Western redcedar response to precommercial thinning and fertilization through 25 years posttreatment

Warren D. Devine and Constance A. Harrington

Abstract: There is little information available on the long-term effects of managing western redcedar (*Thuja plicata* Donn ex D. Don). In a 15- to 20-year-old naturally regenerated second-growth redcedar stand on a poor site on the Olympic Peninsula of Washington, we tested crop tree (largest 250 trees·ha^{-1}) response to precommercial thinning and fertilization in a replicated study. Fertilization treatments were N or N+P applied at study installation and year 13; precommercial thinning occurred at installation. Precommercial thinning without fertilization produced a sustained increase in periodic individual-tree basal area (BA) growth rate from years 3 through 25 posttreatment. However, through year 12, higher BA growth rates resulted from fertilization. During years 13 through 25, when intraspecific competition increased, the highest BA growth rate resulted from the combination of fertilization and precommercial thinning. Compared with the unthinned–unfertilized control, fertilization without thinning increased year-25 crop-tree height by 34% and BA by 137%; thinning without fertilization increased height by 11% and BA by 91%. Height to live-crown base was decreased by thinning but increased by fertilization, while thinning significantly increased stem taper on the lower bole. Treatment responses and foliar analyses indicate crop tree growth was substantially limited by nutrient availability.

Résumé : Il y a peu d'information disponible sur les effets à long terme de l'aménagement du thuya géant (*Thuja plicata* Donn ex D. Don). Dans un peuplement de thuya âgé de 15 à 20 ans, régénéré naturellement après une coupe et établi sur une station pauvre de la péninsule Olympic de l'État de Washington, aux États-Unis, nous avons mesuré la réaction des arbres d'avenir (les 250 plus gros arbres/ha) à une éclaircie précommerciale et à une fertilisation dans un dispositif expérimental comportant des répétitions. Les traitements de fertilisation comprenaient des applications de N ou de N et P lorsque l'étude a débuté et 13 ans plus tard. L'éclaircie précommerciale a été faite au moment où l'étude a débuté. L'éclaircie précommerciale sans fertilisation a produit une augmentation soutenue du taux d'accroissement périodique de la surface terrière (ST) des arbres individuels à partir de la troisième année après le traitement jusqu'à la 25^{e} année. Cependant, jusqu'à la 12^{e} année, la fertilisation a produit un taux de croissance de la ST plus élevé. Au cours des années 13 à 25, période pendant laquelle la compétition intraspécifique a augmenté, la fertilisation et l'éclaircie précommerciale combinées ont produit le taux d'accroissement de la ST le plus élevé. Comparativement au témoin non éclairci et non fertilisé, la fertilisation sans éclaircie a augmenté la hauteur de 34 % et la ST de 137 % alors que l'éclaircie sans fertilisation a augmenté la hauteur de 11 % et la ST de 91 % sur les arbres d'avenir après 25 ans. La hauteur jusqu'à la base de la cime vivante a été réduite par l'éclaircie mais augmentée par la fertilisation, alors que l'éclaircie a significativement augmenté le défilement de la partie inférieure du tronc. Les réactions aux traitements et des analyses foliaires indiquent que la croissance des arbres d'avenir a été substantiellement limitée par la disponibilité des nutriments.

[Traduit par la Rédaction]

Introduction

Compared with the other major conifer species of the Pacific Northwest, there has been little research on the management of western redcedar (*Thuja plicata* Donn ex D. Don) (Curtis et al. 2007). Although second-growth redcedar timber is relatively valuable and as decay resistant as old-growth wood (Freitag and Morrell 2001), concerns regarding establishment, growth rate, and stem form historically limited management of redcedar except on sites where other species were poorly suited (Nystrom et al. 1984; Oliver et al. 1988). In recent years, planting and management of redcedar have increased, particularly in coastal British Columbia (Gonzalez 2004). Beyond the Pacific Northwest, the species has been planted for timber production throughout Europe and in New Zealand, Africa, and elsewhere (Minore 1983; Hermann 1987). In its native range redcedar occasionally occurs in pure stands, but it is most often found in mixed-species stands across a wide range of sites, including sites with low nutrient availability or poor soil drainage (Minore 1990).

The wide nutritional amplitude of redcedar allows it to persist on nutrient-poor soils (Weetman et al. 1988), but several studies have shown growth responses to fertilization, particularly on low-productivity sites. Most of these studies reported significant short-term growth increases of saplings

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or small trees in response to application of inorganic N or N+P fertilizers (Blevins et al. 2006; Negrave et al. 2007) or to various forms of organic amendments (McDonald et al. 1994; Prescott and Blevins 2005). Early results from the study reported here (Harrington and Wierman 1990), and from another study (Weetman et al. 1989), isolated significant growth responses to P fertilization when P was applied in addition to N. Management recommendations for redcedar production on poor-quality coastal sites, where the species is prevalent, include an early N+P application followed by periodic applications of N or N+P (Blevins and Prescott 2002). Control of salal (*Gaultheria shallon* Pursh), which competes strongly for nutrients, is often necessary in young stands (Messier 1993; Prescott 1996). Few data exist on the long-term effects of fertilization on redcedar growth. Early responses to N+P were no longer significant for redcedar in a mixed-species stand after 13 years (Bennett et al. 2003), although, in a redcedar plantation, growth increases associated with fertilization were present 15 years posttreatment (Blevins et al. 2006). The growth rate of redcedar was positively correlated with foliar nutrient concentration across a range of sites in the coastal Pacific Northwest (Radwan and Harrington 1986), and the species' foliar nutrient levels also have been related to soil parent material (Kranabetter et al. 2003).

There is limited information on the response of redcedar to thinning, whether in naturally established stands or in plantations. Five year results from the study reported here indicated that precommercial thinning in a 15- to 20-year-old natural stand significantly increased diameter growth of residual trees (Harrington and Wierman 1990). Based on data from naturally established redcedar stands, Nystrom et al. (1984) suggested that trees could be selected for precommercial thinning by age 10 or when trees reached approximately 4.5 m in height. However, delaying thinning until after lower limbs have died could reduce stem defects such as fluting and large knots, which are exacerbated when live lower limbs are exposed to sunlight (Oliver et al. 1988). Thinning also may influence taper of redcedar, as taper is reduced by maintaining closer spacings (DeBell and Gartner 1997). Spacing studies have shown negative correlations between redcedar planting density and variables including height growth, diameter growth, and individual-tree stem volume growth (Reukema and Smith 1987; Negrave et al. 2007).

The objective of this research was to evaluate the 25 year effects of precommercial thinning and fertilization with N and N+P on growth of young western redcedar. While the study was conducted in a redcedar-dominated second-growth stand that established naturally after clear-cutting, the long-term treatment responses reported here also have implications for management of redcedar in mixed-species stands and in plantations. This analysis focuses on the growth of crop trees (largest 250 trees·ha^{-1}) selected at the time of treatment. Three and five year results from this study were published previously (Harrington and Wierman 1985, 1990).

Methods

Study site

The study is located in the northwestern part of the Olympic Peninsula, approximately 10 km from the Pacific Coast, Clallam County, Washington, USA (48°08′N, 124°38′W; elevation 100 m), in the *Picea sitchensis* zone (Franklin and Dyrness 1988). Under a mild maritime climate, January and August temperatures average 5 and 15 °C, respectively (measured in nearby Quillayute, Washington; Western Regional Climate Center 2008). Long-term mean annual precipitation is 2600 mm; on average, 13% of this precipitation occurs from 1 May through 31 August (Western Regional Climate Center 2008). The study plots are located in a 12 ha area where slope ranges from 0% to 10%. Soils are of the Kydaka series (Typic Humaquepts), formed in glacial lacustrine sediments (averaging 8–20 cm thick) over glacial outwash (Soil Survey Staff 2008). Soils are poorly drained, with a dense layer of glacial till of very low permeability beginning at a depth of 80 to 160 cm. In the Canadian System of Soil Classification, this soil series is approximately equivalent to a Humic Gleysol with mor humus (Soil Classification Working Group 1998). The 50 year site index for redcedar in the study area is approximately 16–18 m (Kurucz 1978).

Prior to clear-cutting in 1961, the study area was dominated by redcedar ranging from 0.5 to 4.0 m in diameter. After clear-cutting, a stand dominated by redcedar originated naturally from seed and, to a lesser extent, from advance regeneration. At the time of study establishment in 1980, redcedar accounted for over 95% of stand basal area (BA). Other tree species present in 1980 included western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and occasional Pacific yew (*Taxus brevifolia* Nutt.), Pacific silver fir (*Abies amabilis* (Dougl.) Forbes), Sitka spruce (*Picea sitchensis* (Bong.) Carrière), red alder (*Alnus rubra* Bong.), and cascara (*Rhamnus purshiana* DC.). The most prevalent shrub species were salal, red huckleberry (*Vaccinium parvifolium* Sm.), and oval-leaf blueberry (*Vaccinium ovalifolium* Sm.). In 1980 there was an average of 5900 trees·ha^{-1} in the study area. The redcedar varied widely in size and age, but the largest 250 trees·ha^{-1} averaged 5.4 ± 0.6 m in height and were predominantly in the 15 to 20 year age range.

Study design and treatments

The study followed a randomized block design, with four blocks arranged according to soil drainage, which varied with topography. Twenty-eight study plots were permanently established in September 1980; each had a 30 m × 50 m treatment area and an interior 20 m × 40 m measurement plot. Treatments consisted of combinations of precommercial thinning and fertilization regimes (Table 1). These treatments were selected in coordination with the site's industrial forest owner to reflect management options that were likely to be implemented operationally on that forest type. The T-0, UT-0, and UT-2NP treatments occurred on four plots each (one per block); both T-2N and both T-2NP treatments occurred on three plots each, as the treatment plots in block 1 did not receive the second of two fertilizer applications. These four plots in block 1 that received only the first fertilizer application are identified as the T-1N treatment and were excluded from statistical analyses. Mean values for this treatment are included in our results with no estimates of variance.

The precommercial thinning treatment, applied in October 1980, favored retention of the largest trees with good form

Table 1. Thinning and fertilization treatments.

Treatment symbol	Thinning	Year-0 fertilization, elemental rate ($kg \cdot ha^{-1}$)	Year-13 fertilization elemental rate ($kg \cdot ha^{-1}$)
T-0	Thinned	—	—
T-2N	Thinned	300 N	300 N
T-2N	Thinned	300 urea-N	300 N
T-2NP	Thinned	300 N, 100 P, 129 Ca	300 N, 100 P
T-2NP	Thinned	300 N, 100 P, 100 K, 41 S, 129 Ca	300 N, 100 P
UT-0	None	—	—
UT-2NP	None	300 N, 100 P, 100 K, 41 S, 129 Ca	300 N, 100 P
T-1N[a]	Thinned	Various	—

Note: Treatments given the same treatment symbol did not differ in preliminary analysis and were combined for the purpose of treatment comparisons. Unless otherwise specified, N was applied as ammonium nitrate, and K and S were applied as potassium sulfate. At year-0 fertilization (March 1981), Ca and P were applied as monodicalcium phosphate, and in year 13 (June 1993), P was applied as triple superphosphate.

[a]This group was composed of one replication each of the four thinned and fertilized treatments (T-2N and T-2NP), but these plots did not receive the year-13 fertilization. Because the four plots all occurred on one block, this treatment group was excluded from statistical analyses.

and produced a residual tree spacing of approximately 3.5 m × 3.5 m (807 $trees \cdot ha^{-1}$). Fertilizers listed in Table 1 were applied to plots by hand from 26 March through 3 April 1981 (i.e., prior to year-1 growing season) and on 21–29 June 1993 (study year 13); treatment areas received two perpendicular passes to ensure uniformity of application. In the 1981 fertilization, monodicalcium phosphate was selected as the P source because it would not increase soil acidity; this fertilizer was not available for the 1993 fertilization, and triple superphosphate was applied instead.

Data collection

In March 1981, 20 redcedar crop trees were selected and tagged in each plot (equivalent to 250 $trees \cdot ha^{-1}$) by selecting trees that were largest in diameter and free from major defects. These crop trees are the subject of this study and, unless otherwise specified, are the only trees referred to herein. Trees were measured for diameter at breast height (DBH; measured to nearest 0.1 cm at a height of 1.3 m) and total height (nearest 0.1 m) in March 1981 (i.e., year 0) and subsequently remeasured after the growing season of study years 1 (i.e., 1981), 2, 3, 5, 10, 12, 16, 20, and 25. Height was not measured in year 12. Height to live-crown base (HLC), defined as the lowest point on the bole where live limbs occurred in three quadrants, was measured in years 16, 20, and 25. In year 25 crown radius was measured in two directions, 180° apart, at the widest point of the crown. Because only three of the 560 trees died during the 25 year study, we did not analyze mortality.

Following the year-17 and year-25 growing seasons, stem taper was assessed by measuring stem diameter of randomly selected trees (n = 77 at year 17; n = 97 at year 25) at heights of 0.3, 1.3, 2.3, and 3.3 m using a ladder. These measurements were made on three blocks in a subset of treatments: UT-0, T-0, UT-2NP, and T-2NP. At the time of the year-25 taper measurements, diameters of two branches per tree were measured, at the proximal end, on the same trees measured for taper. These branches were selected by first determining the azimuth of greatest crown diameter and then bisecting the stem vertically using an azimuth offset 90° from that of greatest crown diameter. On each of the bisected halves, the largest-diameter branch was selected within 2.3 m of stem base. Branch status (living or dead) was recorded.

Samples of year-10 (i.e., 1990) foliar growth were collected 3–4 April 1991 from 10 dominant or codominant trees per plot. These samples were collected from the upper portion of the crown that was exposed to sunlight. Samples were composited by plot and analyzed for total N, P, K, S, Ca, and Mg. Nitrogen analysis followed the Kjeldahl method (Bremner 1965), and other elements were determined by inductively coupled plasma spectroscopy (Jones 1977).

Following year 25 (May 2006), mineral soil in the 0 to 20 cm depth interval was sampled using a steel soil probe at eight systematically arranged locations per plot. At each location, five subsamples were collected, and then all samples were composited by plot. Samples were analyzed for pH (1:1 soil:water, v/v), total C and N (Fisons NA 1500 Elemental Analyzer, Fisons Instruments, Manchester, UK), inorganic N (NH_4 and NO_3; Sims et al. 1995), P (Bray-1 extraction), SO_4-S ($CaPO_4$ extraction), K, and Ca (both via inductively coupled plasma).

Data analysis

Periodic annual increment (PAI; i.e., the average annual growth rate between measurements) of total tree height and individual-tree BA (i.e., cross-sectional area of the stem at breast height) were analyzed by repeated-measures analysis of covariance (ANCOVA) models using the Mixed procedure (Zar 1999; SAS Institute Inc. 2005). The covariate in each model was tree height or BA prior to the year-1 growing season (i.e., year 0). Year-25 height and BA also were analyzed with ANCOVA, using year-0 values as covariates. Year-25 height/diameter ratio (HD), year-10 foliar nutrient concentration, and year-25 soil chemical properties were analyzed using analysis of variance (ANOVA) models. In all models, block was a random effect and treatment was a fixed effect with seven levels. In the repeated-measures model of height PAI, time (i.e., measurement period) had eight levels, while in the repeated-measures model of BA PAI, time had nine levels. Post-ANOVA mean separations were made using preplanned contrasts, which are shown in

Table 2. *P* values indicating contrast significance for individual-tree basal area periodic annual increment of redcedar.

	Study year(s)								
Contrast	1	2	3	4–5	6–10	11–12	13–16	17–20	21–25
Not fertilized: unthinned vs. thinned (T-0 vs. UT-0)	0.82	0.46	**0.02**	0.06	**0.04**	**0.03**	**0.04**	**0.02**	**0.04**
Fertilized: unthinned vs. thinned (T-2NP vs. UT-2NP)	0.81	0.64	0.07	0.06	0.14	0.07	**<0.01**	**<0.01**	**<0.01**
Unthinned: not fert. vs. fert. (UT-0 vs. UT-2NP)	0.33	**<0.01**	**<0.01**	**<0.01**	**<0.01**	0.29	**<0.01**	**<0.01**	**<0.01**
Thinned: not fert. vs. N (T-0 vs. T-2N)	0.56	**<0.01**	**<0.01**	**<0.01**	**<0.01**	0.79	**<0.01**	**<0.01**	**<0.01**
Thinned: N vs. N+P (T-2N vs. T-2NP)	0.36	0.18	0.10	0.30	0.65	0.36	**<0.01**	**<0.01**	**<0.01**

Note: Significant *P* values are shown in bold.

Table 3. *P* values indicating contrast significance for height growth periodic annual increment of redcedar.

	Study year(s)							
Contrast	1	2	3	4–5	6–10	11–16	17–20	21–25
Not fertilized: unthinned vs. thinned (T-0 vs. UT-0)	0.42	0.47	0.16	0.20	0.49	0.46	0.37	0.82
Fertilized: unthinned vs. thinned (T-2NP vs. UT-2NP)	0.57	0.06	0.77	0.67	0.98	0.72	0.66	0.45
Unthinned: not fert. vs. fert. (UT-0 vs. UT-2NP)	0.08	**<0.01**	**<0.01**	**<0.01**	0.25	**<0.01**	**<0.01**	0.65
Thinned: not fert. vs. N (T-0 vs. T-2N)	0.73	**<0.01**	**<0.01**	0.10	0.36	0.07	**<0.01**	0.83
Thinned: N vs. N+P (T-2N vs. T-2NP)	**0.03**	0.21	0.96	0.45	0.82	0.16	0.83	0.30

Note: Significant *P* values are shown in bold.

Table 4. *P* values indicating contrast significance for individual-tree basal area (BA), height, and height/diameter ratio (HD) of redcedar at study year 25.

	Variable		
Contrast	BA	Height	HD
Not fertilized: unthinned vs. thinned (T-0 vs. UT-0)	0.07	0.08	**<0.01**
Fertilized: unthinned vs. thinned (T-2NP vs. UT-2NP)	**<0.01**	0.83	**<0.01**
Unthinned: not fert. vs. fert. (UT-0 vs. UT-2NP)	**<0.01**	**<0.01**	**<0.01**
Thinned: not fert. vs. N (T-0 vs. T-2N)	**<0.01**	**<0.01**	0.09
Thinned: N vs. N+P (T-2N vs. T-2NP)	**0.04**	0.11	0.20

Note: Significant *P* values are shown in bold.

Tables 2, 3, and 4. These contrasts test both T-2N treatments and both T-2NP treatments simultaneously, as preliminary analysis showed no differences between the two T-2N treatments or the two T-2NP treatments. Where ANCOVA models indicated significant treatment × time interactions, these were interpreted by examining contrast significance in combination with plotted treatment means. Because stem taper and branch diameter data were collected on a subset of treatments, these models consisted of a two-way ANOVA, with thinning (presence vs. absence) and fertilization (none vs. N+P) as fixed effects. Analysis of variance also was used to compare 25 year BA growth of crop trees among the four year-0 BA quartiles; these BA quartile assignments were made for the crop trees within each plot. Multiple comparisons among crop tree quartiles were made using the Bonferroni test. For each ANOVA model, assumptions including normality of residuals, treatment homoscedasticity, and lack of covariate × treatment interaction were met. A minimum confidence level of 95% was used in all analyses.

Results

Individual-tree basal area

Basal area PAI was significantly affected by treatment and time ($F = 90.9$, $P < 0.01$; $F = 70.1$, $P < 0.01$, respectively); additionally, there was a significant treatment × time interaction ($F = 4.9$, $P < 0.01$). Year-25 BA was significantly influenced by treatment ($F = 14.8$, $P < 0.01$).

Without fertilization, BA PAI was significantly greater with thinning than without in year 3 and from year 6 through year 25 (Table 2, Fig. 1). Year-25 BA in unfertilized treatments did not differ significantly with thinning (Table 4). Under N+P fertilization, BA PAI was greater with thinning than without from years 13 through 25. At year 25, BA was significantly greater in the T-2NP treatment (810 ± 32 cm^2 (mean ± SE)) than in the UT-2NP treatment (632 ± 38 cm^2).

In the absence of thinning, 2NP fertilization was associated with an increase in BA PAI in years 2–10 and 13–25 compared with no fertilization. Year-25 BA in unthinned treatments also was greater with 2NP fertilization compared with no fertilization (632 ± 38 vs. 267 ± 38 cm^2). Among thinned treatments, BA PAI was greater under N fertilization than without fertilization in years 2 through 10 and 13 through 25. Similarly, year-25 BA among thinned treatments was greater under N fertilization than where unfertilized (740 ± 32 vs. 510 ± 38 cm^2). Also among thinned treatments, BA PAI was greater under N+P fertilization than under N-only fertilization during years 13 through 25. At year 25, BA was greater in the former treatment than in the latter treatment (810 ± 32 vs. 740 ± 32 cm^2). BA PAI in the T-1N treatment was similar to that in the T-2N treatment

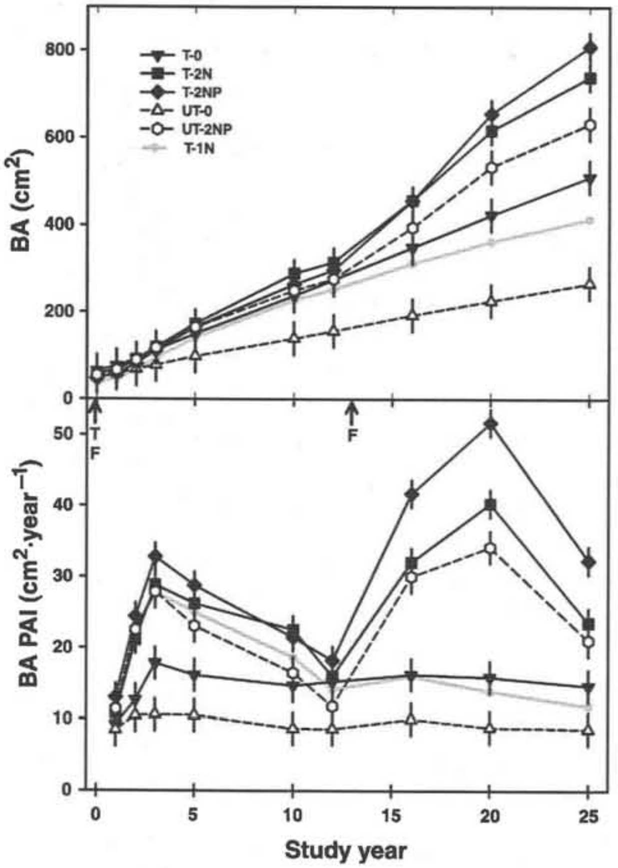


Fig. 1. Basal area (BA) and BA periodic annual increment (PAI), with standard error bars, for redcedar under various combinations of fertilization and thinning (Table 1). Treatment contrasts appear in Tables 2 and 4. T and F indicate timing of thinning and fertilization, respectively.

following the first fertilization but followed the same trend as that in the T-0 treatment after the second fertilization.

In each of the fertilized treatments, 25 year BA growth was greatest for trees that were in the fourth crop tree BA quartile at the time study initiation (Fig. 2). Basal area growth among the first through third crop tree quartiles did not differ. In the unfertilized treatments, there were no significant differences in 25 year BA growth among crop tree BA quartiles.

Height

Height PAI was significantly influenced by treatment and time (F = 33.3, P < 0.01; F = 38.7, P < 0.01, respectively), and there was a significant treatment × time interaction (F = 1.6, P = 0.04). Year-25 height also was significantly affected by treatment (F = 18.4, P < 0.01).

Whether with or without fertilization, height PAI (years 1 through 25) and total height at year 25 were not significantly affected by thinning (Table 3, Fig. 3). Without thinning, height PAI was significantly greater under N+P fertilization than under no fertilization during years 2 through 5 and during years 11 through 20. Also, year-25 height was greater under N+P fertilization (15.9 ± 0.5 m) than in the unfertilized treatment (11.9 ± 0.5 m). With thinning, height PAI was greater in the N fertilization treatments than in the unfertilized treatments, in years 2–3 and 17–20. Year-25 height was greater in the thinned N fertilization treatments (15.2 ± 0.4 m) than in the thinned unfertilized treatment (13.2 ± 0.5 m). Within the thinned treatments, there was no difference in year-25 height between the N fertilization treatment and the N+P fertilization treatment; the only height PAI difference between these treatments occurred in year 1. Height PAI in the T-1N treatment followed a trend similar to that in the T-2N treatment through year 10 but declined more rapidly than in the other fertilized treatments after year 10.

Height/diameter ratio

There was a significant treatment effect on year-25 HD (F = 9.4, P < 0.01). Under N+P fertilization, year-25 HD was significantly lower with thinning than without (56.9 ± 2.2 vs. 67.8 ± 2.2) (Table 4, Fig. 4). Without fertilization, year-25 HD also was significantly lower with thinning (50.7 ± 2.0 vs. 61.8 ± 2.2). In the absence of thinning, N+P fertilization was associated with significantly lower HD, compared with the unfertilized treatment (61.8 ± 2.2 vs. 67.8 ± 2.2). Among thinned treatments, year-25 HD did not differ significantly by fertilization treatment.

Stem taper

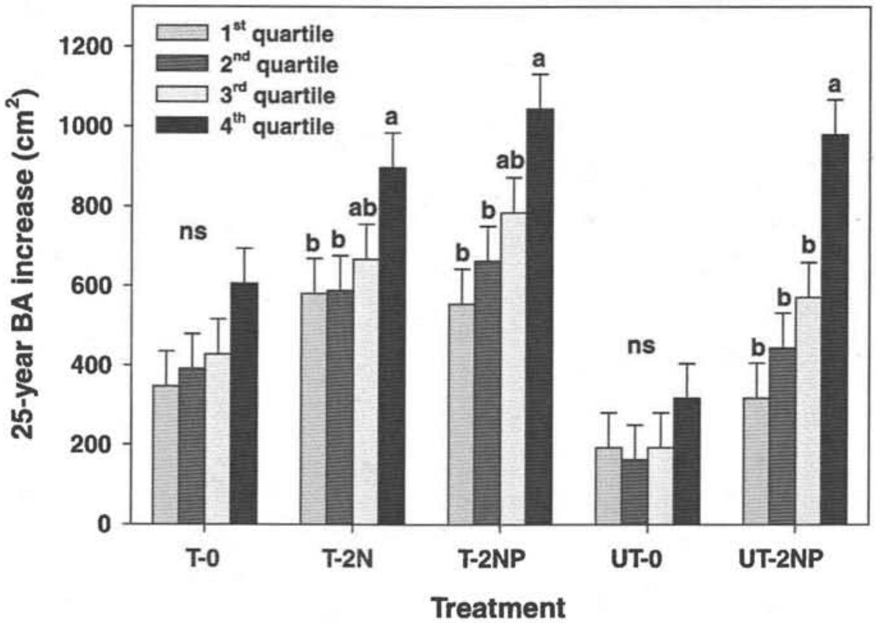
Year-17 stem taper, calculated as the ratio of stem diameter at heights of 0.3, 1.3, or 2.3 m relative to stem diameter at 3.3 m, was greater with thinning at stem heights of 0.3 and 1.3 m (Table 5). Also in year 17, stem taper at a height of 2.3 m diminished with fertilization. At year 25, stem taper was significantly greater with thinning at stem heights of 2.3 and 1.3 m.

Crown

Mean crown radius at year 25 was not significantly affected by thinning (F = 0.7, P = 0.41), but crown radius was significantly greater (F = 16.6, P < 0.01) in the N+P treatment (3.4 ± 0.1 m) than in the unfertilized treatment (2.9 ± 0.1 m). Height to live-crown base was affected by a significant treatment × year interaction (F = 2.0, P = 0.04): treatment affected HLC in year 25 but not in years 16 or 20 (Fig. 5). In year 25, HLC in the UT-2NP treatment was significantly greater than that in the T-2NP treatment (F = 17.9, P < 0.01) and the UT-0 treatment (F = 20.7, P < 0.01). Year-25 HLC also was significantly greater in the T-2N treatment than in the T-0 treatment (F = 5.0, P = 0.03).

The mean diameter of the two largest branches on the lower stem was greater (F = 9.1, P < 0.01) with thinning than without (3.5 ± 0.2 vs. 3.1 ± 0.2 cm). Branch diameter also was greater (F = 9.1, P < 0.01) for trees in the N+P treatments (3.5 ± 0.2 cm) than for unfertilized trees (3.1 ± 0.2 cm). Among live branches only, neither thinning (F = 3.7, P = 0.06) nor fertilization (F = 1.2, P = 0.28) affected branch diameter, but there was a nonsignificant trend toward larger branch size with thinning (3.6 ± 0.2 vs. 3.3 ± 0.2 cm). Overall, 25% of the branches measured were dead in the thinned treatment, while 48% were dead in the unthinned treatment. Forty-three percent of measured branches were dead in the fertilized treatment, and 29% of measured branches were dead in the unfertilized treatment.

Fig. 2. Increase in individual-tree basal area (BA) after 25 years for redcedar crop trees classified by pretreatment crop tree BA quartile. Treatments consisted of various combinations of fertilization and thinning (Table 1). Same letters denote no significant difference ($P \geq 0.05$) in growth among quartiles within a treatment; ns denotes no significant differences within a treatment.



Foliar and soil chemical properties

With the exception of Ca, all year-10 foliar nutrient concentrations were unaffected by treatment and are presented as study means with one standard deviation. Foliar N concentration was 7.62 ± 0.59 g·kg^{-1}, P was 1.15 ± 0.12 g·kg^{-1}, K was 3.29 ± 0.35 g·kg^{-1}, S was 0.86 ± 0.05 g·kg^{-1}, and Mg was 1.13 ± 0.09 g·kg^{-1}. Foliar Ca concentration was greater ($F = 4.6$, $P = 0.04$) in the UT-0 treatment (8.11 ± 0.25 g·kg^{-1}) than in the T-0 treatment (7.36 ± 0.25 g·kg^{-1}). Foliar Ca also was higher ($F = 9.0$, $P < 0.01$) in the UT-0 treatment (8.11 ± 0.25 g·kg^{-1}) than in the UT-2NP treatment (7.07 ± 0.25 g·kg^{-1}).

The majority of year-25 soil chemical properties were not significantly affected by treatment ($P \geq 0.05$) and are presented as overall mean concentrations with one standard deviation. The mean value for soil pH was 4.1 ± 0.1, soil C was 63.4 ± 7.6 g·kg^{-1}, C/N ratio was 29.3 ± 2.2, total inorganic N was 28.0 ± 7.0 mg·kg^{-1}, Bray-1 P was 2.2 ± 2.3 mg·kg^{-1}, sulfate-S was 9.8 ± 7.2 mg·kg^{-1}, K was 30.8 ± 4.4 mg·kg^{-1}, and Ca was 228.1 ± 59.2 mg·kg^{-1}. Soil total N concentration averaged 2.2 ± 0.3 g·kg^{-1}, although N was significantly greater ($F = 4.9$, $P = 0.04$) in the T-0 treatment (2.3 ± 0.1 g·kg^{-1}) than in the UT-0 treatment (2.0 ± 0.1 g·kg^{-1}).

Discussion

Twenty-five years after initial treatment, both precommercial thinning and fertilization significantly increased growth of the 250 largest western redcedar per hectare in a naturally established second-growth stand. Total height of redcedar was greatest in fertilized treatments, regardless of which fertilizer was applied or whether fertilization was accompanied by thinning. Individual-tree BA was greatest in the thinned treatment that also was fertilized with N+P. Comparing the benefit of fertilization with that of precommercial thinning, fertilization without thinning increased total height by 34%, while thinning without fertilization produced a nonsignificant 11% height increase. The combination of these treatments increased height by 31% compared with the unthinned, unfertilized treatment. Fertilization without thinning increased BA by 137%; thinning alone increased BA by 91%. The combination of these treatments increased BA by 203%.

The BA growth response to thinning differed between unfertilized and fertilized treatments. Without fertilization, the magnitude of the thinning response remained very consistent during years 3–25. With fertilization, the thinning response was greatest in years 13–25 (Table 2). The fact that thinning benefited fertilized trees only in the second half of the study suggests that competition among these trees was greater at that time. In the same period, the smaller trees of the unfertilized treatments apparently had not reached the same level of intertree competition. An interaction between thinning and fertilization also occurs among Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco): the individual-tree volume growth response to fertilization is greater in thinned stands than in unthinned stands because fewer trees are competing for the added nutrients (Miller and Fight 1979; Peterson and Hazard 1990).

Although thinning had no statistically significant effect on height growth within the fertilized or unfertilized treatments, there was a trend ($P = 0.08$) toward greater 25 year post-treatment height in the T-0 treatment than in the UT-0 treatment. Increased height growth was associated with lower stand density for unfertilized redcedar planted at 500 to 2500 trees/ha on low-fertility sites, a trend attributed to competition for soil nutrients among trees (Negrave et al. 2007). On a moderately poor site, Douglas-fir planted at comparable densities also showed a negative stand density – height relationship (Curtis and Reukema 1970). In our study,

Fig. 3. Height and height periodic annual increment (PAI), with standard error bars, for redcedar under various combinations of fertilization and thinning (Table 1). Treatment contrasts appear in Tables 3 and 4. T and F indicate timing of thinning and fertilization, respectively.

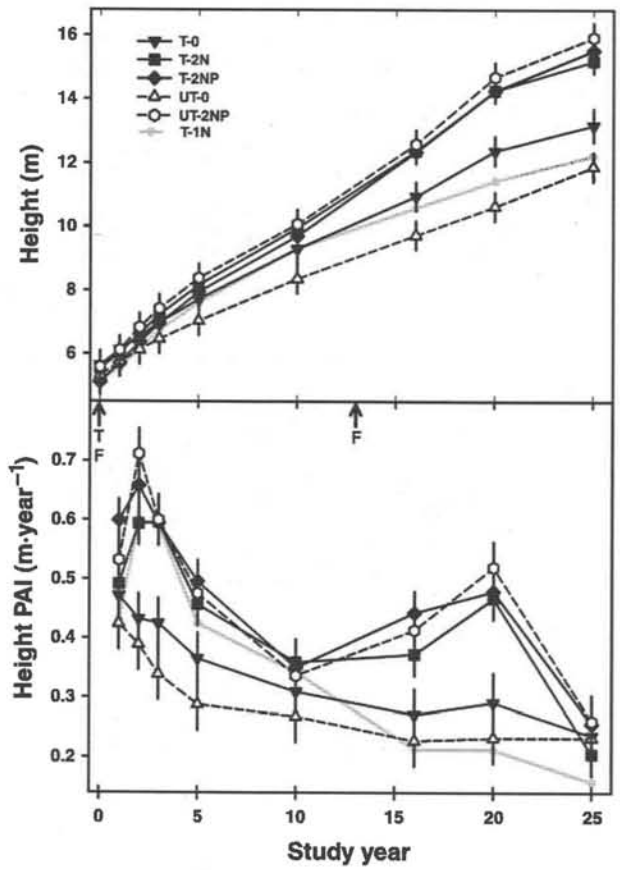
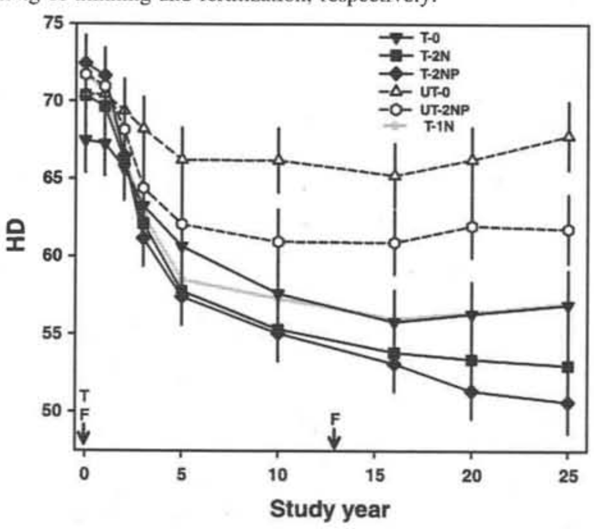


Fig. 4. Height/diameter ratio (HD), with standard error bars, for redcedar under various combinations of fertilization and thinning (Table 1). Treatment contrasts appear in Table 4. T and F indicate timing of thinning and fertilization, respectively.



we also attribute the trend toward reduced height growth in the UT-0 treatment, relative to the T-0 treatment, to greater nutrient competition in the unthinned treatment where density was much higher. This conclusion is supported by the fact that in our fertilized treatments, where nutrient availability was presumably greater, thinning had no effect on height growth (i.e., UT-2NP vs. T-2NP). Also, during the first 5 years of this study, foliar nutrient content analyses indicated that nutrients added via fertilization were apparently depleted more rapidly in the unthinned treatment than in the thinned treatment (Harrington and Wierman 1990).

We observed no evidence of thinning shock, the temporary reduction in height growth rate after thinning, which has been reported for Douglas-fir on similarly poor sites and for many other species (Miller and Reukema 1977; Harrington and Reukema 1983). The lack of thinning shock may be due to the species or to the relatively young stand age (DeBell et al. 2002).

Foliar N concentration in year 10 was lower than most of the values reported previously for redcedar in the region (Radwan and Harrington 1986; Weetman et al. 1988, 1989) and was slightly lower than that reported at year 5 in the same study (Harrington and Wierman 1990). The fact that foliar nutrient concentrations did not differ among fertilization treatments at year 10 was not surprising given that foliar nutrient concentrations among treatments were already converging at year 5 (Harrington and Wierman 1990), and periodic growth response to fertilization had also diminished substantially by year 10. According to regional guidelines, year-10 foliar N concentration was within a range indicating severe deficiency, while foliar P concentration indicated moderate deficiency (Carter 1992). On sites such as the one where this study was located, low N mineralization rates and the inherently low nutrient availability of the young glacially derived soil is exacerbated by root competition from vegetation such as salal, making nutrients the most growth-limiting factor for young trees including redcedar (Messier 1993; Prescott 1996).

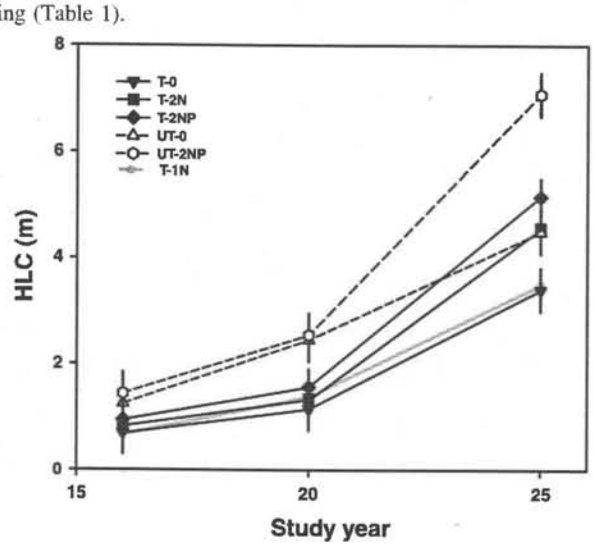
In both thinned and unthinned treatments, the positive effect of the year-0 N fertilization on BA PAI peaked at year 3 and remained significant through year 10 posttreatment. After the year-13 fertilization, the BA PAI response peaked during the period 3 to 6 years after treatment and remained significant through year 25. Based on redcedar site index curves, the projected age-50 height advantage associated with N+P fertilization in our unthinned treatments is 5.0 m (Kurucz 1978). The duration and magnitude of our fertilization responses are similar to or greater than responses reported previously for fertilized redcedar on comparable sites. On Vancouver Island, British Columbia, growth of a young redcedar plantation was increased by N but not by P over a 4 year period (Blevins et al. 2006), while another plantation, fertilized at year 5, had a 10 year growth response to fertilization (Negrave et al. 2007). In a young, mixed-species stand on a similar site, fertilization with N+P increased redcedar height growth during the first 3 years after treatment, but after 13 years, no effect was evident (Weetman et al. 1989; Bennett et al. 2003). While the fertilization responses in the our study were dramatic, they were of finite duration and did not produce sustained increases in periodic growth rate. This trend was especially apparent in

Table 5. Stem diameter at three heights (mean ± SE, expressed as a percentage of stem diameter at 3.3 m) and analysis of variance (ANOVA) results ($P > F$) for the effects of thinning and fertilization (N+P) treatments applied to redcedar in a 25 year study.

Study year	Stem height (m)	Treatment				ANOVA results		
		UT-0	UT-2NP	T-0	T-2NP	Thinning	Fertilization	Thin. × fert.
17	2.3	111.7±1.2	108.6±1.2	114.0±1.2	111.1±1.3	0.06	**0.02**	0.92
	1.3	130.0±2.5	130.8±2.6	136.0±2.7	139.5±2.8	**<0.01**	0.43	0.61
	0.3	167.7±3.7	161.9±3.6	177.6±3.7	185.0±3.7	**<0.01**	0.83	0.08
25	2.3	108.9±1.2	108.3±1.1	112.0±1.2	109.6±1.2	**0.03**	0.14	0.38
	1.3	126.5±2.9	126.6±2.7	130.9±2.8	133.0±2.8	**<0.01**	0.55	0.63
	0.3	168.1±3.6	169.4±3.2	174.6±3.5	172.3±3.5	0.13	0.86	0.57

Note: Significant *P* values are shown in bold.

Fig. 5. Height to live-crown base (HLC), with standard error bars, for redcedar under various combinations of fertilization and thinning (Table 1).



the BA and height PAI responses of the T-1N treatment group (Figs. 1, 3). In contrast, sustained fertilization responses to N+P have been reported for western hemlock on sites similar to ours (Bennett et al. 2003; Blevins et al. 2006). On those sites, nutrient deficiency had severely limited productivity of hemlock, possibly because of the effect of P deficiency on tree physiology or on nutrient cycling. The fact that redcedar on the same sites did not show a sustained response to fertilization was attributed to differences in the species' ability to compete for soil P (Blevins et al. 2006).

Two P applications resulted in a BA that was 9% greater after 25 years compared with the BA obtained with N fertilization alone; the benefit of P fertilization on BA PAI was greater after the year-13 application than after the initial application. The response to P fertilization was not surprising because mean foliar P concentration in year 10 was lower than nearly all of the values reported previously for redcedar stands in the coastal Pacific Northwest (Radwan and Harrington 1986; Weetman et al. 1988). The low foliar P concentrations may have been due, in part, to the low soil pH (4.1), as soil P availability generally declines in relation to pH at pH values below 5.5 (Tisdale and Nelson 1975). Foliar P concentration for redcedar was positively correlated with pH in a regional analysis where pH ranged from 4.0 to 5.2 (Radwan and Harrington 1986). Studies conducted on similar sites have suggested that long-term improvements in site productivity may be achieved by overcoming P limitations (Bennett et al. 2003, 2004; Blevins et al. 2006); however, in these studies responses to P were evident in western hemlock and in herbaceous species rather than in redcedar. After 25 years, we did not observe a significant effect of N+P fertilization on tree height, compared with N-only fertilization, and we conclude that redcedar productivity at our site was primarily limited by N.

In the fertilized treatments, trees that were largest at the beginning of the study had significantly greater 25 year BA growth than smaller trees (Fig. 2). In unfertilized treatments, this pattern was not significant. Thus, the increased nutrient availability apparently contributed to differentiation in BA growth among tree size classes. The magnitude of this trend was greatest in the unthinned, fertilized treatment, emphasizing the importance of initial tree size at higher stand densities, where competition was presumably greater.

Stem taper in the lowest 3.3 m of the bole was greater in the thinned treatment than in the unthinned treatment. While stem taper is a function of many factors, including genetics, crown class, site quality, and management practices (Larson 1963), the high degree of taper that is typical for redcedar is attributed to the relative longevity of its lower branches (Oliver et al. 1988). Unless these branches are controlled through stand density management, many persist and continue to produce photosynthates that contribute to the thickening of the lower stem (Oliver et al. 1988). Thus, it is not surprising that our thinning treatment increased stem taper, given the association among wider spacing, increased crown length (Fig. 5) (Reukema and Smith 1987; DeBell and Gartner 1997), and increased taper (Larson 1963). Height/diameter ratio was significantly reduced by thinning, owing to the increase in stem diameter associated with thinning. Height/diameter ratios in the thinned treatments were comparable to those of plantation redcedar at spacings of 2.7 to 4.6 m (Reukema and Smith 1987). The fact that HD values were not excessively high, even in the unthinned treatments (i.e., <70; cf. Reukema and Smith 1987), was likely due to poor site quality and the fact that the measurement trees were in codominant or dominant crown positions (Larson 1963).

Crown attributes 25 years posttreatment were influenced by thinning and fertilization treatments. Thinning was associated with decreased HLC (Fig. 5) and somewhat larger-diameter limbs within 2.3 m of the ground. These trends were likely due to greater amounts of within- and between-crown light penetration in the thinned treatments. In 35-year-old redcedar plantations, spacing (1.8 to 4.6 m) was positively related to diameter of lower branches, although there was only a 1.0 cm difference between mean branch diameter in the narrowest and widest spacings (DeBell and Gartner 1997). In the same study, spacing did not affect the number of limbs on the butt log. We found an association between fertilization and increased HLC. This may have been a result of increased leaf area resulting from fertilization (Binkley and Reid 1984); greater leaf area may have increased within-crown shading, leading to mortality of lower limbs. Overall, HLC was greatest in the unthinned, fertilized treatment, where trees were tallest and crown spacing was closest. The increases in limb diameter and longevity associated with thinning in this study were small in magnitude, and by the time of harvest, they may not affect log value. Because lower limbs of redcedar persist at wide spacings or where trees are overtopped, the best approach for reducing these limbs in pure even-aged stands is a narrow initial spacing followed by thinning (Oliver et al. 1988).

Redcedar is usually found in mixed-species stands rather than in pure stands, and in mixed stands N+P fertilization is likely to benefit the growth of other species at least as much as that of redcedar (Bennett et al. 2003; Negrave et al. 2007). If fertilization responses of other species are superior to those of redcedar, this may have the adverse effect of promoting their eventual dominance over redcedar. Therefore, precommercial thinning may be an important tool for influencing the desired species mixture. In young mixed-species stands, where other conifers often have similar or greater height growth rates, it is important that redcedar crop trees not become overtopped. Overtopped redcedar has a reduced growth rate and does not self-prune lower limbs owing to its shade tolerance. When overtopped redcedar is released, it does not recover apical control and often develops large spreading limbs that reduce log quality (Oliver et al. 1988).

Our treatment responses and foliar analysis indicate that growth of redcedar crop trees was substantially limited by N availability and, to a lesser extent, by P availability. Large increases in tree growth followed both fertilizer applications, with the growth response to the second application (stand age of 28–33 years) at least as great as the response to the first (stand age of 15–20 years). This suggests that additional applications also would produce significant growth responses on this nutrient-poor site. However, after the second fertilizer application, growth of fertilized crop trees also benefited from the stand density reduction associated with thinning. On sites characterized by low nutrient availability due to low mineralization rates and nutrient competition from salal (Prescott 1996), we would expect fertilization responses comparable to those reported here. Although it is uncertain what effects our treatments would have on a more productive site, a recent Vancouver Island study showed redcedar to be as responsive to N+P fertilization on a medium-fertility hemlock–amabilis fir site as on a low-fertility cedar–hemlock site (Negrave et al. 2007). However, the thinning response and the thinning–fertilization interactions that we observed are likely to differ on more productive sites.

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