Chapter 11

Fertilization Response by Interior Forests: When, Where, and How Much?

P. G. *MIKA*, J. A. *MOORE*, R. P. *BROCKLEY*, *and* R. F. *POWERS*

ABSTRACT. Interest in tree nutrition and the use of fertilizers in forests of the interior West has grown over the last 20 years. Large-scale fertilizer trials have been established to estimate growth response for Douglas-fir, ponderosa pine, and lodgepole pine. Current research focuses on where and why fertilizer response is obtained and how fertilization interacts with other forest management activities. Nitrogen is the major growth-limiting nutrient in these forests. For Douglas-fir, gross volume growth responses to 224 kg N/ha may average up to 25% during the first six years following fertilization. Similar treatments in ponderosa pine and lodgepole pine have produced a 30% volume response in five and six years, respectively. Response has been shown to vary across parent materials and soil types; it is usually less on sites with high levels of mineralizable nitrogen in the soil, high foliar nitrogen concentrations, or high site index. Good response to nitrogen fertilization has been linked to vegetation control in very young stands and to stocking control in older stands. Nitrogen fertilization may increase mortality rates and the incidence of pest problems. While other nutrients usually do not produce a significant growth response when applied singly, response to nitrogen may be limited by natural or induced deficiencies of other nutrients. Lack of sulfur, boron, or copper can reduce growth response to nitrogen in lodgepole pine; low potassium levels may have a similar effect in Douglas-fir; and addition of other nutrients, primarily sulfur, has increased response to nitrogen in ponderosa pine.

At the Forest Fertilization Conference in 1979, the state of the art for fertilization of interior forests was presented in two papers. One discussed four-year response to thinning and nitrogen (N) fertilization by Douglas-fir (*Pseudotsuga menziesii*) and grand fir (*Abies grandis*) in northern Idaho (Scanlin and Loewenstein 1981); the other summarized the results of ponderosa pine (*Pinus ponderosa*) and lodgepole pine (*P. contorta*) fertilizer trials scattered throughout the western United States (Cochran et al. 1981). Since that time, interest and research efforts in fertilization have increased substantially. Several large multitrial fertilizer experiments have been established and the geographical coverage has expanded to an area stretching from northern California to the interior of British Columbia, and from the eastern Cascades to the west slopes of the Rockies. In this chapter we intend to summarize the information that these new trials have produced to date and, based on that information, make some recommendations regarding fertilizer application. We will focus on three areas: (1) fertilizer application—what to apply and when to apply it; (2) fertilizer growth response—how much response we can get, how long it lasts, and what factors seem to control it; and (3) other fertilizer responses—how fertilization affects tree mortality and pest problems.

What and When to Apply

Nitrogen is considered the nutrient most limiting growth in interior forest types, as in other temperate forests. Nitrogen levels have been found to be generally low in interior forests. Foliage samples collected from 90 fertilizer trials in Douglas-fir scattered across eastern Washington, northeastern Oregon, Idaho, and western Montana (Figure 1) showed nitrogen concentrations of unfertilized trees to be quite low throughout the area (Mika and Moore 1990). On control plots, concentrations averaged only 1.13%. This level is well below adequate thresholds found for coastal Douglas-fir (Webster and Dobkowski 1983; Walker and Gessel 1991); thus successful increases in foliar N concentrations produced by nitrogen fertilization should result in increased

---

P.G. Mika is Data Analyst, Intermountain Forest Tree Nutrition Cooperative, University of Idaho, Moscow. J.A. Moore is Professor of Forest Resources, College of Forestry, Wildlife, and Range Sciences, University of Idaho. R.P. Brockley is Research Silviculturist, B.C. Ministry of Forests, Vernon, British Columbia. R.F. Powers is Principal Silviculturist, USDA Forest Service, Redding, California.

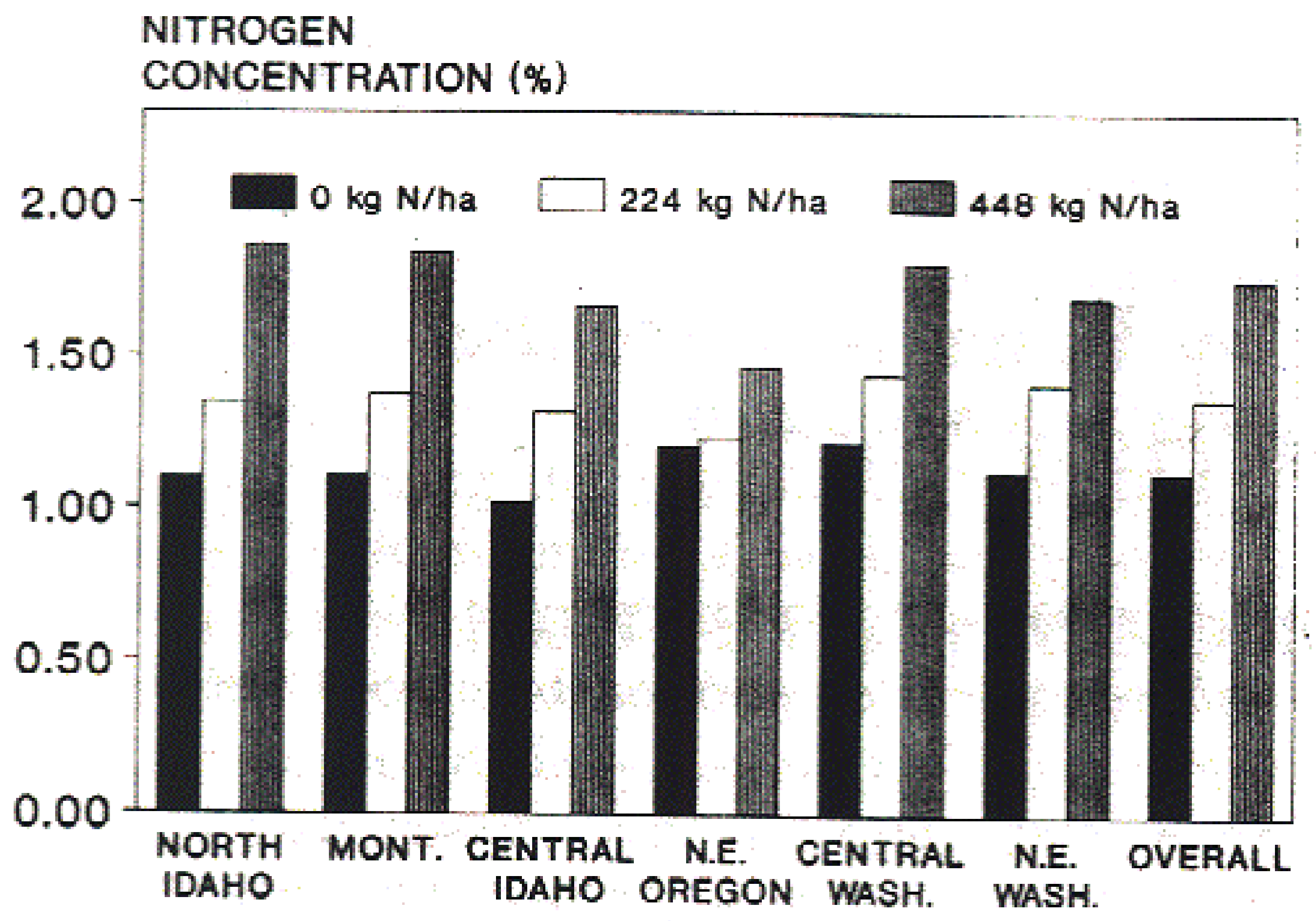

Figure 1. Average nitrogen concentration (% by weight) by geographic region and nitrogen fertilizer treatment for dormant season Douglas-fir foliage collected one year after fertilization. From Mika and Moore (1990).

growth, assuming other factors are not limiting growth. Foliar analysis has also shown severe to very severe nitrogen deficiencies to be common in lodgepole pine stands throughout the interior of British Columbia (Ballard 1986) and in many ponderosa pine (Powers et al. 1988) and true fir (Powers 1981; Powers, this volume) stands in California and Oregon. No other nutrient has been found to be generally lacking over large areas or a wide range of conditions.

Given that nitrogen is generally deficient in interior forests, how should we apply it to achieve greatest response? Decisions must be made regarding the source (e.g., urea or ammonium nitrate), the amount applied (rates of 100 to 675 kg N/ha have been tested), and the application time (fall or spring). At the Forest Fertilization Conference in 1979, Heilman et al. (1981) cautioned that urea should not be applied on top of frozen ground or deep snow or when rainfall sufficient to prevent volatilization losses was unlikely to occur soon. Based on average precipitation and temperature figures for areas east of the Cascade Mountains, they recommended that urea be applied in October and November and suggested that ammonium nitrate might be used to extend the application season. Fertilizer tests on Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) in Sweden had demonstrated greater nitrogen uptake and growth response with ammonium nitrate than urea (Malm and Möller 1975).

Results from a study near Shawnigan Lake on Vancouver Island agreed. Over a seven-year period, Douglas-fir growth increases were 21% and 7% more on ammonium nitrate plots than on urea plots when fertilized with 224 kg/ha and 448 kg/ha N, respectively (Dangerfield and Brix 1981). Initial uptake of nitrogen was greater on ammonium nitrate plots. Possible explanations were: (1) greater movement of nitrate through the soil profile, leading to better nitrogen distribution in the rooting zone and better root uptake, and (2) nitrogen immobilization by soil bacteria with urea application.

Tests in interior types, although limited in extent, have not shown ammonium nitrate to be a superior nitrogen source. Nor have they indicated any problems with spring application of urea. An experiment was conducted on lodgepole pine in interior British Columbia, testing the effect of nitrogen source (urea versus ammonium nitrate) and season of application (fall versus spring) on tree response (Brockley 1989*b*). Nitrogen fertilization (200 kg N/ha) tended to have positive effects on first-year fascicle weight and three-year diameter increment. Nitrogen source had no influence on diameter growth, while fall application did produce greater growth at one site. Nitrogen uptake results were similar to those found at Shawnigan Lake; ammonium nitrate, particularly when applied in the spring, produced greater initial nitrogen uptake. Despite these large increases in foliar N concentrations, the spring ammonium nitrate treatment generally produced lower response than other treatments. This effect was thought to result from negative effects of nitrogen fertilization on sulfur nutrition; nitrogen fertilization (1) produced large increases in foliar N:S ratios that were maintained throughout the three-year period, (2) reduced foliar sulfur concentrations, and (3) seemed to reduce sulfur uptake. The conclusion was that lodgepole pine would respond well, regardless of nitrogen source or season of application, if other factors were favorable. However, on sites with marginal sulfur, spring fertilizer applications, particularly with ammonium nitrate, may reduce growth response by impairing sulfur uptake and nutrition.

Another study focused on differences in fertilizer behavior following applications on snow (Preston et al. 1990). ^{15}N-labeled urea and ammonium nitrate at a 200 kg N/ha rate were applied to a lodgepole pine stand in interior British Columbia. While total recovery of urea and ammonium nitrate sources was quite good, large amounts of nitrate were lost, probably due to leaching and denitrification during snowmelt. Thus urea and ammonium but not nitrate sources are recommended for application on snow.

Two other studies have looked at spring versus fall application of urea. Scanlin (1985) compared two- and six-year growth response to 224 and 448 kg N/ha at eight sites scattered throughout northern Idaho, eastern Washington, and western Montana; stands were dominated by a variety of species: grand fir, western larch (*Larix occidentalis*), lodgepole pine, western white pine (*Pinus monticola*), and ponderosa pine. Basal area and volume response differences between the times of application were not significant, although response to fall application tended to be less. A similar study examined eight-year growth response of four Douglas-fir stands in central Idaho, northeastern Oregon, and eastern Washington (IFTNC 1990). Both application times produced significant basal area and volume response, but neither time was better than the other. Weather records indicated that fertilization was quickly followed by rainfall at all four sites.

Response: How Much and How Long?

Douglas-fir

Most of our knowledge about interior Douglas-fir response to nitrogen fertilizers comes from a series of 94 nitrogen fertilizer trials established from 1980 to 1982 by the Intermountain Forest Tree Nutrition Cooperative (IFTNC). Stands comprising well-spaced, even-aged second-growth Douglas-fir were selected to cover a broad range of site and stand conditions and an area including central Washington, northeastern Washington, northeastern Oregon, northern Idaho, central Idaho, and western Montana. Fertilizer treatments were 224 and 448 kg N/ha applied in the fall as urea. To date, analysis of growth for six years following treatment has been completed (Mika and VanderPloeg 1991; Mika and Moore 1990; Moore et al. 1991).

Volume Growth Response. Six years after treatment, nitrogen fertilization has produced consistent growth response across all regions in the area (Figure 2). Six-year gross volume increments (m³/ha) for both treatments are significantly greater than the control across all geographic regions; increases over control plot growth average 11 and 14 m³/ha for the 224 and 448 kg treatments, respectively. However, only in central Washington and northern Idaho did the 448 kg treatment produce significantly greater gross volume growth than the 224 kg treatment. A similar pattern of response holds for net volume growth.

Duration of Response. The IFTNC data (Mika and VanderPloeg 1991) show that gross basal area response has declined for each successive two-year period in all regions (Table 1). The 224 kg N treatment no longer produced a significant gross basal area response during years 5 and 6 in Montana, central Idaho, and northeastern Washington. The 448 kg N treatment continued to be significantly different from the control in gross basal area increment across all regions. The decline in net basal area response to the fertilizer treatments is even more pronounced than for gross basal area. The only treatment in any region that produced a significant net basal area response for years 5 and 6 was the 448 kg nitrogen treatment in northern Idaho. Mortality is variable by treatment, region, and time period, and this variation contributes to the nonsignificant treatment effect for net basal area.

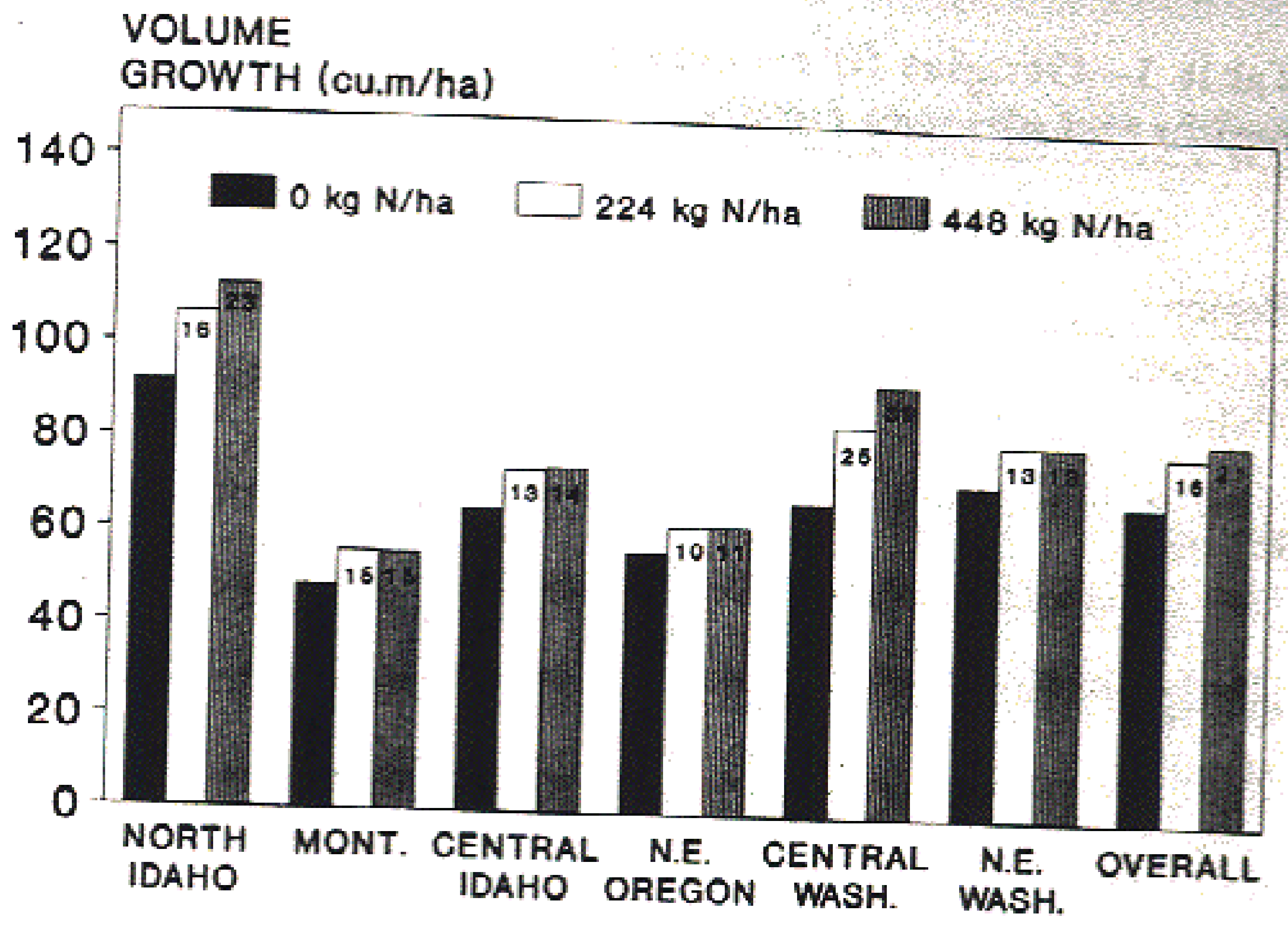

Figure 2. Average Douglas-fir gross volume growth (m³/ha) by geographic region and nitrogen fertilizer treatment for the six years following fertilization. Numbers within the bars are the average fertilizer responses for each region-treatment combination, expressed as a percentage of control growth for that region. Modified from Moore et al. (1991).

Both net and gross basal area increments for the untreated control plots were lowest in years 5 and 6 for all geographic regions except northern Idaho. For Montana, central Washington, and northeastern Washington, there have been successive declines in control plot growth for each two-year period. This decline in growth rate of the control plots is most likely associated with drier than normal years, particularly the last two, and this may explain some of the reduced response to the nitrogen treatments in years 5 and 6.

A separate study of nitrogen fertilizer effects in thinned and unthinned stands of Douglas-fir and grand fir in northern Idaho showed that thinning affected both the magnitude and duration of growth response to nitrogen fertilization (Shafii et al. 1989). Nitrogen applied to thinned stands produced both lower average absolute and relative response during the first four years following treatment as compared to fertilized

Table 1—Douglas-fir average gross and net basal area periodic annual increment for each two-year period by geographic region and nitrogen fertilizer treatment. From Moore et al. (1991).

		Periodic Basal Area Increment (m²/ha/yr)					
		Gross BAI			Net BAI		
Region	Treatment	Years 1-2	Years 3-4	Years 5-6	Years 1-2	Years 3-4	Years 5-6
Northern Idaho	Control	1.35	1.22	1.29	1.45	1.12	1.15
	224 kg N	1.77	1.49	1.35	1.72	1.22	1.17
	448 kg N	1.86	1.65	1.52	1.79	1.29	1.45
Montana	Control	0.83	0.67	0.64	0.76	0.57	0.55
	224 kg N	0.99	0.80	0.69	0.83	0.53	0.53
	448 kg N	0.99	0.78	0.69	0.96	0.37	0.53
Central Idaho	Control	1.03	1.08	0.80	1.01	1.06	0.73
	224 kg N	1.24	1.19	0.87	1.19	1.22	0.69
	448 kg N	1.29	1.19	0.87	1.26	1.08	0.69
Northeastern Oregon	Control	0.85	0.85	0.62	0.78	0.69	0.39
	224 kg N	0.99	0.94	0.69	0.90	0.64	0.18
	448 kg N	1.08	0.96	0.71	0.92	0.69	0.34
Central Washington	Control	1.01	0.96	0.83	0.99	0.96	0.71
	224 kg N	1.35	1.22	0.96	1.31	1.33	0.83
	448 kg N	1.52	1.35	1.06	1.47	1.33	0.83
Northeastern Washington	Control	1.15	1.06	0.85	1.10	0.78	0.64
	224 kg N	1.35	1.19	0.92	1.31	0.94	0.67
	448 kg N	1.40	1.19	0.94	1.35	0.53	0.48
Overall	Control	1.06	0.99	0.87	1.03	0.87	0.73
	224 kg N	1.33	1.17	0.94	1.26	0.99	0.78
	448 kg N	1.40	1.22	1.01	1.33	0.92	0.78

unthinned plots. However, duration of basal area response was short-lived (four years) in unthinned stands, perhaps due to high density, which may have discouraged increases in crown biomass, photosynthetic surface area, and photosynthetic efficiency after treatment. Response in thinned stands remained significant after six years.

Fertilization accelerates the rate of stand development and therefore continues to influence stand dynamics and subsequent development beyond any period of direct effects on tree growth. Nitrogen fertilization in unthinned Douglas-fir and grand fir stands reduced average density by about 260 trees per ha over the 14-year posttreatment period (Table 2). Similar increases in mortality associated with nitrogen fertilization were found in thinned stands. Mortality was concentrated in the smaller size classes, producing an increase in the average tree size relative to the untreated stands.

Table 2—Fourteen-year response of mixed Douglas-fir and grand fir stands in northern Idaho to thinning and nitrogen fertilization. From Shafii et al. (1989).

Treatment	Net Volume (m³/ha)	Trees/ha	Volume/tree (m³)
Control	165	2,357	0.07
Fertilized	166	2,093	0.08
Thinned	171	665	0.26
Thinned, fertilized	173	603	0.29

By the end of the 14-year posttreatment period, all treatments produced approximately the same average total stand volume. Average cubic volume per tree, however, shows an interesting progression: no treatment, 0.07; fertilized only, 0.08; thinned only, 0.26; and thinned and fertilized, 0.29. Thinning increased average tree size without significant reduction in average total cubic volume per hectare. Fertilization produced larger trees in both thinned and unthinned stands. This results from two factors: larger trees in a stand showed more absolute response than smaller trees, and higher mortality rates were observed for smaller size classes in fertilized stands.

Tree Mortality Rates. Nitrogen fertilization changed tree mortality rates, with higher rates associated with heavier nitrogen application (Figure 3). Most of the mortality occurred during the second and third two-year periods; for most regions, the middle period (i.e., years 3 and 4) had the highest mortality rate. The mortality rates were higher for the 448 kg treatment than for the 224 kg, particularly in northeastern Washington. Northeastern Oregon has incurred substantial treatment-related mortality for both nitrogen levels.

The most common causes of mortality differed by region. In northern Idaho and northeastern Washington, the most common causes were windthrow and snow breakage. Although control plots sustained sig-

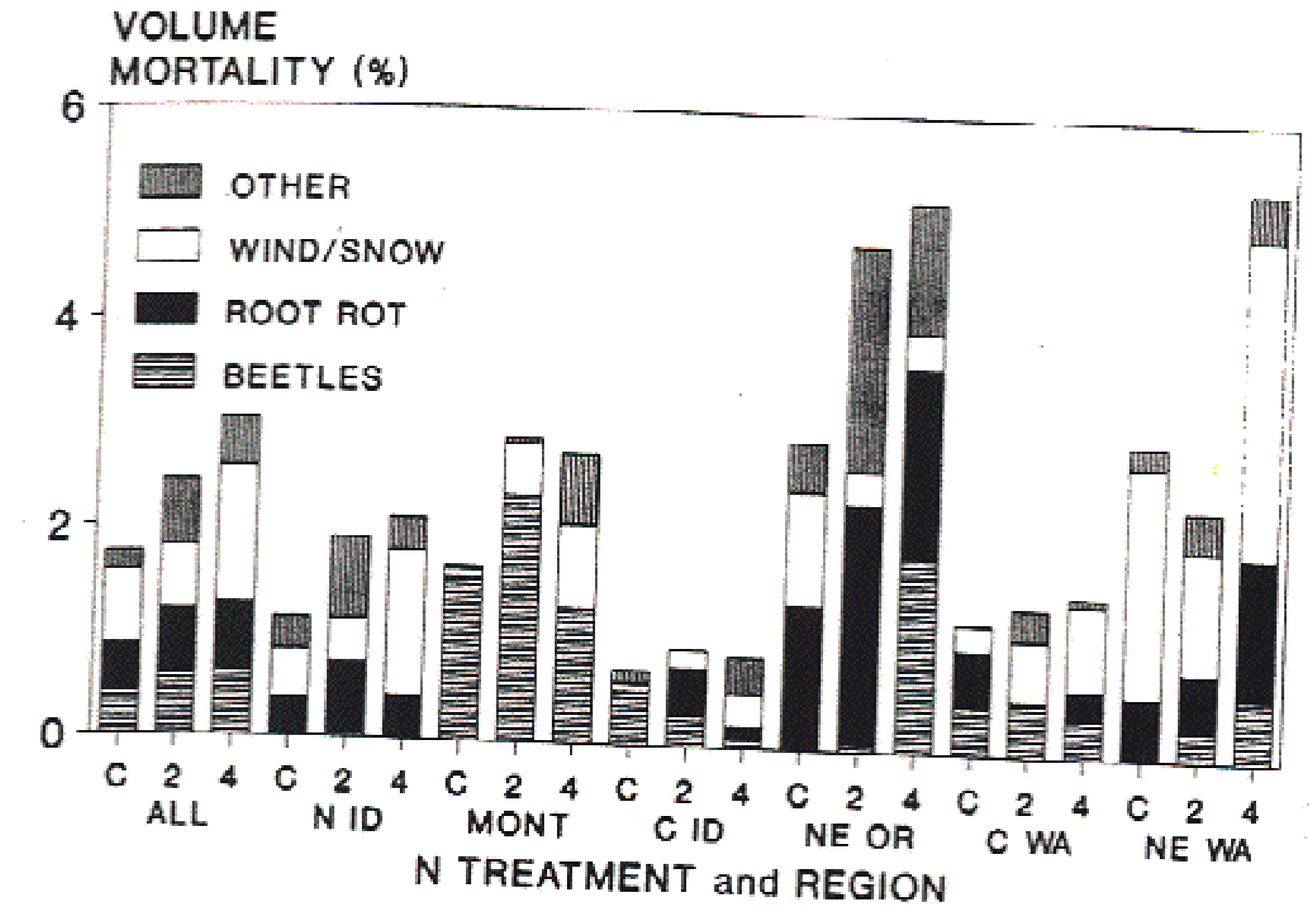

Figure 3. Average Douglas-fir mortality rates (% of total volume) by geographic region, nitrogen fertilizer treatment, and cause of mortality for the six years following fertilization. Fertilizer treatments are 0 (C), 224 (2), and 448 (4) kg N/ha. Modified from Mika and VanderPloeg (1991).

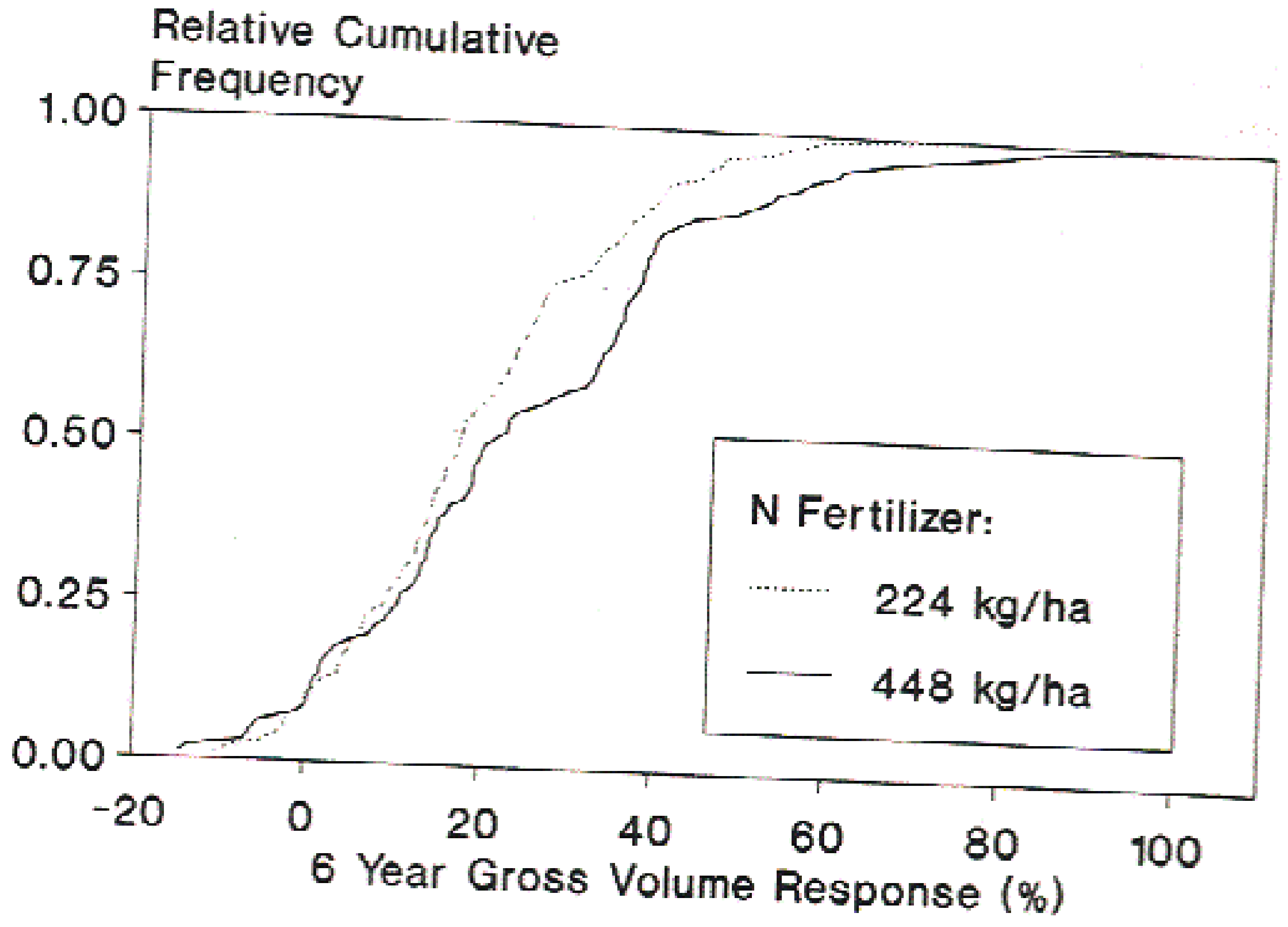

Figure 4. The relative cumulative frequency distribution for Douglas-fir gross volume response (% increase over control growth) for the six years following nitrogen fertilization. Values on the vertical axis represent the proportion of stands responding less than or equal to a response value on the horizontal axis. The different lines indicate the response distribution for different nitrogen fertilizer rates. From Moore et al. (1991).

nificant wind and snow damage, the amount of such mortality on the fertilized plots was substantially higher for the 448 kg treatment. Mortality caused by wind and snow was localized at several installations in both of these regions. Mortality caused by root rot was higher for both nitrogen treatments in northeastern Oregon and for the 448 kg N treatment in northeastern Washington. In Montana and northeastern Oregon, there were mortality factors apparently unrelated to treatment, such as mountain pine beetle in ponderosa pine and spruce budworm. These (and other) external factors that cause mortality are the subject of ongoing research efforts.

Variation in Response. Average responses by region and treatment are useful for making general comparisons and conclusions, but since stands were intentionally selected from a broad range of conditions, it would be unlikely that all installations would respond to nitrogen fertilization. The cumulative distribution of relative gross six-year volume growth response (expressed as a percentage of control plot growth) to the nitrogen treatments (Figure 4) shows that response was quite variable (Moore et al. 1991). In every region some stands responded well to nitrogen fertilization while others showed negligible or even negative response.

Understanding why sites and stands do or do not respond is important to devising an effective operational fertilization or nutrient management program; thus one of the primary objectives in many fertilizer trials has been to explain this variation in response to nitrogen fertilization so that operational treatments can be targeted at those stands with a high probability of "substantial" response. If we could eliminate the poorest responding half from our population of stands to be fertilized, the 75th percentile of the current response distribution would then be our best estimate of the expected response to nitrogen treatments. The 75th percentile responses were 25% and 32% for the 224 and 448 kg N/ha treatments, respectively (Moore et al. 1991).

One site factor often related to fertilizer response is site productivity, as measured by site index or per unit area growth rate. In coastal areas, Douglas-fir response increases as site index decreases (Heath and Chappell 1989). The highly productive sites in these areas are likely to have sufficient nutrients already; thus addition of nutrients should produce little additional growth. However, productivity in interior forests is generally thought to be controlled primarily by moisture availability; thus correlations of fertilizer response to productivity measures may be low for these forest types unless moisture availability is improved through weeding or thinning. Powers et al. (1988) found that on the average, volume growth response to nitrogen fertilization was twice as great in ponderosa pine plantations freed of weed competition than where weeds were not removed. On shallow soils, shrub competition can preclude nitrogen uptake following fertilization, but the effect is not as strong on deeper soils (Powers and

Table 3—Growth response in adjacent, 14-year-old ponderosa pine plantations to nitrogen fertilization with and without shrub control. The "poor" site is a ruptic-lithic-xerochreptic Haploxerult derived from schist (site index 11 m at 50 years). The "better" site is an ultic Haploxeralf formed from basalt (site index 23 m at 50 years). Modified from Powers and Jackson (1978) and Powers (1983).

Treatment	First-year Fascicle Growth (mg)		First-year Height Growth (cm)		Five-year Height Growth (cm)		Five-year Volume Growth (m^3/ha)	
	Poor	Better	Poor	Better	Poor	Better	Poor	Better
Control	140a[1]	262a	12a	41a	60a	144a	0.4a	5.1a
224 kg N/ha	168a	250a	16a	51a	66a	208a	0.5a	8.0ab
Shrub removal	251b	362b	16a	46a	123b	242b	1.4a	10.8bc
Shrub removal + 224 kg N/ha	321c	356b	30b	52a	205c	321c	3.6b	15.7c

[1] Means in a column not sharing common letters differ at p=0.05 by Fisher's protected LSD.

Jackson 1978; Powers 1983). Table 3 indicates that fertilization and competition control effects may be synergistic on poorer sites and additive on better.

A study looking at five-year growth response to nitrogen fertilization across a mixture of interior forest types (ponderosa pine, Douglas-fir, mixed conifer, and true fir) in California found no simple relationship between response and site productivity (Miles and Powers 1988). Since moisture was thought to be the prime limiting factor for those sites, the authors looked at the interaction between total available soil water capacity and site index and were able to then explain much of the variation in response. Sites with low available water capacity showed poor fertilizer response (mean = -4.3%); because moisture was limiting growth, addition of more nutrients had no effect. Sites with adequate water capacity and good site index also failed to respond to fertilization (mean = 8.5%). Such sites are so productive because they have adequate levels of both moisture and nutrients; additional nitrogen would have limited beneficial growth effects. However, sites with adequate moisture capacity but low site index values showed excellent growth response (mean = 48.1%); here, moisture was sufficient to allow utilization of the added nitrogen. Results for interior Douglas-fir generally support these findings of low simple correlation between response and site index (Moore et al. 1991).

Lack of sufficient potassium (K) has been implicated as one reason some stands have failed to respond to nitrogen fertilization (Mika and Moore 1990). Analysis of Douglas-fir foliage indicated that several stands had potassium concentrations and K:N ratios below adequate levels and that potassium concentrations declined slightly and K:N ratios decreased greatly following nitrogen fertilization. Comparison of stands with good pretreatment conditions (K concentration >0.6% and K:N ratios >0.65) to those with poor potassium levels (K concentration <0.6% and K:N ratios 0.50) indicated that growth response was significantly lower for those stands with poor initial potassium levels (Table 4). Gross basal area response to 224 kg N/ha was less in all periods for poor potassium status stands. In addition, while treatment with 448 kg N produced greater gross and net response in stands with good potassium levels, the higher application rate decreased response in stands with poor potassium status. The higher nitrogen rate also increased mortality in the potassium-poor stands, producing negative net growth in the second period. A series of trials with N+K treatments has been established by the IFTNC to test if potassium additions can improve response to nitrogen fertilizer.

Some evidence exists that sulfur (S) may also be limiting Douglas-fir response to nitrogen fertilization

Table 4—Douglas-fir periodic basal area response to fertilization (difference from control) by nitrogen application rate, foliar potassium status, and time period. Modified from Mika and Moore (1990).

N Rate	K Status[1]	Period		
		Years 1-2	Years 3-4	Years 5-6
		Gross Basal Area Increment (m^2/ha/yr)		
224 kg/ha	Poor	0.18	0.12	0.03
	Good	0.32	0.20	0.09
	Other	0.29	0.20	0.08
448 kg/ha	Poor	0.15	0.07	-0.01
	Good	0.38	0.29	0.19
	Other	0.37	0.27	0.15
		Net Basal Area Increment (m^2/ha/yr)		
224 kg/ha	Poor	0.18	0.15	-0.12
	Good	0.33	0.15	-0.07
	Other	0.25	0.15	0.03
448 kg/ha	Poor	0.12	-0.10	-0.12
	Good	0.39	0.24	0.07
	Other	0.35	0.08	0.04

[1] K status was defined as follows:

Poor = K concentration <0.6% and K:N ratio <0.50.
Good = K concentration >0.6% and K:N ratio >0.65.
Other = any other combination.

(Brockley and Swift 1990). Screening trials testing factorial combinations of nitrogen and a "complete mix" (i.e., phosphorus, potassium, calcium, magnesium, sulfur, and micronutrients) fertilizers in five interior Douglas-fir stands in British Columbia found that combined applications of nitrogen and the "complete mix" were more effective in increasing needle weight than single applications of either fertilizer. Foliage of trees receiving only nitrogen had elevated N:S ratios above suggested critical values, while foliar sulfate-S was almost completely exhausted. Such trees may be unable to use any added nitrogen effectively.

Ponderosa Pine

Results from early fertilizer trials in ponderosa pine were summarized at the Forest Fertilization Conference in 1979 (Cochran et al. 1981). The results, mostly coming from small-scale trials, indicated that volume growth responses up to 75% could be obtained, but that stands on some soils failed to respond. When obtained, response would last from four to ten years or more. Response was most likely in thinned, pole-sized stands with low foliar N concentrations. On soils strongly influenced by pumice and volcanic ash, stands responded to sulfur and perhaps phosphorus in addition to nitrogen. Applications of 224 kg N/ha and 34 kg S/ha were recommended for such sites.

Five-year growth data from 43 fertilizer trials on ponderosa pine in south-central Oregon and northern California were combined and analyzed for factors capable of predicting response to nitrogen fertilization (Powers et al. 1988). Response increased fairly linearly with nitrogen application rate (0, 244, and 448 kg N/ha). Comparison to plots receiving a "full" fertilizer indicated that most of the response was due to nitrogen alone, but addition of other nutrients did improve growth response by about one-third. Most stands responded well, with two-thirds showing volume gains of at least 20% over controls. Overall volume growth response (Table 5) averaged 30% for plots receiving 224 kg N/ha.

Response varied considerably with soil type, site index, and stand treatments. Stands on granitic soils responded the least; these were also the most productive (highest site index) sites. Response was much greater in stands on metasedimentary soils. Regression analysis showed that response increased as site index decreased and as foliar N concentration and C:N ratio in the A horizon increased. Foliar N concentration alone could explain 63% of the total variation in response. Trees with current-year foliar N concentrations at or below 1.1% were felt to be experiencing nitrogen deficiency. Management activities in plantations were related to the amount of response obtained. Those plantations freed from brush and grass competition at the time of fertilization averaged almost twice the response of the unweeded plantations, although response was highly variable. In a paired comparison on six sites, weeding plus fertilization produced nine times the response of fertilization alone. Furthermore, response was over three times greater in plantations where topsoil had been scalped into windrows during site preparation than on unscalped sites. Unfortunately, these differences were confounded with site index and soil differences; while half of the unscalped plantations were on granitic soils, nearly all of the scalped plantations were on volcanic or metasedimentary soils.

Table 5—Variation in five-year relative volume growth response of ponderosa pine stands fertilized with 224 kg N/ha as it relates to site and stand attributes. Modified from Powers et al. (1988).

Attribute	Number of Stands	Site Index	Relative Growth Response (%)	
			Mean	Std. Error
All stands	43	67	29.5	5.6
Plantations	25	70	27.7	8.7
Thinned natural stands	18	62	32.0	5.6
Granitic soils	5	85	4.6	5.4
Volcanic soils	29	62	23.7	4.4
Metasedimentary soils	9	65	61.7	19.4
Weeded plantations	6	59	43.5	24.5
Unweeded plantations	19	73	22.7	8.8
Scalped plantations	19	66	33.5	11.3
Unscalped plantations	6	88	9.0	4.0

Significant four-year response to nitrogen fertilization was obtained on five sites in central Washington and five sites in northeastern Oregon (IFTNC 1990); however, the level of response was much less than that found in previous studies. Gross volume response was 10.5% on plots treated with 224 kg N/ha and 11.4% on those treated with 448 kg N; the difference between treatments was not significant. More mortality occurred on the nitrogen-treated plots, particularly on the 448 kg plots in central Washington; consequently, net volume response was nonsignificant.

Lodgepole Pine

A combination of fertilizer screening trials and conventional, permanent sample plot installations has been used to document the fertilization response potential of lodgepole pine in the interior West. Much of this work has been summarized by Cochran et al. (1981), Weetman et al. (1985), Weetman (1988), and Brockley (1991*a*).

Fertilizer screening trials using various replicated "individual-tree" or "mini" research plot designs have been used to rapidly identify nutrient deficiencies and to provide a "quick index" of long-term growth response potential (Weetman and Fournier 1982; Brockley 1989*b*; Brockley 1990). Preliminary growth response information, based on increases in fascicle weight and shifts in foliar concentration of added and nonadded nutrients can be obtained within one year of treatment. In a large screening trial project, nitrogen, phosphorus, and potassium in various combinations were applied to 17 lodgepole pine stands in the interior of British Columbia. First-year results indicated considerable variation in the responsiveness of lodgepole pine to fertilization (Weetman and Fournier 1982). Eight of the stands were moderately or very responsive to nitrogen additions; the remaining nine showed a weak response or none. Most trials were unresponsive to phosphorus or potassium additions. Subsequent remeasurement of 15 stands determined that the pattern of four-year basal area increment generally corresponded with first-season needle weight response (Weetman et al. 1988). Nitrogen applied at rates of 50, 100, and 150 kg/ha increased four-year basal area growth of individual trees by an average of 27, 41, and 48% over the control, respectively.

The largest lodgepole pine fertilizer experiment with conventional, permanent sample plots consists of 11 installations established by the B.C. Ministry of Forests from 1981 to 1983 in the southern and central interior of British Columbia. Composed of pure, fire-origin lodgepole pine, the stands were either thinned at the time of fertilization or had been thinned at least two years previously. With one exception, both installation types were established adjacent to each other at each study location so that the effects of fertilization timing in relation to thinning could be evaluated. Nitrogen was applied at rates of 0, 100, and 200 kg/ha as urea. To date, three- and six-year growth responses have been reported (Brockley 1989*a*, 1991*b*).

Six years after treatment, nitrogen fertilization has had a substantial positive effect on individual-tree and stand volume increment. Total six-year net volume increases over control plot growth averaged 6 (range 1 to 14) m^3/ha and 8 (range -1 to 15) m^3/ha for N application rates of 100 and 200 kg/ha, respectively. In relative terms, these responses averaged 23% (range 2 to 45%) and 30% (range -5 to 51%). The effect of nitrogen application rate on six-year net volume increment was not statistically significant.

However, the favorable effects of fertilization were partially negated in some installations by treatment-related damage and mortality. Snowpress (irreversible bending and breakage) was increased by nitrogen fertilization, presumably because of increased crown size and weight. Incidence of red squirrel feeding damage was also significantly increased by fertilization. In some installations, losses caused by snowpress and full or partial stem girdling by squirrels in fertilized plots all but wiped out per hectare volume gains.

Installations thinned at the time of fertilization were generally most responsive to fertilization in both relative and absolute terms, despite the larger-sized trees in previously thinned installations. When thinning and fertilization are undertaken simultaneously, the added nutrients may be combined effectively with improved light conditions and room for crown expansion to accelerate the recovery from thinning. Unfortunately, the advantages of fertilizing lodgepole pine at the time of thinning may be partially negated by increased susceptibility to red squirrel feeding injuries and snowpress damage. Results indicate that snowpress can be avoided by delaying fertilization for a couple of years following thinning.

Analyses indicate that improved nutrition is directly responsible for the majority of the increased growth in these research trials. However, "indirect" effects resulting from progressively greater tree size and stand volume in fertilized plots will undoubtedly account for a steadily increasing proportion of total growth response in subsequent years. In a lodgepole pine fertilization trial in south-central Oregon (Cochran 1989), heavy application rates of nitrogen (673 kg/ha), phosphorus (336 kg/ha), and sulfur (101 kg/ha) produced large responses in volume and basal area increment for the first eight years and continued though decreased response in years 9 through 13 (Table 6). However, after removing the effect of stocking increases in the previous period (the "indirect" effect) by expressing growth as a percentage of the stocking at the beginning of each period, Cochran showed that "direct" fertilizer effects declined in the second period (years 5 through 8) and were gone by the third period.

Lodgepole pine fertilization response is quite variable: some stands respond extremely well and others respond poorly. Reliable predictors of response are needed so that forest managers can (1) identify which stands have the greatest growth response potential, and (2) isolate site and stand variables that are largely responsible for fertilization growth response or lack of it.

Table 6—Lodgepole pine volume and basal area periodic annual growth for three periods following nitrogen, phosphorus, and sulfur fertilization. From Cochran (1989).

Years	Volume Growth Fertilized	Volume Growth Control	Basal Area Growth Fertilized	Basal Area Growth Control
	—m³/ha/yr—		—m²/ha/yr—	
1-4	4.08	2.40	0.62	0.34
5-8	5.65	3.60	0.74	0.46
9-13	4.57	4.23	0.55	0.48
	—Percent[1]—		—Percent[1]—	
1-4	11.6	5.5	9.9	4.7
5-8	10.9	7.1	8.3	5.3
9-13	6.2	6.3	4.7	4.4

[1]Expressed as a percentage of the stocking at the beginning of that period.

Various measures of foliar N nutrition and soil mineralizable N have been poor predictors of lodgepole pine fertilization response potential (Brockley 1989*a*, 1991*b*), despite the fact that nitrogen is undoubtedly the element that most limits tree growth in the interior West. However, the good predictive capability of various measures of foliar sulfur nutrition (Brockley 1991*b*) indicates that sulfur may have a strong controlling influence on lodgepole pine growth response following nitrogen fertilization. Foliar analysis data indicate that the sulfur status of many stands is marginal before fertilization, and that nitrogen additions result in further deterioration of sulfur nutrition. Foliar N:S ratios often increase dramatically and sulfate-S reserves are often depleted to extremely low levels—an indication that the added nitrogen may not be fully utilized in protein synthesis. Of course, sulfur deficiencies cannot be documented unless stands that are supposedly sulfur deficient can be shown to respond to sulfur fertilization. Yang (1985) reported that a combined application of nitrogen and sulfur was significantly better than nitrogen alone in improving the growth of 30-year-old lodgepole pine in Alberta. In a large lodgepole pine permanent sample plot trial near Prince George, British Columbia, trees within plots receiving urea sulfur (41-0-0-12) responded significantly better than those in plots receiving urea alone (Figure 5). High N:S ratios and low sulfate-S levels were measured in the foliage of trees receiving only nitrogen (Figure 6). The uptake of sulfur from the applied urea sulfur was apparently adequate to maintain favorable sulfur nutrition. In another trial, nitrogen was generally ineffective in increasing the weight of lodgepole pine fascicles produced in the first year after fertilization. However, combined nitrogen and sulfur applications, especially when applied in the form of sulfate, often resulted in relatively large response (Brockley, poster abstract, this volume).

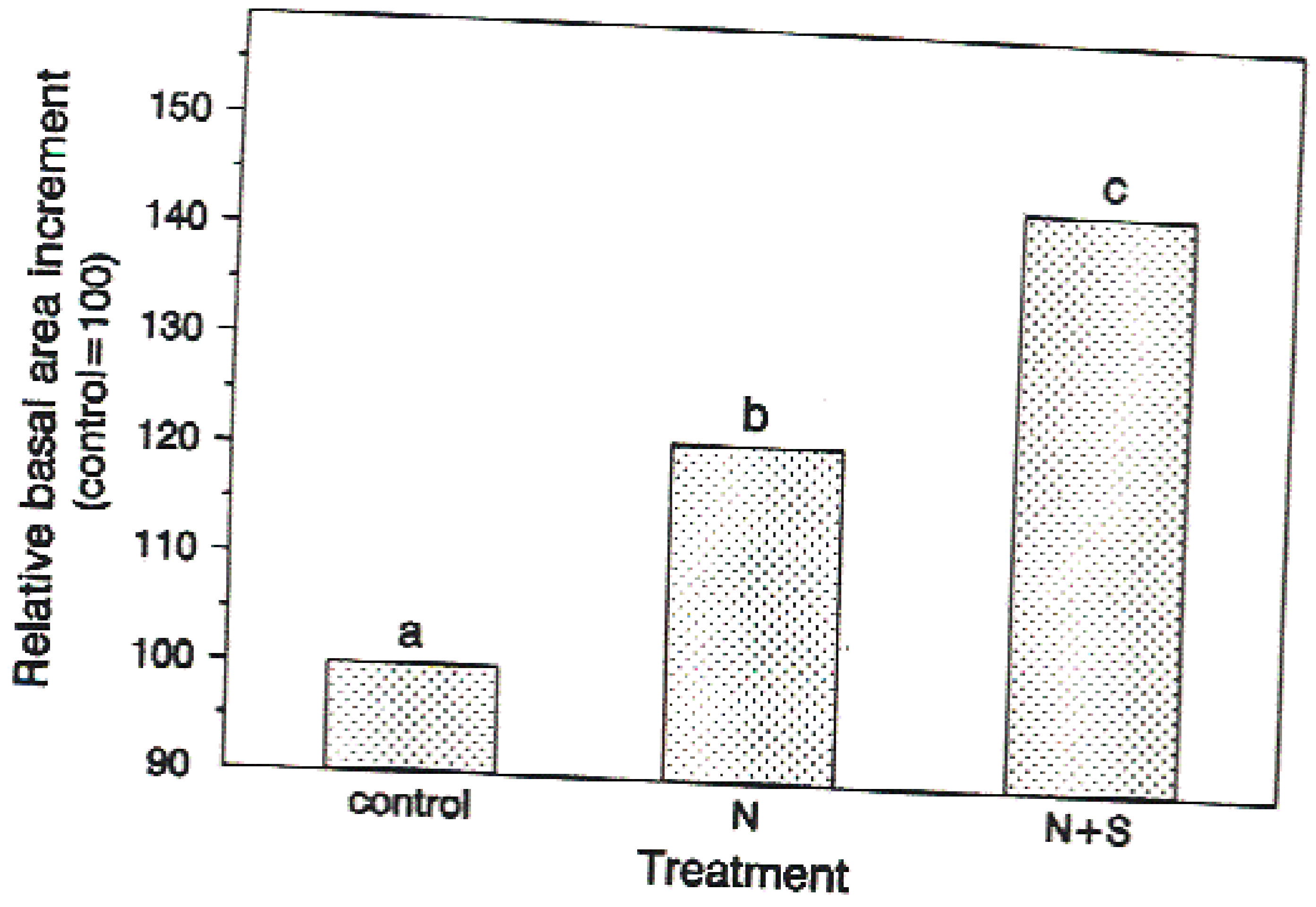

Figure 5. The effect of nitrogen and nitrogen plus sulfur fertilization on three-year individual-tree relative basal area increment of lodgepole pine near Prince George, British Columbia. Bars topped by different letters are significantly different (p<0.05). From Brockley (1991*b*).

Although apparently not as widespread as nitrogen-induced sulfur deficiencies, inadequate boron nutrition may also have an adverse effect on lodgepole pine health and vigor in the interior of British Columbia. In localized areas, boron deficiency symptoms have occurred following nitrogen fertilization (Brockley 1989*a*). Morphologically, the most prominent symptoms are top dieback and multileadered, bushy crowns. On a site near Burns Lake, British Columbia, combined nitrogen and boron application significantly improved branch

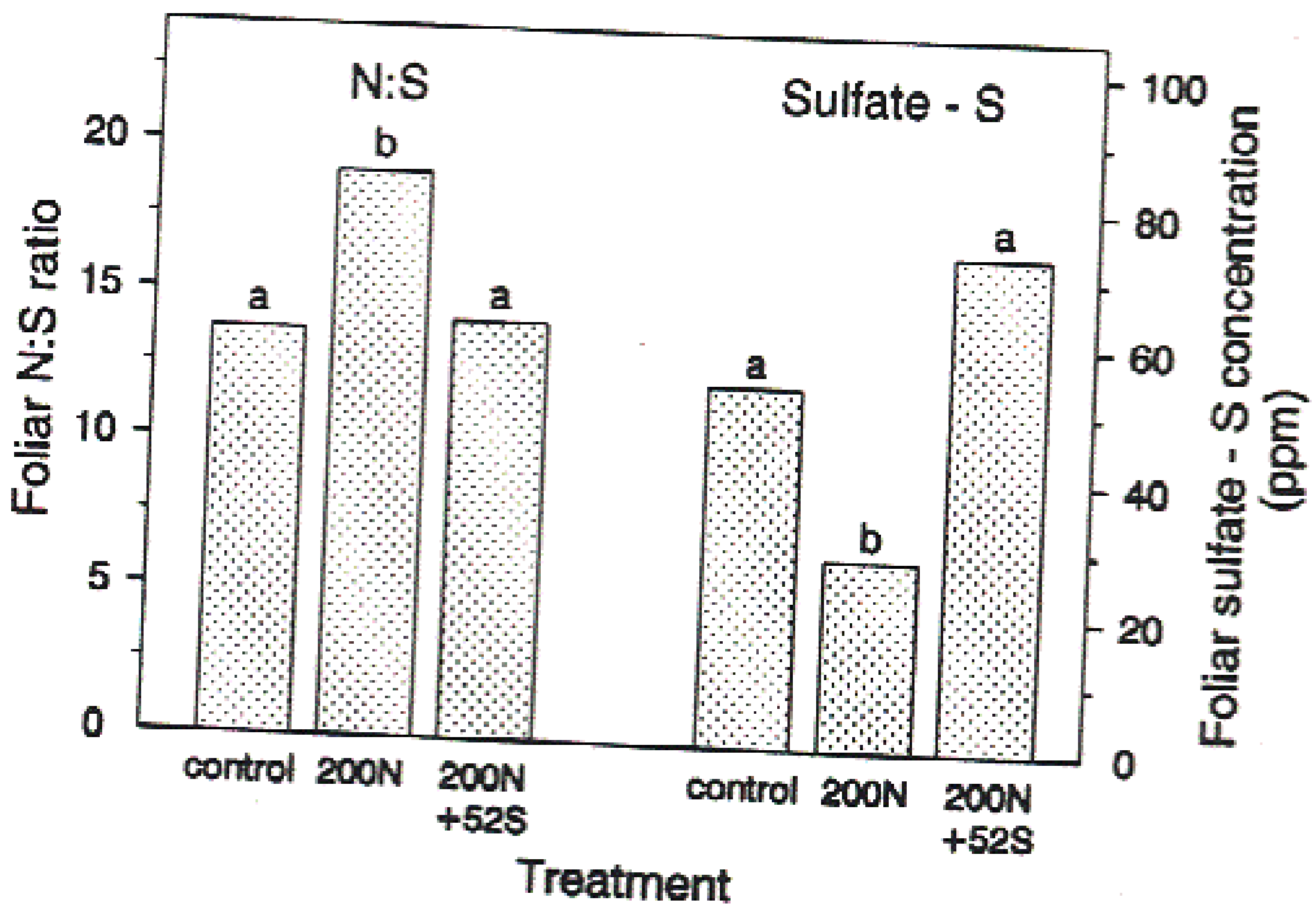

Figure 6. The effect of nitrogen and nitrogen plus sulfur fertilization on first-year foliar N:S ratio and foliar sulfate-S concentration of lodgepole pine near Prince George, British Columbia. Bars topped by different letters are significantly different (p<0.05). From Brockley (1991*b*).

elongation and three-year mean stem volume response over those obtained with nitrogen alone (Brockley 1990; Carter and Brockley 1990). Relatively small boron additions (i.e., 1.5 and 3.0 kg/ha) elevated foliar boron concentrations substantially and have maintained them for six years.

Localized deficiencies of other nutrients may also exist in lodgepole pine stands in the interior West. For example, foliar spray applications of copper sulfate to lodgepole pine alleviated copper deficiencies and produced significant increases in foliage biomass and shoot growth in the second year following treatment (Majid and Ballard 1990).

Other Species of Interior Forests

In the Intermountain region, fertilizer research on other species has been sporadic and limited in geographic coverage. Most species have been found capable of responding to nitrogen fertilization, but response is quite variable. For example, western white pine in northern Idaho responded substantially in two studies (Loewenstein and Pitkin 1963; Ryker and Pfister 1967), but failed to respond in a third study (Graham and Tonn 1985).

Analysis of growth data from eight western larch stands (three in northeastern Washington and five in northern Idaho) showed significant six-year gross basal area (28.3%), gross volume (24.7%), and height (11.1%) response to 224 kg N/ha as urea (IFTNC 1988). No significant additional response was obtained with a 448 kg/ha application rate. Separate analysis of the three northeastern Washington stands showed that significant basal area response (21.6%) was still taking place eight years after treatment.

A number of studies in northern Idaho have shown that grand fir can respond well to nitrogen fertilizer. Fertilization with 168 kg N/ha at one site produced a tremendous gain (91%) in height growth two years after treatment (Loewenstein and Pitkin 1963). Treatment with 224 kg N/ha produced a 30% diameter growth response after five years at another site (Graham and Tonn 1985), but 448 kg N/ha had no further effect. Response during a second five-year period was not significant. A larger study of 36 grand fir and Douglas-fir stands found a 24% basal area response and 23% volume response in four years following fertilization with 224 kg N/ha (Scanlin and Loewenstein 1981). Grand fir basal area response was similar to Douglas-fir response, but grand fir height growth was stimulated much more. A later study using this data, combined with other information, found no difference between grand fir and Douglas-fir response to fertilization (Shafii et al. 1990).

Powers (this volume) concludes that many high elevation fir stands are nitrogen limited. Studying true fir response at 15 sites in northern California, he found that 224 kg N/ha increased five-year volume growth by an average of 35%. Stands of saplings and poles responded better that young sawtimber, and increased their growth rate by as much as 6.5 m^3/ha per year comparable to rates reported for similar size classes of coastal Douglas-fir (Miller et al. 1986). Absolute volume growth in true fir sometimes declined following thinning, but growth could be recaptured when thinning was combined with fertilization. Regardless of stocking control, growth generally declined at higher fertilization rates. Indications from California are that many true fir stands also have phosphorus deficiencies that block their response to fertilization with nitrogen. Fertilizing some stands with both nitrogen and phosphorus improved growth more than with nitrogen alone, and responses lasted for at least ten years. Heninger (1982) found that nitrogen alone increased five-year PAI of pole-sized white fir (*Abies concolor*) on drier Cascade sites by as much as 2 m^3/ha per year, and that nitrogen combined with phosphorus, sulfur, and potassium increased growth by 2.1 to 4.2 m^3/ha per year.

Analysis of first-year needle weight and foliar nutrient concentration data from 12 white spruce (*Picea glauca*) fertilizer screening trials in the interior of British Columbia indicated that growth response may be poor unless other nutrients are added in conjunction with nitrogen (Brockley and Swift 1990). When applied singly, nitrogen and a "complete mix" (i.e., phosphorus, potassium, calcium, magnasium, sulfur, and micronutrients) fertilizer had little effect on the weight of spruce needles produced during the first year after treatment. Combined applications, however, resulted in relatively large increases in needle weight. The extremely high foliar N:S ratios and low sulfate-S reserves measured following fertilization with nitrogen alone indicate that fertilized trees may have been unable to use the added nitrogen effectively. Foliar nutrient concentration data also showed some indication of nitrogen-induced potassium deficiency. Subsequent measurements of these trials will indicate whether these early results also apply to stemwood response.

Fertilization and Pest Problems

Nitrogen fertilization may provide a useful silvicultural tool in managing stands infested by western spruce budworm (*Choristoneura occidentalis*). A field study at King Mountain in the Malheur National Forest, Oregon, showed that fertilization of grand fir with 350 kg N/ha significantly increased the total biomass and individual weight of budworm larvae and pupae for at least four years after treatment (Wickman et al., poster abstract, this volume). Despite these increases in defoliator biomass, the net effect was decreased defoliation on the fertilized trees; apparently these trees produced more new foliage than the increased budworm population could consume. Fertilized trees also showed significantly greater height and radial growth. This suggests that nitrogen fertilization might offset the damage caused by budworm defoliation until the insect outbreak collapses.

Similar sorts of fertilizer effects have been hypothesized for other coniferous pests. Faster growth resulting from fertilization would allow trees to overcome infections by and losses from white pine blister rust, needle casts, and atropellis canker (Navratil and Bella 1988). By increasing tree vigor, fertilizers applied in conjunction with thinning would likely reduce the susceptibility of pine stands to mountain pine beetle (*Dendroctonus ponderosae*) attack (Cole and McGregor 1988).

Other pest problems might be increased by nitrogen fertilization. Increased shoot growth could contribute to higher infection rates of western gall rust by increasing the area of tender shoot tissues susceptible to infection (Navratil and Bella 1988). Nitrogen fertilizer applications leading to nutrient imbalances might increase lodgepole pine susceptibility to western pine shoot borer (*Eucosma sonomana*) infestations (Bella and Stoszek 1988).

Nitrogen fertilization of lodgepole pine has been shown to increase the amount of injury to bark caused by small mammals, presumably due to improved palatability and nutritive quality of the tree tissue following fertilization (Brockley and Sullivan 1988). A study in north-central British Columbia involving untreated, thinned, and fertilized and thinned juvenile lodgepole pine showed that snowshoe hare (*Lepus americanus*) removed nearly three times the area of bark and vascular tissue from the fertilized trees as they did from either controls or thinned-only trees. Ten percent of the fertilized trees were girdled compared with 6.4% of the thinned-only and 3.9% of the control trees (Sullivan and Sullivan 1982). However, damage was less severe in larger (>60 mm dbh) trees, so fertilization of bigger trees may not lead to problems (Sullivan 1985).

Bark damage by red squirrel (*Tamiasciurus hudsonicus*) is considered a greater potential problem, because they attack larger diameter trees, keeping stands at risk for longer intervals (Brockley and Sullivan 1988). In the study mentioned above, squirrels damaged 38.9% and girdled 6.9% of the fertilized trees. None of the unfertilized trees were girdled by squirrels, although they did damage 30.9% of the thinned-only and 14.3% of the control trees (Sullivan and Sullivan 1982). Other studies in thinned lodgepole stands produced similar results. Frequency of attack and damage intensity were higher in fertilized plots and tended to increase as the fertilizer application rate increased from 100 kg/ha to 200 kg/ha of nitrogen. In stands where the risk of squirrel damage is high, the potential impact may warrant delaying fertilization until trees reach a size where the risk of significant damage is reduced (Brockley and Sullivan 1988).

Practical Implications from Fertilization Research

1. Nitrogen is the only nutrient generally limiting growth in interior forest types. Significant growth response can be expected from application of 200 kg N/ha if other factors (moisture, other nutrients) are favorable for increased growth. Fertilization is best confined to sites likely to respond: sites with low foliar N levels or low soil mineralizable N, sites with low productivity in climatic zones that are highly productive.
2. Urea fertilization has generally produced good results. No differences have been demonstrated between early spring and late fall applications. Ammonium nitrate has not been found to yield greater response and may induce sulfur nutrition problems.
3. Other nutrients have been shown to occasionally limit growth or response to nitrogen fertilization: these would include sulfur in ponderosa and lodgepole pine, boron in lodgepole pine, potassium in Douglas-fir, and phosphorus in true firs.
4. For trees to respond well to nitrogen fertilization, they need to be able to build more crown. Thus younger stands or well-spaced stands respond better, at least until crown closure occurs.
5. Nitrogen fertilization tends to accelerate mortality processes. Over a short span (less than five years), death of a few trees can wipe out any average growth gains if mortality cannot be captured. Higher rates of

snow breakage and windthrow can be expected. Pest-related damage and nutrient imbalances may produce increased mortality. Over a longer period (15 years), nitrogen fertilization tends to produce larger individual trees than in untreated stands but similar total net volumes.

Where Do We Go From Here?

Obviously, gaping holes still exist in our knowledge of fertilization response in interior forest types. Fertilization research continues to actively fill these holes. Current research interests cover a range of levels of resolution: from broad-scale conventional trials for testing hypotheses about regional fertilizer response to small experiments looking at local problems, and from tests exploring the economic feasibility of combined pruning and fertilization treatment to experiments aimed at increasing fundamental knowledge by pushing conditions to extremes. Goals for research already under way or planned for the immediate future include:

1. Expanding conventional trials to estimate response for other species and test the influence of other inferred nutrient deficiencies.
2. Collecting more detailed process-oriented measurements of fertilization experiments so that we can better understand why response may not occur and develop more reliable response prediction tools.
3. Achieving a more fundamental understanding of how tree nutrition influences tree growth processes through optimal nutrition studies and complete removal of limiting factors (i.e., competition from other vegetation, impacts of insects and diseases).
4. Understanding fertilization effects on tree vigor, susceptibility and resistance to pathogens and parasites, and mortality.

An example of a new study combining many of these goals is the Garden of Eden plantation study (Koerber and Powers 1986). Applied aims of the study are to determine the biological potential for ponderosa pine growth when soil fertility, plant competition, and insect pest factors are completely controlled from the time of planting. More fundamental aims are to examine how combinations of these factors affect water and carbon use, pest resistance, pesticide decay, plant succession, organic matter decomposition and metal chelation, nitrogen mineralization, mycorrhizal development, and behavior of soil invertebrates. Research on all of these topics is in progress on a variety of sites.

The Garden of Eden study involves a standard experimental design that combines "all or nothing" levels of nutrient, competition, and insect control. This design has been applied to eight field sites on forest industry lands spanning the full range of site quality in northern California. Twenty-four 0.04 ha plots have been planted with superior performing pine families at each field site, producing three replicates of the eight factorial combinations of treatments. Nutrient treatment consists of "ramp" applications (rates that increase over time) of macronutrients and micronutrients at two-year intervals to half of the plots (Table 7). Ramp treatments are meant to match nutrient supply with biological demand as trees get progressively larger (ideally, trees would never experience nutrient stress from supplies that are too low or too high). On half of the plots, vegetative competition is controlled with ground application of appropriate herbicides (principally hexazinone and triclopyr), and insect control is provided through direct spraying of trees with insecticides (principally dimethoate and carbaryl) as often as needed each year.

Results through the fifth growing season indicate that vegetation control is the most important single factor in early stand performance. Where competing vegetation is controlled, tree survival and growth are doubled or tripled. Insect damage has been light, regardless of treatment, although pine reproduction weevil (*Cylindrocopturus eatoni*) activity may be increasing where competing vegetation density is high. Fertiliza-

Table 7—Fertilization rates for nutrients applied in the Garden of Eden ponderosa pine plantation study in California (Koerber and Powers 1986). Rates are based on uptake projections for the next two-year growth period with allowances for leaching and soil fixation, and are meant to maintain optimal nutrient concentrations in tree foliage through the sixth growing season.

Years from Planting	Elements Applied at Each Two-year Interval (kg/ha)								
	N	P	K	Ca	Mg	S	Cu	Zn	B
0	15.5	7.9	7.7	10.1	5.2	4.5	0.5	0.5	0.5
2	43.9	22.5	23.0	24.7	15.0	3.5	1.2	3.0	1.5
4	202.0	103.4	106.0	113.7	69.0	16.0	5.4	14.0	6.9
Total	261.3	133.8	136.7	148.5	89.1	24.0	7.0	14.5	8.9

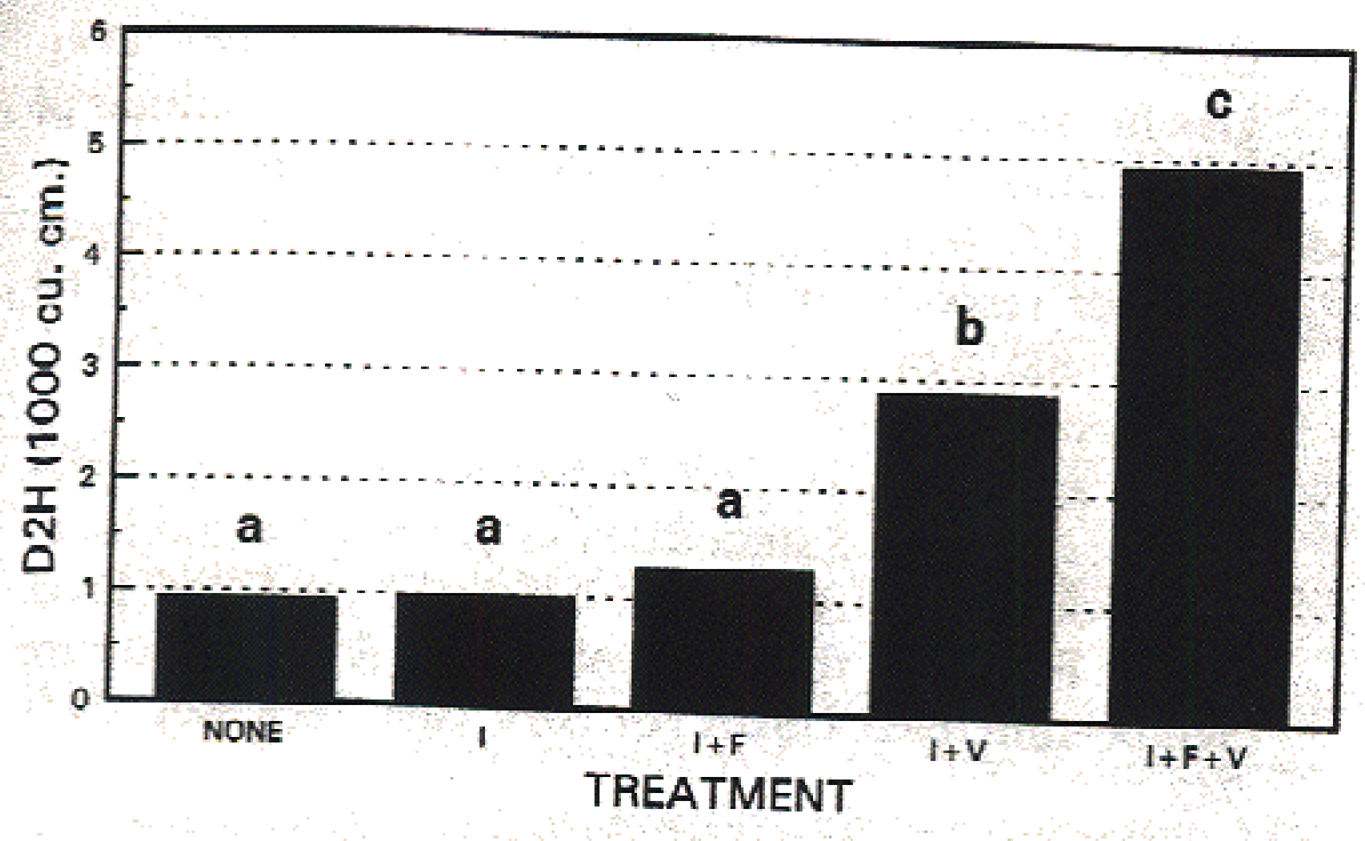

Figure 7. Average tree volume (diameter² x height) of ponderosa pine at the Whitmore Garden of Eden plantation in respect to certain combinations of "all or nothing" treatments. Treatment codes are "None" (no treatment), "I" (regular application of systemic insecticides), "F" (three applications of fertilizer [see Table 7]), and "V" (competing vegetation eliminated using herbicides). Means not sharing common letters differ at p=0.05 by Fisher's protected LSD.

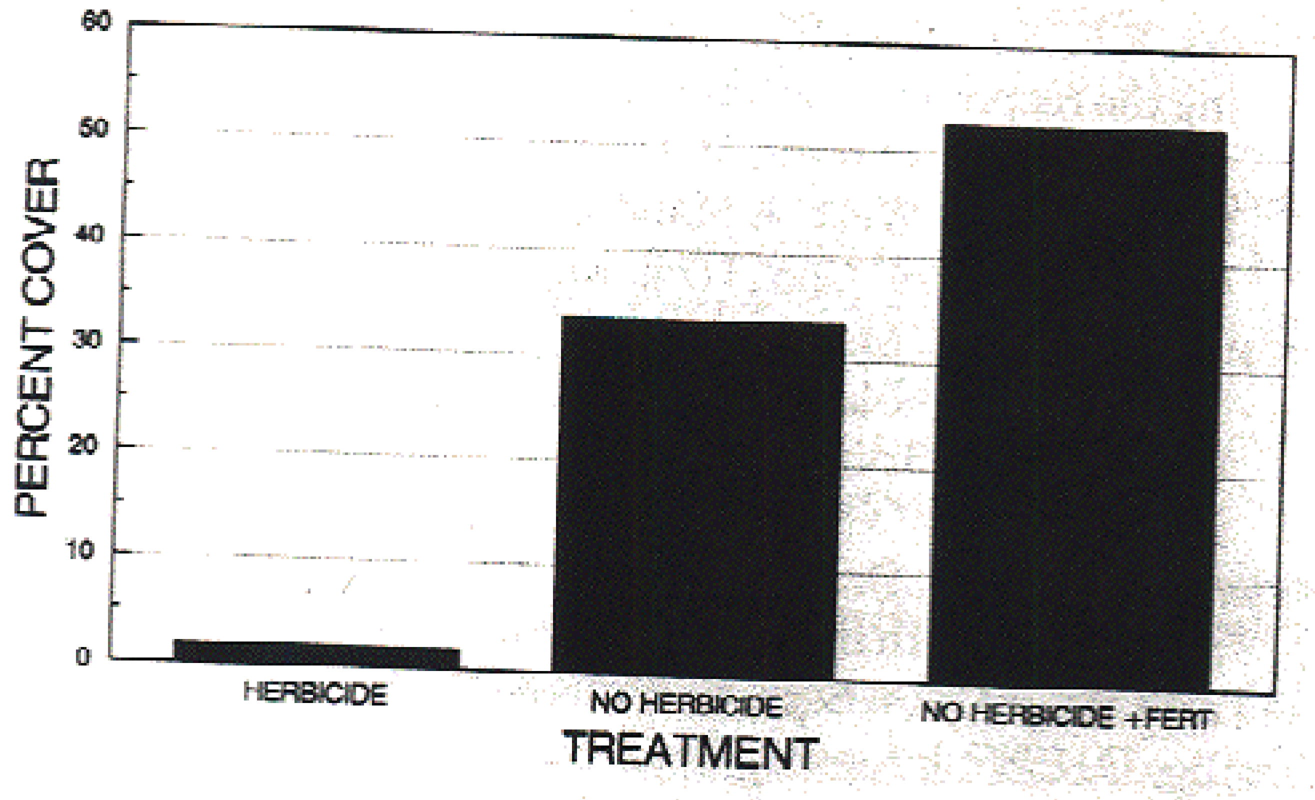

Figure 8. Average percentage cover of competing shrubs (principally *Arctostaphylos* and *Ceanothus*) on the Whitmore Garden of Eden plots. Fertilization (Table 7) increased brush coverage by more that 60%. All means differ significantly at p=0.05.

tion, on the other hand, tends to reduce seedling survival on the poorest sites. Positive effects of fertilization generally are not apparent until at least the third year from planting. As indicated by the oldest plantation ("Whitmore," Figure 7), fertilization combined with vegetation control increases volume growth severalfold, but vegetation must be controlled to show a positive fertilization response. Fertilizing without vegetation control can increase the growth of shrubs competing with trees for site resources (Figure 8) and is not a sound practice for plantation management in drier climates.

Literature Cited

Auchmoody, L.R. 1985. Evaluating growth responses to fertilization. Can. J. For. Res. 15:877-880.

Ballard, T.M. 1986. Overview of forest nutritional problems in the B.C. interior, and methods of diagnosis. p. 1-9 *In* Proc. Interior Forest Fertilization Workshop, Kamloops, B.C., 1986. B.C. Min. For., Victoria.

Bella, I.E. and K.J. Stoszek. 1988. Strategies for reducing impacts of terminal shoot insects. p. 286-297 *In* Schmidt, W.C., ed. Proc. Future Forests of the Mountain West: A Stand Culture Symposium, 1986. USDA For. Serv. Gen. Tech. Rep. INT-243.

Brockley, R.P. 1989*a*. Response of thinned, immature lodgepole pine to nitrogen fertilization: three-year growth response. B.C. Min. For., Victoria, FRDA. Rep. 036.

____. 1989*b*. The response of young lodgepole pine to spring and fall applications of urea and ammonium nitrate fertilizer. FRDA Research Memo No. 120, British Columbia Min. of For., Victoria.

____. 1990. Response of thinned, immature lodgepole pine to nitrogen and boron fertilization. Can. J. For. Res. 20:579-585.

____. 1991*a*. Forest fertilization research in the interior of British Columbia. p. 236-251 *In* Lousier, J.D., H. Brix, R. Brockley, R. Carter, and V.G. Marshall, eds. Improving forest fertilization decision-making in British Columbia. Proc. Forest Fertilization Workshop, 1988. B.C. Min. For., Victoria.

____. 1991*b*. Response of thinned, immature lodgepole pine to nitrogen fertilization: six-year growth response. B.C. Min. For., Victoria, FRDA Rep. *In press*.

Brockley, R.P. and T.P. Sullivan. 1988. Relationship of feeding damage by red squirrels to cultural treatments in young stands of lodgepole pine. p. 322-329 *In* Schmidt, W.C., ed. Proc. Future Forests of the Mountain West: A Stand Culture Symposium, 1986. USDA For. Serv. Gen. Tech. Rep. INT-243.

Brockley, R.P. and K. Swift. 1990. Interior spruce, Douglas-fir, and western larch fertilizer screening trials in the British Columbia Interior. B.C. Min. For., Victoria, FRDA Memo 129.

Carter, R.E. and R.P. Brockley. 1990. Boron deficiencies in British Columbia: diagnosis and treatment evaluation. For. Ecol. Manage. 37:83-94.

Cochran, P.H. 1989. Growth rates after fertilizing lodgepole pine. West. J. Appl. For. 4:18-20.

Cochran, P.H., C.T. Youngberg, E.C. Steinbrenner, and S.R. Webster. 1981. Response of ponderosa pine and lodgepole pine to fertilization. p. 89-94 *In* Gessel, S.P., R.M. Kenady, and W.A. Atkinson, eds. Proc. Forest Fertilization Conf., 1979. Institute of Forest Resources Contrib. 40, Univ. of Washington, Seattle.

Cole, D.M. and M.D. McGregor. 1988. Stand culture/bark beetle relationships of immature tree stands in the inland Mountain West. p. 278-285 *In* Schmidt, W.C., ed. Proc. Future Forests of the Mountain West: A Stand Culture Symposium, 1986. USDA For. Serv. Gen. Tech. Rep. INT-243.

Dangerfield, J. and H. Brix. 1981. Comparative effects of ammonium nitrate and urea fertilizers on tree growth and soil processes. p. 133-139 *In* Gessel, S.P., R.M. Kenady, and W.A. Atkinson, eds. Proc. Forest Fertilization Conf., 1979. Institute of Forest Resources Contrib. 40, Univ. of Washington, Seattle.

Graham, R.T. and J.R. Tonn. 1985. Ten-year results of fertilizing grand fir, western hemlock, western larch, and Douglas-fir with nitrogen in northern Idaho. USDA For. Serv. Res. Paper INT-346. 6 p.

Heath, L.S. and H.N. Chappell. 1989. Growth response to fertilization in young Douglas-fir stands. West. J. Appl. For. 4:116-119.

Heilman, P., S. Webster, E.C. Steinbrenner, and R.F. Strand. 1981. Season for application of urea fertilizer to Pacific Northwest forests. p. 186-191 *In* Gessel, S.P., R.M. Kenady, and W.A. Atkinson, eds. Proc. Forest Fertilization Conf., 1979. Institute of Forest Resources Contrib. 40, Univ. of Washington, Seattle.

Heninger, R.L. 1982. Response of *Abies concolor* to intensive management. p. 319-323 *In* Oliver, C.D. and R.M. Kenady, eds. Proc. Biology and Management of True Fir in the Pacific Northwest Symposium, 1981. Institute of Forest Resources Contrib. 45, Univ. of Washington, Seattle.

Intermountain Forest Tree Nutrition Cooperative (IFTNC). 1988. Eighth annual report. College of Forestry, Wildlife, and Range Sciences, Univ. of Idaho, Moscow.

____. 1990. Tenth annual report. College of Forestry, Wildlife, and Range Sciences, Univ. of Idaho, Moscow.

Koerber, T.W. and R.F. Powers. 1986. Factors influencing maximal growth of young ponderosa pine. Study plan on file at the USDA Forest Service Pacific Southwest Research Station, Redding, California.

Loewenstein, H. and F.H. Pitkin. 1963. Response of grand fir and western white pine to fertilizer applications. Northwest Sci. 37(1):23-30.

Majid, N.M. and T.M. Ballard. 1990. Effects of foliar application of copper sulphate and urea on the growth of lodgepole pine. For. Ecol. Manage. 37:151-165.

Malm, D. and G. Möller. 1975. Differences in volume growth increase after fertilization with urea and ammonium nitrate fertilizer. p. 46-63. Föreningen Skogsträdsförädling, Institutet för skogsförbättring, Årsbok 1974.

Mika, P.G. and J.A. Moore. 1990. Foliar potassium status explains Douglas-fir response to nitrogen fertilization in the Inland Northwest, USA. Water, Air, and Soil Pollution 54:477-491.

Mika, P.G. and J. VanderPloeg. 1991. Six year fertilizer response of managed second-growth Douglas-fir stands in the Intermountain Northwest. p. 293-301 *In* Baumgartner, D.M., ed. Proc. Interior Douglas-fir: The Species and Its Management, 1990. Washington State Univ. Cooperative Extension, Pullman.

Miles, S.R. and R.F. Powers. 1988. Ten-year results of forest fertilization in California. Earth Resources Monogr. 15, USDA For. Serv., Region 5, San Francisco.

Miller, R.E., P.R. Barker, C.E. Peterson, and S.R. Webster. 1986. Using nitrogen fertilizers in management of coast Douglas-fir: I. Regional trends of response. p. 290-303 *In* Oliver, C.D., D. P. Hanley, and J.A. Johnson, eds. Douglas-fir: stand management for the future. Institute of Forest Resources, Univ. of Washington, Seattle.

Moore, J.A., P.G. Mika, and J.L. VanderPloeg. 1991. Nitrogen fertilizer response of Rocky Mountain Douglas-fir by geographic area across the inland northwest. West. J. Appl. For. 6(4):94-98.

Navratil, S. and I.E. Bella. 1988. Impact and reduction strategies for foliage and stem diseases and abiotic injuries of coniferous species. p. 310-321 *In* Schmidt, W.C., ed. Proc. Future Forests of the Mountain West: A Stand Culture Symposium, 1986. USDA For. Serv. Gen. Tech. Rep. INT-243.

Powers, R.F. 1981. Response of California true fir to fertilization. p. 95-101 *In* Gessel, S.P., R.M. Kenady, and W.A. Atkinson, eds. Proc. Forest Fertilization Conf. 1979. Institute of Forest Resources Contrib. 40, Univ. of Washington, Seattle.

____. 1983. Forest fertilization research in California. p. 388-397 *In* Ballard, R. and S.P. Gessel, eds. Proc. IUFRO Symposium on Forest Site and Continuous Productivity. USDA For. Serv. Gen. Tech. Rep. PNW-163.

Powers, R.F. and G.D. Jackson. 1978. Ponderosa pine response to fertilization: influence of brush removal and soil type. USDA For. Serv. Res. Paper PSW-132. 9 p.

Powers, R.F., S.R. Webster, and P.H. Cochran. 1988. Estimating the response of ponderosa pine forests to fertilization. p. 219-225 *In* Schmidt, W.C., ed. Proc. Future Forests of the Mountain West: A Stand Culture Symposium, 1986. USDA For. Serv. Gen. Tech. Rep. INT-243.

Preston, C.M., V.G. Marshall, K. McCullough, and D.J. Mead. 1990. Fate of ^{15}N-labelled fertilizer applied on snow at two forest sites in British Columbia. Can. J. For. Res. 20:1583-1592.

Ryker, R.A. and R.D. Pfister. 1967. Thinning and fertilizing increase growth in a western white pine seed production area. USDA For. Serv. Res. Note INT-56. 3 p.

Scanlin, D. 1985. Intensive forest management project, forest fertilization phase: termination report. College of Forestry, Wildlife, and Range Sciences, Univ. of Idaho, Moscow.

Scanlin, D.C. and H. Loewenstein. 1981. Response of inland Douglas-fir and grand fir to thinning and nitrogen fertilization in northern Idaho. p. 82-88 *In* Gessel, S.P., R.M. Kenady, and W.A. Atkinson, eds. Proc. Forest Fertilization Conf., 1979. Institute of Forest Resources Contrib. 40, Univ. of Washington, Seattle.

Shafii, B., J.A. Moore, and J.D. Newberry. 1990. Individual-tree diameter growth models for quantifying within-stand response to nitrogen fertilization. Can. J. For. Res. 20:1149-1155.

Shafii, B., J.A. Moore, and J.R. Olson. 1989. Effects of nitrogen fertilization on growth of grand fir and Douglas-fir stands in northern Idaho. West. J. Appl. For. 4:54-57.

Sullivan, T.P. 1985. Small mammal damage agents which affect the intensive silviculture of lodgepole pine. p. 97-105 *In* Baumgartner, D.M., R.G. Krebill, J.T. Arnott, and G.F. Weetman, eds. Proc. Lodgepole Pine, the Species and Its Management, 1984. Washington State Univ. Cooperative Extension, Pullman.

Sullivan, T.P. and D.S. Sullivan. 1982. Influence of fertilization on feeding attacks to lodgepole pine by snowshoe hares and red squirrels. For. Chron. 58:263-266.

Walker, R.B. and S.P. Gessel. 1991. Mineral deficiencies of coastal Northwest conifers. Institute of Forest Resources Contrib. 70, Univ. of Washington, Seattle.

Webster, S.R. and A. Dobkowski. 1983. Concentrations of foliar nutrients for trees and the dosage and frequency of fertilizer trials. Weyerhaeuser Company Res. Rep. Proj. 050-3920/3.

Weetman, G.F. 1988. Nutrition and fertilization of lodgepole pine. p. 231-239 *In* Schmidt, W.C., ed. Proc. Future Forests of the Mountain West: A Stand Culture Symposium, 1986. USDA For. Ser. Gen. Tech. Rep. INT-243.

Weetman, G.F. and R. Fournier. 1982. Graphical diagnoses of lodgepole pine response to fertilization. Soil Sci. Soc. Am. J. 46:1280-1289.

Weetman, G.F., R.M. Fournier, and E. Schnorbus. 1988. Lodgepole pine fertilization screening trials: four-year growth response following initial predictions. Soil Sci. Soc. Am. J. 52:833-839.

Weetman, G.F., R.C. Yang, and I.E. Bella. 1985. Nutrition and fertilization of lodgepole pine. p. 225-232 *In* Baumgartner, D.M., R.G. Krebill, J.T. Arnott, and G.F. Weetman, eds. Proc. Lodgepole Pine, the Species and Its Management, 1984. Washington State Univ. Cooperative Extension, Pullman.

Yang, R.C. 1985. Effects of fertilization on growth of 30-year-old lodgepole pine in west-central Alberta. Can. For. Serv., North. For. Res. Centre, Edmonton, Alberta, Inf. Rep. NOR-X-268. 11 p.

Questions and Answers

How many repeat applications of nitrogen are reasonable (realistic) in unthinned Douglas-fir before mortality gets you? Because of the high cost of thinning, will fertilizing low site index areas twice with 448 kg N/ha at age 25 and age 50 to 65 achieve the same results?

Both of the questions deal with the interaction of stand density and nitrogen fertilization. Assuming competition-caused mortality is foremost, nitrogen fertilization seems to accelerate stand development dynamics forward in time; stand response depends on the stand density at the time of fertilization. If a stand is dense enough already to be following a self-thinning trajectory, then nitrogen fertilization will accelerate the self-thinning process. Less dense stands will develop more quickly after fertilization toward a self-thinning condition. Site quality and initial density will determine how quickly a particular stand reaches the self-thinning zone.

The idea of using nitrogen fertilization as a substitute for thinnings is interesting, but is unlikely to satisfy your organization's objectives. Again assuming that any mortality results from competition, the fertilization thinning effect approximates a continuous light thinning from below. This result will be different from a more typical higher intensity crown thinning, and will probably not satisfy your density management objectives. The 14-year results in Douglas-fir and grand fir showed that although net volumes were similar, average tree size was over three times as large on the thinned plots. Even though nitrogen fertilization may produce a "thinning effect," it is not a substitute for thinning.

Lodgepole pine fertilized with 100 kg N/ha showed a three-year volume response of 30% while that fertilized with 200 kg/ha had a 33% response. Was this difference significant?

These values reflect the average net volume per hectare response obtained from 11 lodgepole pine installations. The 3% difference in response between the two treatments was not significant. Response across the 11 installations varied from 4 to 65% for the 100 kg treatment and from 0 to 54% for the 200 kg treatment. Only one installation showed a significant gain with the higher application rate; in five installations, the 200 kg response was actually less than the 100 kg response, although the differences were not significant. Results were similar for gross volume growth.

Do you have any data on IFTNC installations that include potassium with nitrogen treatments?

Based on results indicating that Douglas-fir on potassium-poor sites responded less to nitrogen fertilization, the IFTNC established a series of trials contrasting N alone and N+K treatments. We now have 90 such sites in Douglas-fir scattered across the intermountain region and 6 ponderosa pine sites in western Montana. Two-year response data collection was completed in the fall of 1990; thus early response results should soon be available.

Could low potassium soils be identified by particular exchangeable K concentrations in the soils?

Low potassium sites were identified based on analysis of Douglas-fir foliage. Foliar K concentrations and soil exchangeable K values (determined using the standard ammonium acetate extraction method) were uncorrelated. The IFTNC is currently looking at soil potassium desorption curves as a way to characterize soil potassium status in a manner meaningful to fertilizer behavior and tree growth response.

How do you identify potential mortality problems?

In a number of cases, nitrogen fertilization has increased tree mortality rates. Sometimes this resulted from faster crown differentiation and increased density, producing competition-caused mortality. In other cases, physical processes (snow bending and breakage, windthrow) or biotic disturbances (squirrel damage, root rot mortality) were enhanced by the fertilization.

To identify situations where nitrogen fertilization may accelerate mortality, you need to (1) understand the effects that the fertilizer has on the trees and (2) be aware of mortality agents at work in the area. For example, we know that nitrogen fertilizers shift carbon allocation within the tree toward crown production, thereby increasing crown biomass and the shoot-root ratio. If we are working in an area where windthrow or snow breakage is common, we would anticipate that nitrogen fertilization would increase our mortality rate from those agents, particularly if we opened up the stands through thinnings. Similarly, in an area with substantial root rot mortality, nitrogen fertilization is likely to increase mortality rates by increasing the demand on an already inadequate root system.

Other nitrogen fertilizer effects are more subtle, creating nutrient imbalances or inducing deficiencies within the tree. When we know there is already a problem with other nutrients, we would anticipate that additional nitrogen would exacerbate the situation. Thus nitrogen fertilizer has been shown to aggravate boron deficiency symptoms in lodgepole pine. However, in most cases we have no visible symptoms telling us that other elements are lacking. We need much more information developed about the conditions associated with other nutrient deficiencies before we will be able to predict where nitrogen fertilizer might adversely impact tree nutrition.

Distinguish between direct and indirect effects on response to fertilization.

When we measure response to fertilization, we commonly look at changes in basal area or volume over a certain period. This can be measured on individual trees or plots. Comparisons are then drawn between trees or plots that are initially of the same size or density but are treated differently. Similar starting conditions are necessary because tree growth rates are dependent on size, and plot growth rates are dependent on density. Initial similarity is achieved by careful selection and by numerical adjustment for size or density differences through analysis of covariance.

Let us consider individual-tree comparisons (a similar argument can be made for plots). Assuming there is a positive fertilizer effect on growth, after the first year of growth the treated tree will be larger than the untreated tree. The difference in growth is our measure of response, all of which is attributable to the fertilizer treatment. However, in the second year the treated tree will have started off at a larger size than the untreated; thus some of the differences in growth at the end of the second year are due to the initial size differences. When we calculate total response in the second year, we can partition that response into one portion resulting from initial size differences (an indirect fertilizer effect) and another portion directly attributable to the fertilizer (a direct effect). The indirect effect accumulates so that, as the time since treatment lengthens, an increasing portion of the difference between treated and untreated tree growth can be attributed to past growth increases. Auchmoody (1985) provides a detailed discussion of this topic.