

Fertilization in Coastal Northwest Forests: Using Response Information in Developing Stand-Level Tactics

H. N. CHAPPELL, S. A. Y. OMULE, and S. P. GESSEL

ABSTRACT. The information base available to foresters prescribing fertilizer treatments for stands in the coastal Douglas-fir zone has increased substantially in the past decade. Research programs in the region have produced information that is used to select sites and stands for fertilization and to forecast growth after treatment, and results have become available for long-term responses and from multiple fertilization treatments. About 70% of coastal Douglas-fir stands respond to applications of nitrogen fertilizer. Volume growth after fertilization is increased about 16-18% in unthinned stands and about 20-22% in thinned stands for 8-10 years, and growth increases continue to be statistically significant for 8-16 years after initial treatment. Responses to repeated applications are of similar magnitude but shorter duration. Western hemlock response has not been consistent in trials in the region, and fertilization information for other species is minimal. Results from these and other studies provide the basis for operational fertilization programs in coastal Douglas-fir forests (western Oregon, Washington, and British Columbia). Fertilization recommendations call for nitrogen fertilizer usually applied as urea to Douglas-fir stands over a range of soil and stand types. Generally, the recommended dosage is 224 kg N/ha, and refertilization is prescribed after 7-10 years. About 50,000 to 55,000 hectares in Oregon and Washington and 3,000 to 10,000 in British Columbia are fertilized each year, and future programs will likely be of similar magnitude. Regimes for managed stands in the future are expected to include multiple fertilizer applications in conjunction with thinning.

Forest Nutrition Research in the Pacific Northwest

Forest fertilization has become a silvicultural practice of increasing significance over the past two decades in Pacific Northwest (PNW) forests. The information base available to foresters prescribing treatments to stands has expanded substantially over that time, although there remains room for improvement. This chapter reviews available response information in the context of stand-level tactics for commercial forests in western Oregon, Washington, and British Columbia. Forests considered are low elevation stands west of the crest of the Cascade Mountains in Oregon and Washington and coastal British Columbia. These include the *Tsuga*

heterophylla and *Picea sitchensis* zones in Oregon and Washington (Franklin and Dyrness 1973) and the Coastal Western Hemlock Zone in British Columbia (Klinka et al. 1984). Of particular interest are Douglas-fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*) stands managed for timber production.

Mineral nutrition studies in coastal forests were initiated at the University of Washington about 1950, and began soon afterward in other organizations throughout the region. Early work demonstrated that nitrogen fertilization would increase Douglas-fir tree and stand growth (Crossin et al. 1966; Gessel and Shareeff 1957; Gessel and Walker 1956; Heilman and Gessel 1963; Knight 1963; Steinbrenner 1968) and stimulate reproductive development and seed production (Steinbrenner et al. 1960; Stoate et al. 1961). A series of greenhouse studies conducted in the 1950s by Walker and Gessel (1990, 1991) examined typical deficiency symptoms, mineral contents, and growth rates of tree seedlings under a range of nutrient regimes. These studies provided basic information on mineral requirements of Northwest coniferous species, and were followed by

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field trials at several sites in western Washington (Gessel et al. 1965, 1969).

Promising results in early research projects and the initiation of operational fertilization programs in 1965 were major factors influencing the formation of regional research programs. The two major regional programs discussed in this chapter are the Regional Forest Nutrition Research Project (RFNRP) and the British Columbia Ministry of Forests Experimental Project 703 (EP703), initiated in 1969 and 1971, respectively. The primary objective of both programs was to provide forest managers with information on growth and response to nitrogen fertilization of second-growth stands of Douglas-fir and western hemlock. Other objectives included comparison of fertilizer responses in thinned and unthinned stands, investigation of responses to alternative sources of nitrogen and to other elements, fertilization influences on forest ecosystems, economic aspects of forest fertilization, and effects of fertilization on wood quality. Both programs have an extensive base of permanent-plot field installations (Figure 1).

Although much of the basis for operational forest fertilization in the Pacific Northwest is derived from cooperative research results, significant independent programs have been conducted by Forestry Canada, the USDA Forest Service PNW Research Station, the Washington State Department of Natural Resources, universities, and the forest industry. This work has often addressed research topics more basic than those undertaken by the cooperatives, or has extended cooperative results through collaborative work. Recognition of the substantial contributions of these research programs is important in considering forest fertilization research.

Forest fertilization in Pacific Northwest forests has been the theme for several conferences held over the past two decades. Information on fertilization responses for coastal forests has been presented at these conferences and in many other papers. It may be instructive to consider the topics presented in a recent paper dealing with future information needs to set the stage for discussion of progress and to examine changes in needs and directions. Peterson et al. (1986) identified four future information needs for forest fertilization as "major" for intensive management of Douglas-fir:

1. Identifying responsive and nonresponsive stands.
2. Is the relative increase in growth rate from fertilization density dependent?
3. Does fertilization affect thinning schedules and vice versa?
4. Does fertilization affect wood quality?

Three additional needs were identified as "moderate" for intensive management:

1. What nutrients and fertilizer should be applied, and at which rate? How can the need for elements

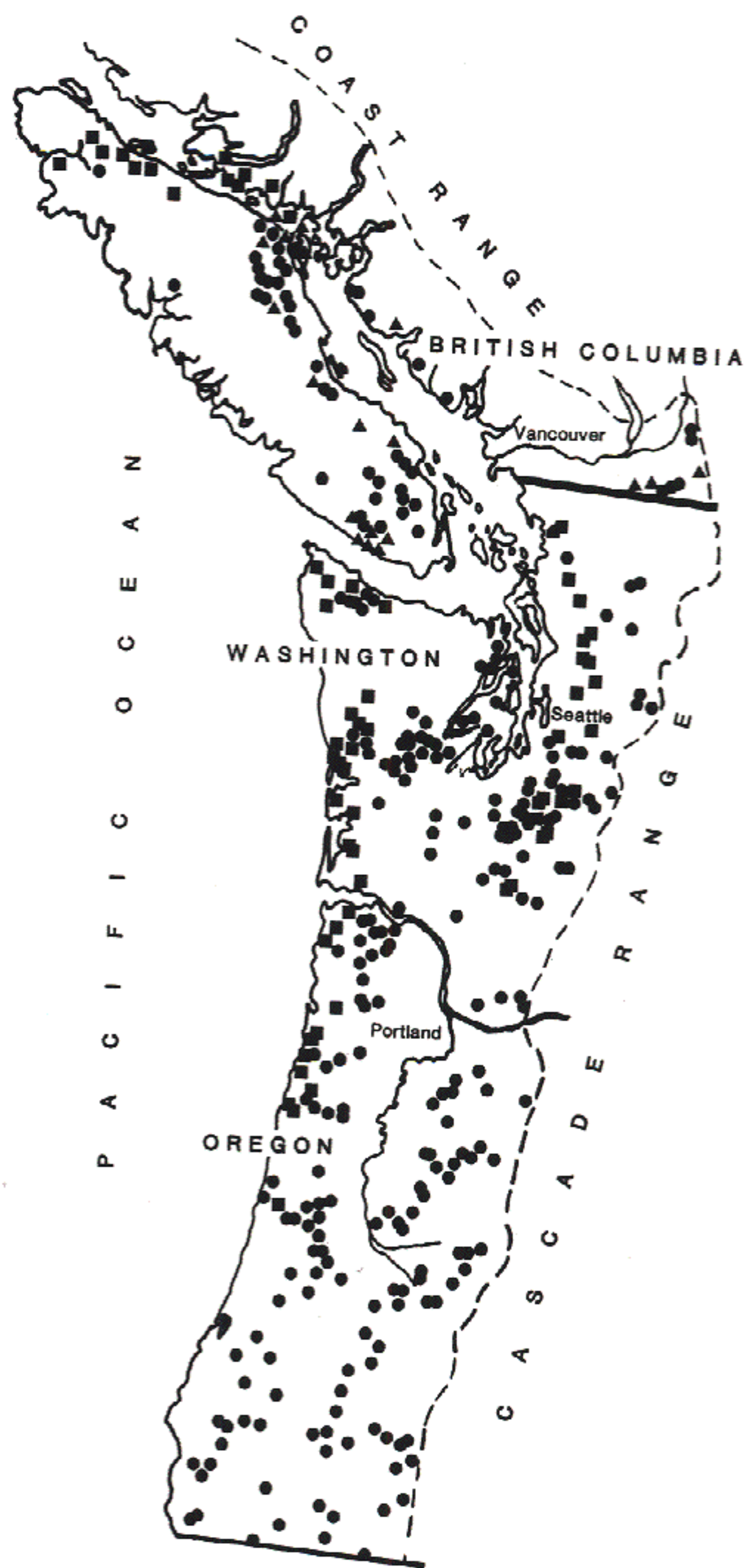


Figure 1. Location and stand type for installations of the Regional Forest Nutrition Research Project in western Oregon and Washington and EP703 installations in coastal British Columbia. Installations in Douglas-fir and western hemlock stands are represented by circles and squares, respectively, and in mixed stands by triangles.

other than nitrogen be predicted or measured?
When should other elements be applied?

2. What are the expected volume gains from fertilization?
3. Dosage and frequency: How often to apply? How much to apply?

While considerable progress has been made, these questions are still relevant today and can serve as a framework for a discussion of forest fertilization information for coastal forests.

Using Fertilizer Response Information in Planning Stand Treatments

Operational forest fertilization programs in coastal Northwest Forests are based on information gained from research projects. This section is organized using a question format to consider how to select stands, what to do, and what to expect, based on an overview of available information.

Which Species?

Operational fertilization with nitrogen has concentrated on Douglas-fir stands, and to a lesser extent on western hemlock stands. This trend is likely to continue, although there appears to be potential for treating stands of other species, such as western redcedar (*Thuja plicata*) and true firs (*Abies* spp.).

Research evidence indicates that fertilizing Douglas-fir with nitrogen frequently improves growth over a wide range of locations, soils, and climate (e.g., Gessel et al. 1981; Miller et al. 1981; Miller et al. 1988; Gardner 1990; Omule 1990; Stegemoeller and Chappell 1990). While significant growth increases after fertilization have been reported for some studies in closed stands of western hemlock, overall response results have been inconsistent, highly variable, and possibly negative on some sites (Lee 1974; DeBell 1975; DeBell et al. 1975; Webster et al. 1976; Olson et al. 1981; Olson 1980; Gill and Lavender 1983; Radwan and Shumway 1983, 1984; Radwan and DeBell 1989; Stegemoeller 1989a; Omule and Britton 1991). Fertilizing western hemlock at establishment has yielded positive responses in several trials (Porada 1987; Weetman et al. 1989a).

The limited research done for western redcedar indicates that closed canopy stands of the species can respond to fertilization (Harrington and Wierman 1990), although Kumi et al. (1991) suggest that the response is erratic. Like western hemlock, western redcedar responded well to fertilization at time of establishment (Weetman

et al. 1989a). Fertilization trials of other species, such as Sitka spruce (*Picea sitchensis*), appear limited to screening trials and to fertilization at time of establishment (e.g., Weetman et al. 1989b).

Which Sites?

Response to fertilization is greatest on those sites deficient in the nutrients applied, where the added nutrients do not induce deficiencies of other nutrients and where other potentially limiting factors such as light and water are in abundant supply. The basic problem in relating response to measures of site quality, such as site index, is that the measures do not take into account all the site factors influencing growth response to fertilization. Fertilizing Douglas-fir on poor sites usually results in positive growth response, and stands on medium- and high-quality sites can also respond well to fertilization. Limitations to relating fertilization growth response to site index include the fact that areas of the same site index do not necessarily have the same nutrient-moisture regime (e.g., Gessel et al. 1990; Peterson and Hazard 1990). Other potential indices that could be related to fertilizer growth response include environmentally based indices such as British Columbia's BEC system (Klinka et al. 1984), mineralizable soil N (Shumway 1984; Klinka and Carter 1990), and others discussed previously in this conference (Carter).

For Douglas-fir, most analyses suggest that initially greater benefits occur on poorer sites (Gessel et al. 1965; RFNRP 1980, 1982; Miller et al. 1986b, 1988; Radwan and Shumway 1984). Other studies suggest that the best results are obtained with nitrogen fertilization in stands that are naturally most productive (Steinbrenner 1968; Handley and Pienaar 1972; Mallonee and Strand 1976; Omule 1990), and some results suggest that response is unrelated to site index (Heilman 1971; Anonymous 1976).

The relationship of site index to western hemlock fertilization response remains unclear, and information is not available for other species. Site index has had little relation to western hemlock response in field studies (Webster et al. 1976; Olson 1980; RFNRP 1979; Radwan and Shumway 1984; Omule and Britton 1991).

At What Age?

Regional analyses have found that volume growth response is similar across age classes, although there is a trend for more response in younger stands. Positive growth responses to fertilization have been demonstrated for thinned and unthinned Douglas-fir stands of midrotation age classes (Miller et al. 1986b; RFNRP

1987, 1989) as well as for much older stands (≥ 75 yr) (Harrington and Miller 1979; Miller and Harrington 1979; Miller and Reukema 1974; Miller and Webster 1981). Relative increases in volume periodic annual increment (PAI) after fertilization for young Douglas-fir stands (≤ 25 yr) (Heath and Chappell 1989; Peterson 1984) and western hemlock stands (Omule and Britton 1991) have been shown to be comparable to responses in older stands. Other studies indicate that fertilizing can induce larger gains in younger Douglas-fir and western hemlock stands compared to older stands (Steinbrenner 1968; Mallonee and Strand 1976; Olson et al. 1981; RFNRP 1982; Miller et al. 1988).

Greater response may be expected in younger stands, especially those with early stocking control, since they probably have more efficient crowns and more room for crown expansion to take advantage of the added nutrients. Competition has generally been greater in older stands, resulting in lower crown ratios, higher stocking levels, and therefore less room for crown expansion. Operational fertilization programs often tend to favor younger stands over older stands, although for economic reasons stands approaching harvests (commercial thinning or final harvest) are also commonly fertilized.

Growth responses have been demonstrated for tree seedlings, in both greenhouse and field trials. Considerable early work dealt with seedling growth responses and tissue nutrient levels, and field studies emphasized survival and growth after planting (Austin and Strand 1960; Rothacher and Franklin 1964; Strand and Austin 1966). Other studies dealt with nursery fertilization regimes (van den Driessche 1977, 1979) and effects of nursery fertilization on growth after outplanting (Anderson and Gessel 1966; van den Driessche 1980). Seedling mortality problems due to poor quality of planting stock and inappropriate handling before planting have been specifically addressed in recent years, and fertilization of seedlings may be an effective means to increase early growth on some sites. Several recent trials have examined growth responses to fertilization at time of planting, some with slow-release fertilizers (Carlson 1981; Carlson and Preisig 1981; Porada 1987; Thies and Nelson 1988). In recent coastal Washington trials, five-year seedling height growth was increased as much as 15% by a combined N+P treatment applied at time of planting (Porada 1987; and data on file at RFNRP). Height growth responses of 12-31% were observed in a series of trials on Vancouver Island where fertilizers were applied at planting (van den Driessche 1988). Other promising results have renewed interest in seedling fertilization as a possible adjunct or alternative

to site preparation or vegetation management treatments in order to meet stand establishment objectives.

What Stand Density?

Preference for fertilization is usually given to thinned stands. Recent results from the British Columbia trials indicate greater gains from fertilizing thinned Douglas-fir stands over unthinned stands, and similar trends were reported for RFNRP installations (Stegemoeller and Chappell 1990). Results from these analyses are summarized in a later section.

Fertilizing dense western hemlock stands can increase mortality (Miller 1976). Response to fertilization increased when the treatment was combined with thinning in several western hemlock trials (DeBell 1975; DeBell et al. 1975; Webster et al. 1976; Omule and Britton 1991).

In a 15 to 20-year-old western redcedar stand on a poor quality coastal Washington site, five-year height and basal area growth was greater after fertilization for unthinned and thinned plots (Harrington and Wierman 1990). The greatest responses were observed for fertilization treatments that included nitrogen and phosphorus. These results are limited by the relatively short observation period and the single location, and information relating stand density to fertilizer for other coastal species is even more limited or anecdotal.

Fertilization of dense stands can increase stocking level (Strand and DeBell 1981) and mortality and winter damage (Gessel and Shareeff 1957; Crossin et al. 1966; Gessel et al. 1969; Heilman 1971; Reukema 1968; Miller and Pienaar 1973; Miller and Tarrant 1983). Combined thinning and fertilization is often recommended (Steinbrenner 1968; Mallonee and Strand 1976; Barclay et al. 1982; Miller et al. 1981) because together they result in greater foliar biomass and photosynthesis (Brix 1971, 1981a, 1981b, 1983), a synergistic effect increasing growth. Fertilizing thinned stands can result in higher value response because the gain in growth due to the fertilizer treatment is distributed among fewer, larger stems, thereby increasing value of logs and reducing extraction costs.

Economic Considerations

While the factors discussed so far are obviously important, economic factors ultimately determine whether a stand is fertilized or not. Costs of fertilizer application, cost of future treatments, harvest accessibility, and length of investment period are vital economic considerations. These costs are influenced by factors such as stand age, slope, location and access to

stands, type and cost of fertilizer, snow presence, and others. Benefits primarily relate to increases in timber and fiber yields, although value of logs from fertilized stands may be positively or negatively influenced by log grade changes or redirection to different products, and these effects may be important in evaluating treatments. Another potentially important consideration relates to tree sizes where stand development has been accelerated by fertilization: current regulations link tree size to wildlife habitat and harvest area limits, and manipulation of growth rates may directly affect management planning for large areas of timberland. The influence of these factors and others on economic decision making is discussed elsewhere in this volume.

What Nutrients to Apply? In What Form?

Beginning with results from the earliest work by Gessel and his colleagues, nitrogen is the only applied nutrient element that has consistently produced positive growth responses throughout the region. There have been indications from other studies that other elements may be in limited supply on some sites, or may appear as secondary deficiencies after nitrogen limitations are addressed. Phosphorus has been implicated as a growth-limiting factor in some studies, notably in coastal western hemlock trials, although phosphorus applications have not consistently produced positive growth responses (Radwan and Shumway 1983 and 1984; Webster et al. 1976).

Sulfur nutrition has been investigated in several studies, with an indication that response to applied nitrogen may be limited by inadequate sulfur supply (Turner et al. 1977; Blake et al. 1988). Soil sulfur levels were not correlated to response by Douglas-fir or western hemlock in an analysis by Radwan and Shumway (1984). Blake et al. (1990) found that information on soil sulfate-S levels did not improve prediction of response to fertilization with nitrogen and sulfur. These mixed results indicate that additional work on understanding soil and foliar sulfur levels and dynamics and identifying efficient sources is needed before sulfur fertilization can be recommended.

Growth limitations due to inadequate micronutrient supply have been indicated in only a few trials. Boron deficiencies were identified in Douglas-fir and Pacific silver fir stands on some coastal sites in British Columbia (Carter et al 1986; Carter and Brockley 1990). Possible response to boron fertilization by Douglas-fir at one Oregon location was reported by Blake et al. (1990). Information on deficiencies of other micronutrients in coastal forest stands is not available.

Sources of applied nitrogen have been investigated in several studies, and have included applications of ammonium nitrate, slow-release nitrogen sources, ammoniated phosphates, foliar nitrogen solutions, and other sources (Barclay and Brix 1984; Dangerfield and Brix 1981; Miller et al. 1986a; Opalach 1987; Stegemoeller 1989b). Results from these studies rarely indicate that one nitrogen source is superior to another when applied at the same rate. Urea ($\text{CO}(\text{NH}_2)_2$) has the highest nitrogen content (46%) of granular fertilizers and is therefore the most cost-effective source to use in aerial applications, delivering more nitrogen per ton of fertilizer applied to the site. Most forest fertilization programs specify large forestry-grade granules for their better ballistic properties and crown penetration in aerial application.

How Much to Apply?

The biologically optimum rate for a single fertilizer application to a Douglas-fir stand appears to be between 135 and 270 kg N/ha, but there is no comparable information for other species. Early research examined fertilizer application rates (Gessel et al. 1965, 1969), and regional trials have included dosages between 112 and 900 kg N/ha for single applications. Higher dosages produce greater increase in growth over a longer period, but with added risk of snow or wind breakage (Miller and Pienaar 1973). The cost effectiveness of higher dosages is less in terms of added volume produced per kilogram of applied nitrogen.

There is limited information for multiple fertilizer applications, and no published dosage studies for repeated applications in the Pacific Northwest. RFNRP installations have been refertilized at four-year intervals with 224 kg N/ha, and responses to refertilization are similar to response after initial treatment (these results are presented in a later section).

Generally, the recommended fertilizer dosage is 224 kg N/ha for Douglas-fir stands, and refertilization is prescribed after 7-10 years with the same application rate. Recommendations for other species and other nutrients have not been developed for coastal forests.

When to Fertilize?

Two aspects of timing are important for planning forest fertilization operations: stand age and season of year. Stand age as a factor in response is covered in a previous section of this chapter, and also relates to strategic considerations covered in other chapters (Daoust; Shumway and Olson).

Season of the year is another important consideration in planning fertilizer applications. A basic principle in fertilizer application is to deliver the applied nutrient to the plant so that the maximum benefit can be derived. This involves placement of the fertilizer so that it can be taken up at a time when plants are actively growing, thus minimizing loss of applied nutrient. There is little evidence that one season of the year is better than another for fertilizer application in terms of long-term growth, implying that cycling within the ecosystem dampens short-term effects over several years.

However, other considerations, especially immobilization and loss of applied nutrients and nitrogen volatilization, do require attention; Marshall (1991) provides a good review of factors determining the fate of nitrogen fertilizers relevant to coastal forests. Volatile losses of ammonia-N after surface application of urea can be significantly affected by temperature and soil and forest floor moisture, as demonstrated in laboratory studies (DeBell 1973; Watkins et al. 1972) and field experiments (Nason et al. 1988). Significant amounts of nitrogen may be immobilized in forest floor layers under some conditions. Excess moisture can also be a concern, since significant nitrogen movement in surface and groundwater can occur. Unhydrolyzed urea is readily transported by water, a possibility of concern in coastal forests because of the potential for runoff during high intensity rainfall or rapid thaw of snowpack. Preston et al. (1990) found that urea and ammonium sources may be applied on snowpack, but recommended against fertilization with nitrate because of nitrate's susceptibility to leaching. Since dissolved fertilizer may also be carried in meltwater through a snowpack, avoiding fertilizer applications over ground covered with snow is prudent.

The potential for losses in groundwater has been investigated in several studies. Soil water examinations in several lysimeter studies have shown very little loss of applied nutrients by downward movement through the soil profile (Cole and Gessel 1965; Cole et al. 1975).

Considering the information above and other factors, guidelines for urea application to coastal forests can be proposed. Application of urea or other ammonium sources when there will be 1-2 cm of rain in the next 24 hours and when temperatures are below about 10°C will greatly diminish the likelihood of volatilization of nitrogen. Avoiding fertilizer applications to snowpack or frozen soils reduces potential for movement in runoff or groundwater. Heilman et al. (1981) developed recommendations for Washington (Table 1) which can be extended to other subregions in coastal forests with similar climate. Judgment is required to extrapolate

Table 1—Recommended times of the year for urea fertilization in western Washington. From Heilman et al. (1981).

Area	Time for Urea Application
Coastal area	October through April, except during high rainfall in midwinter (December and January)
Puget Sound Lowlands	End of October through first of March
Western Cascades	Mid-October to first of April
Low rainfall areas (e.g., rain shadow area of north Puget Sound)	November and December

these recommendations to local conditions and to suspend operations during unseasonable weather.

What Is the Probability of Response?

Positive growth response to nitrogen fertilization is likely in most coastal Douglas-fir stands. For British Columbia trials, volume growth in fertilized plots was greater than growth in control plots for 76% of Douglas-fir plots and 60% of western hemlock plots, over all thinning levels (Figure 2). For RFNRP trials, gross volume growth increases greater than 10% were found for 75% of the trials in unthinned Douglas-fir stands and 88% of those in thinned stands (Miller et al. 1986b). For unthinned stands, the likelihood of positive response was greater on lower quality sites: Miller et al. (1988) found that nitrogen fertilization increased growth in about 70% of unthinned and thinned Douglas-fir stands in southwestern Oregon, and in none of the eight western hemlock installations evaluated. Information available for other species is too limited to make a regionwide assessment of likelihood of response.

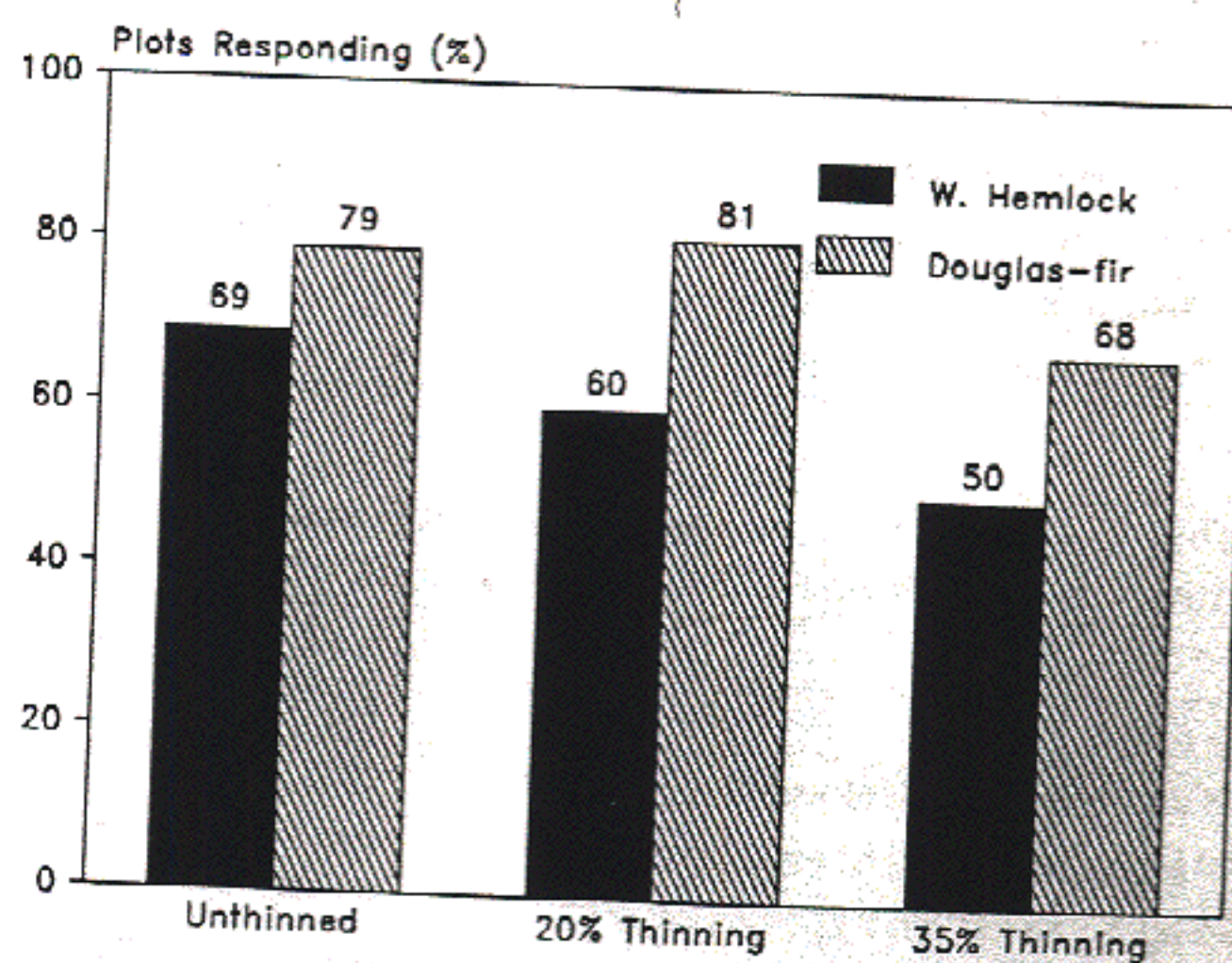


Figure 2. Likelihood of response in British Columbia fertilization trials: percentage of EP703 plots with gross volume PAI response >0, across all fertilizer levels, for Douglas-fir and western hemlock.

What Are the Expected Volume Gains?

Much of the forest fertilization work in coastal forests has focused on development of accurate response estimates to fertilizer treatments, and response estimates from RFNRP and EP703 analyses provide the most substantial information base. Recent analyses of 16-year results for RFNRP Douglas-fir installations and 12-year results for EP703 Douglas-fir and western hemlock installations are summarized here.

RFNRP installations in unthinned and thinned stands used in this analysis span a range of sites, ages, and initial stand density levels; mean initial stand conditions are summarized in Table 2. Fertilization treatments included 224 kg and 448 kg N/ha initially, and refertilization of a subset of plots with 224 kg N/ha after 8 and 12 years (Table 3). Thinned installations had 40% of initial basal area removed from below at the time of study establishment, and plots were rethinned after 10 years to relative density 40 (Curtis 1982). Plots were measured and growth was calculated at two-year intervals.

Average responses to initial fertilization and refertilization after 8 and 12 years were statistically significant in unthinned- and thinned-stand installations (Stegemoeller and Chappell 1990). Gross volume responses in unthinned stands ranged from 1.1 to 5.3 m³/ha annually in the first four two-year growth periods following initial applications of 224 and 448 kg N/

Table 2—Initial stand conditions for Douglas-fir installations in RFNRP trials in western Oregon and Washington. From Stegemoeller and Chappell (1990).

Variable	Unthinned Stands	Thinned Stands
Number of installations	80	34
Breast height age (yr)	31	30
Site index (m at 50 yr)	36	35
Stems per hectare	1,804	840
Basal area (m ² /ha)	46	28
Total volume (m ³ /ha)	452	265

Table 3—Treatment codes for RFNRP installations in unthinned and thinned Douglas-fir stands.

Treatment	Unthinned	Thinned
No fertilization	0N	0T
224 kg N/ha at time of establishment	2N	2T
448 kg N/ha at time of establishment	4N	4T
224 kg N/ha at 8 and 12 years after establishment	0NR	0TR
224 kg N/ha at establishment + 224 kg N at 8 and 12 years after establishment	2NR	2TR
448 kg N/ha at establishment + 224 kg N at 8 and 12 years after establishment	4NR	4TR

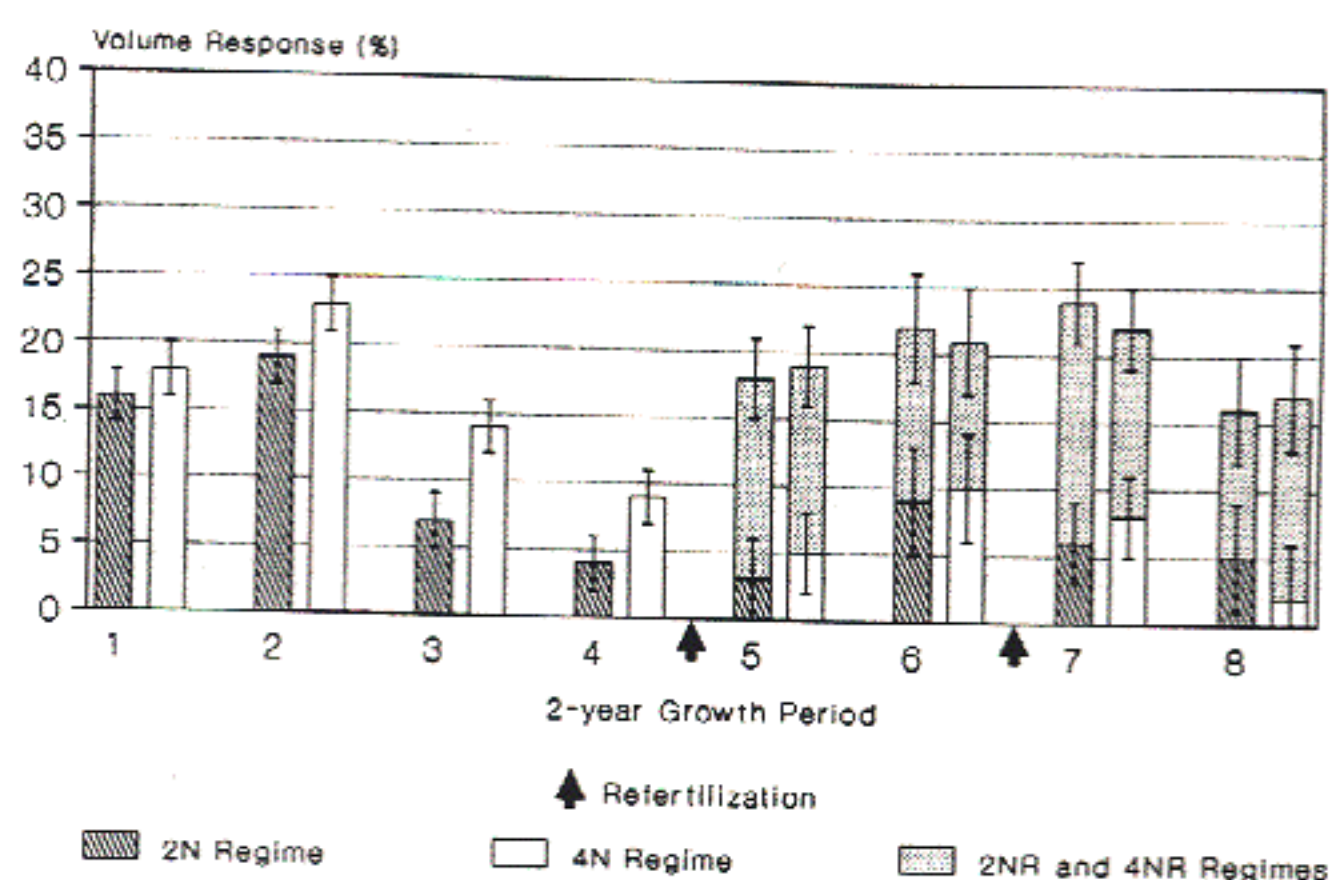


Figure 3. Relative volume growth response (± 1 SE) by two-year growth period, for RFNRP installations in unthinned Douglas-fir stands. From Stegemoeller and Chappell (1990).

ha. Refertilization with 224 kg N/ha after 8 and 12 years (periods 4 and 6) produced significant responses of similar magnitude. The same treatments in thinned stands resulted in responses ranging from 0.8 to 5.9 m³/ha annually in the first four growth periods after initial fertilization, and similar results after refertilization. Relative volume growth responses by two-year growth period are shown in Figure 3 for unthinned stands and in Figure 4 for thinned stands.

As with RFNRP installations, Douglas-fir installations in EP703 were selected to span a range of sites, ages, and initial stand density levels. Mean initial stand conditions are summarized in Table 4. Fertilization treatments included 224 kg and 448 kg N/ha initially, and thinning treatments called for 20% and 35% of initial basal area removal in a modified crown thinning at the time of plot establishment (Table 5). Plots were

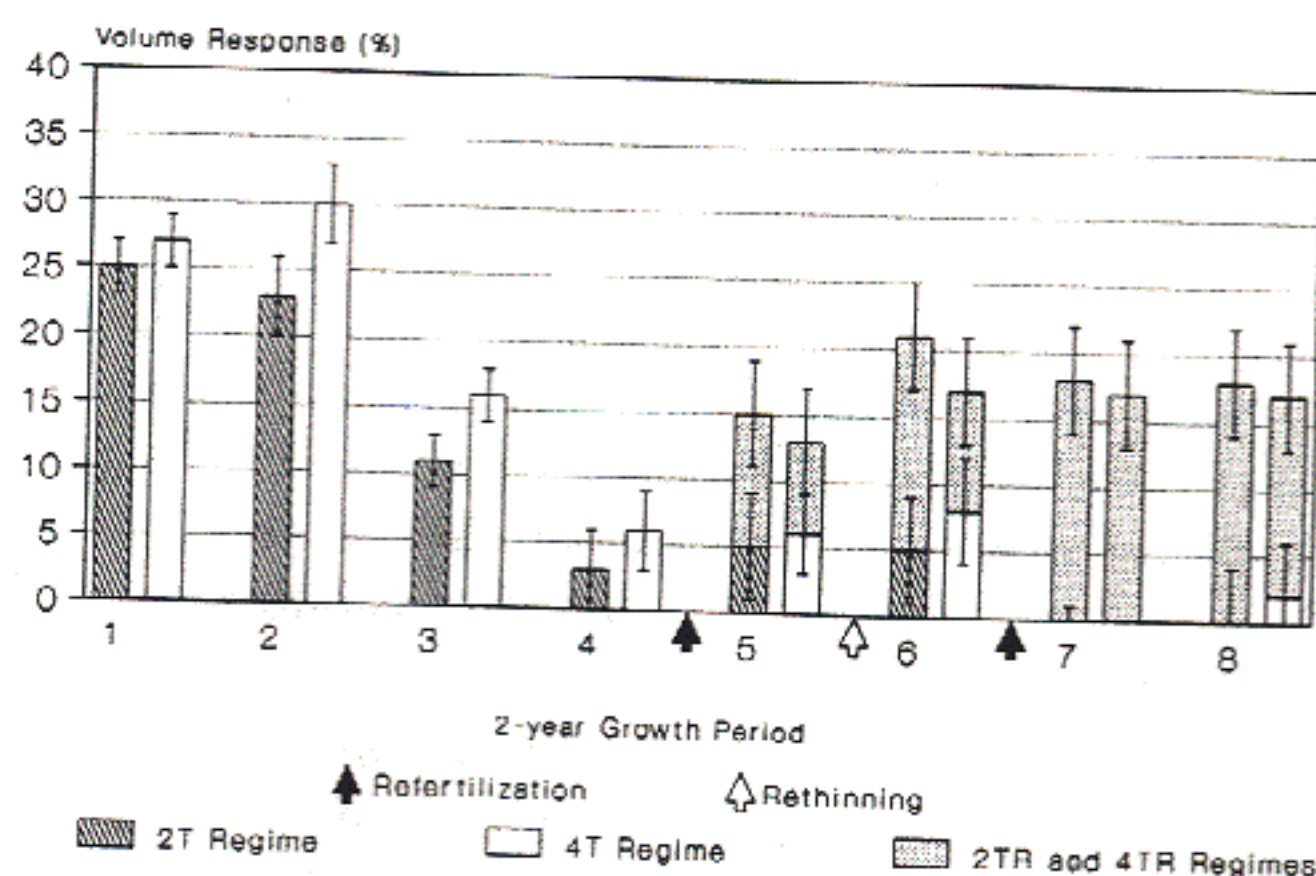


Figure 4. Relative volume growth response (± 1 SE) by two-year growth period, for RFNRP installations in thinned Douglas-fir stands. From Stegemoeller and Chappell (1990).

Table 4—Initial stand conditions for Douglas-fir and western hemlock installations in EP703 trials in coastal British Columbia.

Variable	Douglas-fir	Western Hemlock
Number of installations	21	16
Total age (yr)	35	44
Site index (m at 50 yr)	32	32
Stems per hectare (before thinning)	2,412	3,460
Basal area (m ² /ha)	41	71
Total volume (m ³ /ha)	811	811

measured and growth was calculated at three-year intervals. Patterns of response similar to RFNRP results were observed for unthinned stands, with significant increases in volume growth for two and three three-year growth periods for the 224 and 448 kg N/ha treatments, respectively. Fertilized plots at both thinning levels had significantly greater growth than unfertilized thinned plots, with more response to the higher fertilizer application rate (Figure 5). For the entire response period of 12 years, fertilization significantly increased growth over controls at all thinning levels, with gains ranging from 2.2 to 5.4 m³/ha annually (Figure 6).

Western hemlock installations in the British Columbia trials were also selected to span a range of site and stand conditions, and included the same fertilization and thinning treatments as the Douglas-fir installations (Tables 4 and 5). As for previous fertilization trials in western hemlock, responses were inconsistent and generally nonsignificant (Figure 7). Fertilizer responses in the first three-year period after treatment were significant for T0 and T2 thinning treatments, but not for T1 plots. Responses in subsequent growth periods were generally nonsignificant, and 12-year response was significant only in unthinned plots (Figure 8).

Table 5. Thinning and fertilization treatments for EP703 installations in Douglas-fir and western hemlock stands. (Only treatments reported in this chapter are listed here.)

FERTILIZATION TREATMENTS

- F0 Control (no fertilization)
- F1 224 kg N/ha at time of establishment
- F2 448 kg N/ha at time of establishment

THINNING TREATMENTS

- T0 Control (no thinning)
- T1 20% basal area removed; crown thinning at establishment
- T2 35% basal area removed; crown thinning at establishment

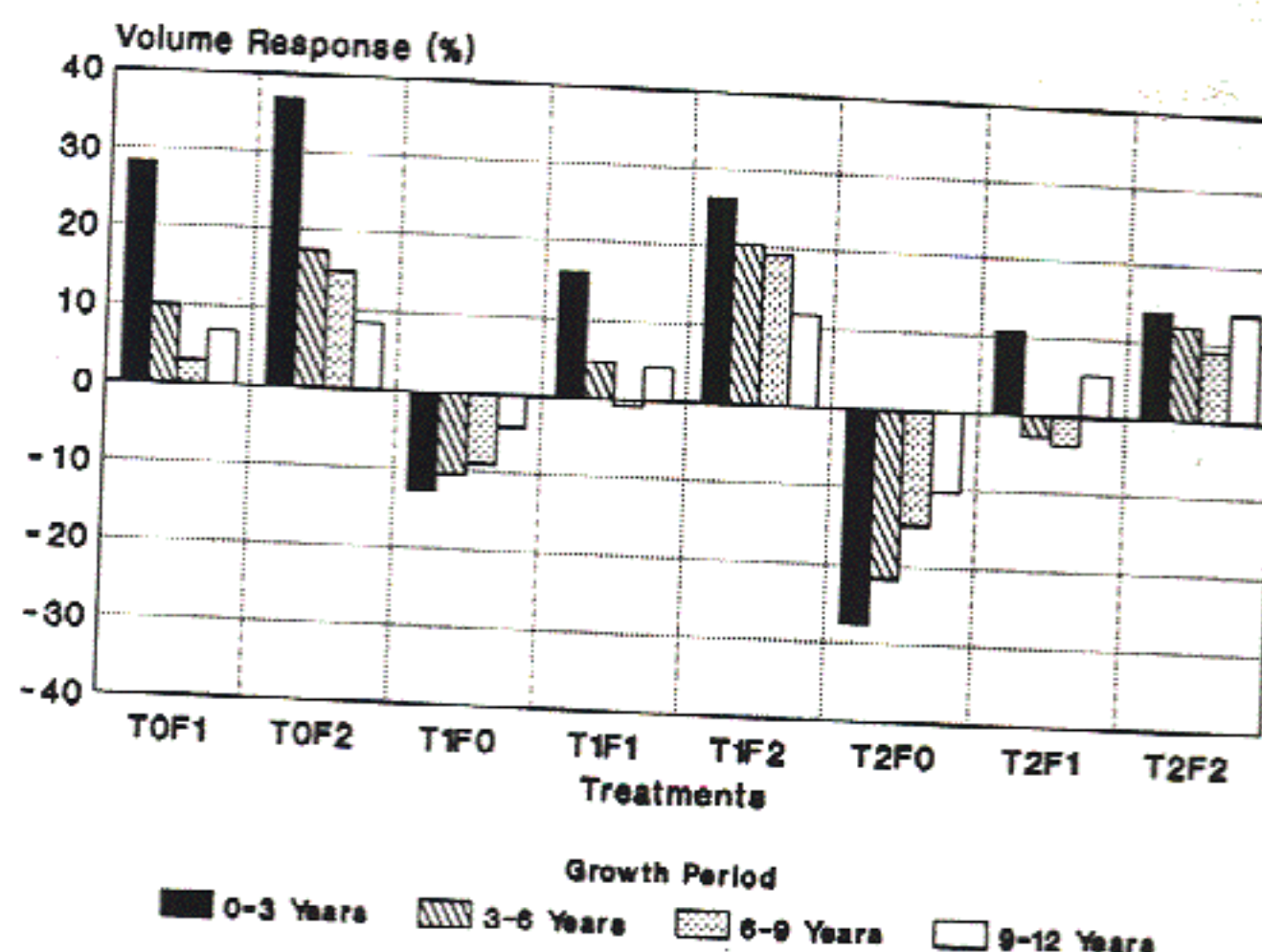


Figure 5. Relative volume growth responses by three-year growth period for thinning and fertilization treatments in EP703 Douglas-fir installations. Response is relative to TOFO (no thinning, no fertilization).

Miller et al. (1988) analyzed responses to nitrogen fertilization in southwestern Oregon Douglas-fir stands and found volume gains comparable to broad regional averages for the same site and age combinations. For a range of ages and site indices, they predicted net volume growth increases on fertilized plots of as much as 4.8 m³/ha annually over a 10-year period.

Based on long-term fertilization studies, a range of mean volume growth rates can be developed. Using RFNRP and EP703 long-term averages to single applications of 224 kg N/ha, approximate gross volume gains 10 years after fertilization are 22-25 m³/ha for unthinned

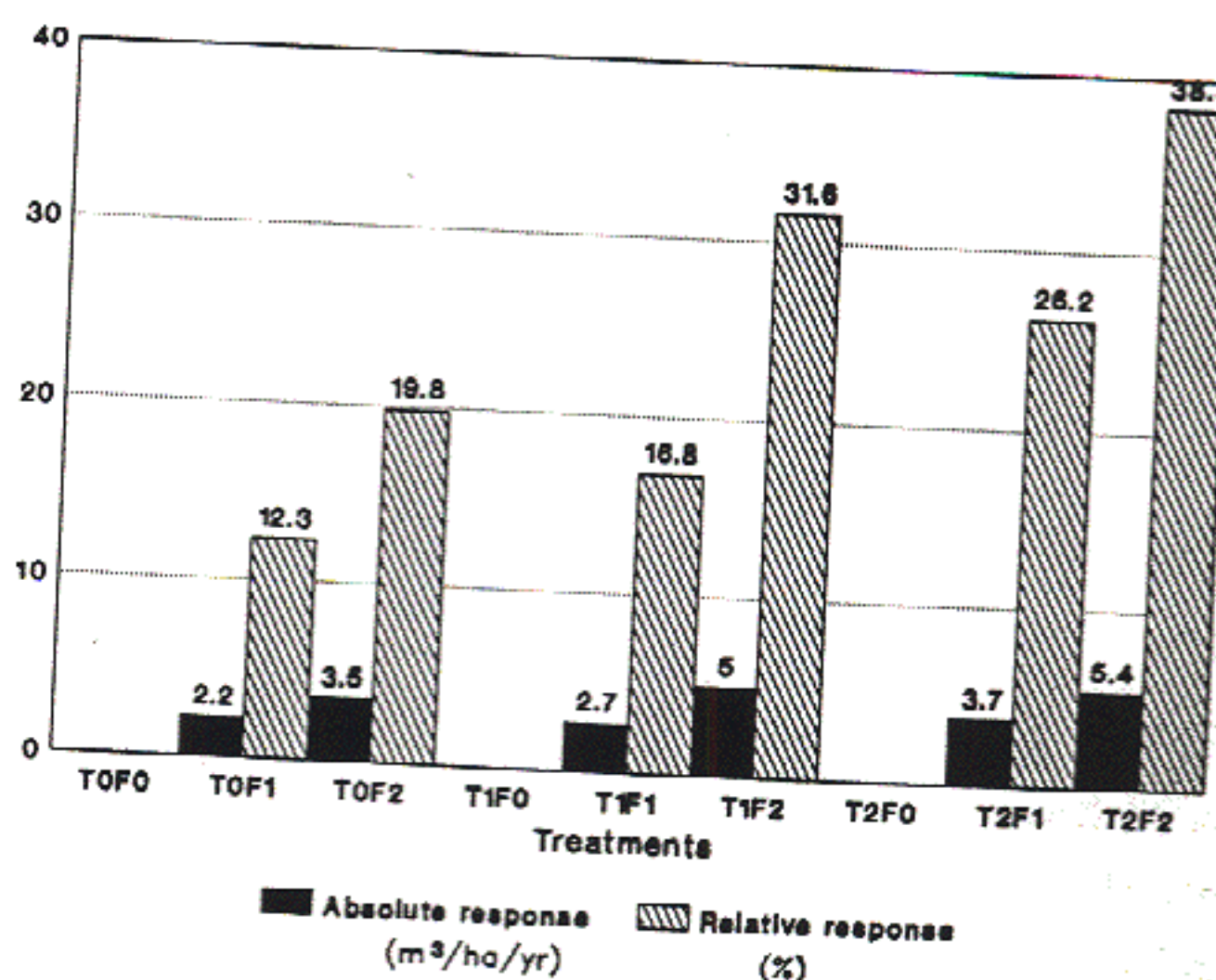


Figure 6. Absolute and relative volume growth responses for 12 years after thinning and fertilization in EP703 Douglas-fir installations. Response is relative to T*FO (unfertilized stands at the same thinning level).

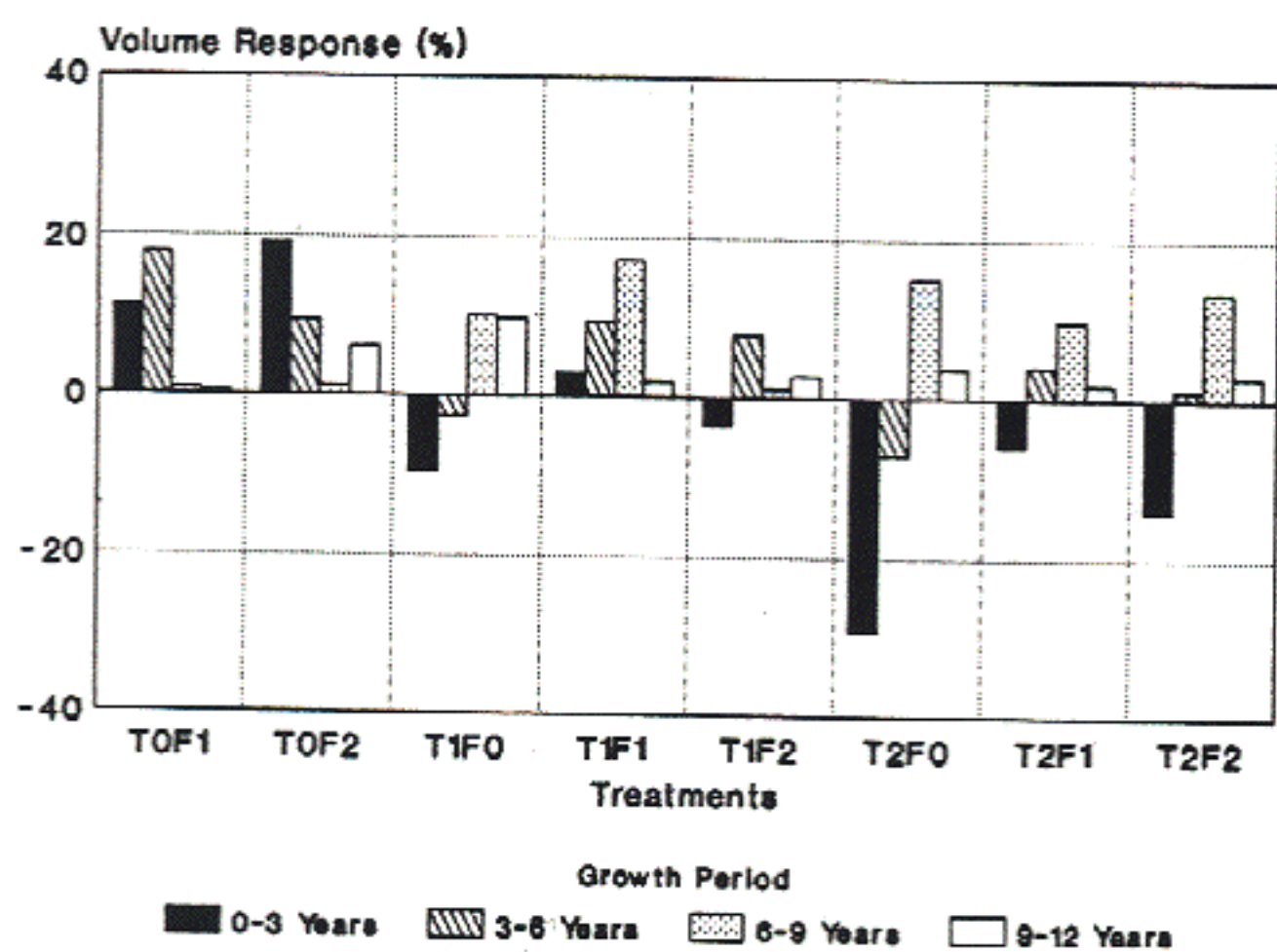


Figure 7. Relative volume growth responses by three-year growth period for thinning and fertilization treatments in EP703 western hemlock installations. Response is relative to TOFO (no thinning, no fertilization).

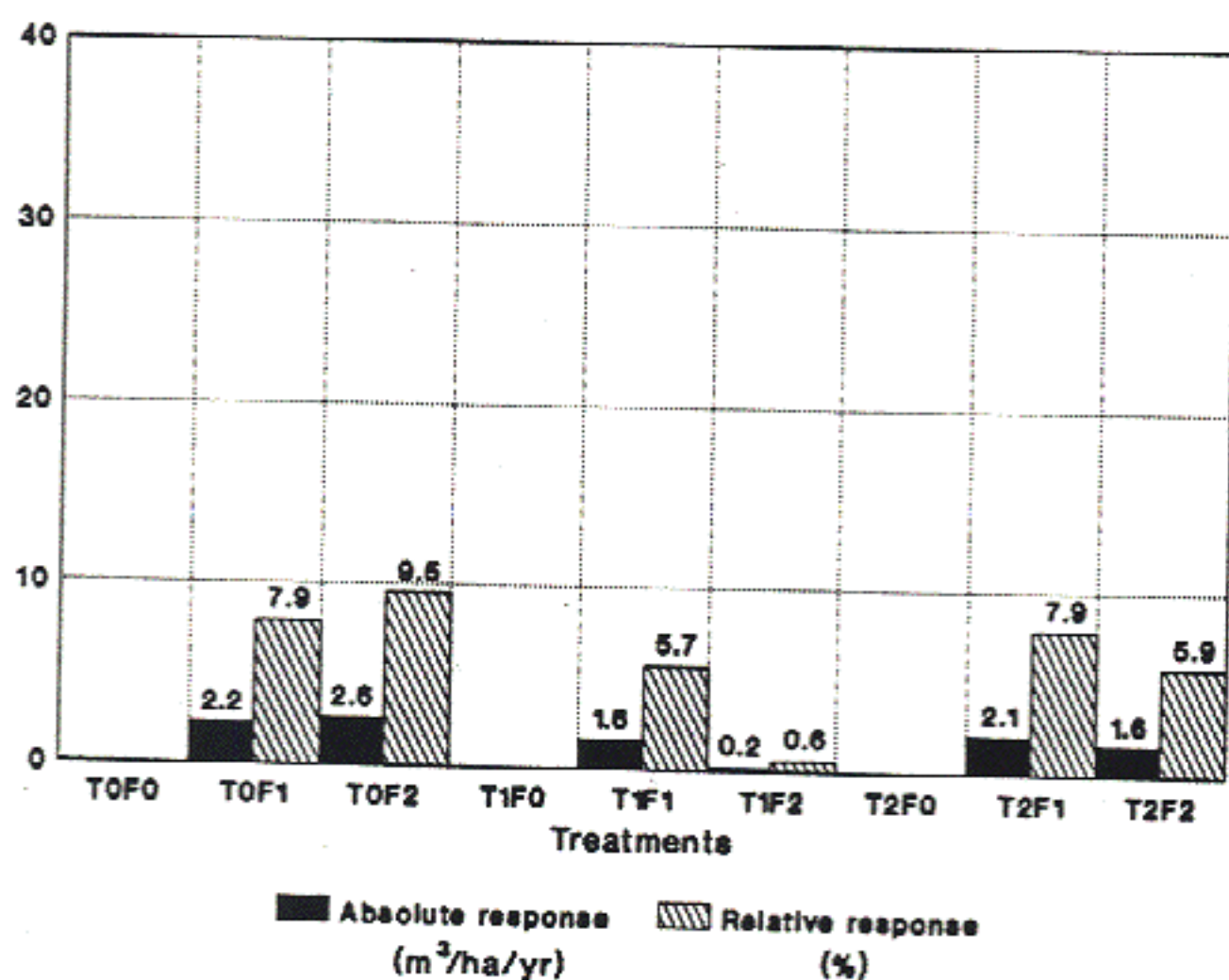


Figure 8. Absolute and relative volume growth responses for 12 years after thinning and fertilization in EP703 western hemlock installations. Response is relative to T*FO (unfertilized stands at the same thinning level).

stands and 27-32 m³/ha for thinned stands. These estimates are intended to roughly describe the magnitude of response, rather than to be used for yield forecasting. Statistically valid estimates of response published in more detailed reports are required to predict growth and yield after treatment.

How Long Does Response Last?

The duration of gross volume growth response to a single fertilizer application in RFNRP Douglas-fir trials is between approximately 8-10 years in thinned stands

and 12-14 years in unthinned stands (Stegemoeller and Chappell 1990) (Figures 3 and 4). Responses to a second fertilizer application after eight years were significant for at least two growing seasons. Site quality may influence response duration, with growth increased longer on poor quality sites (Miller et al. 1986b).

Growth response to fertilization can be partitioned into direct and indirect effects. Direct effects on tree growth response are due to improved nutrition; indirect effects are due to altered stocking resulting from response to treatment in previous growth periods. For RFNRP plots fertilized once with nitrogen, almost all of the response observed after 12 years is due to increased stocking level (indirect effect) (Opalach and Heath 1988).

How Does Fertilization Influence Incidence and Severity of Stand Damage?

Incidence of winter damage may increase in fertilized stands, with higher dosages of nitrogen leading to increased breakage and mortality at one location (Miller and Pienaar 1973). Fertilization increases the amount and surface area of foliage, and increased accumulation of snow and/or ice and greater resistance to wind results in more breakage.

Only limited research has been conducted on the influence of fertilization on insects and diseases in coastal forests. Nelson (1972) examined fertilization effects on root rots in RFNRP plots and concluded that *Phellinus* and *Fomes* problems would not be increased by fertilization. Sinclair (1975) found that plant parasitic nematodes on Douglas-fir seedling roots were suppressed by urea fertilization in a Washington nursery. Forest soil microbial populations are influenced by changes in nutrient substrate, especially C:N ratio, so it may be that repeated fertilizer treatments will directly or indirectly affect soilborne pathogens and therefore host-disease relationships. While there is little information on this subject, we may conclude that improved tree growth due to better nutrition has good ameliorative potential.

The relationship of fertilization response to incidence and severity of animal damage is unclear, although negative effects have not been a significant concern in the region. Several studies have found no clear indications that black-tailed deer (*Odocoileus hemionus columbianus*) prefer shoots from fertilized Douglas-fir seedlings over those from unfertilized seedlings (Oh et al. 1970; Radwan et al. 1974). Feeding damage by black bears (*Ursus americanus*) to Douglas-fir trees was found to be significant in a stand in Oregon, where bears preferentially stripped bark of larger trees in fertilized plots over trees in control plots (Nelson

1989). Fertilization influences on growth and vigor of trees may provide localized indirect effects that enhance or diminish effects of damage by rodents, deer, bear, and other animals.

Information on other species and for other fertilizer treatments and treatment combinations with regard to damage potential is quite limited and includes anecdotal observations on very few sites.

Some Unanswered Questions

The research needs presented in an earlier section have been addressed through ongoing research programs, but substantive issues remain in several areas. As well as a need for greater understanding of the topics discussed, additional questions have arisen due in part to the success of research projects and operational fertilization programs. Many of these "new" questions relate to the interactions of treatments, such as combined effects of fertilization and thinning. Issues for the future are covered in another chapter in this volume (DeBell et al.); we briefly discuss several here that we feel have immediate practical significance to planning and implementing fertilization programs in coastal forests.

How does fertilization interact with other treatments? Silvicultural treatments such as vegetation management, thinning, and pruning affect tree and stand development, and are being implemented on varying scales for areas allocated to intensive management. Many of the same stands will have one or more fertilizer applications during the rotation. There is inadequate information available for reliable prediction of harvest quantity and quality from stands where several treatments have been applied.

How will fertilizer response x genotype interactions affect development of future plantations? There has been limited work to date examining interactions between fertilization treatments and genotypic variation for coastal species. Family x fertilizer interactions for open-pollinated families of Douglas-fir were significant for potted seedlings in several trials (Rediske et al. 1968; Wilson and Anderson 1974; Bell et al. 1979), but were not significant for a 12-year-old field study (DeBell et al. 1986). For western hemlock, Radwan et al. (1990) concluded that selection of superior families may be made equally well with or without fertilizer, based on nonsignificance of family x fertilizer interactions in a seedling study. Plantations established in coastal areas will increasingly be established with selected genotypes, and information is needed on genotype x site x fertilizer interactions to project growth and development of these stands.

What about response information for other species? As evident in this chapter, response information is very limited for species other than Douglas-fir and western hemlock. Fertilization trials have been conducted in western redcedar, Sitka spruce, and a few other species in coastal forests, but the information base is inadequate for effective recommendations. Better understanding of nutrition of all coastal species will result in better species-site matching and more effective nutrient management regimes.

How can we best prescribe/predict responses for mixed-species stands? Information available on responses in mixed-species stands is very limited, yet many managers foresee that management of mixed-species stands will be more common in the future. Analysis of data from about 200 plots established in mixed Douglas-fir and western hemlock stands in British Columbia will help. Response information for other species mentioned above could be utilized in developing interim guidelines.

What about fertilization in uneven-aged stands? Current trends in forest management imply that uneven-aged stands will be more common in the future. Can fertilization be an effective silvicultural tool in these stands? What information is needed to accurately predict responses to fertilization, and to develop prescriptions?

Application of Response Information

Response information is used to build, calibrate, and validate growth models, and to assist forest managers in selecting candidate stands and treatment levels for fertilizer application. The magnitude of responses indicated by research results is not necessarily the same as that expected operationally, and managers can take several approaches to adjust for particular conditions and management objectives.

The response estimates reported in research trials are usually based on uniform application of treatments to small, uniform plots. However, silviculturists often want estimates of the magnitude of growth response under operational conditions for their treated stands. It is inappropriate to apply research results to entire ownerships because the range of site and stand conditions encountered is much greater than the conditions sampled by field studies. If the land base is adequately stratified, research results can be utilized directly to predict operational responses for stands within the range of conditions covered by the research trials. Methods used can vary from simple stand growth projections to sophisticated optimization exercises taking into account the variation in responses in the research data base and the variation in the timber stand inventory. In

applying any research information, it is the responsibility of the user to ensure that direct use of research data is appropriate for the purpose at hand.

Another approach is to estimate growth response falldown (the difference between research growth predictions and growth response under operational conditions), which is a consequence of treatment and stand variability under operational conditions. According to Strand and Promnitz (1981), such estimates for fertilization treatment "can be used to develop more realistic expectations of cost/benefits of fertilization. They can also be used to assess the limits of economic investment to achieve greater degrees of application uniformity."

How do we estimate operational growth response? A direct method that has been applied in British Columbia (Barber 1991) has involved establishment of plots in operationally treated stands, along with "control plots" in nearby untreated stands. The difference in growth between the treated and control plots then gives operational growth response. This direct approach will likely fail because: (1) it is extremely difficult, if not impossible, to match treated and control plots under operational conditions; (2) the number of plots required to detect any response, and to obtain an estimate applicable to a wide area, is prohibitively high, given the treatment and stand variability; (3) the method does not use the research-based estimates; and (4) the estimates may be biased (e.g., why was the nearby stand not treated?).

An indirect and more appropriate method to determine operational growth response, as supported by Strand and Promnitz (1981), is to reduce research growth response by a factor to account for treatment and stand variability under operational conditions. This indirect method is analogous to the way Mitchell and Cameron (1985) derived their operational managed stand yield tables. Information needed to estimate growth response falldown could be obtained during selection of stands for treatment (e.g., site occupancy, site and stocking variability) and during treatment audit (e.g., operator variability). Derivation and use of growth response falldown factors must be carefully done by those planning treatments, with a clear understanding of the assumptions involved.

Summary and Conclusions

Considerable progress has been made in the last decade in understanding responses to fertilization in coastal forests. The current state of knowledge reflects the maturity of several regional data bases, which include many years of growth and response data for research

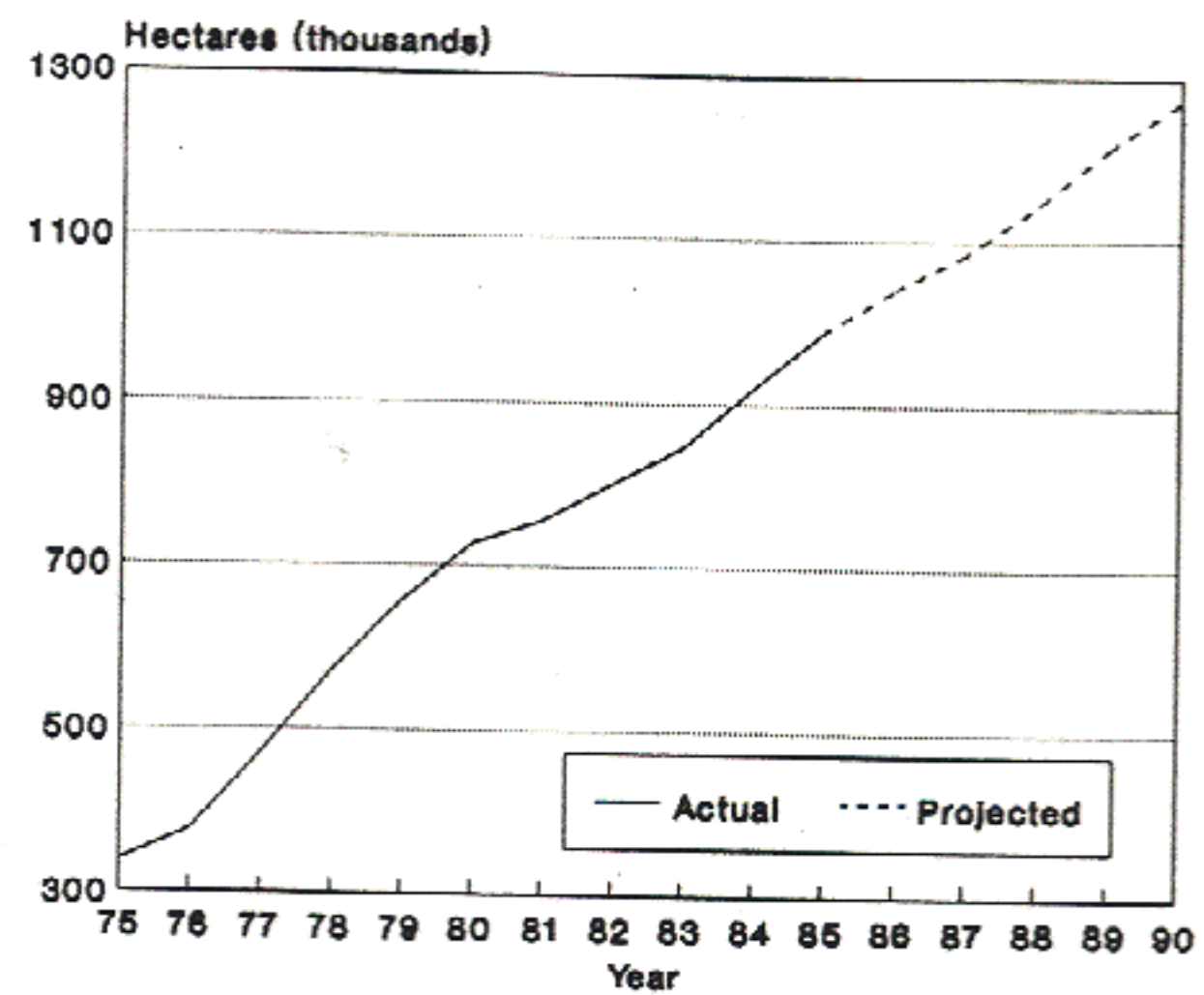


Figure 9. Cumulative area fertilized in western Oregon and Washington, 1975-90 (1986 RFNRP survey data).

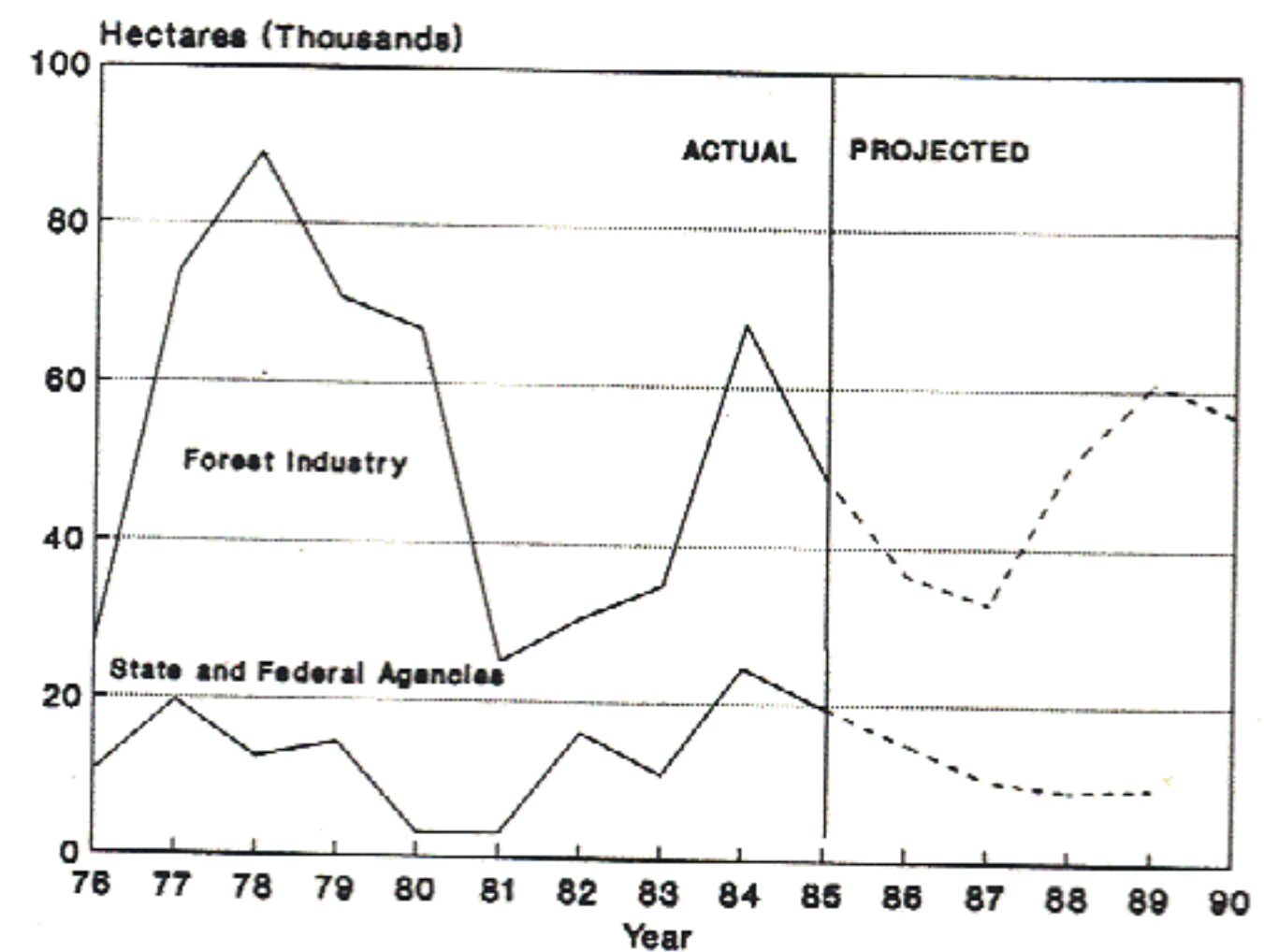


Figure 10. Annual fertilization by forest industry and state and federal agencies in western Oregon and Washington, 1976-90 (1986 RFNRP survey data).

studies. Forest fertilization research has provided a sound basis for operational fertilization programs in coastal forests, and continued improvement is desirable. Information available to forest managers today can be used with confidence to prescribe fertilization treatments and project responses for a range of site and stand conditions. Still needed is information regarding multiple fertilizations, combinations with thinning and other silvicultural treatments, precise site-specific response estimates, and treatment effects on long-term site productivity. Ongoing programs are directed specifically at these needs.

Operational fertilization recommendations in coastal forests call for nitrogen fertilizer usually applied as urea to Douglas-fir stands over a range of soil and stand types (Chappell and Opalach 1984). Generally, the recommended fertilizer dosage is 224 kg N/ha, and refertilization is prescribed after 7-10 years. More than one million hectares have been fertilized in western Oregon and Washington since 1965 (Figure 9), and about 50,000 to 55,000 are fertilized each year (Figure 10). In British Columbia about 3,000 to 10,000 hectares are fertilized annually. Future programs are expected to be of similar magnitude, and regimes for managed stands are likely to include multiple fertilizer applications in conjunction with thinning and possibly pruning. These interacting treatments will affect the character of managed stands in the region, with consequent changes in the quantity and quality of timber produced in the future.

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Questions and Answers

If a thinned Douglas-fir stand and an unthinned stand of similar density were fertilized, would response be significantly different?

If primary stand characteristics are truly similar, then it is likely that response to nitrogen fertilization will also be similar. Conditions for this similarity include stand age, site quality, tree vigor, and characteristics related to stand density, notably crown dimensions. Growth of stands recently thinned from high density levels—where crowns are small due to intertree competition—to low density levels probably will not increase as much as for unthinned stands that have been at lower density levels for some time. Trees in the unthinned low density stands are likely to have larger crowns and more room for crown expansion and therefore potentially greater ability to respond, if nitrogen is a factor limiting growth.

Some papers report that unthinned stands showed more response than thinned stands, and some report the opposite. There must be something said about tree-level versus stand-level response as well as degree of thinning. Can you expand?

This question includes the lead-in to its answer: most results reported are for stand-level responses, and the nature of thinning is an important factor. Regional results show greater stand growth responses after fertilization in thinned versus unthinned stands. Single trials may give better site-specific information, but extrapolation to other stands is limited due to site, stand, and treatment differences. All other things being equal, trees with adequate crowns and room for crown expansion

will exhibit the best response, so thinned stands will *usually* have greater response, at both the tree and stand level. Thinning treatments vary widely, not only in degree of stocking reduction but in stand structure changes and the stage of stand development at the time of thinning.

Another point to consider in comparing results is to examine the type of growth response—gross versus net—used in the analysis. Long-term gross responses, especially in unthinned stands, may include substantial mortality. Growth increases in thinned stands will apply to fewer, larger trees, with practical implications for log value and extraction costs.