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Response of a Poor-Site Western Redcedar Stand to Precommercial Thinning and Fertilization

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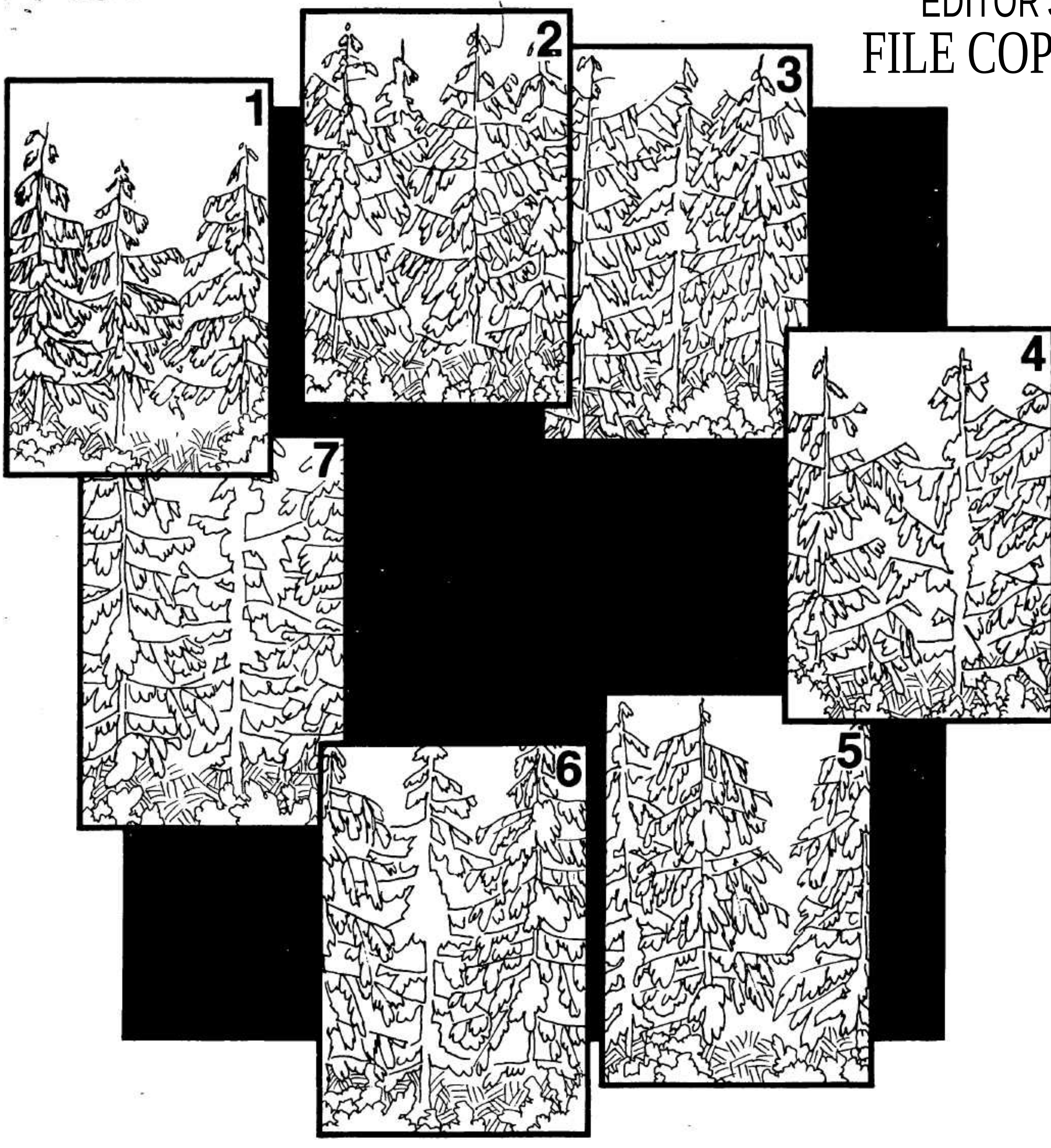

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Abstract

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Seven silvicultural treatments were applied in a 20-year-old natural western redcedar *(Thuja plicata)* Donn ex D. Don) stand on a poor site in coastal Washington: (1) control (unthinned, unfertilized); (2) unthinned, fertilized with ammonium nitrate, monodicalcium phosphate, and potassium sulfate; (3) thinned, unfertilized; (4) thinned, fertilized with urea; (5) thinned, fertilized with ammonium nitrate; (6) same as treatment 5 plus monodicalcium phosphate; (7) same as treatment 6 plus potassium sulfate. Treatments 2 through 7 resulted in significantly better 3-year height and diameter growth of the 20 tallest trees per plot (250 tallest trees per hectare) than did the control treatment (1). Increases in growth over the control trees were least for treatment 3. Thinning alone (3) resulted in much smaller increases in growth than fertilization alone (2). There were no differences in growth between the thinned treatments fertilized with ammonium nitrate and urea (4 and 5), and both treatments had significantly better growth than thinning alone. The thinned treatment fertilized with monodicalcium phosphate plus ammonium nitrate (6) was more effective in increasing growth than the thinned treatment fertilized with ammonium nitrate alone (5). Addition of potassium sulfate (7) did not increase growth significantly over treatment 6. Three-year height and diameter growth of the 20 tallest trees per plot ranged from 1.1 m and 2.0 cm in treatment 1 to 1.8 m and 4.4 cm in treatment 7. Analysis of 2-year growth of the total stand showed that all sizes of trees responded to treatment. Foliar concentrations of nitrogen, phosphorus and sulfur were positively correlated with growth rates.

Keywords: Fertilizer response (forest tree), thinning effects, precommercial thinning, silvicultural treatments, site class (-increment, western redcedar, *Thuja plicata.*

Summary

Seven silvicultural treatments were tested in a heavily stocked, 20-year-old, natural western redcedar *(Thuja plicata* Donn ex D. Don) stand growing on a poor quality site near the northwest coast of the Olympic Peninsula in western Washington. Each treatment was randomly assigned to four 30- by 50-m plots. The treatments included combinations of precommercial thinning and fertilization with nitrogen or nitrogen plus other elements. The trees rapidly responded to most treatments with increases in both height and diameter growth. Based on 3-year results, we can conclude the following:

(1) Thinning alone resulted in small, generally nonsignificant increases in height and diameter growth. Differences between thinned and unthinned plots in annual growth rates of the 20 tallest trees per plot were significantly different only for 3d-year diameter growth.

(2) Fertilizing thinned plots with nitrogen, applied either as urea or ammonium nitrate, increased both height and diameter growth. Compared to the thinned, unfertilized treatment, 3-year diameter growth on thinned plots fertilized with urea and thinned plots fertilized with ammonium nitrate averaged 40 percent greater; 3-year height growth averaged 25 percent greater. There were no significant differences in growth between plots receiving the two sources of nitrogen. Both treatments had significantly higher levels of foliar N after all three growing seasons than did unfertilized plots.

(3) Fertilizing thinned plots with both ammonium nitrate and monodicalcium phosphate resulted in significantly greater increases in growth than fertilizing with only ammonium nitrate. Thinned plots treated with both fertilizers had 3-year height and diameter growth rates for the 20 tallest trees per plot that were 40 and 63 percent greater than growth rates on the thinned, unfertilized plots.

(4) Thinned plots fertilized with potassium sulfate, ammonium nitrate, and monodicalcium phosphate had the greatest mean 2-year diameter growth for all trees and the greatest mean 3-year diameter and height growth for the 20 tallest trees per plot. Differences in growth between this treatment and the thinned plots fertilized with ammonium nitrate and monodicalcium phosphate, however, were small and not statistically significant.

(5) Unthinned plots fertilized with ammonium nitrate, monodicalcium phosphate, and potassium sulfate had excellent growth despite high stocking (5570 stems per hectare). Two-year basal area growth was more than twice the growth in the control (unthinned, unfertilized) plots. Three-year height and diameter growth of the 20 tallest trees per plot in the unthinned, fertilized treatment were 60 and 93 percent greater than in the control plots.

(6) Height and diameter growth of the 20 tallest trees per plot were increased by both fertilization and thinning, and the growth increases associated with these treatments applied singly were additive when the treatments were combined.

(7) Increases in growth of the 20 tallest trees per plot were generally correlated with higher foliar concentrations of nitrogen, phosphorus, and sulfur.

Contents

Introduction

Western redcedar *(Thuja plicata* Donn ex D. Don) is a commercially important softwood species in the Pacific Northwest. Harvest of old-growth trees has been proceeding at a rate more rapid than current growth rates; thus available inventories are declining (Bolsinger 1979). Young-growth redcedar cannot be used for all the same purposes as old-growth logs, but it is still valuable, often bringing the same price for sawlogs as young-growth Douglas-fir (Washington Crop Reporting Service 1982). Because young-growth redcedar stands have been mostly ignored by forest managers and researchers, there is little information on how to manage the species (Fowells 1965, Minore 1983). This report documents the initial response of a 20-year-old natural western redcedar stand on a poor site to precommercial thinning and fertilization. Initial growth response has been excellent and demonstrates the responsiveness of the species to silvicultural treatment.

Materials and Methods

Study Area

The study area is located in Clallam County about 30 km north-northwest of Forks, Washington, and 10 km from the Pacific Coast (fig. 1). The mild marine climate has a 220- to 250-day frost-free period with annual precipitation averaging 2700 mm. The previous stand of timber, predominantly old-growth western redcedar, was logged in 1961; many old stumps 2-4 m in diameter are present. Two salvage sales have been held in the area since the original logging, but large amounts of both sound and rotten woody material remain on the site.

The soil series is Kydaka (medial acid, mesic Typic Humaquept), a moderately deep, poorly drained, silty clay loam that formed in loess and glacial till over dense, compact glacial till. Soil pH averages 4.6. Some large, glacially-carried boulders are present. Elevation averages 100 m; topography of the area is flat with maximum slope less than 10 percent. Based on the soil series and tree height at age 20, site index for western redcedar (50-year base) is probably 18-22 m (Kurucz 1978).

Species composition in 1980 was predominantly western redcedar (95 percent or more by basal area). Western hemlock *(Tsuga heterophylla* (Raf.) Sarg.) was present throughout the area, and there were scattered trees of Pacific yew *(Taxus breyifolia* Nutt.), Pacific silver fir *(Abies amabilis* Dougl. ex Forbes), Sitka spruce *(Picea sitchensis* (Bong.) Carr.), red alder *(Alnus rubra* Bong.), and cascara *(Rhamnus purshiana* DC). Salal *(Gaultheria shallon* Pursh) and red and blue huckleberry *(Vaccinium parvifolium* Smith, *V. ovalifolium* Smith) were common in the shrub layer. In portions of the area, both the ground and the partially decayed logs had heavy moss cover.

There was a substantial range in tree size in 1980. An occasional pole- to small sawlog-size redcedar and hemlock were present. These trees would have been part of the understory of the stand harvested in 196.1. In addition, some advanced reproduction (in the form of small seedlings) that was present at the time of logging responded to release. The majority of stand, however, probably developed from seed that germinated following logging; in 1980, these trees were 15 to 20 years old and 5 to 6 m tall. Stocking varied throughout the area but averaged 5900 stems per hectare. Low stocking was usually associated with areas having large stumps, downed logs, and other woody debris present.

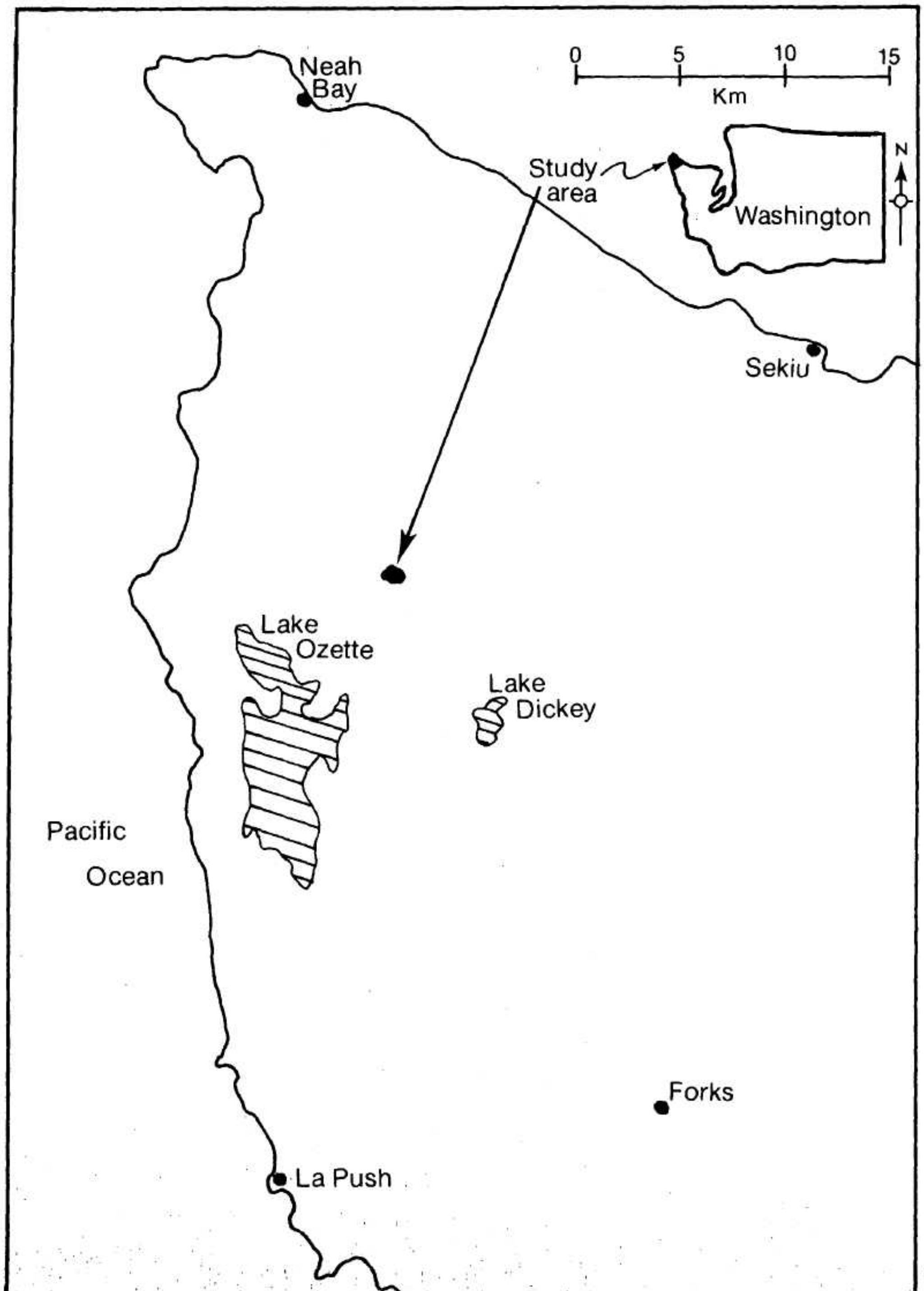

Figure 1.—Location of study area.

Study Design and Treatments

The study used 28 plots, each with a 30- by 50-m treatment area and a 20- by 40-m interior measurement plot. Several practices were employed to help increase the uniformity of stand conditions between plots. Within and adjacent to the study plots, pole- and small sawlog-size trees left after the 1961 logging operation were felled or were girdled if felling would damage potential crop trees. In addition, all trees other than western redcedar that were 3.0 m tall or taller were cut. Most plots were contiguous; however, plot boundaries were shifted to avoid including nontypical site or stand conditions.

The study had seven treatments with four replicate plots in each treatment. The following treatments were randomly assigned:

(1) Unthinned, unfertilized (control);
(2) Unthinned, fertilized with ammonium nitrate N(AN), monodicalcium phosphate (P-Ca), and potassium sulfate (K-S);
(3) Thinned, unfertilized;
(4) Thinned, fertilized with urea N(U);
(5) Thinned, fertilized with N(AN);
(6) Thinned, fertilized with N(AN), P-Ca; and
(7) Thinned, fertilized with N(AN), P-Ca, K-S.

In treatments 3-7, western redcedar crop trees were thinned to an approximate 3- by 3-m spacing (approximately 1100 trees/ha or 88 trees/measurement plot). Final tree selection opted for the best potential crop trees rather than exact spacing. All thinning was done during October 1980; thinning slash was left on the site.

Fertilizers used in this study supplied elements according to the following schedule:

Fertilizer source	Element supplied and elemental rate of application (kg/ha)
Urea	N, 300
Ammonium nitrate	N, 300
Monodicalcium phosphate	P, 100; Ca, 129
Potassium sulfate	K, 100; S, 41

Fertilizers were manually applied between March 26 and April 3, 1981. Half of each fertilizer was applied in north-south rows; the other half was cross-applied in east-west rows. At the time of application, the soil and soil surface were wet. Weather conditions during and immediately following fertilization were variable but generally cool and wet (table 1). Under these conditions, nitrogen losses from volatilization of urea should have been quite low.

Table 1— Weather conditions during and following fertilization in a western redcedar stand, 1981[1/]

Date	Fertilizer applied	General weather conditions	24-hour precipitation	Temperature Maximum	Temperature Minimum
			mm	- - - - °C - - - -	
March:					
25		Overcast, light rain, mostly calm	16	14	4
26	X	Partly sunny, 15-20 kph wind	trace	16	1
27	X	Overcast, 15-20 kph wind, light rain	2	14	8
28		Overcast; rain, heavy at times	42	9	6
29		Overcast; rain, heavy at times	32	9	4
30	X	Overcast; steady light rain; mostly calm, occasional gusts to 15 kph	52	9	4
31	X	Mostly overcast, some periods partly sunny, some hail and rain showers	25	11	3
April:					
1	X	Mostly clear and sunny, occasional rain showers, no wind	7	9	-1
2	X	Overcast, steady light rain, light gusts to 15 kph	15	10	0
3	X	Overcast, light winds 5-15 kph	--	6	3
4		Partly cloudy, rain showers	10	7	1
5		Overcast; rain, heavy at times	21	7	2
6		Partly cloudy, light rain	3	8	2
7		Overcast, rain	7	8	1
8		Overcast, rain mixed with snow	24	8	3
9		Overcast, rain	6	8	0
10		Overcast, rain	14	3	0

* Indicates dates on which fertilizers were applied.

1/ Recording thermograph and rain gauge were located at the study site.

Growth Measurements and Analyses

Prior to fertilization, all trees 1.3 m or taller were numbered and measured for total height and diameter at breast height (1.3 m). Trees below breast height were tagged and measured for height on thinned plots but not on unthinned plots because of their excessive number. After the second growing season, all tagged trees were remeasured for height and diameter. The 20 tallest trees per plot were remeasured for height and diameter after the first, second, and third growing seasons.

Two-year height, diameter, and basal area growth for the total stand were analyzed using analysis of variance; when treatment effects were significant (p = 0.05), means were separated using Tukey's test. Height and diameter growth of the 20 tallest trees per plot were analyzed for the 1st, 2d, and 3d years using analysis of covariance to adjust for differences in site quality or for previous stand conditions; initial height or diameter was used as the covariate. When treatment effects were significant (p -0.05), treatment means were separated using Scheffe's test for adjusted means.

Foliage Collection and Analyses

During the dormant season following the first three growing seasons (January 1982, November 1982, and December 1983), a composite foliage sample was collected from 10 to 12 dominant or codominant trees in each plot. Only current year's foliage from the upper third of the crown was sampled. The samples were processed by plucking or stripping the secondary branchlets from the woody central portion of the foliage spray. The foliage was then dried at 65 °C and sent to the Plant and Soil Analytical Laboratory at the University of Idaho for chemical analysis. Concentrations of the following elements were determined: total N (Kjeldahl), and P, K, S, Ca, and Mg (by wet ash procedure described in Horwitz (1980)). The results were analyzed using analysis of variance; Tukey's test was used to separate treatment means when the effects of treatment were significant. Simple correlation coefficients were determined between mean foliar nutrient concentrations per plot and mean annual height or diameter growth of the 20 tallest trees per plot. Correlations were calculated between growth in the growing season (year n) and foliar concentrations measured either prior to the growing season (year n-1) or following the growing season (year n).

Results and Discussion

Stand and Tree Growth

Total stand.—Mean 2-year height growth of the total stand differed by treatment (table 2). Trees in the unthinned, unfertilized (control) treatment had significantly less height growth than trees in the treatment that was unthinned and fertilized with AN, P-Ca, and K-S. Because the mean number of trees per plot was similar for the two unthinned treatments, the difference in growth between these treatments can be attributed primarily to the effects of fertilization. Differences in growth of the total stand between unthinned and thinned treatments, however, can only be partially attributed to a direct beneficial effect of thinning on individual tree growth. Part of the apparent effect of thinning is due to the fact that thinned plots had many of the smaller, slow growing trees removed in the thinning. Height growth in the thinned, unfertilized treatment was significantly less than growth in the two thinned, fertilized treatments that resulted in the most growth (N(AN), P-Ca; N(AN), P-Ca, K-S) but did not differ from the thinned, nitrogen-only treatments (AN; U). The two nitrogen-only treatments did not differ from each other or from the other treatments fertilized with N plus other elements.

Effects of treatment on 2-year diameter growth of the total stand (table 2) were also significant. Compared to the control, mean diameter growth was almost two times greater in the unthinned, fertilized treatment and was three times greater in the thinned treatment fertilized with AN, P-Ca, and K-S.

Two-year basal area growth per hectare also differed by treatment (table 2). Basal area growth in the unthinned, fertilized treatment was more than double that in any other treatment. There were no significant differences in basal area growth between the other treatments. Thus, even though thinning substantially reduced initial basal area, the thinned and thinned-plus-fertilized plots had absolute increases in basal area that were similar in magnitude to the increases in the control plots.

Individual tree response of the total stand can be shown by initial height class (table 3). Response to treatment was not limited to only the taller trees: all size trees responded. The percentage increases in growth with treatment were actually greatest in height class 1, which had the shortest trees. The greatest absolute increases in growth, however, generally occurred in height class 3.

Table 2—Initial characteristics and 2-year growth of all trees in a western red-cedar stand by treatment

Treatment 1/	Items per hectare	Height		Diameter		Basal area	
		Initial	2-year growth 2/	Initial	2-year growth	Initial	2-year growth 2/
		- - - - m - - - -		- - - cm - - -		- - - m^2/ha - - -	
Unthinned, unfertilized	6290	2.57	0.41a	2.26	0.65a	4.24	0.44a
Unthinned, fertilized with N(AN), P-Ca, K-S	5570	2.60	.89bc	2.25	1.23ab	3.92	.92b
Thinned, unfertilized	890	3.95	.76b	5.08	1.30ab	2.45	.29a
Thinned, fertilized with N(U)	920	3.58	1.01bc	4.47	1.78bc	2.00	.38a
Thinned, fertilized with N(AN)	1115	3.93	.92bc	4.81	1.65bc	2.54	.45a
Thinned, fertilized with N(AN), P-Ca	985	3.59	1.11c	4.35	1.94bc	1.87	.41a
Thinned, fertilized with N(AN), P-Ca, K-S	915	3.51	1.09c	4.19	2.06c	1.73	.42a

1/ N = nitrogen, AN = ammonium nitrate, P-Ca = monodicalcium phosphate, K-S = Potassium sulfate, u = urea.

2/ Within a column, means followed by the same letter are not significantly different (p = 0.05).

Twenty tallest trees per plot.—Treatment responses of the 20 tallest trees per plot (250 tallest per hectare) can be separated by year. Crop tree response can be compared more directly than in the analysis of growth of the total stand because evaluation is based on an equal number of trees per plot.

Treatment effects on height growth of the 20 tallest trees per plot were not statistically significant the 1st year but were significant in the subsequent 2 years (fig. 2A). In both the 2d and 3d years, unfertilized treatments had significantly lower height growth than fertilized treatments. Differences between the thinned, unfertilized treatment and the unthinned, unfertilized treatment were not signifycant, and none of the fertilized treatments differed from the others.

Table 3—Two-year height and diameter growth of all trees in a western red-cedar stand by initial height class and treatment

Treatment 1/	2-year height growth per tree by height class 2/			2-year diameter growth per tree by height class 2/		
	1	2	3	1	2	3
	- - - - - - m - - - - - -			- - - - - - cm - - - - - -		
Unthinned, unfertilized	0.28	0.54	0.77	0.47	0.69	1.11
Unthinned, fertilized with N(AN), P-Ca, K-S	.82	1.00	1.16	1.01	1.44	1.91
Thinned, unfertilized	.51	.73	.96	.90	1.12	1.74
Thinned, fertilized with N(U)	.85	1.09	1.04	1.32	1.79	2.08
Thinned, fertilized with N(AN)	.73	.93	1.06	1.14	1.59	2.04
Thinned, fertilized with N(AN), P-Ca	.92	1.08	1.21	1.39	1.88	2.28
Thinned, fertilized with N(AN), P-Ca, K-S	1.00	1.14	1.15	1.64	2.10	2.46

1/ N = nitrogen, AN = ammonium nitrate, P-Ca = monodicalcium phosphate, K-S = potassium sulfate, U = urea.

2/ Height class 1 = trees less than 3.0 m, height class 2 = trees 3.0 - 4.5 m, height class 3 = trees>4.5 m.

Treatment effects on height growth can also be seen in the trends over time (fig. 2A). Unfertilized treatments had lower mean annual height growth the 3d year than the 1st year, whereas all fertilized treatments had greater mean height growth the 3d year than the 1st year. Plots receiving urea had the poorest 1st-year growth of the fertilized treatments, but height growth during the 2d and 3d years was comparatively much improved.

For cumulative 3-year height growth (fig. 2B, table 4), the treatments stratmea into three groups: (1) unfertilized, (2) thinned and fertilized with N only, and (3) fertilized with P-Ca and AN. Height growth over the 3-year period was 60 percent greater in the treatments resulting in the most growth than in the control. Amount of height growth generally decreased over time for trees in treatment group 1, thus the differences in cumulative heights between treatment group 1 and groups 2 and 3 will probably continue to widen in the future.

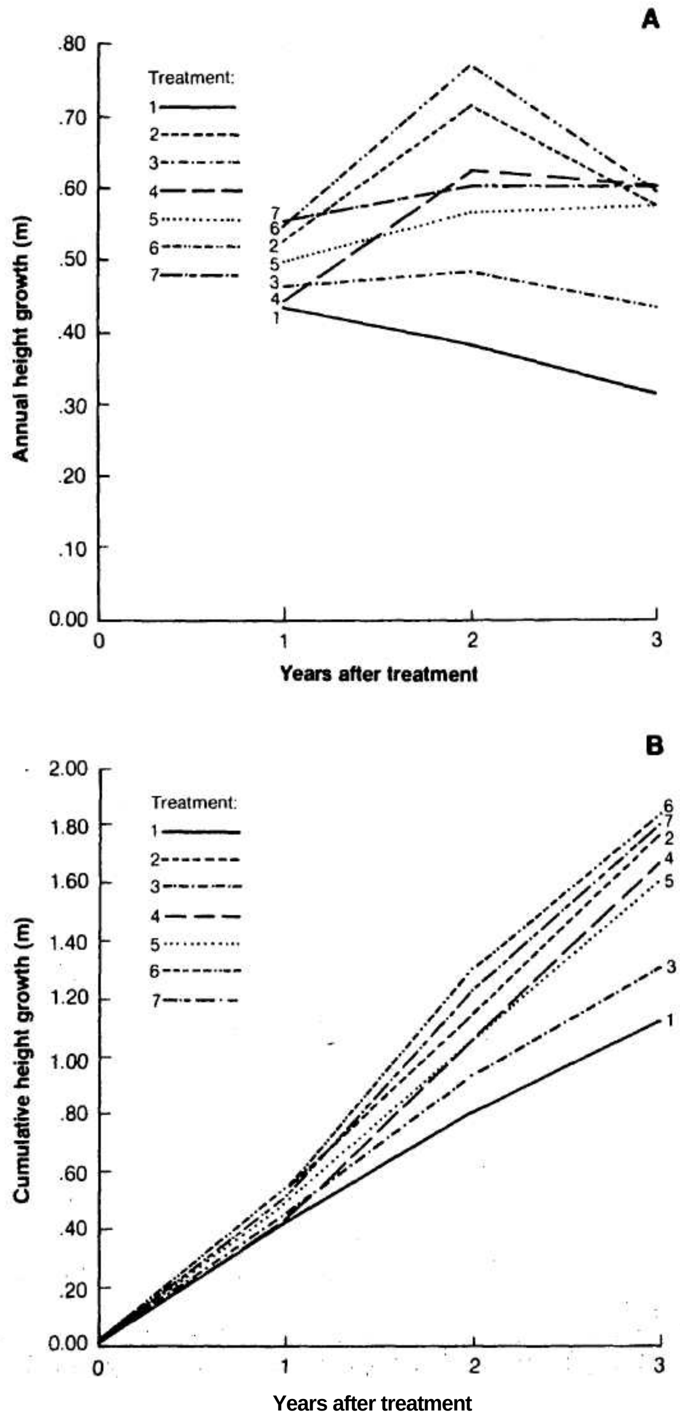

Figure 2 —Height growth of the 20 tallest trees per plot by treatment:,A, Mean annual height growth; B, Cumulative height growth. Treatment.1 = unthinned, unfertilized; 2.=. unthinned, fertilized with N(AN), P-Ca, K-S; 3 = thinned, unfertilized; 4 = thinned, fertilized with N(U); 5 = thinned, fertilized with N(AN); 6= thinned, fertilized with N (AN) I P-Ca; 7 = thinned, fertilized with N(AN), P-Ga, K-S.

Table 4—Initial characteristics and 3-year height and diameter growth of the 20 tallest trees per plot in a western redcedar stand by treatment

Treatment 1/	Initial height	3-year height growth 2/	Initial diameter	3-year diameter growth 2/
	- - - - m - - - -		- - - - cm - - - -	
Unthinned, unfertilized	5.27	1.15a 1/	7.74	1.97a
Unthinned, fertilized with N(AN), P-Ca, K-S	5.58	1.83b	8.02	3.80cd
Thinned, unfertilized	5.66	1.33a	8.64	2.62b
Thinned, fertilized with N(U)	5.24	1.69b	7.63	3.73c
Thinned, fertilized with N(AN)	5.42	1.63b	8.07	3.63c
Thinned, fertilized with N(AN), P-Ca	5.15	1.86b	7.33	4.28de
Thinned, fertilized with N(AN), P-Ca, K-S	4.94	1.79b	7.22	4.42e

1/ N = nitrogen, AN = ammonium nitrate, P-Ca = monodicalcium phosphate, K-S = potassium sulfate, U = urea.

2/ Within a column, means followed by the same letter are not significantly different (p = 0.05).

Diameter growth of the 20 tallest trees per plot was not significantly different by treatment the 1st year but was significant the 2d and 3d years (fig. 3A). The treatments stratified into two groups the 2d year, with unfertilized treatments having significantly lower diameter growth than fertilized treatments; however, neither differences between the two unfertilized treatments nor differences between the five fertilized treatments were significant.

In the analysis of 3d-year diameter growth, treatments stratified into four groups: (1) control plots had significantly lower growth than the other treatments; (2) the thinned, unfertilized treatment had significantly better 3d-year diameter growth than did the control but poorer growth than any of the fertilizated treatments; (3) the unthinned, fertilized treatment and thinned treatments fertilized with N; and (4) thinned treatments fertilized with P-Ca and AN. Third-year diameter growth of treatment group 4 was almost three times greater than diameter growth of the control.

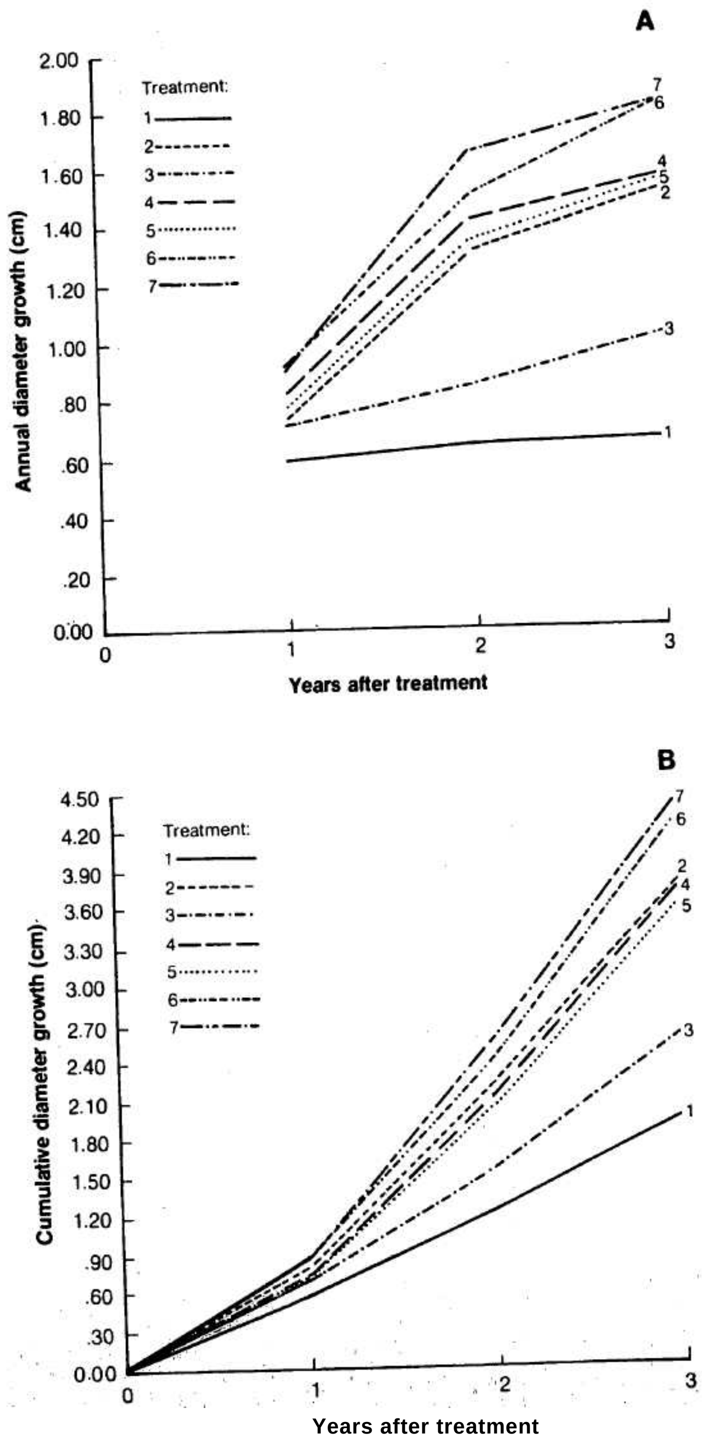

Figure: 3.—Diameter growth of the 20 tallest trees per plot by treatment: A, Mean annual diameter growth; **B**, Cumulative diameter growth. Treatment 1 = unthinned, unfertilized; 2 = unthinned, fertilized with N(AN), P-Ca, K-S; 3 = thinped, unfertilized; 4.= thinned, fertilized with N(U); 5 = thinned, fertilized with N(AN); 6 = thinned, fertilized with N(AN), P-Ca; 7-thinned, fertilized with N(AN), P-Ca, K-S:

The separation of treatments into groups over time can also be seen by plotting mean cumulative diameter growth per treatment (20 tallest trees per plot) (fig. 2B). Fertilization had a greater positive impact on the 3-year diameter growth rates than did thinning even though thinning alone also increased diameter growth. Thinning may result in greater growth in the future, however, after the trees have had a few years to build larger crowns. Also, crop tree growth in the unthinned stand will probably decline because of competition, making the overall thinning effect appear more positive.

When 3-year diameter growth (table 4) of the unfertilized treatments (thinned and unthinned) and the treatments fertilized with AN, P-Ca, and K-S (thinned and unthinned) are compared, the effects of thinning and fertilization appear to be additive. Over the 3-year period, treatments resulting in the greatest growth averaged 120 percent more diameter growth than did the control. Differences between treatments in diameter growth will probably continue to diverge over time.

Foliage Analysis

Foliar nutrient concentrations of most measured elements were altered by treatment (table 5). Increases in concentrations were evident after one growing season on plots fertilized with nitrogen or monodicalcium phosphate. Levels of N (and possibly K) were apparently increased by thinning.

The differences in N concentrations between treatments were significant all 3 years. After the 1st year, the two unfertilized treatments had significantly lower concentrations than did the fertilized treatments. The unfertilized treatments did not differ significantly from each other and there were no significant differences between the fertilized treatments. After the second growing season, the two unfertilized treatments continued to have significantly lower levels of N than did the fertilized treatments. The unfertilized treatments did differ significantly, however, with the thinned, unfertilized treatment having higher levels of N than the control. The four treatments containing ammonium nitrate did not differ among themselves, but the urea treatment had a significantly higher N concentration than aid the treatments fertilized with ammonium nitrate.

The range in N concentrations between treatments decreased with time since treatment; however, treatment effects were still evident after the third growing season. The urea treatment continued to have the highest N concentration whereas the control had the lowest.

Table 5—Concentrations of N, P, K, S, Ca, and Mg in dormant season foliage of western redcedar by silvicultural treatment and number of growing seasons since treatment[1/]

(In percent)

Treatment 2/	N			P			K		
	1 3/	2	3	1	2	3	1	2	3
Unthinned, unfertilized	1.09a	1.05a	0.91a	0.13a	0.17a	0.13	0.50a	0.63ab	0.58a
Unthinned, fertilized with N(AN), P-Ca, K-S	1.43b	1.45c	1.22d	.20b	.29b	.25b	.59a	.72b	.66a
Thinned, unfertilized	1.17a	1.21b	1.02ab	.14a	.17a	.14a	.55a	.70ab	.66a
Thinned, fertilized with N(U)	1.70b	1.59d	1.36d	.12a	.14a	.13a	.53a	.62ab	.63a
Thinned, fertilized with N(AN)	1.47b	1.41c	1.18bcd	.13a	.16a	.16a	.55a	.60ab	.56a
Thinned, fertilized with N(AN), P-Ca	1.57b	1.47c	1.24cd	.20b	.26b	.23b	56a	.52a	.56a
Thinned, fertilized with N(AN), P-Ca, K-S	1.55b	1.44c	1.16bc	.20b	.28b	.24b	.61a	.72b	.71a

Treatment 2/	S			Ca			Mg		
	1	2	3	1	2	3	1	2	3
Unthinned, unfertilized	0.10a	0.11a	0.12a	0.80b	0.78ab	0.78a	0.13a	0.12a	0.11a
Unthinned, fertilized with N(AN), P-Ca, K-S	.11b	.15b	.14a	.94b	.97cd	.93a	.12a	.12a	.13b
Thinned, unfertilized	.10a	.12ab	.12a	.79b	.75a	.94a	.13a	.12a	.11ab
Thinned, fertilized with N(U)	.11b	.14ab	.14a	.73a	.84abc	.86a	.12a	.11a	.12ab
Thinned, fertilized with N(AN)	.11b	.13ab	.14a	.78b	.93bcd	.97a	.12a	.12a	.12ab
Thinned, fertilized with N(AN), P-Ca	.11b	.15b	.15a	.92b	1.03d	.97a	.12a	.12a	.13ab
Thinned, fertilized with N(AN), P-Ca, K-S	.11b	.15b	.14a	.93b	.96cd	.84a	.12a	.12a	.12ab

1/ Within a column for each nutrient, means followed by the same letter are not significantly different (p = 0.05).

2/ N = nitrogen, AN = ammonium nitrate, P-Ca = monodicalcium phosphate, K-S = potassium sulfate, U = urea.

3/ 1 = samples collected following the first growing season since treatment (1981), 2 = samples collected following the second growing season (1982), 3 = samples collected following the third growing season (1983).

Foliar N levels in our study ranged from 0.9 percent in the control to 1.7 percent in the thinned treatment fertilized with urea. Walker and others (1955) reported values below 1.5 percent N to be associated with visual deficiency symptoms for western redcedar seedlings; this level is higher than levels stated in other published reports. Imper and Zobel (1983) summarized their own research findings and values in the literature for nutrient levels in western redcedar foliage; they noted N concentrations ranging from 0.7 to 1.6 percent with most values between 1.0 and 1.4 percent. The stand in our study responded to nitrogen fertilization with increases in both height and diameter growth. In addition, foliage in plots not fertilized with nitrogen was chlorotic whereas foliage in fertilized plots was noticeably greener a few months after treatment. After 3 years, foliage in fertilized plots was still greener than foliage in unfertilized plots. Thus, N levels in the control plots, 0.9 to 1.1 percent, were probably suboptimum and may have been close to a critical deficiency. Nitrogen levels in fertilized plots (1.2 to 1.7 percent), however, were probably well above deficiency for trees of this age.

Treatment effects on concentrations of foliar P were significant all 3 years and were consistent from year to year. The three treatments fertilized with phosphorus had significantly higher P concentrations than did treatments without phosphorus fertilization. There were no significant differences among the three treatments receiving phosphorus or among the treatments without. The levels of P within a treatment did not change much over time.

Concentrations of P from treatments without monodicalcium phosphate ranged from 0.12 to 0.17 percent. Walker and others (1955) reported 0.13 percent P for foliage of western redcedar seedlings to be associated with visual deficiency symptoms. By their standard, trees in treatments without monodicalcium phosphate were deficient or close to being deficient in P. Other researchers, however, reported P levels as low as 0.06 to 0.08 percent in foliage of older (11- to 100-year-old) healthy trees (Gessel and others 1951). Imper and Zobel (1983) sampled western redcedar foliage at five sites and found P concentrations ranging from 0.12 to 0.24 percent. In our study, nitrogen fertilization increased growth, an unlikely response if P were deficient. Foliar concentrations of P prior to fertilization with monodicalcium phosphate were probably suboptimal, however, as indicated by the increases in growth associated with the increases in P levels following fertilization.

Treatment effects were significant the first 2 years in foliar Ca concentrations. Treatments including monodicalcium phosphate had higher levels of foliar Ca than did treatments without calcium. After the 1st year, however, only the urea treatment had significantly lower Ca than the other treatments. The 2d year, the unfertilized treatments had significantly lower Ca levels than did treatments with monodicalcium phosphate; they did not differ from treatments fertilized with only urea or ammonium nitrate. Concentration of foliar Ca from the urea treatment differed only from the treatment with the highest level of Ca (thinned, fertilized with ammonium nitrate and monodicalcium phosphate). There were no significant differences in Ca concentrations between treatments the 3d year.

Foliar levels of Ca in our study ranged from 0.8 to 1.0 percent. Previous reports indicate foliar levels of Ca from 1.0 to 2.0 percent (Beaton and others 1965, Gessel and others 1951, Imper and Zobel 1983, Ovington 1956). Walker and others (1955) reported visual deficiency symptoms in western redcedar seedlings when Ca concentrations ranged from 0.10 to 0.20 percent. Although Ca levels in our study were substantially greater than those associated with deficiency symptoms, the levels were not necessarily high enough for optimum growth. It is not known whether western redcedar accumulates Ca unnecessarily (luxury consumption) or whether the species requires high levels of Ca for good growth.

After one growing season, treatments did not differ in their levels of K; however, trees in the two treatments that received potassium sulfate did have the highest K concentrations. Treatment effects were significant the 2d year, but only one treatment (thinned, fertilized with N(AN) and P-Ca) had significantly lower amounts of K than did the two fertilization treatments that included potassium sulfate. Thinning alone may have caused a slight but not significant increase in foliar K. Treatment effects after the 3d year were not significant, although the fertilization treatments that included potassium sulfate had the highest levels of foliar K.

Foliar levels of K ranged from 0.5 to 0.7 percent. These values are similar to those reported by Imper and Zobel (1983) and probably indicate that K was not limiting growth.

For the first 2 years, treatment effects on S levels were small but statistically significant. The two unfertilized treatments had lower levels of S than did any of the fertilized treatments, including those without potassium sulfate. The reason for this increase in S is unknown; possibly the additions of nitrogen increased the rate at which organic material decomposed, which may have made more S available for uptake. Differences in foliar concentrations of S were not significant the 3d year; however, the unfertilized treatments continued to have the lowest concentrations of S. Levels of foliar S were low compared to those previously reported for western redcedar seedlings (Walker and others 1955).

Foliar levels of magnesium varied little between treatments or over time. The range of Mg in our study was 0.11 to 0.13 percent; these values were in the middle of the range (0.06 to 0.23 percent) reported by Imper and Zobel (1983).

First-year height growth of the trees fertilized with urea was relatively poor considering the high levels of N found in foliage at the end of the growing season. Although western redcedar has an indeterminate pattern of height growth over a season, the majority of height growth usually occurs in the first part of the growing season (Buckland 1956), when soil moisture is adequate. Some of the urea may have been temporarily immobilized in the forest floor and, thus, may not have been available for uptake by tree roots as early in the growing season as ammonium nitrate. Increased N uptake did occur during the first year, however, as evidenced by the high concentrations of foliar N measured at the end of the growing season.

Both urea and ammonium nitrate were effective in increasing levels of foliar N the 1st year. Foliar concentrations were consistently higher, however, in trees from the urea treatment than in trees from the ammonium nitrate treatments. The concentration of Ca was significantly lower the 2d year in trees from the urea treatment; the reason for this apparent depression is not known. Foliar levels of other elements were similar between the two sources of nitrogen.

Treatments fertilized with monodicalcium phosphate had higher 1st-year foliar concentrations of P and Ca than did treatments without. Thus, monodicalcium phosphate was either taken up or was effective in promoting uptake of native P and Ca during the first growing season following fertilizer application. Levels of K and S, however, were not much affected until the 2d year, possibly indicating the potassium sulfate fertilizer was not available for plant uptake as rapidly as the other fertilizers used.

Correlations Between Annual Growth and Foliar Nutrient Concentrations

Annual growth of the 20 tallest trees per plot was significantly correlated with foliar concentrations of several nutrients (table 6). Both height and diameter growth were positively correlated with concentrations of N and S all 3 years. Concentrations of P were positively correlated with height growth all 3 years and with diameter growth the first 2 years. Concentrations of K and Ca were positively correlated with either height or diameter growth for 1 year but had very low correlations the other 2 years. Concentrations of Mg were both positively and negatively correlated with growth in different years; this lack of consistency from year to year probably indicates the relationship has no biological significance.

The thinned plots fertilized with both ammonium nitrate and monodicalcium phosphate had significantly better growth than plots fertilized with only ammonium nitrate. We cannot say whether the observed increase in growth associated with the application of monodicalcium phosphate was caused by the phosphorus component of the fertilizer, by the calcium component, or by the combination of the two elements. Differences in foliar concentrations of P between the treatments with and without monodicalcium phosphate were significant all 3 years; differences between concentrations of Ca, however, were nonsignificant. In addition, height and diameter growth were more consistently correlated with foliar concentrations of P than with Ca. Thus, it seems likely that most of the growth response resulted from phosphorus.

Table 6—Correlations between growth of the 20 tallest trees per plot and foliar nutrient concentrations in a western redcedar stand[1/]

Time of measurement and nutrient	Height growth			Diameter growth		
	1 2/	2	3	1	2	3
End of growing season prior to year growth was measured:						
N		0.63	0.84		0.77	0.71
P		.53	.49		.64	.22
K		.24	-.05		.51	.01
S		.41	.84		.60	.63
Ca		.21	.62		.27	.28
Mg		.23	.06		.46	-.21
End of growing season when growth was measured:						
N	0.30	0.74	0.69	0.43	0.80	0.65
P	.49	.48	.57	.47	.58	.36
K	.62	.01	.05	.53	.11	.17
S	.37	.67	.55	.39	.83	.51
Ca	.09	.42	.07	.07	.55	.07
Mg	-.32	.23	.63	-.42	.14	.52

1/ Correlation values needed for significance: 0.37 (p = 0.05), 0.48 (p = 0.01).

2/ Number of growing seasons since treatment.

Management Implications

Specific recommendations for forest managers must wait until data are available on long-term growth from this and other research installations. We have shown, however, that substantial increases in short-term growth can be achieved in a poor-site, coastal, western redcedar stand. For example, 3-year height and diameter growth of the 20 tallest trees per plot averaged 1.8 m and 4.4 cm in the thinned plots fertilized with ammonium nitrate (AN), monodicalcium phosphate (P-Ca), and potassium sulfate (K-S) but averaged only 1.1 m and 2.0 cm in control (unthinned, unfertilized) plots. We suspect that on this site, response to thinning alone will be small compared to increases in growth that can be achieved when fertilization with nitrogen or nitrogen plus phosphorus is combined with thinning. Both nitrogen sources, urea and ammonium nitrate, were equally effective in increasing height and diameter growth; and monodicalcium phosphate plus ammonium nitrate was more effective in increasing growth than was ammonium nitrate alone. Research in other geographic locations has shown responses to phosphorus to be long-lived (Fisher and Garbett 1980, Pritchett 1976); thus, increased growth response in our study may persist for many years.

Response to fertilization without thinning was surprisingly good. In spite of the fact that unthinned plots fertilized with N(AN), P-Ca, and K-S had six times as many trees per hectare as did the thinned plots fertilized with the same elements, there was no difference in 3-year height growth of the 20 tallest trees per plot, and 3-year diameter growth in the unthinned, fertilized treatment was 86 percent of the growth achieved in the thinned, fertilized treatment. Because of the greater stocking in the unthinned, fertilized plots, 2-year basal area growth of the total stand was more than double the growth in the thinned, fertilized plots.

Preliminary results from this and other studies (O'Carroll 1967; Zasoski and Bledsoe 1980) indicate that western redcedar is capable of excellent growth response to silvicultural treatments and may warrant greater consideration in future forest management plans.

English Equivalents

1 millimeter (mm) = 0.03937 inch
1 centimeter (cm) = 0.3937 inch
1 meter (m) = 39.37 inches
1 kilometer (km) = 0.621 mile
1 kilogram (kg) = 2.205 pounds (avoirdupois)
1 hectare (ha) = 2.471 acres
1 square meter per hectare (m^2/ha) = 4.356 square feet per acre
1 kilogram per hectare (kg/ha) = 0.892 pounds per acre
°C = 5/9(°F-32)

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Seven silvicultural treatments were applied in a 20-year-old natural western redcedar (*Thuja plicata)* Donn ex D. Don) stand on a poor site in coastal Washington: (1) control (unthinned, unfertilized); (2) unthinned, fertilized with ammonium nitrate, monodicalcium phosphate, and potassium sulfate; (3) thinned, unfertilized; (4) thinned, fertilized with urea; (5) thinned, fertilized with ammonium nitrate; (6) same as treatment 5 plus monodicalcium phosphate; (7) same as treatment 6 plus potassium sulfate. Treatments 2 through 7 resulted in significantly better 3-year height and diameter growth of the 20 tallest trees per plot (250 tallest trees per hectare) than did the control treatment (1). Increases in growth over the control trees were least for treatment 3. Thinning alone (3) resulted in much smaller increases in growth than fertilization alone (2). There were no differences in growth between the thinned treatments fertilized with ammonium nitrate and urea (4 and 5), and both treatments had significantly better growth than thinning alone. The thinned treatment fertilized with monodicalcium phosphate plus ammonium nitrate (6) was more effective in increasing growth than the thinned treatment fertilized with ammonium nitrate alone (5). Addition of potassium sulfate (7) did not increase growth significantly over treatment 6. Three-year height and diameter growth of the 20 tallest trees per plot ranged from 1.1 m and 2.0 cm in treatment 1 to 1.8 m and 4.4 cm in treatment 7. Analysis of 2-year growth of the total stand showed that all sizes of trees responded to treatment. Foliar concentrations of nitrogen, phosphorus and sulfur were positively correlated with growth rates.

Keywords: Fertilizer response (forest tree), thinning effects, precommercial thinning, silvicultural treatments, site class (-increment, western redcedar, *Thuja plicata.*

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