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Thinning Shock and Response to Fertilizer Less than Expected in Young Douglas-Fir Stand at Wind River Experimental Forest

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Abstract

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Three thinning treatments (thinned to 3.7 by 3.7 m, thinned to 4.3 by 4.3 m, and an unthinned control treatment with nominal spacing averaging 2.6 by 2.6 m) were installed in a 10-year-old Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) plantation growing on a low-quality site at the Wind River Experimental Forest in southwest Washington. Two years after thinning, two fertilizer treatments were superimposed on the design (0 and 224 kg per ha of nitrogen applied as ammonium nitrate). Diameter growth increased with increasing spacing throughout the 6-year study period, and it was also increased by fertilizer in both the thinned and unthinned (control) treatments. Thinning shock, a reduction in height growth after thinning, was expected at this study site because severe thinning shock had been documented in earlier nearby trials. Height growth was initially reduced slightly by thinning, but by the third 2-year period after thinning, height growth in thinned, unfertilized treatments was equal to or greater than height growth in the unthinned, unfertilized treatment. Fertilizer application increased height growth on average by 13 percent in the first 2 years after fertilization. In the third and fourth years after fertilization, however, fertilizer increased average height growth by 9 percent, but the increase was substantial (16 percent) only in the unthinned control treatment. The mild, ephemeral nature of thinning shock in our study was in contrast to the severe, long-lasting shock in earlier studies at Wind River. The milder shock in our study could be related to one or more of the following: (1) thinning was done at an early age, (2) impacts of fire (natural or prescribed) preceding planting were minor, and (3) seed source of the planted stock was appropriate for the location. Based on comparisons with other studies at Wind River and elsewhere, we suspect that use of nonlocal, maladapted seed sources in the earlier studies may have predisposed those trees to thinning shock. Furthermore, we suspect that the much higher responses to fertilizer application reported in the earlier studies may be associated with intense natural fires prior to planting, and the reduced nutritional status of those sites may have been further exacerbated by the use of maladapted seed sources.

Keywords: Thinning, thinning shock, fertilization, nitrogen, seed source, fire, Wind River.

Summary

Long considered the “cradle of forestry research” in the Douglas-fir region, the Wind River Experimental Forest in southwest Washington served as the type location and initial trial site for many practices used in Pacific Northwest forests today. In several instances, the results and trends in the Wind River studies were more dramatic than those subsequently observed in other locations and in other species. Such differences have been particularly evident in growth responses to thinning and fertilization, two common silvicultural practices in young-growth stands of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco). A few years ago, we established a new study of thinning and fertilizing in a young plantation at Wind River to refine knowledge of thinning shock (a reduction in height growth after thinning) and the role that nitrogen (N) fertilizer may play in overcoming it. Our study site is near the stands in which severe thinning shock and dramatic growth increases with fertilization have been observed. Three thinning treatments (thinned to 3.7 by 3.7 m, thinned to 4.3 by 4.3 m, and an unthinned control treatment with nominal spacing averaging 2.6 by 2.6 m) were installed in a 10-year-old Douglas-fir plantation growing on a low-quality site. Two years after thinning, two fertilizer treatments were superimposed on the design (0 and 224 kg per ha of nitrogen applied as ammonium nitrate). Diameter growth increased with increasing spacing throughout the 6-year study period, and it was also increased by fertilizer in both the thinned and unthinned (control) treatments. Height growth was initially reduced slightly by thinning, but by the third 2-year period after thinning, height growth in thinned, unfertilized treatments was equal to or greater than height growth in the unthinned, unfertilized treatment. Fertilizer application increased height growth on average by 13 percent in the first 2 years after fertilization. In the third and fourth years after fertilization, however, fertilizer increased average height growth by 9 percent, but the increase was substantial (16 percent) only in the unthinned control treatment. The mild, ephemeral nature of thinning shock in our study was in contrast to the severe, long-lasting shock in earlier studies at Wind River. The milder shock in our study could be related to one or more of the following: (1) thinning was done at an early age, (2) impacts of fire (natural or prescribed) preceding planting were minor, and (3) seed source of the planted stock was appropriate for the location. Based on comparisons with other studies at Wind River and elsewhere, we suspect that use of nonlocal, maladapted seed sources in the earlier studies may have predisposed those trees to thinning shock. Furthermore, we suspect that the much higher growth responses to fertilizer application reported in the earlier studies may be associated with intense natural or prescribed fires prior to planting, and the reduced nutritional status of those sites may have been further exacerbated by the use of maladapted seed sources.

Introduction

Long considered the "cradle of forestry research" in the Douglas-fir region, the Wind River Experimental Forest served as the type location and initial trial site for many practices used in Pacific Northwest forests today. In several instances, the results and trends in the Wind River studies were more dramatic than those subsequently observed in other locations and in other species. Such differences have been particularly evident in growth responses to thinning and fertilization, two common silvicultural practices in young-growth stands of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco).

Thinning affects tree growth primarily by reducing the number of stems per unit area and concentrating existing site resources on remaining crop trees. Diameter growth is substantially increased, and height growth is usually unaffected or slightly enhanced. In some instances, however, thinning causes a reduction in tree growth, especially height increment. This phenomenon, sometimes called thinning shock, was first measured quantitatively in a respacing trial in a 25-year-old Douglas-fir plantation on the Wind River Experimental Forest by Staebler (1956a). The reduction in growth at that site, however, was substantial and continued for 10 to 15 years after thinning, particularly in the widest spacings (Harrington and Reukema 1983). Shock was also severe in another thinning (and fertilizing) test at Wind River, even resulting in negligible response in diameter growth (Miller and Reukema 1977).

Nitrogen (N) fertilizer applications in the Pacific Northwest usually cause an increase in tree growth and stand productivity by increasing total nutrient resources available at a forest site. Regionwide trials indicate 70 percent of Douglas-fir stands show moderate to large growth increases after N application at 224 kg per ha, and response is slightly more consistent and somewhat greater in thinned than in unthinned stands (Chappell and others 1992, Peterson and others 1986). Miller and others (1986) evaluated these same regionwide trials and found that stands growing on sites of low quality had greater relative (and absolute) response to fertilizer than did stands on sites of high quality. They also suggested that N application would be most beneficial biologically when crown development is rapid and trees begin to fully use other site resources. Some of the most impressive growth responses to N applications have occurred in Douglas-fir plantations at Wind River (Miller and Reukema 1977, Miller and Tarrant 1983).

Where N fertilizer has been applied in experimental stands that manifested thinning shock, the shock symptoms have been reduced or mitigated (Brix 1993, Crown and others 1977). Such benefits were particularly evident in a thinning-fertilizing test in a 20-year-old plantation at Wind River; thinning reduced height growth by 25 percent, and diameter growth showed no improvement over a 5-year period, whereas fertilizing the thinned trees nearly doubled height growth and increased their diameter growth by 84 percent (Miller and Reukema 1977).

Some foresters, recognizing that many of the above-described results of the Wind River studies differ at least in degree from the norm, have suggested that the poor site quality and a harsher climate at Wind River than is typical for its latitude and elevation may contribute to such differences in response. Silen and Olsen (1992) comment, however, that although the Wind River valley is surrounded by mountains, and thus has greater precipitation and a shorter growing season than would be expected for its elevation, the "climate is typical of major valleys for much of the area along the west slopes of the Cascade Range in Oregon and Washington."

A few years ago, we established a new study of thinning and fertilizing in a young plantation at Wind River to refine knowledge of thinning shock and the role that N fertilizer may play in overcoming it. Our study site abuts the stand in which substantial thinning shock and dramatic growth increases with fertilization were reported by Miller and Reukema (1977) and is within a few kilometers of another study where severe and long-lasting thinning shock has been observed (Harrington and Reukema 1983, Staebler 1956a). Responses in the new study, however, were more moderate than anticipated–thinning shock was minor and response to fertilizer was low in relation to earlier trials. We therefore compared characteristics of the new study with older Wind River trials and developed some hypotheses regarding site and stand factors associated with differences in the nature of responses. This paper describes the new study, presents 6-year results, and offers thoughts on factors influencing responses and the implications for management elsewhere.

Study Methods

Study Area

The study area is a long, narrow 23-ha plantation on the Wind River Experimental Forest near Carson, Washington. It is located along a gentle (10 to 15 percent) east-facing slope at 650 m elevation. Precipitation averages 2540 mm per year, but only about 10 percent falls during the May 1-September 30 period of the growing season. Soils at the study site are moderately deep to deep, well-drained loams of the Stabler series, and have developed from volcanic ash and pumice. Vegetation is transitional between the western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and Pacific silver fir (*Abies amabilis* Dougl. ex Forbes) zones (Franklin and Dyrness 1973), and between the western hemlock/salal (*Gaultheria shallon* Pursh) and Pacific silver fir/salal habitat types (Brockway and others 1983). Larger Douglas-fir trees in the plantation averaged a little over 10 m tall at a breast height age of about 15 years; thus, Douglas-fir productivity is site class IV on a 50-year base (King 1966).

The study area was previously occupied by an old-growth stand of mostly Douglas-fir, western hemlock, and Pacific silver fir. It was logged by tractor in 1973, and logging slash was tractor piled on landings and burned. In late April and early May 1975, the unit was planted with 2-1 Douglas-fir grown from seed collected in seed zone 440, the same seed zone as the study area. Target planting density was 740 trees per ha (about 3.7 by 3.7 m), but abundant natural regeneration also contributed to stocking. Other tree species that became established on the site (originating as new seedlings or advanced regeneration) were western hemlock and Pacific silver fir; shrub species included vine maple (*Acer circinatum* Pursh) and Pacific dogwood (*Cornus nuttallii* Aud.); and ground vegetation was made up mostly of salal, Oregongrape (*Berberis nervosa* Pursh), huckleberry (*Vaccinium* spp.), and beargrass (*Xerophyllum tenax* (Pursh) Nutt.).

Treatments

The study site was divided into three blocks of about equal size, and precommercial thinning prescriptions were developed to provide a range of stand densities within each block. The prescriptions were applied at random to the subsections delineated for various thinning treatments within each block. A contract crew conducted the operational thinning in fall 1984; the slash generated by the thinning was left in place. Three distinct thinning levels were achieved: T0, an unthinned control with a nominal spacing of 2.6 by 2.6 m, averaging 1,462 trees per ha; T1, with a nominal spacing of 3.7 by 3.7 m, averaging 744 trees per ha; and T2, a nominal spacing of 4.3 by 4.3 m, averaging 536 trees per ha. In spring 1987, two growing seasons after thinning, two N fertilizer treatments were added to the experimental design: F0, unfertilized control, and F1, ammonium nitrate applied by hand at 224 kg of N per ha.

Plot Installation and Data Collection

Before the 1985 growing season, 27 temporary plot centers were established, and the 25 trees closest to the center stake were tagged and measured for height and diameter. One 25-tree plot was located in each unthinned control area (except for one block which had been thinned throughout), and two or three plots were located in each of the other thinning treatments in each block. These 25-tree plots provided a measure of treatment effects on diameter growth for the first two growing seasons after thinning and served to identify spots where fixed-area plots were subsequently installed.

In fall 1986, 43 permanent fixed-area plots of two sizes were established: 14 large (0.2 ha) plots and 29 small (0.03 ha) plots; the smaller plots were installed primarily to assess short-term response to fertilizer. All trees were tagged and measured for diameter at breast height (d.b.h.), and a sample of trees on each plot were measured for total height. One or more large plots were positioned within each of the three thinning treatments (T0, T1, and T2); none of the large plots received fertilizer. Most of the smaller plots (24) plus a 3-m surrounding buffer received fertilizer application, and the others (5) served to complete the replicated design for assessment of tree growth at all thinning and fertilizer levels in all three blocks. Trees were remeasured for diameter again at the end of the 1990 growing season.

In spring 1991, past annual height increments were assessed retrospectively. On the larger plots (0.2 ha), the 20 tallest trees per plot were selected, and the height at whorls representing the end of growing seasons 1980 through 1990 were measured. On small plots (0.03 ha), the 10 tallest trees per plot were measured in a similar way. All selected trees were in dominant or strong codominant crown positions.

Data Analysis

All data related to growth after treatment were summarized and analyzed in terms of three 2-year growth periods: period 1 (1985 and 1986) included the first 2 years after thinning but before application of fertilizer; period 2 (1987 and 1988) included the third and fourth years after thinning and the first 2 years after fertilization; and period 3 (1989 and 1990) included the fifth and sixth years after thinning and the third and fourth years after fertilization. Only data from trees surviving through 1990 were used in the analyses of growth; mortality was minimal (3 percent), unrelated to treatment, and caused primarily by root rot disease.

Quadratic mean diameter growth during period 1 was analyzed by using data from the temporary 25-tree plots; fertilizer had not yet been applied and the data were analyzed as an unbalanced randomized block with three blocks and three thinning treatments by using a general linear model (SAS Institute 1988). Diameter growth for combined periods 2 and 3 was evaluated with data collected on the permanent plots. The analysis, which was done by using a mixed model procedure (SAS Institute 1996), was an unbalanced, 3 by 2 split-plot factorial (fertilizer treatment was the subplot) with three random blocks.

The retrospective height growth data were used to examine the effects of thinning intensity and N fertilizer on mean height growth of the tallest trees–dominants and large codominants–during the three 2-year periods mentioned above. In period 1, fertilizer had not yet been applied; thus, the data were analyzed as an unbalanced random block with three blocks and three thinning treatments. Height growth data for periods 2 and 3 were analyzed as an unbalanced, 3 by 2 split-plot factorial with three random blocks. In addition, the retrospective height measurement data for the 2 years prior to thinning (1983 and 1984) were evaluated for pretreatment differences in growth.

Preplanned comparisons of mean diameter growth and height growth were made among thinning treatments within each fertilizer treatment for all periods, and also between fertilizer levels within each thinning treatment for periods 2 and 3. Means were considered significantly different if $p \leq 0.10$.

Comparison with Other Studies

To compare the tree growth in this study with growth in other studies in the area, we compiled a list of the other thinning and fertilization trials in young-growth stands in the Wind River Experimental Forest. We then evaluated each study to determine its fire history and, if planted, the site preparation method and seed source used. We ascertained the mapped soil unit for each study area from a geographic information system layer provided by the Gifford Pinchot National Forest and asked a soil scientist familiar with the area to convert the mapping units to the best-fit soil series used by the Natural Resources Conservation Service.

Precipitation during the growing season (May 1 through September 30) was calculated for the initial response period for each study from the records for nearby weather stations located at the Wind River Nursery (1953-1977) and the Carson Fish Hatchery (1978-1997). Long-term records for these stations were available online at www.wrcc.dri.edu. Mean, minimum, and maximum precipitation values for the growing seasons that corresponded with the years of growth measured were evaluated to examine the possibility that growth for individual studies might have been influenced by one or more years of unusually dry or wet conditions. The oldest study did not have weather records available for examination.

Table 1—Tree and stand characteristics immediately after thinning

Thinning treatment	Diameter[a]		Height		Prior height growth[b]		Stocking	
	Mean	Range[c]	Mean	Range	Mean	Range	Mean	Range
	- - Centimeters - -		*- - - - - - - - - - - Meters - - - - - - - - - - -*				*- - Trees per hectare - -*	
T0	6.0a[d]	5.2 - 6.5	4.2a	3.7 - 4.5	1.5a	1.3 - 1.6	1462a	1005 - 1825
T1	6.2a	6.0 - 6.4	4.4a	4.2 - 4.5	1.4a	1.4 - 1.5	744b	706 - 810
T2	6.0a	5.5 - 7.4	4.2a	3.8 - 4.8	1.4a	1.3 - 1.6	536c	508 - 568

[a] Quadratic mean diameter.
[b] Height growth in 1983 and 1984, 2 years before thinning, based on retrospective measurement of height increment.
[c] Ranges are based on plot means.
[d] Means in a column followed by the same letter are not significantly different at $p \leq 0.10$.

For each study, we determined initial stand conditions (age, height, diameter, and density) and the type of treatment (for thinning treatments, the new stand densities and for fertilizer treatments, the rate and type of fertilizer used). Mean tree growth for each treatment was obtained and compared to that in untreated plots. For several studies, the published reports did not contain all the information we required; when possible, we consulted unpublished reports from our office files. Data from Installation 171 of the Forest Regional Nutrition Research project were obtained from the Stand Management Cooperative, College of Forest Resources, University of Washington, Seattle, Washington.

Results and Discussion

Tree and Stand Characteristics After Thinning

Despite the operational nature of the precommercial thinning, tree characteristics were fairly uniform among plots immediately after thinning within each treatment (table 1). Although mean tree size is commonly increased somewhat with level of thinning (because smaller trees are cut), the young, undifferentiated stage of this plantation apparently mediated against such effects associated with treatment implementation. Thus, the uniform initial conditions in the three thinning treatments should have provided a sensitive test of treatment differences in growth rates of trees of similar size. In addition, height growth during the 2 years before treatment (based on retrospective measurements) was remarkably similar among thinning treatments ($p = 0.91$, table 1). Measurements obtained in the fixed-area plots indicated that T1 had, on average, only about one-half the trees that were present in T0, the control; and T2 had only about one-third as many as the control. All thinning treatments differed significantly from each other in tree density, with no overlap among plots in trees per hectare in the different thinning treatments.

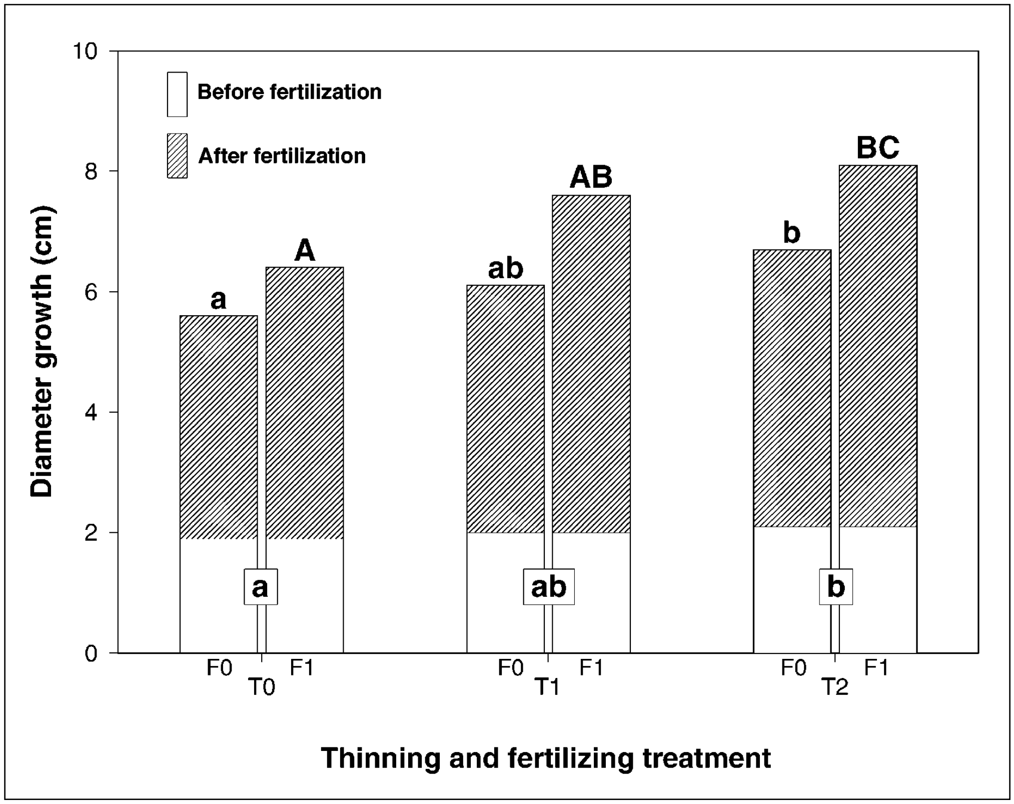

Figure 1—Diameter growth by thinning and fertilizing treatment. Letters centered over the thinning treatment designations indicate differences in growth in period 1 (prior to application of the fertilizing treatments) among the three thinning treatments. Letters on top of the bars indicate differences in growth in periods 2 plus 3 by thinning treatment within a fertilizing treatment (bars topped by the same letter are not significantly different at $p \leq 0.10$; lower case letters refer to the F0 treatment and uppercase letters to the F1 treatment).

Diameter Growth

Assessment of data from the 25-tree temporary plots revealed that diameter growth in the first 2 years increased with the amount of thinning (fig. 1). Growth in the heavier thinning (T2) was about 10 percent greater than in the unthinned control (T0). Growth in the lighter thinning (T1) averaged 5 percent greater than that of the control but did not differ significantly from either the control or the heavier thinning.

Quadratic mean diameter growth response increased in combined periods 2 and 3. In unfertilized plots, diameter growth response averaged 18 percent greater in the heavier thinning than in the unthinned control. Response to thinning in the fertilized plots was greater in absolute amount but similar in relative terms, increasing from about 10 percent in T1 to 18 percent in T2. Response to fertilizer application was significant overall and was similar in all thinning treatments, averaging about 32 percent.

If diameter growth in period 1 and combined periods 2 and 3 (fig. 1) is added to initial diameter (table 1), it is apparent that trees nearly doubled in diameter in the unthinned, unfertilized plots between ages 10 and 16–to nearly 12 cm. During the

Table 2—Height growth of Douglas-fir as related to thinning and fertilization treatments by 2-year periods

Thinning treatment	Period 1[†] (1985-86)	Period 2 (1987-88)			Period 3 (1989-90)		
	Before fertilization	Unfertilized	Fertilized	Difference	Unfertilized	Fertilized	Difference
				Meters			
T0	1.42a[≠]	1.64a	1.87a	0.23*	1.50a	1.74a	0.24*
T1	1.33ab	1.61a	1.76a	.15	1.55a	1.66ab	.11
T2	1.27b	1.56a	1.82a	.25*	1.50a	1.58b	.07

† After thinning.
≠ Means in a column followed by the same letter are not significantly different at $p \leq 0.10$.
* The difference between fertilized and unfertilized was significant at $p \leq 0.10$.

same period, trees in fertilized plots with the heavier thinning grew to 14.4 cm. Thus, when combined, the two cultural practices increased tree diameter by about 20 percent in 6 years.

Height Growth

In contrast to diameter growth, height increment of the selected tallest trees during the first 2-year period after thinning decreased slightly with the intensity of thinning (table 2). Height growth in the heavier thinning treatment was about 11 percent lower than in the unthinned control plots.

In the second 2-year period, height growth in the thinned treatments of the unfertilized plots continued to be slightly lower than in unthinned plots on average (table 2), but such reductions did not approach significance (p = 0.49). Differences among thinning treatments in fertilized plots were negligible. Thus, trees in all treatments recovered from shock by the end of the fourth growing season if not earlier. Response to fertilizer overall was highly significant. Differences between fertilized and unfertilized plots were largest (14 percent and 16 percent) in the unthinned and more heavily thinned plots, and only 9 percent in the lighter thinning treatment.

In the third 2-year period, there were no differences among thinning treatments in height growth in unfertilized plots (table 2); therefore, trees had recovered from the shock evident in earlier measurements. In fertilized plots, however, height growth decreased with thinning, and growth in the heavier thinning was significantly lower than in unthinned plots. Although such a pattern may seem odd, especially given the similarity of growth among thinning treatments in period 2, the renewed reduction in growth with thinning can most likely be linked to development of increased competition from understory shrubs and herbs in thinned and fertilized plots. In a study near Shawnigan Lake on Vancouver Island, Stanek and others (1979) found that the treatment with the heaviest thinning (about two-thirds basal area removed) plus fertilization at 224 kg of N per ha resulted in greater understory biomass than the other thinning and fertilizing treatments tested in the Shawnigan Lake study; bracken fern (*Pteridium aquilinum* L.) biomass was more than six times greater and salal biomass more than double after 5 or 6 years as compared with biomass of these two species in the unthinned, unfertilized (control) treatment. A comparison at Shawnigan Lake involving one unreplicated plot showed that understory removal during the first 5 years after thinning and fertilizing increased tree growth (in this case, the measure was d.b.h.) (Brix 1993). Recent observations on a subsample of plots in our study were consistent with the understory competition hypothesis; that is, understory plants appeared to be taller and denser in the heavily thinned plots that had received an application of N fertilizer (224 kg of N per ha). As trees grow and crowns expand, however, the understory will become shaded and less vigorous, and the relations of height growth to treatment are likely to change.

Over all periods and thinning treatments, fertilization increased height growth and was statistically significant, but means between the fertilized and unfertilized treatments differed significantly only for the unthinned plots (T0). Lack of significant growth responses to fertilizer in the thinned plots (T1 and T2) is probably related to increased competition for moisture and nutrients associated with enhanced development of the understory.

During the 6 years after thinning, mean height of the selected tallest trees more than doubled–increasing from 4.2 to about 8.7 m, on average, in unfertilized plots and to about 9.0 m in fertilized plots (tables 1 and 2). Initial reductions in height growth associated with thinning faded after the first 2 years; by the sixth year, trees in the T2 thinning differed in total height from those in unthinned plots by only 2.6 percent in the unfertilized plots and 3.9 percent in the fertilized plots. Mean tree heights in fertilized plots at all thinning levels were taller than those in the unfertilized, unthinned plots; therefore, fertilizer application more than compensated for any height growth reduction associated with thinning. Still, the increase in mean tree height associated with combined heavy thinning and fertilization amounted to only 2 percent after 6 years, or in the most productive combination (no thinning but fertilization), only 5 percent; thus, compared with an increase in diameter of about 20 percent, effects of the two cultural practices on height growth were minor.

Comparing Results with Other Studies at Wind River and Elsewhere

We determined that eight other silvicultural studies at Wind River would be of interest to compare with the results in our study (table 3); these studies were located on Trout Creek Hill (as was our study site) or in the nearby drainages of Planting Creek or Martha Creek (fig. 2). These studies were spacing and species mixture trials on Trout Creek Hill (studies 2a and 2b in figure 2 and table 3); the thinning and fertilization trial in a plantation adjacent to our study on Trout Creek Hill (study 3); the wide spacing (study 4), “spot” thinning (individual tree release) (study 6), and fertilization trials (study 5) in the plantation in the Planting Creek area; the “spot” thinning (study 7) and dominance thinning (study 8) trials in natural stands in the Martha Creek area; and a fertilization trial in a natural stand (study 9) on Trout Creek Hill. The studies are all in the same general area and differ little in elevation (fig. 2). In addition, although not identical, they share the same general soil type (ash-influenced, deep, well-drained, mostly loamy soils). The weather stations are nearby and at similar or somewhat lower elevations (fig. 2).

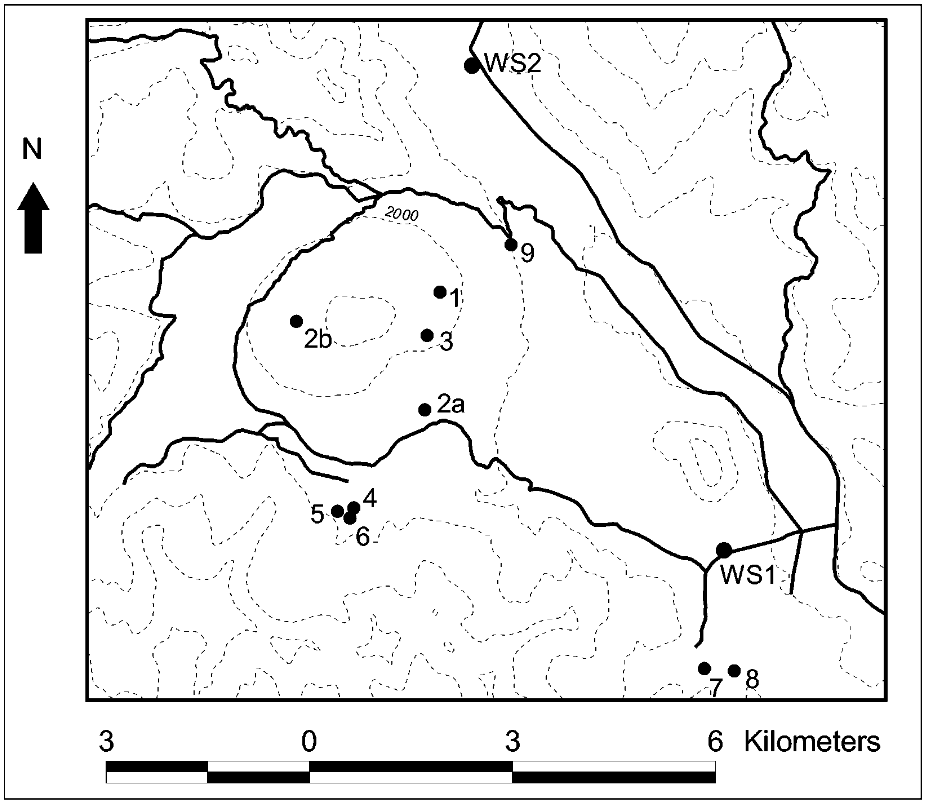

Figure 2—Location of nine silvicultural trials in young-growth stands on the Wind River Experimental Forest and two weather stations (WS1 and WS2) nearby. The numbers in the figure are associated with the studies listed in table 3; 2a and 2b refer to two different trials planted 1 year apart. Major roads are shown as bold lines. Contours are shown as dashed lines with the interval between contour lines 400 m in elevation.

Height and diameter growth in our study were similar to those measured in the nearby young spacing trials on Trout Creek Hill (studies 2a and 2b in table 3); thus, we have some confidence that the growth rates in our study were not atypical for the area. Early responses to both thinning and fertilizing treatments, however, differed substantially among these other studies at Wind River. The specifics of those studies are discussed below.

Miller and Reukema (1977) found that thinning the adjacent planted stand (study 3 in figure 2 and table 3) from 1,110 to 730 trees per ha (about 3.7 by 3.7 m) reduced height growth by 25 percent as compared to trees in unthinned plots and had negligible effect on diameter growth (-4 percent) during the first 5 years. Applying fertilizer to the thinned stand, however, nearly doubled height growth and increased diameter growth by more than 30 percent during the same period. There was no unthinned, fertilized treatment to compare with the new study, however.

Table 3—Comparison of site and stand characteristics and tree growth in nine silvicultural studies at Wind River in southwestern Washington

	Site information		Initial stand conditions					Postthinning					Fertilization			
									Growth		Response			Response		
Study number and name[a]	Site class	Fire history	Seed source[b]	Age	Ht.	D.b.h.	Density	Density	Ht.	D.b.h.	Ht.	D.b.h.	N	Ht.	D.b.h.	Comments
				Years	*m*	*cm*	*Trees per hectare*		*m/yr*	*cm/yr*	*- Percent -*		*kg/ha*	*- Percent -*		
Plantations:																
1 TCH this study	IV	Old growth logged, some piles burned	PS	13	4.2	6.0	1,460	T_0 1,460	0.8	0.9	- -	- -	224	15	22	Thinning response based on 6 years. Fertilization response based on 4 years. N applied as AN.
								T_1 740	0.8	1.0	13	10	224	8	37	
								T_2 540	0.7	1.1	5	20	224	10	30	
2 a and b TCH Units 4 and 8[c]	IV	Old growth logged, slash piles burned	PS	13	4.9	6.7	1,110	- -	0.7	0.8	- -	- -				Initial spacing trial nearby (not thinned). Growth based on 5 years.
				14	5.0	6.5	1,110	- -	0.7	1.0	- -	- -				
				14	4.8	6.6	620	- -	0.7	1.1	- -	- -				
3 TCH M and R[d]	V	Old growth logged, boadcast burned	PU	20	6.1	7.4	1,400	T_0 1,400	0.5	0.6			- -	- -	- -	Ht responses adjusted for a covariate. Fertilizer response based on 6 trees. Response based on 5 years. N applied as urea.
								T_1 730	0.4	0.6	-25	-4	336	191	84	
4 PC WST[e]	V	Major wildfires 1902, 1927	PU	28	8.8	10.0	1,600	T_0 1,600	0.5	- -	- -	- -				T_0 comparison not available for diameter as all treatments thinned. Response based on 5 years.
								T_x 140 to 890	0.2	- -	-60	- -				

Table 3—Comparison of site and stand characteristics and tree growth in nine silvicultural studies at Wind River in southwestern Washington (continued)

Study number and name[a]	Site information: Site class	Site information: Fire history	Initial stand conditions: Seed source[b]	Initial stand conditions: Age	Initial stand conditions: Ht.	Initial stand conditions: D.b.h.	Initial stand conditions: Density	Postthinning: Density	Postthinning Growth: Ht.	Postthinning Growth: D.b.h.	Postthinning Response: Ht.	Postthinning Response: D.b.h.	Fertilization: N	Fertilization Response: Ht.	Fertilization Response: D.b.h.	Comments
				Years	*m*	*cm*	*Trees per hectare*		*m/yr*	*cm/yr*	*- Percent -*		*kg/ha*	*- Percent -*		
5 PC Fertilization trial[f]	V	Major wildfires 1902, 1927	PU	36	13.7	14.2	1,550	T_0 1,500	0.4	0.3	- -	- -	157	54	79	All plots unthinned. N applied as AN. Responses based on 4 years.
													314	74	152	
													471	60	160	
6 PC Spot thin[g]	V	Major wildfires 1902, 1927	PU	28	9.8	11.6	1,550	T_0 1,550	0.4	0.4						Dominant trees in T_3 grew 8% more in ht and 22% more in d.b.h than T_0. Codominant trees in T_3 had 38% less ht growth and 6% less d.b.h. growth than in T_0. Responses based on 6 years.
								T_1 -1C[h]	0.4	0.4	-9	-2				
								T_2 -2C	0.4	0.5	-9	2				
								T_3 -3C	0.4	0.5	-13	11				
Natural stands:																
7 MC Spot thin[i]	IV	Old growth logged, slash broadcast burned	Nat.	41	20.4	19.6	--[j]	T_0 --[j]	0.3	0.2	- -	- -				Ht trees damaged in T_1 and T_2. Dominant trees in T_3 had equal ht growth and 50% more d.b.h. growth than in T_0. Codominant trees in T_3 had 37% less ht growth and 11% more d.b.h. growth than in T_0. Growth based on 5 years.
								T_1 -1C[h]	na	0.3	- -	23				
								T_2 -2C	na	0.3	- -	46				
								T_3 -3C	0.2	0.4	-20	54				

Table 3—Comparison of site and stand characteristics and tree growth in nine silvicultural studies at Wind River in southwestern Washington (continued)

	Site information			Initial stand conditions				Postthinning					Fertilization			
									Growth		Response			Response		
Study number and name[a]	Site class	Fire history	Seed source[b]	Age	Ht.	D.b.h.	Density	Density	Ht.	D.b.h.	Ht.	D.b.h.	N	Ht.	D.b.h.	Comments
				Years	*m*	*cm*	*Trees per hectare*		*m/yr*	*cm/yr*	*- Percent -*		*kg/ha*	*- Percent -*		
8 MC Dom. thin[k]	IV	Old growth logged, slash broadcast burned	Nat.	10	2.2	3.3	11,300	T_0 11,300 T_S[l] 1,240 T_D[l] 1,260	0.4 0.3 0.4	0.6 0.6 0.7	- - 1 -5	- - 28 71				Growth for dominant trees only. Growth rates adjusted for initial differences in tree size. Plots not replicated. Growth based on 5 years.
9 THC RFRNP[m] Inst. 171	IV	Old growth logged, slash broadcast burned	Nat.	50	24.3	18.4	2,120	2,120	0.3	0.2	- -	- -	224 as urea 224 as AN	6 41	53 55	All plots unthinned, growth on 3 urea and 2 AN plots compared to 1 control plot. Growth based on 4 years.

[a] Major locations are Trout Creek Hill (TCH), Planting Creek (PC), and Martha Creek (MC). Ht = height, d.b.h. = diameter at breast height, AN = ammonium nitrate. Study numbers match those in figure 2.
[b] PS = planted, source was same seed zone, PU = planted, unknown or nonlocal seed source, Nat. = naturally seeded stand.
[c] Study C-45, data on file, Olympia Forestry Sciences Laboratory.
[d] Miller and Reukema 1977.
[e] Staebler 1956a, Harrington and Reukema 1983.
[f] Reukema 1968, Miller and Tarrant 1983.
[g] Krueger 1959, Reukema 1963 (report on study P27 on file, Olympia Forestry Sciences Laboratory, 16 p.).
[h] Treatments in the spot thinning removed 1, 2, or 3 competitors; stand density not estimated.
[i] Staebler 1956b, Reukema 1961, Reukema 1963 (report on study P20 on file, Olympia Forestry Sciences Laboratory, 18 p.).
[j] Stand density not measured, the stand was described as well stocked, dense, and crowded.
[k] Isaac 1926 (report on study P20 on file, Olympia Forestry Sciences Laboratory, 14 p.), Steele 1955.
[l] T_S = thinning based on spacing, T_D = thinning to release dominant trees.
[m] RFNRP = Regional Forest Nutrition Research Project. Data on file with: Stand Management Cooperative, College of Forest Resources, University of Washington, P.O. Box 352100, Seattle, WA 98195-2100.

Similar contrasts are also evident in studies in the nearby Planting Creek area of Wind River Experimental Forest. Height growth of trees on thinned plots in the wide-spacing trial (study 4 in table 3) where thinning shock was first quantified (Staebler 1956a) was about 60 percent less than that of control trees during the first 5 years; during the 6- to 10-year period, trees in most thinning treatments recovered somewhat although height growth remained about 16 percent lower than that in control trees (Harrington and Reukema 1983). Height growth in the widest spacing (9.1 by 9.1 m) did not recover until 11 to 15 years after the thinning.

A trial of varying degrees of individual tree release (study 6) adjacent to the wide spacing trial in the Planting Creek area and in the same plantation showed overall reductions in height growth of 9 to 13 percent during the first 6 years after treatment at age 28 (Krueger 1959). Response varied by crown class, however. Dominant trees released from three competitors grew more than unreleased dominant trees (about 8 percent in height and 22 percent in diameter), but codominant trees released from the competition of three surrounding trees exhibited a severe reduction in height growth (38 percent) and a modest reduction (6 percent) in diameter growth as compared to growth of unreleased codominant trees.

A fertilization trial in an unthinned area, also adjacent to the wide spacing trial in Planting Creek (study 5 in table 3), yielded one of the largest and most long-lasting responses to N fertilizer ever documented (Miller and Tarrant 1983); during the first 4 years, height growth was increased 54 to 74 percent and diameter growth 79 to 160 percent with 157 to 471 kg of N per ha applied as ammonium nitrate (Reukema 1968). Volume responses were 51 to 111 percent and continued undiminished for at least 15 years (Miller and Tarrant 1983).

Thus, initial reductions in height growth after thinning were less, and increases in diameter growth were greater in our study than in the above thinning trials in **older plantations**. And though fertilization caused significant increases in diameter and height growth in our study, such responses were markedly less than those obtained in the adjacent plantation or in the Planting Creek area. On the other hand, diameter growth response to thinning in the two studies in the natural stand at Martha Creek (studies 7 and 8 in table 3) was quite positive (Reukema 1961, Staebler 1956b, Steele 1955) and increased with degree of thinning release; the greatest release resulted in 54 and 71 percent greater diameter growth than trees on unthinned plots. Height growth was similar for all treatments in one trial (study 8 had a maximum difference among treatments of 5 percent in 5-year height growth). Height growth in response to thinning in the other trial (study 7) is more difficult to assess as the sample of trees measured for height growth was small and several height trees were damaged. Dominant trees in the treatment with the greatest degree of release (T3) had height growth rates equal to those of the unthinned trees. The fertilization trial in the natural stand on Trout Creek Hill (study 9) reported substantial 4-year diameter growth responses to N application (more than 50 percent greater in fertilized than in unfertilized plots) and positive but varying responses in height growth.

Considering Reasons for Contrasting Results

We next consider the similarities and differences in the site and stand conditions among the various trials and discuss the possible reasons for the observed differences in response to treatments. The nearby plantation trials that manifested more severe thinning shock and greater response to fertilizer application differed from our study plantation as follows: stands at thinning or fertilizing in the earlier trials were older, site quality as determined by early growth rate was lower, effects of recent wildfires or site preparation burns were more severe, and geographic sources of planting material were nonlocal and now considered to be maladapted. In the following discussion, we examine these matters as well as precipitation, soil, and other site factors to see if similarities and differences in such factors offer explanations consistent with the observed responses of the various studies at Wind River. In addition, results from thinning and fertilizing studies in Douglas-fir stands at other locations in western Oregon, Washington, and British Columbia are discussed as appropriate.

Stand Age

In contrast to the previous suggestion by Harrington and Reukema (1983) that thinning shock is more likely when stands on poor sites are heavily thinned later than the recommended age for precommercial thinning, we now believe that stand age is unlikely to be the major cause of the observed differences in thinning shock or in response to fertilizer. It is true that our study was precommercially thinned within the preferred age range of 10 to 15 years (Reukema 1975) and the other studies with substantial thinning shock were thinned at 20 to 28 years. When we compare the results from the spot thinning at Martha Creek in a 41-year-old, fully stocked natural stand (study 7 in table 3) with the results from the same treatment at Planting Creek in a 28-year-old plantation (study 6 in table 3), however, we see much better early response in diameter growth of dominants, codominants, and intermediates in the older stand (Reukema 1961, Staebler 1956b); and as discussed above, dominant trees at Martha Creek had equal height growth in unthinned and heaviest thinning treatments (study 7 in table 3). Moreover, shock was ephemeral (Rocky Brook, thinned at age 27 years) or absent (Stampede Creek, thinned at age 32 years) in other stand-level Douglas-fir thinning studies when the initial thinnings were done at older ages (Williamson 1976, Williamson and Staebler 1971). Regionwide analyses have indicated that response to N fertilizer is similar across age classes, although there is a trend for greater response in younger stands (Chappell and others 1992). The fertilizer trial established in a 50-year-old natural stand on Trout Creek Hill (study 9 in table 3) also showed height and diameter responses to N (particularly ammonium nitrate) that were generally much greater than those of our study. We do not intend to suggest that stand age (and associated tree and stand traits) does not affect responses to thinning and fertilization–only that age seems unlikely to be the major contributing factor in differences in type and magnitude of responses observed in our study versus those of earlier Wind River studies.

Site Quality

Reported instances of thinning shock in Douglas-fir stands all have occurred on sites of poor quality (IV and V). In addition, west of the Cascade Range in Oregon and Washington, the response of Douglas-fir to N fertilizer is greater on low-quality than high-quality sites (Miller and others 1986). Site quality was estimated to be site V in the severely shocked nearby plantations (study 4, Staebler 1956a; Harrington and Reukema 1983; study 3, Miller and Reukema 1977), whereas it appears to be site IV in our study. Note, however, that the Miller and Reukema study and our study are immediately adjacent, and soils and microclimate are nearly identical.

Furthermore, publications on the Planting Creek thinning studies (study 4, Harrington and Reukema 1983; study 6, Krueger 1959) indicate that the site for the plantation trees was classified as site V, whereas the site for the adjacent fertilizer study (study 5) was considered to be site IV (Miller and Tarrant 1983). One of the other more distant studies (Rocky Brook) that showed only ephemeral shock (first 2 years after thinning) was also site IV (initially reported as site V by Williamson (1976) but subsequently determined to be site IV by Curtis and Marshall (1986)) and another (Shawnigan Lake) was borderline between site IV and site V (Brix 1993, Crown and Brett 1975, Crown and others 1977). The thinning in the young natural stand at Martha Creek (study 8), which was considered to be site V, showed large, early positive responses in diameter growth and little or no difference in height growth (Steele 1955). In addition, the other thinning trial at Martha Creek (study 7) that had excellent initial diameter growth response to release was on site IV ground (Reukema 1961, Staebler 1956b). Thus, it does not appear that differences between site IV and site V per se are strongly related to the observed differences in thinning shock. And all studies mentioned previously–whether on site IV or site V land–responded substantially more to fertilizer than did trees in our study.

Precipitation

The Wind River area has fairly droughty summers with often 2 or more months with minimal precipitation; thus, precipitation during the growing season is generally considered to be one of the factors that can account for year-to-year differences in growth rates. If differences in precipitation influenced response to silvicultural treatment, we might expect a lower tendency for shock to be exhibited in periods of above-average precipitation. Growing season precipitation (May 1 to September 30) in the years after thinning and fertilizing treatments averaged 270 mm per yr (based on 41 years of record) and varied substantially (minimum of 117 mm, maximum 433 mm). Precipitation levels, however, do not help explain the observed differences in response to thinning, as the two trials that had the greatest shock had about average growing season precipitation (mean of 253 mm per yr in study 4) or above-average growing season precipitation (298 mm per yr in study 3) the years after thinning. Growing-season precipitation in our study averaged 221 mm per yr for the 6 years after thinning with a minimum value one year of 166 mm.

Fire Severity

Recent fire history differed among the various study areas in that the Planting Creek area had been burned intensely in the Yacolt fire of 1902 and reburned in 1927, and it is probable that the older trial adjacent to our study (study 3, Miller and Reukema 1977) had received a hot prescribed burn because of heavy slash remaining after clearcutting the previous old-growth stand. In contrast, burning in our study was limited to piles on a few landings, and there was little if any burning over most of the area. Other studies that exhibited only mild and ephemeral shock, however, also had experienced rather severe burns. The Shawnigan Lake site had a fire history similar to the Planting Creek area. It had burned in 1925, was salvage logged in 1927, regenerated naturally, and reburned in 1942 to the point that the ground was devoid of slash and had little humus (Crown and Brett 1975). Yet thinning shock lasted only 2 years and recovery was so rapid that increased growth in the third year more than made up for the initial reductions. Although we believe that fire history is unlikely to account for differences in thinning shock, we suspect that it may play a role in influencing response to N fertilizer. All the Wind River plantation studies that had large positive responses to N fertilization, as well as the very responsive, 50-year-old natural stand on Trout Creek Hill (study 9 in table 3) were established after one or more wildfires or slash fires after harvest of old-growth timber. The effects of these fires on soil properties would have been much more intense than occurred in our study area where the only recent fires were restricted to log landings.

Seed Source

The planted stands in the Planting Creek area that exhibited severe shock (study 4, Harrington and Reukema 1983, Staebler 1956a) or dramatic early and long-lasting response to N fertilizer (study 5, Miller and Pienaar 1973, Miller and Tarrant 1983, Reukema 1968) are known to have originated from a seed source from Roy, Washington. This seed source is about 140 km NNW and about 500 m lower in elevation than the areas at Wind River where it was planted; this nonlocal seed source is now considered to be poorly suited to the area. Moreover, the thinning and fertilizer trial adjacent to our study (study 2, Miller and Reukema 1977) was established in 1952, and considering the date of establishment and rather poor growth of the plantation in comparison with our study and other nearby plantings (studies 2a and 2b in figure 2 and table 3), it seems probable that it too was established with a nonlocal and maladapted seed source. Conversely, the stands that had only mild, ephemeral shock (similar to that in our study) or no shock were established naturally (study 8, Staebler 1956b), had abundant natural fill-in (Crown and Brett 1975, Williamson 1976), or were planted with presumably suitable stock (Crown and Brett 1975). Thus, we think it is likely that poor adaptation associated with nonlocal seed sources may predispose trees to experience more severe and long-lasting shock after thinning. It is also probable that maladapted seed sources (in addition to burning history) contribute to the particularly large responses to fertilizer observed in earlier trials at Wind River; the plantations in which these studies were established tend to be chlorotic and have fewer years of foliage and less dense foliage than plantations established in recent years with known suitable seed sources. Moreover, genetic researchers[1] have observed general chlorosis in plantings for the Douglas-fir heredity study, much of which consisted (by design) of nonlocal sources at any given installation.

Management Implications

Thinning shock–as manifested in reduced height growth–was minor and of short duration, and diameter growth was positively impacted by thinning in this trial. Of several possible reasons for differences between this experience and that in other nearby studies, we do not think that its younger age, slightly higher inherent site index (IV vs. V), and lack of recent fire offer adequate explanations. The maladapted seed sources used in planting the Planting Creek area and, presumably, also the adjacent stand studied by Miller and Reukema (1977), however, remain a likely cause of the differences between our study and the earlier trials at Wind River in the magnitude and duration of "thinning shock." Because N fertilizer seems to compensate for initial height growth reductions where it has been tested and companion fertilizer studies have given much greater response on sites where thinning shock was most severe, we suspect that either low available native N or a decreased ability of trees to extract it after thinning also may be contributing factors.

[1] Roy Silen and Frank Sorenson. 2001. Personal communications. Principal plant geneticists (retired), USDA Forest Service, Pacific Northwest Research Station. Forestry Sciences Laboratory, Corvallis, OR 97331.

The lower than expected height and diameter growth response to fertilizer in our study and its shorter duration may be linked more closely to lack of recent fire, and presumably higher levels of available native N, at our study site. The nearby fertilization test in an older natural stand (study 9 in table 3) gave much higher growth response to applied N, but the site had been logged and burned intensely (old-growth logging slash broadcast burned) immediately before stand establishment.

Based on our study and comparison with earlier research, we believe that regardless of reasons for shock, precommercial thinning in plantations established from appropriate genetic stock should result in negligible shock, even on poor quality (site IV or V) forest land. Fertilizing sites that have low available N at about the same time as thinning may be desirable because responses have been good and any tendency toward shock has been overcome.

In the broader context of technology development and management-research interrelations, we acknowledge the value of Wind River Experimental Forest not only as a cradle of initial forestry research but also as a location where responses of trees and shrubs to cultural practices have sometimes been particularly large and long lasting. Such dramatic responses have stimulated both early management interest in the practices and the development and testing of related scientific hypotheses. And although we recognize that management decisions, that is, to act or not to act, must always be made based on the information available at the time, results of the present followup study should caution us not to base long-term expectations and decisions about practices on either short-term responses or on results from only one or two studies–even when applying the practices in the same geographic location as the initial study. Other seemingly unrelated management changes—such as genetic makeup of new stands or current utilization standards and approaches to hazard reduction or site preparation–could lead to major differences in response to a practice. Some form of research, adaptive management, or operational monitoring is therefore desirable as a standard component of forest management operations.

Literature Cited

Brix, H. 1993. Fertilization and thinning effect on a Douglas-fir ecosystem at Shawnigan Lake: a synthesis of project results. Victoria, BC: Forestry Canada Pacific Forestry Centre, BC Ministry of Forests, Research Branch. 64 p.

Brockway, D.G.; Topik, C.; Hemstrom, M.A.; Emmingham, W.H. 1983. Plant association and management guide for the Pacific silver fir zone, Gifford Pinchot National Forest. R6-Ecol-130a-1983. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region. 122 p.

Chappell, H.N.; Omule, S.A.Y.; Gessel, S.D. 1992. Fertilization in coastal Northwest forests: using response information in developing stand-level tactics. In: Chappell, H.N.; Weetman, G.F.; Miller, R.E., eds. Forest fertilization: sustaining and improving nutrition and growth of western forests. Contrib. 73. Seattle: University of Washington, College of Forest Resources, Institute of Forest Resources: 98-113.

Crown, M.; Brett, C.P., eds. 1975. Fertilizer and thinning effects on a Douglas-fir ecosystem at Shawnigan Lake: an establishment report. Rep. BC-X-110. Victoria, BC: Department of Environment, Canadian Forest Service. 45 p.

Crown, M.; Quenet, R.V.; Layton, C. 1977. Fertilization and thinning effects on a Douglas-fir ecosystem at Shawnigan Lake: 3-year growth response. Rep. BC-X-152. Victoria, BC: Department of Environment, Canadian Forest Service. 36 p.

Curtis, R.O.; Marshall, D.D. 1986. Levels-of-growing-stock cooperative study in Douglas-fir: report no. 8–the LOGS study: twenty-year results. Res. Pap. PNW-356. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 173 p.

Franklin, J.F.; Dyrness, C.T. 1973. Natural vegetation of Oregon and Washington. Gen. Tech. Rep. PNW-8. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 417 p.

Harrington, C.A.; Reukema, D.L. 1983. Initial shock and long-term stand development following thinning in a Douglas-fir plantation. Forest Science. 29(1): 33-46.

King, J.E. 1966. Site index curves for Douglas-fir in the Pacific Northwest. Pap. 8. Centralia, WA: Weyerhaeuser Company Forestry, Western Forestry Research Center. 49 p.

Krueger, K.W. 1959. Diameter growth of plantation-grown Douglas-fir trees under varying degrees of release. Res. Note 168. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 5 p.

Miller, R.E.; Barker, P.R.; Peterson, C.E.; Webster, S.R. 1986. Using nitrogen fertilizers in management of coast Douglas-fir. I. Regional trends of response. In: Oliver, C.D.; Hanley, D.P.; Johnson, J.A., eds. Douglas-fir: stand management for the future. Contrib. 55. Seattle, WA: University of Washington, College of Forest Resources, Institute of Forest Resources: 290-303.

Miller, R.E.; Pienaar, L.V. 1973. Seven-year response of 35-year-old Douglas-fir to nitrogen fertilizer. Res. Pap. PNW-165. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 24 p.

Miller, R.E.; Reukema, D.L. 1977. Urea fertilizer increases growth of 20-year-old thinned Douglas-fir on a poor quality site. Res. Note PNW-291. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 8 p.

Miller, R.E.; Tarrant, R.F. 1983. Long-term growth response of Douglas-fir to ammonium nitrate fertilizer. Forest Science. 29(1): 127-137.

Peterson, C.E.; Webster, S.R.; Barker, P.R.; Miller, R.E. 1986. Using nitrogen fertilizer in management of coast Douglas-fir. II. Future information needs. In: Oliver, C.D.; Hanley, D.P.; Johnson, J.A., eds. Douglas-fir management for the future: proceedings of a symposium. Contrib. 55. Seattle, WA: University of Washington, College of Forest Resources, Institute of Forest Resources: 304-309.

Reukema, D.L. 1961. Response of individual Douglas-fir trees to release. Res. Note PNW-208. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 4 p.

Reukema, D.L. 1968. Growth response of 35-year-old, Site V Douglas-fir to nitrogen fertilizer. Res. Note PNW-86. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 9 p.

Reukema, D.L. 1975. Guidelines for precommercial thinning of Douglas-fir. Gen. Tech. Rep. PNW-30. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 10 p.

SAS Institute. 1988. SAS/STAT users guide release 6.03. Cary, NC: SAS Institute, Inc. 1028 p.

SAS Institute. 1996. SAS system for mixed models. Cary, NC: SAS Institute, Inc. 633 p.

Silen, R.R.; Olson, D.L. 1992. A pioneer exotic tree search for the Douglas-fir region. Gen. Tech. Rep. PNW-298. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 44 p.

Staebler, G.R. 1956a. Evidence of shock following thinning of young Douglas-fir. Journal of Forestry. 54(5): 339.

Staebler, G.R. 1956b. Effect of controlled release on growth of individual Douglas-fir trees. Journal of Forestry. 54(9): 567-568.

Stanek, W.; Beddows, D.; State, D. 1979. Fertilizer and thinning effects on a Douglas-fir ecosystem at Shawnigan Lake on Vancouver Island: some observations on salal and bracken fern undergrowth. Rep. BC-R-1. Victoria, BC: Department of Environment, Canadian Forestry Service. 11 p.

Steele, R.W. 1955. Thinning nine-year-old Douglas-fir by spacing and dominance methods. Northwest Science. 29(2): 84-89.

Williamson, R.L. 1976. Levels-of-growing-stock cooperative study in Douglas-fir: report no. 4–Rocky Brook, Stampede Creek and Iron Creek. Res. Pap. PNW-210. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 39 p.

Williamson, R.L.; Staebler, G.R. 1971. Levels-of-growing-stock cooperative study in Douglas-fir: report no. 1–description of study and existing study areas. Res. Pap. PNW-111. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 12 p.

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