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Stand development following precommercial thinning and fertilization treatments in a western redcedar (*Thuja plicata*) dominated forest

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Abstract: Western redcedar (*Thuja plicata* Donn ex D.Don.) is an important North American tree species, but little information is available on its long-term responses to silvicultural treatments. Stand responses (mortality, ingrowth, basal area and volume growth, and distributions of trees by diameter and height classes) were followed for 25 years after thinning and fertilization treatments (alone and in combination) were applied to a naturally regenerated, low site quality western redcedar stand on the Olympic Peninsula in western Washington, USA. Mortality was low overall, but the densest stands experienced competition-related mortality. Thinning resulted in additional stem recruitment; after 25 years, the number of ingrowth trees exceeded the number of trees in the cohort left after thinning. Fertilization (with nitrogen and phosphorus) flattened size distributions and skewed them to larger size classes. Thinning plus fertilization resulted in the largest individual trees and the most large trees, but also many trees in a wide range of diameter classes. The recruitment of a second cohort did not result in a two-storied stand. Fertilization without thinning resulted in the greatest stand basal area and volume, as well as trees with fewer live lower branches.

Résumé : Le thuya géant (*Thuja plicata* Donn ex D. Don.) est une espèce d'arbre importante en Amérique du Nord, mais peu d'informations sont disponibles concernant sa réaction à long terme aux traitements sylvicoles. Les réactions à l'échelle du peuplement (la mortalité, le recrutement, la croissance en surface terrière et en volume, ainsi que la distribution des arbres par classes de diamètre et de hauteur) ont été mesurées pendant la période de 25 ans qui a suivi l'application de traitements d'éclaircie et de fertilisation (seuls ou combinés) dans un peuplement de thuya géant naturellement régénéré sur une station de faible qualité de la presqu'île Olympique dans l'ouest de l'État de Washington, aux États-Unis. La mortalité était globalement faible, mais les peuplements les plus denses ont subi une mortalité induite par la compétition. L'éclaircie a provoqué le recrutement additionnel de nouveaux arbres; après 25 ans, le nombre d'arbres recrutés dépassait le nombre d'arbres de la cohorte laissée après l'éclaircie. La fertilisation (avec de l'azote et du phosphore) a aplani la distribution de la taille des arbres tout en l'étirant vers les classes constituées des plus gros arbres. La combinaison de l'éclaircie et de la fertilisation a produit les plus gros individus et la plus grande quantité de gros arbres, mais aussi plusieurs arbres distribués dans une large gamme de classes de diamètre. Le recrutement d'une deuxième cohorte n'a pas créé un peuplement bi-étagé. La fertilisation sans éclaircie a produit les plus grandes valeurs de surface terrière et de volume de même que des arbres avec le moins de branches vivantes dans le bas de la cime.

[Traduit par la Rédaction]

Introduction

Western redcedar (*Thuja plicata* Donn ex D.Don.) is a shade-tolerant component of a variety of forest types in the coastal and interior US Pacific Northwest and British Columbia (Minore 1990). Although naturally established, pure western redcedar stands occur infrequently, western redcedar plantations are becoming increasing common (Gonzalez 2004). At rotation lengths of 40 to 60 years, cubic volume production of pure western redcedar was estimated to be comparable with that of Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco; Nystrom et al. 1984). However, over the same rotation, the growth rate of western redcedar in mixed stands is usually reduced, because early height growth of other species is typically greater than that of western redcedar, which is thus relegated to lower crown positions and reduced growth rates in mixed-species stands (Oliver et al. 1988). Therefore, western redcedar products that require longer rotations are better produced in pure stands than in mixed stands (Oliver et al. 1988; Minore 1990; Klinka and Brisco 2009). In spite of the ecological and economic values associated with western redcedar, there is very little information on the development of western redcedar dominated stands. Several studies have examined growth rates of seedlings and saplings (c.f. summary of studies by Klinka and Brisco (2009) and Harrington (2010)), but with one notable

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exception (Nystrom et al. 1984), longer-term development of pure and mixed western redcedar stands has rarely been studied.

This study's objective was to determine how precommercial thinning and fertilization of young western redcedar influence stand-level development. The research was conducted on a poor quality site in western Washington where second-growth western redcedar regenerated naturally following the clear-cutting of an old-growth western redcedar stand. Tree size information for a stand can be summarized or quantified in many different ways, e.g., calculating the mean (arithmetic or otherwise), minimum, and maximum values and measures of variability (e.g., standard error). A graphical method is to plot the frequency distribution of trees into (usually) equal size classes. Size-class distributions may provide information on the number of trees meeting specific minimum size cutoffs for merchantability standards. In addition, such distributions may provide information about stand structure, age structure, and stand stability (Gorgoso-Varela et al. 2008). The first mathematical description of a diameter distribution was done by de Liocourt in 1898 (as cited in Bailey and Dell 1973; Gorgoso-Varela et al. 2008); he demonstrated that the frequency distribution of an all-age (uneven-aged) stand was a reverse-J-shaped curve. A young even-aged stand can also exhibit a reverse-J-shaped curve but will shift into a normal distribution as stand development proceeds. The Weibull distribution was proposed for modeling distributions of tree diameters by Bailey and Dell in 1973. It is relatively simple to apply and flexible in fitting data from different stand conditions. Other functions such as the normal, gamma, beta, finite mixture, and modifications of these and the Weibull distributions (Zasada and Cieszewski 2005; Zhang and Liu 2006; Gorgoso-Varela et al. 2008) have been used. In addition, other approaches (e.g., Johnson's S_B function) have been used to model tree size distributions for tree growth models (Siipilehto 2000). Those methods may be superior for modeling specific types of stand conditions (e.g., multimodal or irregular stands) or modeling several classes of trees within a stand. We chose to use the Weibull function to quantify differences among treatments both initially (as a function of thinning) and over time as stand development was influenced by ingrowth of new stems, as well as the response of the initial cohort to growing space and nutrition. Others have looked at the effects of competing vegetation or vegetation control treatments on Weibull parameters (e.g., Harrington et al. 1991; Knowe 1992; Knowe et al. 1992), but the long-term effects of precommercial thinning, fertilization, and ingrowth on size-class distributions have not been studied, nor have the effects of stand development without treatment been documented in western redcedar stands.

One of the primary purposes of thinning is to reallocate growing space to a smaller number of trees (Smith 1962). Thinning treatments are not usually designed to promote regeneration; however, existing regeneration may benefit from thinning and new regeneration may develop. Light thinnings, especially on sites of moderate to high site quality, only result in increased resources to the understory for a limited period of time as the overstory tree crowns and root systems of the residual overstory trees quickly expand and utilize those resources (Oliver and Larson 1990). Thus, both aboveground (e.g., light) and belowground resources quickly become limiting for many species, and development of regeneration is halted or eliminated throughout most of the stand. On poor quality sites, however, thinning can result in new waves of regeneration, and these new plants can survive and grow for decades. Although it has long been recognized that regeneration may result from thinning, there are very few studies in which regeneration after thinning has been assessed and monitored for long periods of time (c.f., Bailey and Tappeiner 1998).

Three- and 5-year results were reported previously (Harrington and Wierman 1985, 1990). This report covers the 25-year response of stand-level factors, including mortality, ingrowth, basal area (BA), volume, and distributions of tree sizes by height and diameter classes. Response of crop trees only (largest 250 trees per hectare) was reported in Devine and Harrington 2009.

Methods

Study site

The study was installed on the Olympic Peninsula in Washington, USA, approximately 10 km inland from the Pacific Coast, at an elevation of 100 m above mean sea level (48°08′N, 124°38′W). The study plots are within a 12 ha area where slope ranges from 0% to 10%. The site is in the *Picea sitchensis* Zone (Franklin and Dyrness 1988) and has a mild, maritime climate. January and August temperatures average 5 and 15 °C, respectively (Western Regional Climate Center (WRCC) 2008). Long-term mean annual precipitation is 2600 mm, but on average, only 340 mm occurs from 1 May through 31 August (WRCC 2008).

Soils at the study site are classified as the poorly drained Kydaka series (Typic Humaquepts), formed in glacial lacustrine sediments (8 to 20 cm thick) overlaying glacial outwash and a dense layer of glacial till (Soil Survey Staff 2008). This layer of compact till begins below a depth of approximately 80 cm and is of very low permeability. In the Canadian System of Soil Classification, this soil is approximately equivalent to a Humic Gleysol with mor humus (Soil Classification Working Group 1998). At study year 25, soil pH throughout the study area averaged 4.1, soil total C concentration was 63.4 $g \cdot kg^{-1}$, and the C-to-N ratio (C:N) was 29.3 in the 0 to 20 cm mineral soil depth (Devine and Harrington 2009). The 50-year site index for western redcedar in the study area is approximately 18 m (Kurucz 1978).

The study site was formerly occupied by an old-growth stand dominated by western redcedar ranging from 0.5 to 4.0 m in diameter at breast height (dbh). The stand was clear-cut in 1961, and prior to study establishment in 1980, scattered residual pole-sized to small sawlog-sized trees were cut to improve stand uniformity in the study area. All trees other than western redcedar that were greater than 3.0 m in height also were cut prior to the study. At study establishment in 1980, the site was dominated by western redcedar (>95% of stand BA) that had naturally regenerated from seed after clear-cutting or, less commonly, from advanced regeneration (seedlings or saplings present at the time of clear-cutting). There were 5900 $trees \cdot ha^{-1}$, predomi-

Table 1. Precommercial thinning and fertilization treatments.

Treatment	Symbol	Precommercial thinning	Year-0 fertilization (kg·ha^{-1})	Year-13 fertilization (kg·ha^{-1})
1	T0	Thinned	None	None
2	T2N	Thinned	300 N	300 N
3	T2N	Thinned	300 urea-N	300 N
4	T2NP	Thinned	300 N, 100 P, 129 Ca	300 N, 100 P
5	T2NP	Thinned	300 N, 100 P, 100 K, 41 S, 129 Ca	300 N, 100 P
6	UT0	None	None	None
7	UT2NP	None	300 N, 100 P, 100 K, 41 S, 129 Ca	300 N, 100 P
*	T1N	Thinned	Various	None

Note: 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. Preliminary analyses showed no effect of different year-0 fertilization treatments within T2N or T2NP treatments, so treatments 2 and 3 (T2N) and treatments 4 and 5 (T2NP) were combined for presentation.

*This group consists of one replication each of treatments 2 through 5 that did not receive year-13 fertilization. Because these four plots occurred on the same block, this group was excluded from statistical analyses.

nantly in the 15- to 20-year age range, with the largest 250 trees·ha^{-1} averaging 5.4 m in height.

The only species other than western redcedar occurring throughout the study area was western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), although there were occasional Pacific yew (*Taxus brevifolia* Nutt.), Pacific silver fir (*Abies amabilis* (Dougl. ex Loud.) Dougl. ex Forbes), Sitka spruce (*Picea sitchensis* (Bong.) Carr.), red alder (*Alnus rubra* Bong.), and cascara buckthorn (*Frangula purshiana* (DC.) Cooper). The most prevalent shrub species in 1980 were salal (*Gaultheria shallon* Pursh), red huckleberry (*Vaccinium parvifolium* Sm.), and oval-leaf blueberry (*Vaccinium ovalifolium* Sm.). Species present on all study plots were western redcedar, western hemlock, salal, and deer fern (*Blechnum spicant* (L.) Sm.). Vegetation consistent with the Sitka spruce – salal – deer fern plant association (which describes potential climax vegetation) was present on all plots and dominant on all but one plot. This plant association has not been formally described; it is ecotonal between the Sitka Spruce Zone and the Western Hemlock Zone (Henderson et al. 1989). It occurs in high rainfall areas that also receive some summertime fog, but the fog effect is far less for this association than for other Sitka spruce plant associations. Wetter areas with skunkcabbage (*Lysichiton americanus* Hultén & H. St. John) occur within some plots but account for less than 5% of the total area in any individual plot.

Study design and treatments

The study consists of 28 permanent plots, arranged in a randomized block design, with four blocks designated according to soil drainage. The study plots, established in September 1980, consist of 30 m × 50 m treatment plots, each with a 20 m × 40 m interior measurement plot. Seven treatments were combinations of precommercial thinning and several types of fertilization treatments (Table 1). The precommercial thinning treatment took place in October 1980 and created a residual spacing of approximately 3 m × 3 m (1100 trees·ha^{-1}). Large trees with good form were favored for retention. Slash resulting from the thinning was left on the site.

The initial fertilization treatments took place prior to the first growing season of the study (i.e., year 0); a second fertilizer application occurred in year 13. The fertilization treatments in year 0 in thinned stands were two forms of nitrogen (N) (urea or ammonium nitrate), N+P/CA, and N+P/CA+K/S (Table 1). The N+P/Ca+K/S fertilizer formulation was also applied in the unthinned, fertilized treatment. For the second fertilization application, it was decided to combine some of the treatments to allow for a possible future separation of plots that would compare three fertilizations versus two (the third fertilization has not been done). Thus, at year 13, three plots each from treatments 2 and 3 (thinned plots previously treated with urea or ammonium nitrate) were retreated with ammonium nitrate, and three plots each from treatments 4 and 5 (thinned and previously fertilized with ammonium nitrate and monodicalcium phosphate or ammonium nitrate, monodicalcium phosphate, and potassium sulfate) were fertilized with ammonimum nitrate and triple superphosophate. Because four of the plots in one block did not receive the year-13 fertilization, these plots were dropped from statistical analysis, although mean values for these four plots are included in the results as treatment T1N. Fertilizers were applied by hand to treatment plots, using two perpendicular passes, from 26 March through 3 April 1981 (year 0) and from 21 through 29 June 1993 (year 13). Monodicalcium phosphate was selected in year 0 as the P source so that soils would not be acidified by the P fertilization. This formulation was not available for the 1993 fertilization, so triple superphosphate was applied instead. Conditions were cool and wet following the 1981 application of urea.

Data collection and analysis

After the precommercial thinning treatment, but prior to the year 1 (1981) growing season, all trees on each measurement plot greater than 1.3 m in height were tagged with unique numbers and measured for dbh (measured at a height of 1.3 m) and total height. Diameter at breast height of all trees was remeasured after the growing season in years 2, 5, 10, 16, 20, and 25. At each remeasurement, untagged trees (i.e., ingrowth) that were 4.0 cm dbh or greater were tagged, measured, and remeasured in subsequent years. In 1980, 5350 trees were measured, and by study year 25, the total had increased to 8365. There were 24 veglings (trees of vegetative origin, in this case arising from a branch) in the study. Their growth rates were similar to those of trees of seed origin and so they were combined with the trees of seed origin for all analyses.

Table 2. *P* values indicating contrast significance for number of trees per hectare and basal area (BA) per hectare for all trees and for ingrowth only at study year 25. Data appear in Figs. 1 and 2.

	Trees (no.·ha^{-1})		BA (m^2·ha^{-1})	
Contrast	All trees	Ingrowth	All trees	Ingrowth
Not fertilized: unthinned vs. thinned (T0 vs. UT0)	**<0.01**	0.54	0.10	0.51
Fertilized: unthinned vs. thinned (T2NP vs. UT2NP)	**<0.01**	**0.01**	**<0.01**	**0.01**
Unthinned: not fertilized vs. fertilized (UT0 vs. UT2NP)	0.15	0.46	**<0.01**	0.24
Thinned: not fertilized vs. N only (T0 vs. T2N)	0.75	**0.03**	**<0.01**	**0.03**
Thinned: N only vs. N+P (T2N vs. T2NP)	0.77	0.12	0.76	**<0.01**

Note: Values in bold were significant at $P \leq 0.05$.

Total height of all initial trees was remeasured in years 2 and 5. In years 10, 16, 20, and 25, height was measured on a subset of trees (approximately 12%) from the full range of diameters present. This subset of trees was composed of the two most prevalent tree species, western redcedar and western hemlock, which together comprised over 97% of trees in the study. Other species were typically in subcanopy crown positions. At the last three measurements, height to live crown (HLC) was also measured on all trees selected for height measurements.

Stand density (i.e., number of trees per hectare) and BA per hectare were analyzed using repeated-measures analysis of variance (ANOVA) models (Zar 1999; PROC MIXED, SAS Institute Inc. 2005). In these models, treatment and year had seven levels each (seven treatments and seven measurement years), and block was a random effect with four levels. Post-ANOVA mean separations were made using single degree of freedom contrasts (Table 2) or Tukey's HSD test (Zar 1999). Contrasts were designed to combine the two T2N treatments, as preliminary analysis showed no differences between these treatments. Likewise, the two T2NP treatments were combined. Thus, for most graphs and tabular summaries, five treatments are presented. For individual-species analyses of density and BA per hectare, data were log-transformed to meet normality assumptions. For all final ANOVA models, assumptions of residual normality and treatment homoscedasticity were met.

Distributions of dbh (in each year measured) and height (year 25) in each plot were modeled using a three-parameter Weibull distribution model with maximum likelihood estimation (Bailey and Dell 1973; PROC NLP and PROC CAPABILITY, SAS Institute Inc. 2005). Parameters in this model were shape, which indicates the degree of positive or negative skewness of the distribution (a value of 3.6 approximates a normal distribution and smaller shape values are right-skewed distributions), and threshold, which defines the point on the x axis where the distribution begins. The third parameter, scale, is the 63.2 percentile and thus is an indication of how broadly the data are distributed on the x axis relative to the threshold. Our threshold values do not represent ingrowth trees less than 4.0 cm dbh, as these trees were not measured. Visual analysis of the fitted functions against the distributions of size classes indicated that the Weibull function provided a good fit of the data. Model parameters were compared among treatments using ANOVA (year-25 height distribution) and repeated-measures ANOVA (diameter distribution in each study year).

For trees that had no height measurement in year 25, height was predicted from dbh. This was accomplished with equations developed using the subset of trees that was measured for height within each treatment using PROC NLIN (SAS Institute Inc. 2005). The equation took the following form:

$$H = 1.3 + \exp(b_0 + b_1 D^{b_2})$$

where H is total height (m), D is dbh (cm), and b_0, b_1, and b_2 are parameters estimated from the data (Wang and Hann 1988). For western redcedar, a separate equation was developed for each treatment, whereas one equation was used to predict height of western hemlock. Stem volume outside bark was predicted for western redcedar and western hemlock using equations developed by Smith and DeBell (1973). Residual distributions were checked graphically for all models. A minimum confidence level of 95% was used in all analyses.

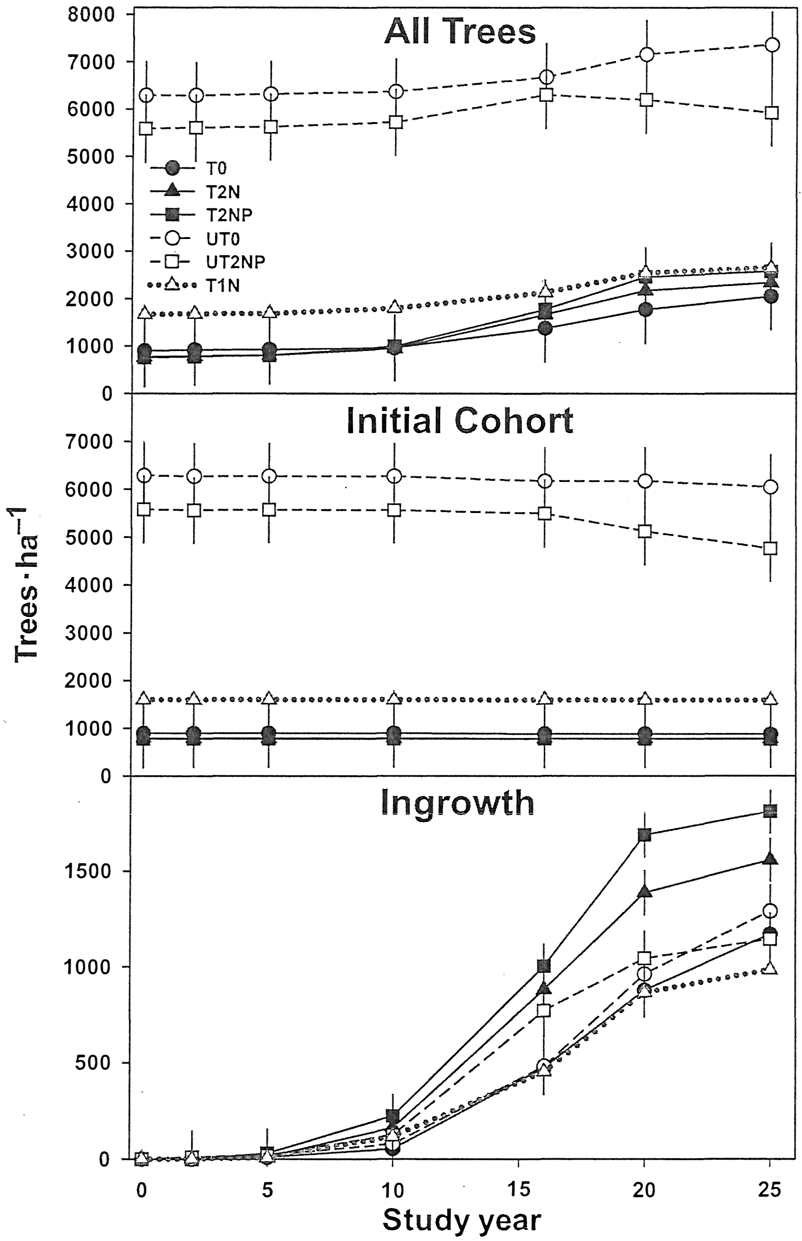
Results

Damage and mortality

Damage was coded at each measurement, but overall, very few trees were damaged. The most common types of damage were broken leader, dead top, and sapsucker damage. However, none of these types of damage individually accounted for even 1% of trees per treatment per measurement interval, and all types of damage combined was usually less than 2% of trees per treatment per interval. Some trees in the plot buffer area were observed with bark stripping by bears at one measurement interval, but no boles in the measurement plots were bark stripped. A few (<15) small trees were cut to improve access during three salvage operations for western redcedar blocks (harvested from logs or stumps created during the 1961 harvest).

Mortality was negligible in the thinned treatments, with no more than three trees per hectare per treatment dead in any measurement interval (see changes in initial cohort in Fig. 1). Mortality in unthinned treatments was first evident in year 16 when 25 trees per hectare were recorded as dead in both the UT0 and UT2NP treatments. The dead trees were western redcedar from the initial cohort that had averaged 1.7 cm dbh at the previous measurement. At study year 20, 59 and 400 trees per hectare had died in the UT0 and UT2NP treatments, respectively, since the previous measurement. The dead trees in these two treatments averaged 2.3 cm dbh at their last measurement; more than 97% of these dead trees were western redcedar from the initial cohort. At year 25, mortality was 97 and 275 trees per hectare in the UT0 and UT2NP treatments, respectively, and the

Fig. 1. Number of trees per hectare for all trees, for the initial cohort only, and for ingrowth, with standard error bars, under various combinations of fertilization and thinning (Table 1).



dead trees in these treatments averaged 3.2 cm dbh; 93% of this mortality was western redcedar from the initial cohort. In general, the trees that died in the unthinned treatments were some of the smallest trees and apparently died from competition-related mortality. Less than 1% of all mortality occurred among trees greater than 15 cm in diameter; cause of mortality in these larger trees was not determined.

Although the western redcedar trees that died were, on average, quite small, it is worth mentioning that many small trees did not die but had no or very little measureable growth during the 25 years of the study. For example, of the trees that were less than 2 cm dbh at the beginning of the study, 25 years later, 30% of those trees were still less than 2 cm dbh in the UT0 treatment and 11% were still less than 2 cm dbh in the UT2NP treatment.

Density

Tree density was influenced by the year-0 thinning treatment, mortality, and recruitment of new trees (ingrowth). The number of trees per hectare for all species combined was significantly affected by treatment ($F = 69.8$, $P < 0.01$) and year ($F = 4.1$, $P < 0.01$), with no treatment × year interaction. Throughout the study, all treatments except UT2NP showed either no change or an increase in number of trees per hectare at every remeasurement, with the most notable increases due to ingrowth evident in years 16 and

Table 3. Number of trees per hectare and basal area (BA) per hectare, by species, for five treatments at study year 25 (mean ± 1 SE).

	Trees (no.·ha^{-1})			BA (m^2·ha^{-1})		
Treatment	Western redcedar	Western hemlock	Other species	Western redcedar	Western hemlock	Other species
T0	1091±206b	884±299a	84±38a	24.3±2.3c	3.8±0.8b	0.2±0.1a
T2N	1273±125b	940±66a	175±62a	41.8±2.9b	5.0±0.4ab	0.6±0.2a
T2NP	1368±245b	1144±154a	156±142a	44.3±1.9b	8.8±1.3a	0.9±0.7a
UT0	6250±1604a	1031±83a	88±40a	28.1±4.1c	4.5±0.6ab	0.3±0.1a
UT2NP	5219±635a	691±161a	19±25a	57.5±4.2a	4.9±1.4ab	0.1±0.1a

Note: Western redcedar, *Thuja plicata*; western hemlock, *Tsuga heterophylla*; Other species (in order of frequency): cascara buckthorn (*Frangula purshiana*), Sitka spruce (*Picea sitchensis*), and red alder (*Alnus rubra*). Values followed by the same letter within the same column do not differ according to Tukey's HSD test ($P \geq 0.05$). SE, standard error.

20 (Fig. 1). The UT2NP treatment showed nonsignificant decreases in number of trees per hectare in years 20 and 25. At year 25, both unthinned treatments averaged nearly three times as many trees per hectare as the thinned treatments; there were no differences in number of trees per hectare due to fertilization (Table 2).

The number of ingrowth trees per hectare in year 25 was significantly influenced by treatment ($F = 5.9$, $P < 0.01$) and year ($F = 124.3$, $P < 0.01$), with no interaction between these effects. There were 58% more ingrowth trees in the T2NP treatment than in the UT2NP treatment. Among the thinned treatments, there were 33% more ingrowth trees in the N-only fertilization treatment than in the unfertilized treatment.

At year 25, density of western redcedar was four to five times greater in the unthinned treatments than in the thinned treatments, whereas density of hemlock and other species did not differ significantly among treatments (Table 3). Among the thinned treatments, the number of western redcedar per hectare averaged 26% greater than the number of western hemlock per hectare; in the unthinned treatments, there were six to seven times as many western redcedar as western hemlock. Species other than western redcedar and western hemlock were least prevalent in the UT2NP treatment (<1% of trees) and most prevalent in the T2N treatment (7% of trees). Although all non-western-redcedar species present at study year 25 were ingrowth, the percentage of western redcedar that were ingrowth varied by treatment. In the T0, T2N, and T2NP treatments, 19%, 31%, and 35%, respectively, of western redcedar present at year 25 were ingrowth. In the UT0 and UT2NP treatments, 3% and 8%, respectively, of western redcedar were ingrowth. In addition to ingrowth by western redcedar and western hemlock, other species recruited in small numbers were Sitka spruce, Pacific yew, Pacific silver fir, red alder, and cascara buckthorn.

Basal area

As would be expected, stand BA increased over time in all treatments. Basal area per hectare for all species combined was affected by treatment ($F = 57.4$, $P < 0.01$), year ($F = 558.9$, $P < 0.01$), and a treatment × year interaction ($F = 8.0$, $P < 0.01$). Although BA in the unfertilized treatments increased steadily over the 25-year study, the rate of BA increase in the fertilized treatments increased between years 5 and 20 (Fig. 2). Year-25 BA was 15% greater in the unthinned treatment than in the thinned treatment on N+P-fertilized plots, but thinning had no significant effect on BA on unfertilized plots (Table 2). In unthinned treatments, N+P fertilization significantly increased year-25 BA by 92%. In thinned treatments, N fertilization increased year-25 BA by 70%, whereas N+P fertilization increased BA by 94%. By year 16, the thinned and fertilized treatments (T2N, T2NP) had surpassed the untreated (UT0) treatment in BA.

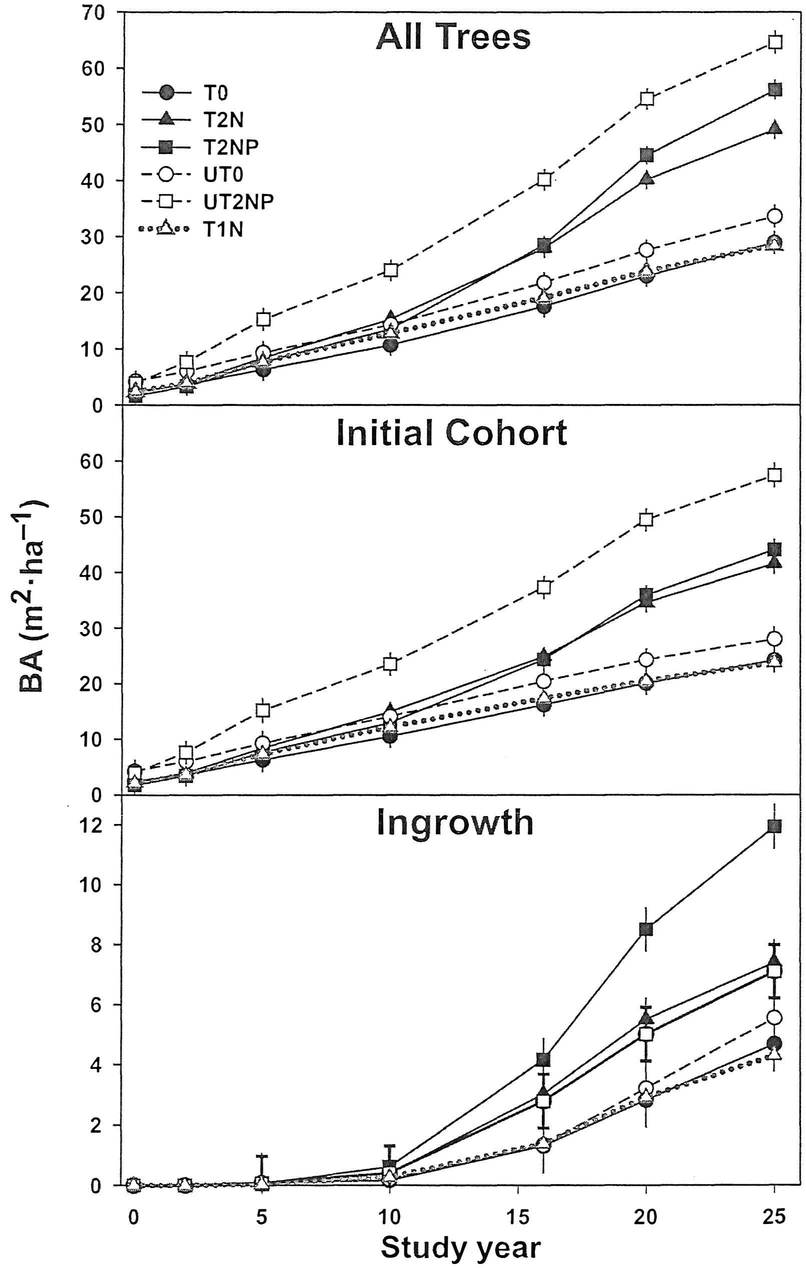
Basal area of ingrowth was influenced by treatment ($F = 8.3$, $P < 0.01$) and year ($F = 69.2$, $P < 0.01$); there was no treatment × year interaction. Among thinned treatments, ingrowth BA at year 25 was increased 58% by N fertilization and 155% by N+P fertilization (Fig. 2). Under N+P fertilization, ingrowth BA was 68% greater in the thinned treatment than in the unthinned treatment. Western redcedar BA at year 25 was greatest in the UT2NP treatment, followed by the T2N and T2NP treatments; western redcedar BA was least in the unfertilized treatments (Table 3). Western hemlock BA was greatest in the T2NP treatment, least in the T0 treatment, and intermediate in the other treatments. The portion of total BA composed of western hemlock ranged from 8% in the UT2NP treatment to 16% in the T2NP treatment.

Diameter at breast height distributions

The initial cohort of trees at study year 0 exhibited a reverse-J-shaped distribution of stems (i.e., the distribution was strongly right-skewed) by dbh class (see inset graph in lower left of Fig. 3). The 1980 thinning both reduced stem density and altered the distribution of stems in dbh classes to a bell-shaped curve (see inset graph in upper left of Fig. 3). At year 25, the greatest number of trees in each of the treatments once again occurred in the small (i.e., ≤10 cm) dbh classes (Fig. 3) for all treatments. However, the species composition and origin of the trees in these classes differed between the thinned and unthinned treatments. In the unthinned treatments, the small dbh classes were dominated by the initial cohort of western redcedar that had been present at study initiation; in the thinned treatments, these classes were dominated by western hemlock and western redcedar ingrowth and, to a lesser extent, other species. Across all treatments, the larger dbh classes (i.e., ≥20 cm) were heavily dominated by western redcedar stems that were already present at study initiation.

Values for Weibull parameters describing dbh distributions differed significantly among treatments during the study (Table 4). The shape and threshold parameters were affected by significant treatment × year interactions ($F = 3.7$, $P < 0.01$, and $F = 2.0$, $P < 0.01$, respectively). The scale parameter was affected by treatment ($F = 20.7$, $P < 0.01$) and year ($F = 35.9$, $P < 0.01$). In unthinned treatments,

Fig. 2. Basal area (BA) per hectare for all trees, for the initial cohort only, and for ingrowth, with standard error bars, under various combinations of fertilization and thinning (Table 1).



the shape value decreased gradually from year 5 through year 25 (Fig. 4), indicating an increasing right-skewness of the distribution. Among thinned treatments, the shape values differed initially, but all declined relatively rapidly through year 20 (increasing right-skewness), although the year at which this decline initiated differed by treatment. At year 25, a significantly smaller shape value indicated that the T0 treatment was more right-skewed than the UT0 treatment. Scale values increased throughout the study for unthinned treatments, with values for the UT2NP treatments becoming significantly greater than for the UT0 treatment from year 16 onward, indicating a broader distribution. Scale values for thinned treatments were similar throughout the study, increasing through year 10 and changing little thereafter. Significantly greater scale values at year 25 (contrasts in Table 4) indicated that both thinning alone (T0 versus UT0) and fertilization alone (UT2NP versus UTO) produced a broader range of dbh classes than no treatment. Threshold values for unthinned treatments increased slightly during the study, whereas for thinned treatments, the threshold values increased through year 15 and then remained relatively constant. At year 25, differing threshold values signified

Fig. 3. Tree diameter at breast height (dbh) class distribution for five treatments (Table 1) at study year 25 and for thinned and unthinned treatments at year 0 (inset graphs): redcedar, western redcedar (*Thuja plicata*); hemlock, western hemlock (*Tsuga heterophylla*); other (in order of frequency): cascara buckthorn (*Frangula purshiana*), Sitka spruce (*Picea sitchensis*), and red alder (*Alnus rubra*).

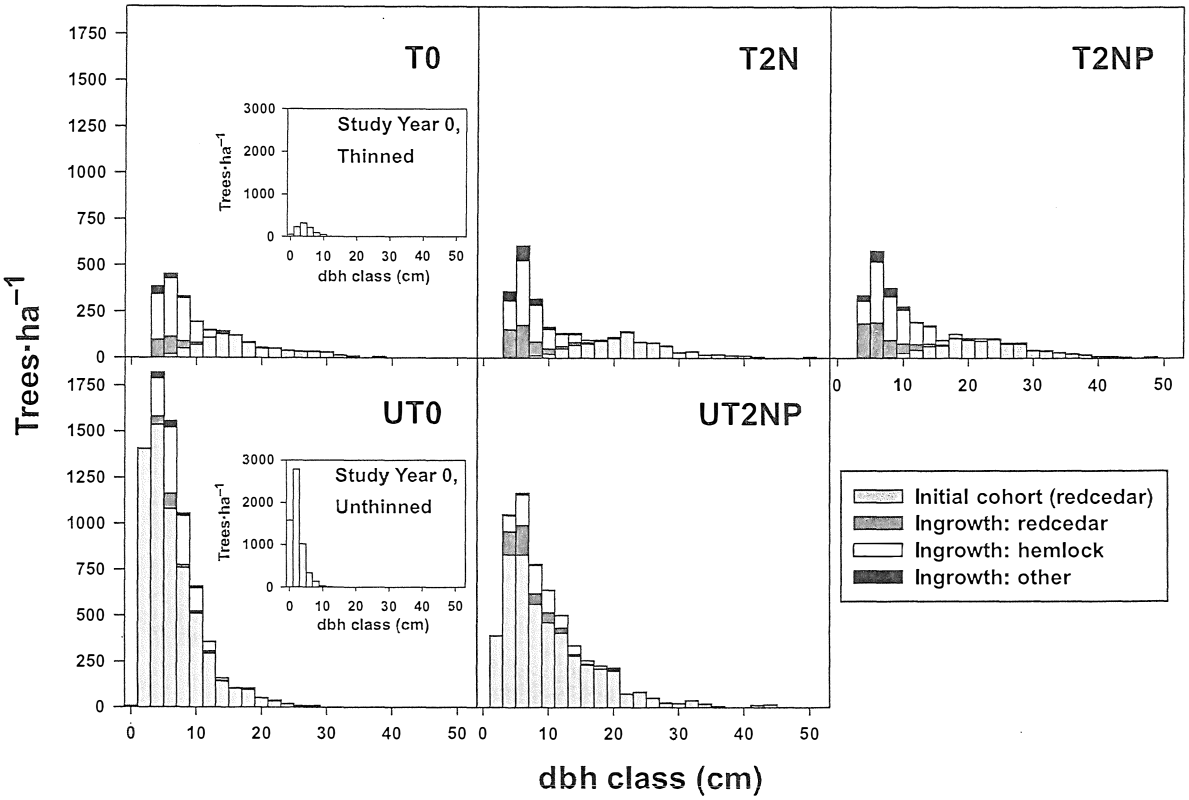


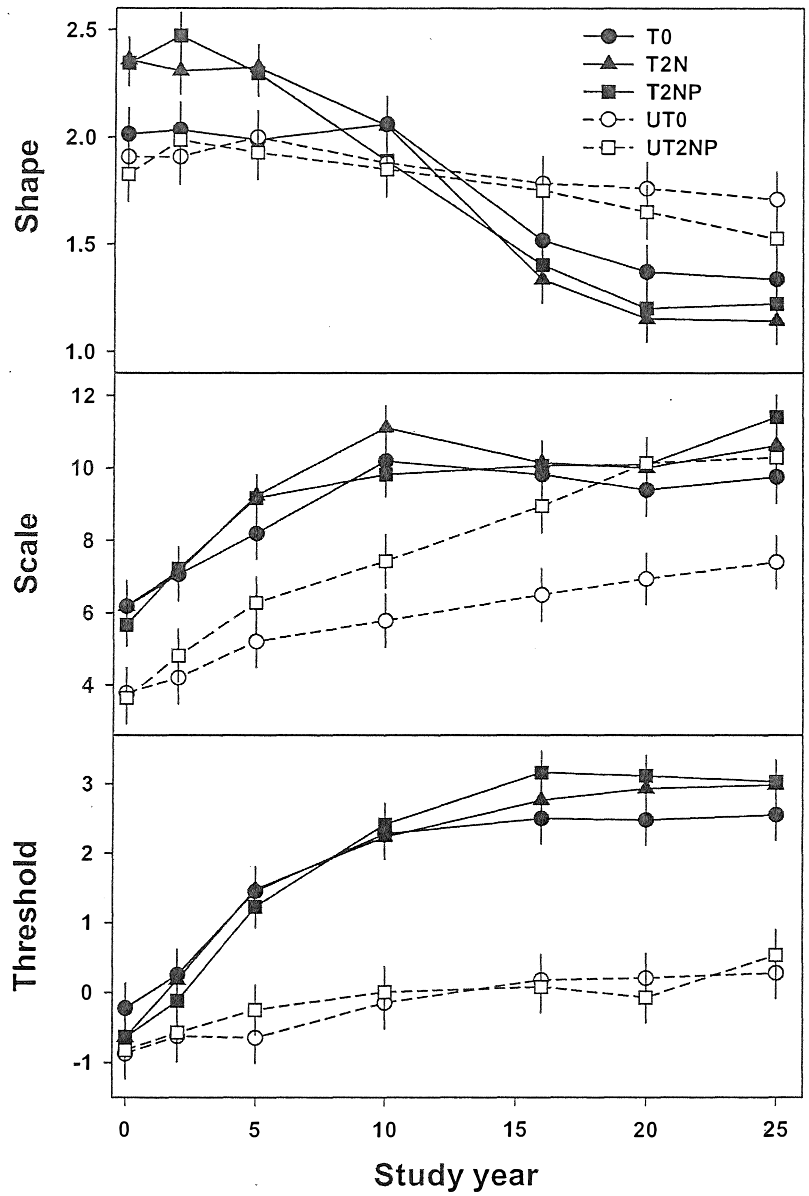
Table 4. *P* values indicating significance treatment contrasts for shape, scale, and threshold values for three-parameter Weibull distributions describing diameter at breast height (dbh; cm) of all tree species in five treatments (Table 1).

		Study year						
Parameter	Contrast	0	2	5	10	16	20	25
Shape	T0 vs. UT0	0.52	0.44	0.94	0.27	0.10	**0.02**	**0.02**
	T2NP vs. UT2NP	**<0.01**	**0.04**	0.22	0.85	0.26	**0.02**	0.17
	UT0 vs. UT2NP	0.61	0.63	0.66	0.86	0.84	0.50	0.26
	T0 vs. T2N	**0.02**	0.07	**0.03**	0.96	0.22	0.14	0.19
	T2N vs. T2NP	0.90	0.22	0.84	0.22	0.61	0.71	0.55
Scale	T0 vs. UT0	**0.02**	**<0.01**	**<0.01**	**<0.01**	**<0.01**	**0.02**	**0.03**
	T2NP vs. UT2NP	0.11	0.10	0.06	0.08	0.06	0.80	0.16
	UT0 vs. UT2NP	0.90	0.56	0.31	0.12	**0.02**	**<0.01**	**<0.01**
	T0 vs. T2N	0.99	0.93	0.27	0.34	0.73	0.53	0.36
	T2N vs. T2NP	0.54	0.93	0.93	0.13	0.93	0.91	0.36
Threshold	T0 vs. UT0	0.21	0.09	**<0.01**	**<0.01**	**<0.01**	**<0.01**	**<0.01**
	T2NP vs. UT2NP	0.78	0.23	**<0.01**	**<0.01**	**<0.01**	**<0.01**	**<0.01**
	UT0 vs. UT2NP	0.92	0.92	0.44	0.77	0.85	0.59	0.33
	T0 vs. T2N	0.38	0.88	0.95	0.92	0.58	0.34	0.37
	T2N vs. T2NP	0.99	0.48	0.55	0.66	0.34	0.66	0.91

Note: Shape quantifies the skewness of the distribution, scale is the 63.2 percentile, and threshold is where the distribution begins on the *x* axis. Year-25 distributions are shown in Fig. 1. Values in bold were significant at $P \leq 0.05$.

that the dbh distribution of the UT0 treatment included smaller dbh trees than the T0 treatment and that the UT2NP treatment included smaller dbh trees than the T2NP treatment. At age 25, the UT0 treatment had no trees greater than 30 cm and very few trees greater than 20 cm dbh. In contrast, the thinned and fertilized treatments had trees up to 48 or 50 cm dbh, and more than half of the initial cohort left after thinning were equal to or greater than 20 cm dbh.

Fig. 4. Shape, scale, and threshold values, with standard error bars, for three-parameter Weibull distributions describing diameter at breast height (dbh; cm) of all tree species in five treatments during 25 years after treatment (Table 1). Shape indicates the degree of skewness of the distribution, scale is the 63.2 percentile, and threshold defines the point on the x axis at which the distribution begins. See text for more details.



Height distributions

Thinning altered the height distribution of the initial cohort at study year 0, shifting it from a reverse-J-shaped (right-skewed) distribution to a bell-shaped distribution (inset graphs in Fig. 5). By study year 25, the tallest trees in each of the five treatments were predominantly western redcedar (Fig. 5). Among the intermediate height classes, the occurrence of ingrowth trees did not differ substantially by treatment; however, as would be expected, the number of western redcedar from the initial cohort was much greater in the unthinned treatments than in the thinned treatments. Within the thinned treatments, the year-25 height distribution of western redcedar from the initial cohort was affected by fertilization: the modal height class was 10 m for the T0 treatment and 14 m for the T2N and T2NP treatments. In the unthinned treatments, the modal year-25 height class for the initial cohort of western redcedar was 4 m without fertilization and 8 m under N+P fertilization.

Weibull scale and threshold parameters for tree height distribution differed among treatments (Table 5). The scale value for the T2NP treatment was smaller than that for the UT2NP treatment, signifying that trees in the former treatment occurred within a narrower range of heights. Similarly, the smaller scale value of the UT0 treatment compared with

Fig. 5. Tree height class distribution for five treatments (Table 1) at study year 25 and for thinned and unthinned treatments at year 0 (inset graphs): redcedar, western redcedar (*Thuja plicata*); hemlock, western hemlock (*Tsuga heterophylla*).

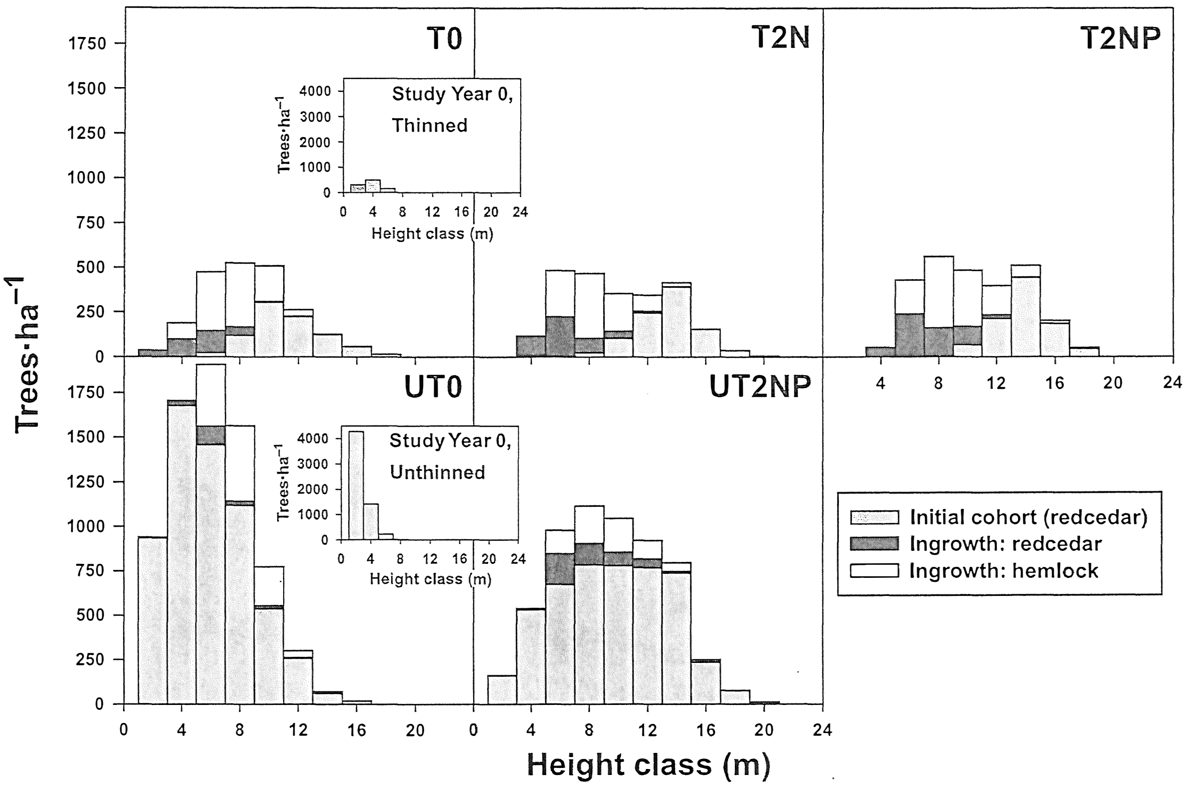


Table 5. Shape, scale, and threshold values for three-parameter Weibull distributions describing heights (m) of western redcedar and western hemlock in five treatments (Table 1) at study year 25, with *P* values indicating significance of contrasts among treatments.

(*a*) Shape, scale, and threshold values.

Treatment	Shape (mean ± SE)	Scale (mean ± SE)	Threshold (mean ± SE)
T0	2.56±0.37	8.11±0.47	4.10±0.50
T2N	2.78±0.09	9.85±0.44	4.01±0.25
T2NP	3.29±0.20	9.29±0.42	5.23±0.24
UT0	2.98±0.28	7.61±1.19	3.53±1.06
UT2NP	3.21±0.45	12.19±0.62	2.13±0.40

(*b*) *P* values for contrasts among treatments.

	Shape	Scale	Threshold
T0 vs. UT0	0.32	0.61	0.48
T2NP vs. UT2NP	0.56	**<0.01**	**<0.01**
UT0 vs. UT2NP	0.59	**<0.01**	0.10
T0 vs. T2N	0.56	0.07	0.91
T2N vs. T2NP	0.15	0.49	0.08

Note: SE, standard error; western redcedar, *Thuja plicata*; western hemlock, *Tsuga heterophylla*. Shape quantifies the skewness of the distribution, scale is the 63.2 percentile, and threshold is where the distribution begins on the *x* axis. Distributions are shown in Fig. 2. Values in bold were significant at $P \leq 0.05$.

that of the UT2NP treatment indicated a narrower range in height distribution in the UT0 treatment. A smaller threshold value in the UT2NP treatment than in the T2NP treatment resulted from a greater number of trees in the small height classes of the former treatment.

Live crown

There was a strong treatment influence on HLC: at study year 25, only 15% of the trees in the initial cohort of the T0 treatment had HLC values equal to or greater than 6 m compared with 66% of the trees in the initial cohort in the

Table 6. Percentage of western redcedar (*Thuja plicata*) trees above or below thresholds of height to live crown (HLC) and live-crown ratio (LCR) at study age 25.

	Initial cohort			Western redcedar ingrowth		
Treatment	HLC ≥ 6 m	LCR ≤ 0.2	LCR ≤ 0.4	HLC ≥ 6 m	LCR ≤ 0.2	LCR ≤ 0.4
T0	15	4	7	14	5	32
T2N	31	1	3	16	2	29
T2NP	45	2	3	28	4	23
UT0	29	5	12	9	12	42
UT2NP	66	9	17	37	31	58

Table 7. Estimated volume per hectare (mean ± SE) for western redcedar and western hemlock at study year 25.

	Total volume ($m^3 \cdot ha^{-1}$)		Western redcedar volume ($m^3 \cdot ha^{-1}$) by tree dbh			
Treatment	Western redcedar	Western hemlock	≥ 40.0 cm	≥ 35.0 cm	≥ 30.0 cm	≥ 25.0 cm
T0	140.9±19.5b	15.4±3.3b	9.5±5.8a	14.4±8.6a	36.4±16.3ab	67.2±24.8bc
T2N	266.9±22.7a	22.7±2.1b	27.0±8.5a	60.1±18.3a	94.7±24.4ab	158.1±26.9ab
T2NP	283.9±11.5a	46.6±8.1a	31.3±10.0a	66.9±14.2a	116.7±14.4a	182.2±19.8a
UT0	160.7±23.5b	18.9±3.5b	0.0±0.0a	0.0±0.0a	2.9±1.7b	9.9±7.2c
UT2NP	351.1±36.2a	24.9±7.3ab	38.7±25.4a	46.3±26.4a	85.2±34.6ab	120.4±40.7abc

Note: SE, standard error; dbh, diameter at breast height; western redcedar, *Thuja plicata*; western hemlock, *Tsuga heterophylla*. The same letter within a column denotes no significant difference ($P \geq 0.05$).

UT2NP treatment (Table 6). In both thinned and unthinned treatments, fertilization increased the percentage of trees with HLC of 6 m or more. If we compare live-crown ratio (LCR) at a HLC of 6.0 m, LCRs were lower in the unfertilized treatments (0.49) than in the fertilized treatments (0.60). LCRs of the initial cohort remained fairly high in all treatments after 25 years, but treatment effects are evident on the western redcedar ingrowth, with the percentage of trees per treatment having a LCR of less than or equal to 0.4 ranging from 23% (T2NP) to 58% (UT2NP).

Volume

Total estimated stem volume per hectare for western redcedar was significantly greater in fertilized treatments than in unfertilized treatments at study year 25 (Table 7). Western hemlock stem volume was greatest in the T2NP treatment. Western redcedar volume per hectare in the larger dbh classes (i.e., ≥35 or ≥40 cm dbh) did not differ significantly among treatments, although there was a numerical trend toward greater volume in fertilized treatments. Volume of western redcedar trees equal to or greater than 30 cm dbh was greatest in the T2NP treatment and least in the UT0 treatment. Volume of western redcedar trees equal to or greater than 25 cm dbh was greatest in the fertilized treatments.

Discussion

Silvicultural treatments applied to a young, naturally regenerated western redcedar stand on a nutrient-poor site had dramatic effects on the largest trees of the stand (Devine and Harrington 2009) and perhaps an even greater effect on stand structure. From a silvicultural viewpoint, the study area would initially have been considered a single stand because only minor variations in stand density and understory composition occurred. However, responses to the study treatments were dramatic and long-lasting; thus, individual treatment plots developed differently and the study area by year 25 had become a mosaic of different stand conditions that will likely persist for decades.

When the study began, approximately 20 years after clear-cutting, the stands were still in the initiation stage of stand development (Oliver and Larson 1990), with a large number of trees in the small dbh classes. In the unthinned stands, this dbh distribution extended to larger dbh classes (became more right-skewed) over the course of the 25-year study but did not change substantially in shape. Although ingrowth occurred in these stands, the new trees did not markedly affect the overall dbh distributions. By study year 20, mortality was becoming evident in the UT2NP stands, and because this mortality was restricted primarily to the smallest diameter class, these stands appears to have entered the stem-exclusion stage of stand development (Oliver and Larson 1990). Although the UT0 stands maintained more stems per hectare than the UT2NP stands throughout the study, the transition of the UT0 stands to the stem-exclusion stage was apparently delayed by its far lower BA per hectare owing to the lack of fertilization. In the thinned stands, fertilization shifted the diameter distribution of the initial cohort to larger size classes while retaining its bell-shaped distribution (Smith 1962). However, many stems were recruited into the smaller size classes in all thinned stands, recreating a reverse-J-shaped distribution similar to that found in the unthinned stands.

Precommercial thinning had several notable effects on the development of stand structure. At the outset, thinning removed a sufficient number of stems per hectare to shift the stand structure back to a bell-shaped distribution typical of early stages of stand initiation. However, over time, dbh distributions in thinned stands became significantly more right-skewed, as evidenced by the decreasing shape parameter of the Weibull distributions. This occurred during study years 5 through 20 in T2N and T2NP stands and slightly later, during years 10 through 20, in the T0 stands. The increasing positive skewness of the dbh distributions in thinned stands resulted primarily from a combination of two trends: the emergence of relatively large-diameter trees and the large number of stems in the small dbh classes. The emergence of large-diameter trees is evident across all stands (Fig. 3), though to a lesser extent in UT0 stands, and is reflected in the degree to which the value of the scale parameter increased through year 25 (Fig. 4). The small stems present in thinned stands at year 25 are comprised of shade-tolerant ingrowth that first became a notable stand component in year 10 and increased rapidly in number through year 20 in all stands, creating a reverse-J-shaped dbh distribution. At year 25, this ingrowth was still primarily confined to subcanopy crown positions, although ingrowth density and BA per hectare were significantly increased by fertilization and many of these trees grew well. The impact of ingrowth on overall stand structure was smaller in unthinned stands because a large number of small western redcedar trees were already present in those stands. Although fertilization dramatically increased growth, the precommercial thinning treatment was also successful in altering stand structure in that it reduced competition among the residual trees and resulted in greater per-hectare stem volume allocated to the largest-diameter trees by study year 25 (Reukema 1975).

Height class distributions at year 25 were flatter than the dbh distributions and did not exhibit the strong right-skewness present in the dbh distributions. In the unthinned stands, initial trees and recruited trees did not stratify into separate height cohorts, although recruited trees at year 25 occurred in fewer height classes than the initial cohort. Thus, for recruited western redcedar and western hemlock, both shade-tolerant species, height growth in unthinned stands was remarkably good, as their attained height at study year 25 was comparable with that of the western redcedar in the initial cohort. There are several possible explanations for this effect. First, ingrowth was generally recruited into the more open portions of the unthinned stands where conditions for growth were more favorable. This phenomenon may benefit neighboring western redcedar trees, which are prone to developing poor form when given too much growing space (Minore 1983; Oliver et al. 1988). Second, height growth was favored over diameter growth under the shaded conditions present in these stands. Third, the lower dbh limit of 4 cm for ingrowth does not include the shortest trees in the unthinned stands, although there did not appear to be many of these trees. In the thinned stands, where substantial recruitment is still occurring, there are two overlapping tree height distributions — one for the initial cohort and one for the younger ingrowth cohort. As with the distribution of dbh, fertilization broadened the tree height class distribution in unthinned stands but not in thinned stands.

On this nutrient poor site, foliage retention appeared to be poor, and precommercially thinning to a 3 m spacing (1100 trees·ha^{-1}) did not result in canopy closure or natural pruning for many years. Based on the measurements of HLC for crop trees presented in Devine and Harrington (2009), the live crowns of trees in the unthinned stands did not recede above 2 m until almost 20 years after the study was established (stand age 40–45 years). By study year 25, however, HLC was receding not only among the crop trees (Devine and Harrington 2009), but also among the smaller trees and the ingrowth. Western redcedar is a shade-tolerant species, and its lower branches often live for many years after canopy closure. However, silvicultural treatments such as thinning and fertilization can alter branch survival through their effects on stand and foliar density, which, in turn, affect the amount of light reaching the lower crown. This study found that year-25 HLC among the smaller trees and the ingrowth was increased in fertilized stands; this is the same pattern that we reported earlier for crop trees (Devine and Harrington 2009). We attributed this trend to increases in crown density and subsequent shading of the lower limbs in fertilized stands. Owing to the relatively slow initiation of self-pruning that we observed, pruning may be a desirable option to produce trees with clear boles, assuming market conditions justify it. If pruning is not planned, early stand thinning on similar nutrient-poor sites is probably best delayed until branch abscission is underway (Oliver et al. 1988), thus preventing the branches from continuing to grow after thinning. Although initial ages for thinning have been proposed (Hamilton and Christie 1971; Nystrom 1980; Minore 1983), it may be best to base thinning decisions on observations of crown recession rather than stand age and site quality.

Although there is substantial anecdotal information on the effects of thinning (or other disturbances) on regeneration, there is very little quantitative information (c.f. Bazzaz 1983; Oliver and Larson 1990; Kozlowski 2002). It is generally accepted that wide spacings are necessary to successfully recruit a new cohort of trees (Bailey and Tappeiner 1998; Maas-Hebner et al. 2005), but perhaps it is less well appreciated that thinning to a spacing of 3 m on a poor quality site can result in substantial regeneration that will persist for decades. Based on observations on site, this is due to both the limited foliage retention (at the ends of the branches) and the crown architecture of western redcedar that results in long branches with relatively narrow display of foliage. Stands on higher quality sites will go through the phases of stand development more quickly and thus will reach the maximum density line sooner (Harrington and Gould 2010); fertilization in this study resulted in stand development rates closer to what would be seen on a higher quality site. The effects of fertilization will vary depending on which elements are limiting; for example, fertilization of western redcedar and western hemlock with N, P, or N+P resulted in different effects by species and treatment (Blevins et al. 2006). In that study on Vancouver Island, B.C., N alone substantially increased growth for both species, but the effects were short lived, whereas P and N+P resulted in a longer-term response, especially for western hemlock.

Relatively little information has been available to guide management of western redcedar stands, but recent publications have synthesized existing knowledge (Klinka and Brisco 2009; Harrington 2010). The economic viability of management alternatives such as fertilization and precommercial thinning depend on specific stand and market conditions. For this site, two fertilizer applications in unthinned stands resulted in greater basal area and stand volume, as well as better log quality, than thinning alone. Faster growing trees produce more heartwood, more sapwood, and a greater proportion of heartwood than slower growing trees (DeBell and Lachenbruch 2009). These stands are beginning to incur density-dependent mortality among the smallest trees, indicating they are reaching the stem-exclusion stage of development. Regardless of whether stands were thinned or not, fertilization increased overall growth rates and shifted trees into larger size classes than were attained in unfertilized stands by stand age 40–45 years. Thinning transitioned the stands from a reverse-J-shaped diameter distribution back to a bell-shaped distribution that persisted over time, while recruited trees repopulated the small diameter classes. Recruited trees grew rapidly in height and by year 25 did not produce a stratified stand in terms of height distribution. If management objectives included maintaining forest cover or growing some very large diameter trees and site and market conditions permitted, it would seem feasible to create and then manage such a stand with multiple age classes by repeated thinning. To accomplish the same objectives on higher quality sites would require management scenarios to include heavier thinning (spacing to a wider initial stem density) or thinning that was repeated more frequently.

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