen

Ecological conditions in the subalpine forest should lead to primary deficiencies of nitrogen and perhaps secondary deficiencies of phosphorus (Powers and Edmonds, this volume). Findings from these studies support this hypothesis. On the average, true fir forests seem to be under substantial nutrient stress. Compared with other California forest types, true fir ranked low in nitrogen and phosphorus (Table 2). Stands fertilized with 224 kg N/ha grew more than 30% faster in volume than unfertilized stands during the first five years following treatment—a response comparable to averages for other forest types, and superior to that found in the more fertile mixed-conifer forest (Table 2). But growth of true fir, unlike other California forest types, did not continue to improve with fertilization rate. In 70% of the trials, growth was less at 448 kg N/ha than at 224 kg N/ha.

Relative growth response—the percentage difference in five-year growth between fertilized and control plots—was greatest in small trees, and declined with increasing mean stand diameter (Table 3). Absolute growth also depended on tree size. Volume growth of saplings and poles (stands with dbh averaging between 5 and 15 cm) doubled in five years (Table 3). Interestingly, absolute volume gains attributable to nitrogen fertilization for this size class averaged more than 4 m^3/ha per year—response rates fully comparable to those reported regionally for coastal Douglas-fir (Miller et al. 1986). Clearly, stands of true fir up to 25 cm mean dbh respond very strongly to nitrogen fertilization. Fertilization apparently reduced growth in stands of large trees, although differences were not always statis-

Table 2—Average nutritional characteristics of four California forest types, and percentage changes in growth rate for the first five years after treatment with 224 and 448 kg N/ha, based on 66 experiments from Miles and Powers (1988). Growth changes are in height for trees less than 5 cm dbh, and in volume for larger trees.

Forest Type (number of studies)	Pretreatment Nutrient Concentration (and critical level)[1] Soil min. N (ppm)	Foliar N (%)	Foliar P (%)	Mean Change in Growth: Unthinned stands 224N (%)	Unthinned stands 448N (%)	Thinned stands 224N (%)	Thinned stands 448N (%)
True fir (22)	15 (15)	1.10 (1.15)	0.14 (0.15)	35	18	33	9
Douglas-fir (12)	32 (15)	1.20 (1.20)	0.19 (0.15)	37	54	28	50
Mixed conifer (4)	40 (14)	1.21 (1.15)	0.15 (0.13)	21	23	5	2
Ponderosa pine (28)	19 (12)	1.28 (1.10)	0.17 (0.08)	25	35	46	69

[1]Critical levels for soil mineralizable N derived from Powers (1981, 1983, 1984*a*). Critical levels for foliar N and P from Powers (1983) and Powers et al. (1988). Mixed-conifer critical levels estimated from means of other three forest types.

Table 3—Five-year volume growth response of *Abies* stands to 224 kg N/ha, by size class.

Dbh Class (cm)	Number of Sites	Five-year Growth Response[1] Relative (%)	Absolute (m³/ha) Mean	Absolute (m³/ha) Range
< 5	4	108	Trees too small	
5-15	3	101	22.0	6.7 - 34.0
15-25	4	30	12.4	-0.1 - 25.2
25-35	6	10	8.0	-11.2 - 22.7
35 +	5	-9	-14.0	-48.3 - 23.1

[1]Average growth difference between fertilized and control plots. Differences are in height for trees less than 5 cm dbh, and in volume for larger trees.

tically significant. At one site (Haskell Peak) fertilization combined with thinning decreased growth by nearly 10 m³/ha per year from that in thinned-only plots. Yet fertilization without thinning increased growth by 4.6 m³/ha at the same site. Even stands of large trees can respond positively to nitrogen (Table 3), but much remains to be learned about mechanisms controlling their response.

Growth Responses to Other Treatments

Other Fertilizers. In an administrative study at Bonta Original, where logging slash had been piled and burned following clearcutting, N only, N+P+S, and lime treatments were applied to three-year-old red fir regeneration (Powers 1981). After five years, height growth response to lime was only moderate, but response to any treatment containing nitrogen was sizable (Table 4). At age 11, eight years after the initial fertilization, a new experiment comparing "quick release" and "slow release" forms of nitrogen was superimposed (Bonta Re-treat, Table 1). Half of the four original treatment replications received no further treatment, while 224 kg N/ha as either urea or ureaformaldehyde was applied to each of the remaining two replications. Trees then were measured at five-year intervals through ages 16 and 21.

Some of the administrative study plots at Bonta Original had been established in ashbeds where logging slash had been piled and burned. Although the reduction in replicates at Bonta Re-treat and microsite confounding in the original placement of plots preclude meaningful statistical analyses, Table 4 offers some insight on both long-term effects of fertilization and the relative merits of slow- and quick-release forms of nitrogen fertilizer. Regardless of the combination, all fertilizer treatments produced taller trees than the control at each measurement interval, and absolute differences increased with time. On the average, fertilized trees were taller than controls: 27 cm taller after 5 years, 35 cm after 8 years, 54 cm after 13 years, and 72 cm taller after 18 years. The effect of a second treatment 8 years after the first fertilization was not impressive, but seemed to

Table 4—Average progression in tree height (cm) for red fir at Bonta Original and Re-treat following first fertilization at age 3.

Fertilizer Treatment[1] at Age 3	Height at Age 8	Height at Age 11	16-year Height[2] (0)	16-year Height[2] (SR)	16-year Height[2] (QR)	21-year Height[2] (0)	21-year Height[2] (SR)	21-year Height[2] (QR)
Control	86	125	163	143	183	201	175	207
Lime only	104	146	216	235	204	273	286	252
N only	119	178	225	241	226	273	321	269
N + lime	116	158	212	205	276	268	249	310
N + P + S	113	159	216	244	241	275	280	302

[1]Lime = 426 kg Ca/ha. Nitrogen = 112 kg N/ha. Phosphorus = 62 kg P/ha. Sulfur = 112 kg S/ha.

[2](0): no further fertilization. (SR): treated again at age 11 with "slow release" ureaformaldehyde, N at 224 kg/ha. (QR): treated again at age 11 with "quick release" urea, N at 224 kg/ha.

Table 5—Average ten-year height growth (cm) at Bonta Re-treat in relation to fertilization at age 3 and refertilization at age 11.

Fertilized at Age 3	Fertilized at Age 11: No	Fertilized at Age 11: Yes
No	76	66
Yes	112	123

be most successful if trees had been fertilized at age 3 (Table 5). The lack of response in trees not fertilized initially but fertilized at age 11 may trace to greater amounts of snow bending in smaller trees. Height growth was twice as great in refertilized plots. Differences between slow- and quick-release forms of N seemed negligible. Mean height increment between ages 11 and 21 averaged 109 and 115 cm for ureaformaldehyde and urea treated plots, respectively, and 105 cm for plots without repeat fertilization.

Bonta Original was a confounded experiment because trees growing in ashbeds were much larger and more vigorous than those in any other plots, including the best fertilization treatments. Foliar analyses of these trees indicated that phosphorus concentrations were nearly twice those of trees in other plots. Therefore, I established a more carefully designed experiment at a higher and steeper position on the same clearcut. Bonta 1980 was installed as a randomized block of four treatments in 1980 when the stand was 11 years old, and consisted of a control, N only, N+P, and a complete macronutrient treatment.

Growth analysis of Bonta 1980 at five and ten years after treatment indicates that N, N+P, and complete macronutrient treatments increased height growth significantly in the first five years after fertilization (Table 6). Height growth was similar for all treatments in the second five-year period, probably because differences were masked by snow bending. The N+P treatment, however, produced substantially more diameter growth (making trees more resistant to snow bending), and volume growth was more than twice that of control trees. Over the full ten-year period, trees treated with N+P were two and a half times larger than the controls.

Similar results were found at Swain Mountain, where height growth in the full treatment was over twice that for the control and two-thirds better than with nitrogen alone. There, the principal effect of the full treatment was improved phosphorus nutrition once nitrogen de-

Table 6—Growth response of red fir saplings at Bonta 1980 in consecutive five-year periods following fertilization at age 11. Nutrient concentrations are shown for current-year needles collected ten years after treatment.

Fertilizer Treatment[1]	Diameter Growth (cm) 1st 5	Diameter Growth (cm) 2nd 5	Height Growth (cm) 1st 5	Height Growth (cm) 2nd 5	Volume Growth (cm^3) 1st 5	Volume Growth (cm^3) 2nd 5	Foliar N (%)	Foliar P (%)	Foliar K (%)	Foliar Ca (%)	Foliar Mg (%)	Foliar S (ppm)
Control	1.7a[2]	4.7a	53.7a	50.6a	1,772a	13,834a	1.04	0.18	0.90	0.40	0.10	825
N only	2.1a	5.1ab	75.9b	50.8a	2,840a	17,691a	1.12	0.18	0.87	0.49	0.12	848
N + P	2.9b	5.5b	94.8c	58.8a	6,009b	32,653b	1.12	0.21	0.86	0.49	0.13	891
Complete	2.1a	4.9a	71.8b	45.6a	2,691a	17,064a	1.08	0.19	0.92	0.41	0.12	886

Foliar Concentration after 10 Years.

[1]Fertilizer rates, in kg/ha: N (224), P (448), K (112), Ca (238), Mg (56), and S (22).

[2]Means within a column not followed by common letters differ at p = 0.05 by Fisher's protected LSD. Foliar nutrient concentrations showed no significant treatment effects.

ficiency had been corrected (Powers 1981). At Bonta, ten years after treatment, nitrogen concentrations were slightly higher in the N, N+P, and full treatments than in the control (Table 6), and foliar P concentrations were highest in the N+P treatment. Foliar P concentrations were greater in N+P trees than in control trees in every block, and were consistently as great as those for any other treatment. However, overall means were not judged to be statistically significant ten years after treatment. The reason for the poor growth response shown by the full treatment could not be explained by differences in foliar nutrient concentrations measured one decade after fertilization.

Thinning. Thinned stands did not always respond to fertilization. At Haskell Peak and Clavey River, the two sites with the largest trees, growth was less on thinned and fertilized plots than on plots that were only thinned. Where stand density was high and foliar N was near the critical level of 1.15% (Powers, 1981, 1983), fertilization sometimes increased growth once the stand was thinned. For example, nitrogen concentrations in current needles at Fowler Peak averaged just above critical level at 1.17%. Basal areas in unthinned plots ranged up to 92 m^2/ha, and fertilization had no effect on growth. However, fertilized plots thinned to 46 m^2/ha increased their growth by 23 m^3/ha over thinned but unfertilized plots in the five years following treatment. Presumably, creating room for crown expansion permitted trees to use fertilizer nitrogen efficiently.

If stand densities were high and nitrogen availability was judged *extremely* low, fertilization and thinning had a synergistic effect similar to that reported for nitrogen-deficient pine under extreme shrub competition (Powers 1983). This effect is illustrated by red fir responses at Pumice Stone Mountain, where foliar N (1.09%) and mineralizable soil N (5 ppm) were judged critically low (Figure 1). There, three spacing treatments (no thinning, 16,680 stems/ha; intermediate, 4,444 stems/ha; wide, 1,111 stems/ha) were crossed factorially with 300 kg N/ha. Net volume growth apparently was increased by 7 m^3/ha per year in unthinned plots (although differential snow damage in control plots may have magnified this effect). However, in plots with intermediate spacing, fertilization increased growth by 5 m^3/ha, essentially recapturing the increment lost through stocking reduction in thinning.

Treatment Effects of Water Quality

The remoteness of many high elevation sites prevented collecting soil solutions more often than two or three times a year, but ten study sites were accessible enough to allow several collections in fall and spring. These sites were sampled repeatedly following treatment. Results from the chemical analysis of soil solutions for these ten sites support a preliminary finding (Powers 1981) that nitrate-N concentrations are very low in untreated fir plots, and that they remain relatively low below the rooting zone following fertilization.

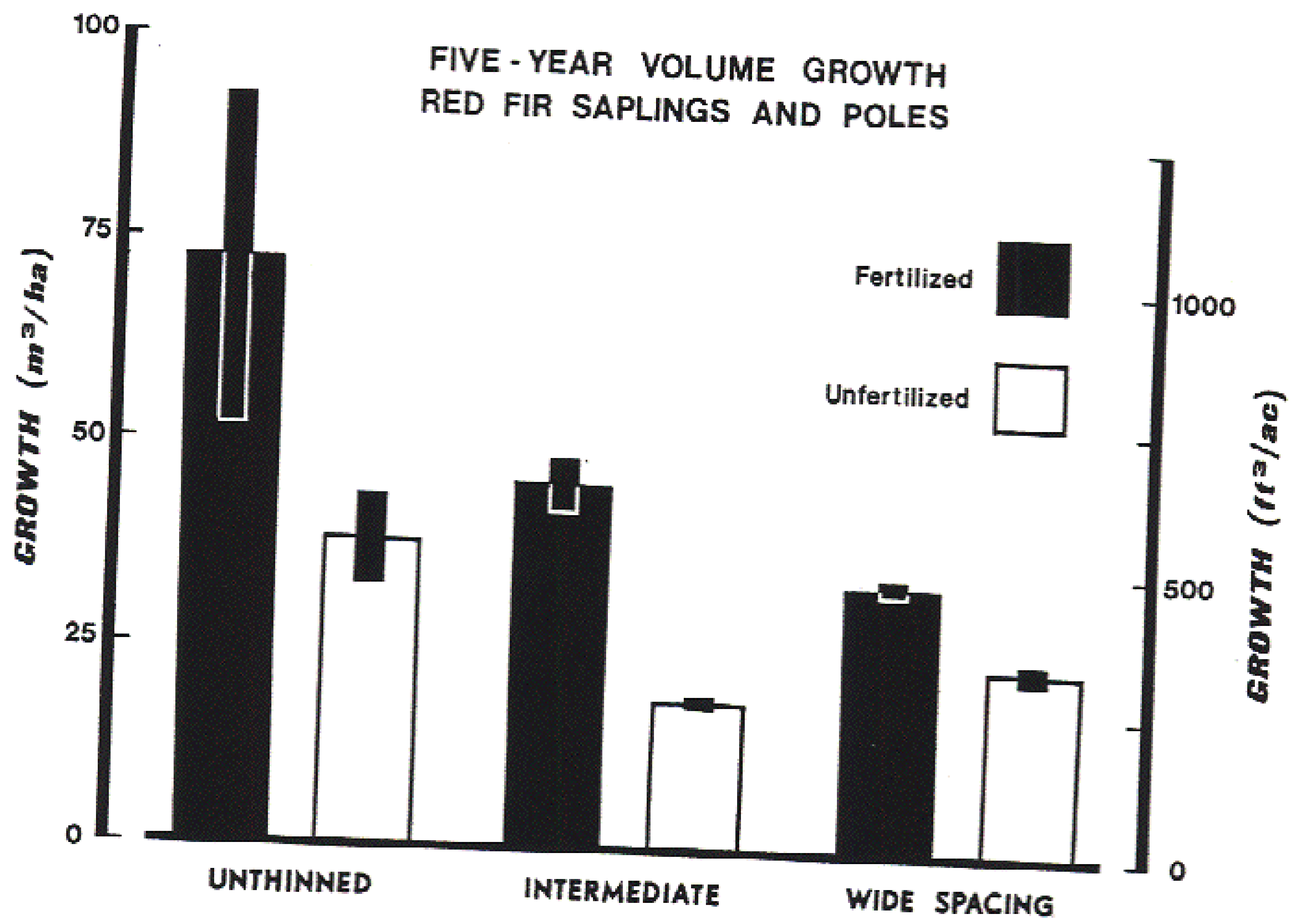

Figure 1. Five-year volume growth in a 60-year-old stand of California red fir at Pumice Stone Mountain. Urea fertilization (300 kg N/ha) is combined with three levels of spacing. Means and standard error bars are for three replicates per treatment.

Table 7—Effects of nitrogen fertilization (0, 224, and 448 kg N/ha) and thinning on concentrations of nitrate-N in the soil solution at 20, 50, and 100 cm depths in the first year following treatment. Basis: ten true fir sites.

Soil Depth (cm)	Mean (and Maximum) Nitrate-N Concentration in Soil Solution (mg/L)					
	Unthinned			Thinned		
	0N	224N	448N	0N	224N	448N
20	0.45	9.11	9.52	1.11	12.54	26.26
	(5.20)	(74.40)	(94.00)	(8.10)	(96.00)	(196.53)
50	0.79	3.20	9.72	0.31	2.31	17.14
	(10.80)	(49.60)	(148.80)	(6.10)	(12.00)	(220.00)
100	0.24	0.52	5.47	0.09	1.33	1.25
	(0.50)	(5.80)	(50.00)	(0.75)	(14.20)	(7.43)

Time trends in soil solution chemistry for all forest types show that the greatest changes occur in the first year after treatment, particularly in the first spring and subsequent fall (Miles and Powers 1988). The true fir sites followed this pattern, with nitrate-N concentrations in fertilized plots dropping to control levels by the second year. Nitrate concentrations increased markedly with fertilizer rate, but decreased rapidly with depth (Table 7). Although nitrate-N concentrations often exceeded the public health limit of 10 mg/L within the upper 50 cm of fertilized plots, concentrations fell well below that by 100 cm depth. Occasionally, pulses above 10 mg/L were measured at depth in unthinned plots receiving 448 kg N/ha, and in thinned plots receiving 224 kg N/ha.

Screening for Responding Sites

Soil Analysis. Powers (1981, 1983) proposed that stands of true fir under nitrogen stress were characterized by mineralizable soil N concentrations below 15 ppm in the 18 to 22 cm depth zone, and by foliar N concentrations at or below 1.15% in current-year needles. Stands in the more extensive study reported here were grouped into five classes of mineralizable N measured before treatment. Table 8 shows that the proportion of stands with strong fertilization response (growth gains of more than 20% in the first five years following nitrogen fertilization) generally declined as mineralizable N increased. All stands testing less than 5 ppm increased their growth by more than 20%, and averaged 77%. Four of five sites testing between 5 and 10 ppm and two of four testing between 10 and 15 ppm responded positively. Response declined quickly thereafter, but some stands on sites testing at higher levels also responded well. Fertilized and thinned plots at Fowler Peak increased their growth by 47% despite testing 37 ppm mineralizable soil N.

Foliar Analysis. Nutrient concentrations in well-lighted foliage collected near the seasonal end of height growth offer good measures of nutrient sufficiency and deficiency, and can reveal the principal limiting nutrient if a true deficiency exists (Powers 1984*a*). If other nutrients are satisfactory, concentrations of nitrogen below critical level will indicate a true nitrogen deficiency, and nitrogen fertilization should increase growth. If one or more other nutrients also are deficient, their scarcity must be corrected before appreciable response to nitrogen can occur. Results from the true fir studies indicate that response to nitrogen fertilization is constrained by the relative availability of phosphorus. Powers (1983) had proposed that trees testing less than 0.15% P in current-year needles were phosphorus deficient. If this is true, trees critically low in phosphorus should not respond well to nitrogen fertilization, regardless of their nitrogen status.

Stands in this study were classified into three categories relative to foliar concentrations of nitrogen and

Table 8—Average five-year volume growth of true fir stands in response to 224 kg N/ha, and proportion of stands with growth responses exceeding 20%, by mineralizable soil N classes.

Characteristic	Mineralizable Soil N Class before Treatment (ppm)				
	< 5	5-10	10-15	15-20	> 20
Mean growth increase (%)	77	91	9	5	14
Stands responding more than 20%	3 of 3	4 of 5	2 of 4	1 of 7	1 of 3

Table 9—Average five-year volume growth of true fir stands in response to 224 kg N/ha, and proportion of stands with growth responses exceeding 20%, by initial foliar nutrient concentrations.

Characteristic	Foliar Nutrient Concentration before Treatment		
	N < 1.15% P > 0.15%	N < 1.15% P < 0.15%	N >1.15% P< 0.15%
Mean growth increase (%)	82	5	19
Stands responding more than 20%	7 of 8	2 of 9	1 of 5

phosphorus before treatment. Classes were based on presumed critical levels of 1.15% N and 0.15% P (Powers 1983). Seven of eight stands judged adequate for phosphorus but critically low in nitrogen showed growth responses of more than 20% following nitrogen fertilization (Table 9). Five-year growth in such stands was increased an average of 82%. Only two of nine stands critically low in nitrogen *and* phosphorus responded to fertilization, and only one of five responded if nitrogen was judged adequate and phosphorus was judged critically low.

Discussion and Conclusions

California's subalpine true fir forests respond strongly to nitrogen fertilization. On the average, 224 kg N/ha triggers volume responses in true fir equaling those of other forest types throughout the Pacific Northwest. However, growth rates were reduced by higher rates of urea fertilization, the cause of which is unknown but may be related to damage to surface roots. Vogt et al. (1981) found that more than 80% of fine roots in Pacific silver fir stands were in the top 15 cm of mineral soil and the forest floor—proportions twice as great as noted for young stands of mixed conifers under more mesic conditions (Powers 1980). The consistency of growth reduction in California true fir suggests that the highest rates of fertilization may cause some damage to surface fine roots and mycorrhizae from the alkalinity accompanying urea hydrolysis. This phenomenon was proposed by Gill and Lavender (1983) to help explain fertilizer-induced growth reduction in *Tsuga heterophylla* (western hemlock), which also concentrates its fine roots in the O and A horizons. In fertilizer trials in western Washington and Oregon, growth reductions did not accompany high rates of ammonium nitrate fertilization—a fertilizer that does not have an alkaline reaction (Chappell and Bennett, in preparation).

Stands with mean diameters of 15 cm dbh and less showed strong, positive response to nitrogen fertilization. Possibly this reflects the phase of growth when crown mass and uptake are peaking. Once crown mass stabilizes, nitrogen nutrition shifts primarily from uptake to internal retranslocation from senescing foliage within the crown (Miller 1984). Once crowns have closed, between 40 and 50% of the nitrogen and 50 to 80% of the stand's phosphorus needs are met internally in subalpine species (Prescott et al. 1989). Thus stands that have reached high densities in their canopies are at high foliar carrying capacity and should not respond much to nitrogen fertilization unless densities are limited by nitrogen availability, or unless the canopy has been opened enough through thinning to permit crown expansion.

Judging from the sustained height growth at Bonta Original after a single application of 112 kg N/ha, the response extends longer than had been projected based on five-year foliar analyses (Powers 1981), and the value of re-treating small trees within eight years seems marginal (Table 4). Findings from limited trials with multiple-nutrient fertilizers support the premise that nitrogen is a primary and phosphorus a secondary nutritional constraint to productivity in subalpine fir forests (Powers and Edmonds, this volume). If Bonta and Swain Mountain are typical of other sites, fertilizing young stands with nitrogen and phosphorus should shorten the period of height growth suppression from snow bending because of rapid growth during the size stage when trees are susceptible to snow damage.

Interestingly, lime treatments at Bonta Original improved growth as effectively as nitrogen treatments containing phosphorus. One possible explanation is that a calcium deficiency may exist that was corrected by lime. However, foliar calcium concentrations in control plot trees averaged 0.19% (Powers 1981), well above the proposed critical level of 0.12% (Powers 1983). Another and perhaps more plausible explanation is that lime may have raised soil pH sufficiently to decrease the solubility of polyvalent metal cations. This could have two effects: first, metal toxicity may have been reduced through less uptake; second, lower solubilities would reduce the precipitation of phosphorus in such insoluble compounds as $Al(OH)_2H_2PO_4$. Failure to get substantive growth response to fertilizer P when combined with N (Table 4) may be due simply to fertilization rates that were too low to overcome the soil's P-sorption capacity (Powers et al. 1975). In fact, foliar P concentrations did not differ appreciably between any of the treatments five years into the study (Powers 1981). The fact that phosphorus response was demonstrated at much higher rates of phosphorus application (Bonta 1980, Table 6) illustrates that phosphorus deficiencies do limit stand response to nitrogen. With the possible exception of calcium, I found no evidence of nutrient deficiencies beyond nitrogen and phosphorus in the subalpine true fir zone.

Soil solution nitrate-N concentrations in unfertilized plots were very low even following thinning (Table 7), supporting Powers and Edmonds's conclusion (this volume) that nitrification usually is not a very active process in subalpine forests. However, concentrations were no lower than those reported for control plots of Douglas-fir in Washington (Otchere-Boateng and Ballard 1978) or mixed conifers in California (Frazer et al. 1990), and occasional pulses within the upper 50 cm were surprisingly high. The fact that nitrate-N concentrations did rise following fertilization suggests that nitrification is held in check more by the scarcity of ammonium substrate than by cold temperatures per se. In fact, some first-year pulses were appreciably greater than those reported for high rates of urea fertilization in Douglas-fir (Otchere-Boateng and Ballard 1978). Nitrate concentrations in the upper 20 cm of fertilized plots tended to be lower in unthinned plots than in thinned, possibly reflecting greater nitrogen uptake rates in fully stocked stands. Interestingly, concentrations at 100 cm were lower in thinned plots receiving 448 kg N/ha, which may reflect dilution from greater levels of soil moisture below the main rooting zone following thinning. Overall, fertilization rates of 224 kg N/ha or less should pose no threat to groundwater quality.

Prospective fertilization sites can be screened for their probable response to fertilization using either soil or foliar analysis. Soil analysis has the advantage of simplicity. The disadvantage of a single soil test is that it cannot account directly for other nutrients limiting growth. Other disadvantages are the artifacts caused by spatial and seasonal variation and by subtle differences in laboratory technique (Powers 1984*b*). However, where other deficiencies are rare, a single soil test can be useful. Table 8 indicates that stands on soils testing less than 15 ppm mineralizable soil N at 18 to 22 cm soil depth are likely to respond favorably to fertilization with urea at 224 kg N/ha. Thus, 15 ppm mineralizable soil N continues to serve as a useful critical level for separating stands into high and low response groups.

Chemical analysis of current-year foliage taken in late summer, close to the culmination of height growth, is a more direct and objective measure of tree nutrient status than soil analysis, provided it includes more than just nitrogen. The principal disadvantages are the physical problems of obtaining samples during a brief sampling period, rather than the conventional dormant period when trees are no longer taxing the site for nutrient uptake (Powers 1984*a*), and of obtaining upper-crown samples from tall trees. Another disadvantage is variability between analytic labs and the high cost of commercial laboratory analyses. These problems aside, stands testing less than 1.15% foliar N and more than 0.15% foliar P should respond very well to urea fertilization at 224 kg N/ha (Table 9). Stands testing less than 0.15% foliar P are unlikely to respond well to nitrogen fertilization unless phosphorus fertilizer is applied too.

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Questions and Answers

You said that net growth in your fir stands was better at 224 kg N/ha than at 448. Was mortality increased by the higher rate of fertilization?

There was very little mortality in any of the stands in the first five years after fertilization. Generally, fertilization will increase the foliar mass of overstory trees. Increased canopy density may shade out weakened trees in lower crown classes, but this isn't a big factor with shade-tolerant fir. Thus I can't attribute reduced growth to increased mortality. Whatever the cause, it was sublethal. As stated previously, a likely cause is damage to surface roots.

You indicated that biological response to fertilization was greatest in young stands; however, value response might be greater in older stands of larger trees even though volume increases may be less. If this is so, what age or size classes would you target for fertilization in order to get "the biggest bang for the buck"?

There may be a place for fertilization in nearly all age or size classes, depending on the market for the products. For instance, fertilizing at the seedling and sapling stages as was done at Bonta may get trees above the snowpack sooner and into the accelerated phase of height growth, although this may only add up to a five- or six-year jump-start. Fertilization also can produce dark green, dense-crowned Christmas trees in five years that are far more attractive than untreated trees, and this suggests a pretty good financial return. A problem is that snow may keep you from your Christmas tree production area at the time you wish to harvest.

Sapling and small pole size classes are biologically the best responders. Often, stocking is such that they are approaching the site's carrying capacity for crown mass and are near their peak rates of nutrient demand. Although the commercial value of small trees isn't great, a timely fertilization—particularly if coupled with a thinning—helps trees reach a more valuable size class sooner. Once crown mass stabilizes, half or more of the forest's nutritional demand is met through internal recycling, and you can't expect much fertilization response unless the site is under severe nutritional stress. However, combining fertilization with thinning could show a good rate of return in ten years.

If I had to pick the ideal stand for a low risk, economically favorable return on my fertilizer investment, I'd look for a stand with a mean dbh of 20 to 25 cm. I would thin the stand to a basal area between 35 and 40 m^2/ha, and I'd apply no more than 300 kg N/ha along with about the same amount of phosphorus. If I wanted to sleep even more soundly, I'd confirm through foliar analysis that the stand was truly nutrient limited.

In your Bonta 1980 study you applied phosphorus at a rate much higher than any I've seen used in forestry. Why such a high rate, and what form of fertilizer did you use?

I used triple superphosphate, but that's not the reason I applied so much. I believe that unusually high amounts of phosphorus must be applied in order to get a reasonable biological response on volcanic soils. In the South and Southeast, where phosphorus fertilization is routine, it's a different story. There, sedimentary soils of the Upper and Lower Coastal Plains are not nearly as effective as our volcanic soils at "fixing" phosphorus into insoluble compounds of aluminum, manganese, and iron. This means that much of the phosphorus entering the soil following fertilization is biologically available. Consequently, fertilization rates rarely exceed 100 kg P/ha, and 25 to 50 kg P/ha are more the norm.

Fertilization studies in the West that do include phosphorus tend to use it at rates similar to those in the South, but such studies seldom show much growth response, leading researchers to conclude that phosphorus is not deficient. I think that poor response relates as much to soil mineralogy as to greater phosphorus contents of western forest soils. Unlike many Coastal Plain soils, forest soils of the Cascades are mineralogically rich in aluminum, iron, and manganese. When fertilizer P enters the soil as $H_2PO_4^-$ it reacts readily with these cations to form low-solubility Al-, Fe-, or Mn-phosphates. Fixation is so great that phosphorus is rendered insoluble before it penetrates very far into the soil.

Volcanic soils are notorious fixers of phosphorus, and can tie up at least five times more than metasedimentary soils (Powers et al. 1975). To give you a sense of scale, one California study followed the fate of phosphorus applied at 1,100 kg P/ha to a volcanic Ultisol (Ulrich et al. 1947). This is a rate that is 10 to 20 times higher than the usual forestry prescription. One year later, 85% of the P remained in the top 15 cm of soil. You have to overcome this high fixation capacity to improve the biological availability of phosphorus, and that's why I used such high rates.

What part of the soil profile do you sample for mineralizable N, and why?

My index depth has always been 18 to 22 cm below the mineral soil surface. There are two reasons for this. The first has to do with biological logic, in that the depth should reflect a zone of high root activity and nitrogen turnover. The second has to do with passive intransigence ("if it ain't broke, don't fix it"). Because this test has been used so widely, some historical perspective is in order.

I came upon this test in the agricultural literature during my graduate studies in the early 1970s and began calibrating it against forest conditions. In my 1980 paper I showed that both mineralizable N and its absolute variability decrease rapidly with soil depth, and that samples from 30 cm deep were only half as variable as those from 10 cm. I also showed that root distributions of young conifers were concentrated near the soil surface, that distributions in the 0 to 10 and 10 to 20 cm depth zones were not significantly different, and that amounts fell off rapidly below 20 cm. I settled on the 18- to 22-cm depth zone because (1) it reduced absolute variability from that found nearer the surface, (2) it still kept me in a zone of high root density, and (3) it reduced the possible analytic problem of undecomposed organic matter floating to the top of the soil suspension during anaerobic incubation, thereby causing both aerobic and anaerobic conditions to exist (surface samples would have more organic matter). This could lead to an underestimate in mineralizable N. Next, I calibrated mineralizable N from this depth against pine site index and foliar N, and also growth response to nitrogen in a dozen fertilizer trials.

Because these calibrations showed trends that made sense biologically, 18 to 22 cm has been my depth sampling standard ever since. It doesn't mean that some other depth wouldn't be just as good, or possibly better. But for the reasons stated above, this has been my standard depth since I first adapted this test to forest trees in the early 1970s. Shumway, headquartered in Redding when he was with the Shasta-Trinity National Forest in the mid-1970s, learned of the test from me and applied it to Douglas-fir when he moved to Washington. Obviously, my numbers are not interchangeable with those developed for Douglas-fir. For the same site, mine would be lower because they come from deeper in the soil profile.

Based on your research in California, would you recommend fertilization of Pacific silver and subalpine stands in the Washington Cascades?

Yes and no. I think upper-slope stands of Pacific silver fir saplings and poles would show excellent response to nitrogen and phosphorus fertilization because frigid and cryic soil temperatures would limit the mineralization of nitrogen and phosphorus from organic matter. By and large, they should be nitrogen and possibly phosphorus deficient. Pacific silver fir is similar silvically to our California red fir. It is capable of high stand densities and good volume growth. Preliminary screening trials by Chappell and Bennett (in preparation) are showing very encouraging results. Before starting any operational program, though, I would analyze foliar and soil chemistry.

I wouldn't advocate fertilizing subalpine fir. I believe that this species would respond well, but I doubt that growth rates would justify the investment. Too many other factors limit growth in the main subalpine fir zone.

Would you recommend fertilizing sites that have been severely degraded due to past management activities, such as severe burns?

Yes, I would, but not for short-run commercial reasons. If you're a public land manager, you have a legal imperative to rehabilitate degraded sites to maintain and protect their long-term productivity. It isn't a question of economics. If you're a private manager, you have an ethical imperative. There, it probably *is* a question of economics, but it's also the right thing to do. Either way, fertilization can help you, but it isn't the whole answer. Preventing erosion, getting crown closure quickly, regenerating a forest floor, and pumping organic matter back to rehabilitate degraded soil structure are major goals. Fertilization can help you get there sooner.

How does one go about getting "accurate" foliar analyses? We've sent similar samples to the same lab and received different results.

I've had the same experience. Field samples are costly to collect, and you sure don't want to waste a good investment at the field end with sloppy work in the lab. The best thing you could do is get a researcher experienced in forest nutrition to run the samples for you. The probability that he or she will agree to do this is somewhat greater than zero, but not much. Land-grant universities sometimes have provisions for running analyses for the public, and of course there are several commercial laboratories listed in the yellow pages. There's an old saying that "Yer gets what yer pays for," and that certainly is true of commercial labs. Those offering cut-rate prices usually provide second-rate results. "Word-of-mouth" is a pretty good guide. That way, you benefit from the experience of others who have traveled that path before.

The first thing you should do with a commercial lab is get a list of recent customers and contact some of them. You should also ask lab managers about the analytic procedures they plan to use and check them out with a researcher experienced in lab technique. Also, in preparing a contract, you might work out an agreement that you'll be providing blind duplicates. If the duplicate analyses don't match within, say, 10%, the lab has to rerun the entire batch of samples at no cost to you. You could agree to organizing samples into small batches, each with blind duplicates, so that the lab could isolate where the problem was. The downside is that you may get another batch of results just as goofy as the first. At this point, you write it off to experience and go shopping again.

Another suggestion for foliar analysis is to include a "reference sample" with a known chemical composition (there is no analogue for soil). The material should be similar to your foliar sample (in other words, don't send the lab sugar beet leaves if they'll be analyzing fir needles). Such samples are available through the National Bureau of Standards for a price. Most researchers have their own standards that they have analyzed repeatedly, and they may be willing to share some with you. These could be incorporated into the contract and inserted into the sample stream in place of blind duplicates, but the lab shouldn't be tipped off where they are until analyses are completed.

Do you foresee any potential for using remotely sensed spectral data (which might correlate with foliar chemistry or water stress) as a potential diagnostic tool?

I think that for the foreseeable future, precise diagnosis at the stand level will require ground-level sampling. But I'm intrigued by the prospects of using spectral imagery for sensing the physiological condition of landscapes. On an experimental basis, the applications are exciting in their possibilities. For example, thermal imagery has been used not only to detect moisture stress in trees, but to define subsurface moisture patterns beneath forest stands (Vicek and King 1983). In the greenhouse, reflectance spectroscopy has been used to estimate foliar N concentrations of seedlings quickly and accurately (Tsay et al. 1982). Wessman et al. (1988) used similar technology to accurately assess nitrogen and lignin concentrations in dried and ground plant samples. And while it is a big jump from dried samples to forest stands, these studies illustrate the technological potential for assessing limiting factors on an extensive basis. Forest health and global climate concerns could be served particularly well by remote sensing techniques, as they could help pin down stress conditions over the broad forest landscape.