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Effects of Pre-commercial Thinning after 15 Years on Growth and Yield of Mixed Western Hemlock and Amabilis Fir Stands in Coastal British Columbia (EP1211)

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Prepared by
Louise de Montigny and Sophie Le Noble[1]
B.C. Ministry of Forests, Lands, Natural Resource Operations and Rural Development
P.O. Box 9513 Stn Prov Govt
Victoria, B.C.

Gordon Nigh
B.C. Ministry of Forests, Lands, Natural Resource Operations and Rural Development
P.O. Box 9512 Stn Prov Govt
Victoria, B.C.

[1]Current address: Memorial University, Corner Brook, Nfld.

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ABSTRACT

Dense stands of western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and amabilis fir (*Abies amabilis* Dougl. ex Forbes) are a significant source of timber supply for British Columbia's coastal forest industry. Following clearcut harvesting, naturally regenerated stands have very high densities, which leads to questions about whether and at what densities these stands should be thinned to meet management objectives. An 18-year-old naturally regenerated mixed-species stand in the Callaghan Valley near Whistler, B.C. was studied (Experimental Project 1211). Surveys and destructive sampling were used to examine species composition, density, height, and age of the naturally regenerated stand at 18 years. A completely randomized experiment was then established to test five levels of pre-commercial thinning (PCT): 550, 800, 950, 1200, and 1600 stems per hectare (sph) against an unthinned control. Over the 15-year study period, competition-induced mortality reduced the density in the unthinned control from 22 000 to 5900 sph (73%), while mortality in the PCT stands remained low (2–6%). As expected, the PCT stands had total volumes that were significantly less (32–60%) and average quadratic mean diameter that was significantly larger (up to 100%) than the unthinned control. Of the thinned stands, the 1200 sph treatment had 52–152 m^3/ha more total volume in diameter classes > 25 cm than more widely spaced stands (550–800 sph). Pre-commercial thinning treatments to between 950 and 1200 sph appear to provide the best trade-off between piece size and volume.

Keywords Western hemlock, amabilis fir, forest management, growth and yield, incremental silviculture, thinning and spacing, stand density, stand trending

ACKNOWLEDGEMENTS

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1 INTRODUCTION

Dense stands of mixed western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and amabilis fir (*Abies amabilis* Dougl. ex Forbes) dominate almost one million hectares of forest land in coastal British Columbia (B.C. Ministry of Forests, Lands, Natural Resource Operations and Rural Development 2018). More than 70% of the area consists of stands older than 80 years, and these stands are a significant source of timber supply for the coastal forest industry. Following the harvest of these stands, natural regeneration will likely develop into dense stands of mixed western hemlock and amabilis fir that are characteristically clumpy and overstocked (Klinka et al. 1992).

There are many reasons for silviculturists to consider using pre-commercial thinning (PCT) treatments to reduce stocking in these dense young stands. Pre-commercial thinning in young stands usually targets the removal of the smallest trees to reduce stand density and stimulate growth of the remaining larger trees, but PCT can also address other forest values such as enhancing wildlife habitat, managing tree species with regard to climate change adaptation, preparing stands for future silviculture treatments such as fertilization and commercial thinning, and reducing future fuel loads. On the timber harvesting land base in coastal forests of British Columbia, the objectives of PCT are to concentrate growth on higher-value tree species, produce uniform piece sizes, and increase lumber recovery to reduce harvesting and manufacturing costs by shortening the time to reach merchantable piece size (FRDA 1996).

Mixed western hemlock and amabilis fir stands respond to thinning in a manner similar to other species: as distance between trees increases, total stand volume and basal area decrease while mean stand diameter and crop tree volume and basal area increase (Griffith 1959; Hoyer and Swanzy 1986; Curtis 2008; Newton and Cole 2012; Curtis 2013; Reynolds and de Montigny 2015). Height growth response to PCT is either unaffected (BC Forest Products Limited 1979; Dilworth 1980; Hoyer and Swanzy 1986; Reynolds and de Montigny 2015) or reduced, with evidence of a possible thinning shock (Shortreid and Steward 1978; Curtis 2008).

However, PCT is expensive (Can$1400/ha, 2016 dollars), which raises concerns that low returns on investment may not justify thinning in these stands. There is much uncertainty in the assumptions made for PCT prescriptions for mixed western hemlock and amabilis fir stands. Economic analyses have been conducted to determine the optimum post-thinning density that will yield the greatest financial return in mixed coastal western hemlock stands, but recommended densities vary greatly from 740 stems per hectare (sph) (Dilworth 1980) to 1600 sph in mixed western hemlock and Sitka spruce stands (Reynolds and de Montigny 2015). This wide range of recommended post-thinning densities indicates that more research is required to understand the biology of these stands and the effectiveness of PCT in meeting various management objectives in coastal British Columbia.

This study examines the stand characteristics of an 18-year-old naturally regenerated mixed western hemlock and amabilis fir stand and the effects of a range of post-thinning densities on growth and yield 15 years after PCT.

2.1 Study Area

The 20-ha study site (Experimental Project 1211) is located in the Callaghan Valley near Whistler, B.C., approximately 90 km north of Vancouver, B.C. The site is in the Southern Moist Submaritime Coastal Western Hemlock biogeoclimatic variant (CWHms1) (Meidinger and Pojar 1991). The CWHms1 has a climate that is transitional between the British Columbia coast and interior, and is characterized by moist, cool winters and cool but relatively dry summers (May to September precipitation is 265 mm). Mean annual snowfall is relatively heavy (657 cm). The study site has an east aspect with an average slope of 26% and an elevation of 760 m. The topography is rolling, and the site is located at the lower slope, with small gullies in the centre of the block. Soils are silty loams, with 35–70% coarse fragment content and moderately good drainage, the humus form is a Moder, with a depth of 8–12 cm, and the rooting depth is 50 cm, with a root-restricting layer at 100 cm. The site series is BaCw[1] – Devil's club, with a soil moisture and nutrient regime of moist to very moist and rich to very rich, respectively. The site index at 50 years is 28 m for western hemlock.

The area was logged between 1977 and 1980, was spot burned in 1979, and then was allowed to regenerate naturally. In 1996, the resulting young stand of amabilis fir and western hemlock was identified as eligible for PCT using standard guidelines (FRDA 1996), which included the following: the major crop tree species were western hemlock and amabilis fir, the average height of the leave trees after PCT was between 4 and 12 m, the average functional live crown ratio for the crop trees was ≥ 30%, the average height-to-diameter ratio was < 0.9, the total coniferous density was > 1500 sph, the site index for the target crop tree species in the stand was ≥ 20 m, and there were no identified forest health agents. The stand management prescription for the stand called for a target density of 800 (± 10%) sph.

2.2 Reconnaissance Survey

Due to the observed variability of the site, a reconnaissance survey was conducted in the summer of 1997 to produce a detailed map that indicated the location of gullies and unstocked wet areas where treatment plots could not be established, and to estimate the variability of tree density across the site. A 25-m grid system was established across the research area, starting at the northeast corner and covering the site with a total of 217 grid points. At each grid point, trees were sampled within a 3.99-m radius plot (0.005 ha). Each tree within the plot was categorized by species and height class (< 2 m, 2–4 m, 4–6 m, and > 6 m), and height was measured on the largest amabilis fir and western hemlock trees. In this way, an estimate was made of density, species mix, average height, and dominant tree height for every grid point. The percent cover of non-tree vegetation and its modal height was also estimated at each grid point within a 2.99-m radius (0.0028-ha) plot with the goal of recording the five most plentiful species of competing shrubs and herbs to determine if site differences existed across the area. The resulting map was then used to identify contiguously treed areas that were suitable for establishing treatment plots.

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[1] BaCw – Amabilis fir and western redcedar (*Thuja plicata* (Donn ex D.Don)).

2.3 Experimental Design

Six levels of thinning (including the non-treated controls) were used to examine the effects of PCT on the growth and yield of amabilis fir and western hemlock. The targeted densities included the prescribed treatment of 800 sph and a wider range of densities: 500, 1100, 1400, and 1800 sph; and an unthinned control. Careful study of the reconnaissance survey map and the data on tree density and vegetation indicated that the most uniform and consistently stocked areas within the overall site could accommodate up to 24 plots; thus, four replicates were established for each level of thinning. The plot sizes ranged from 0.03 to 0.10 ha (Table 1) and were chosen to incorporate at least 50 trees and preferably 70 trees per plot after the thinning treatment, with a surrounding 10-m treated buffer. The random allocation of the treatments to this range of plot sizes was complicated by the non-uniformity of the site. Operationally, it was necessary to locate the largest plots first. Therefore, the assignment of locations for the plots started with the T550 treatment. The possible locations for these plots were numbered (relative to the grid), and then the actual plot location was randomly selected. This was repeated for progressively smaller treatment units until all plots had been located.

TABLE 1 *Treatment summary information*

	Target		Actual		Percentage	
Treatment	**Density (sph)**	**Spacing (m)**	**Density (sph)**	**Plot size (ha)**	**Amabilis fir**	**Western hemlock**
T550	500	4.5	565	0.10	59.0	41.0
T800	800	3.5	789	0.09	51.1	48.9
T950	1100	3.0	957	0.07	60.4	39.6
T1200	1400	2.7	1 180	0.05	53.4	46.6
T1600	1800	2.4	1 606	0.04	64.6	35.4
Control	n/a	n/a	22 008	0.03	30.5	69.5

2.4 Plot Establishment

In the field, the plots centres were located at or near the pre-selected grid points, and plot boundaries were adjusted based on plot size and actual site conditions. The sides of each plot were traversed by a two-person crew using a Vertex hypsometer to obtain rough distances, and a combination of a Brunto pocket transit and metric fiberglass chain was used to establish the exact slope-corrected plot corners. Initially, aluminum rods were used to mark plot corners to avoid any compass distortion. Once the plot was fully surveyed, the aluminum rods were replaced with 1-cm diameter and 1-m long rebar firmly set at all eight corners (four plot and four buffer corners). Hollow, white PVC pipe was placed over the rebar at all eight corners, with the top 30 cm spray painted orange for the plot corners and blue for the buffer corners. Figure 1 shows the relative size and proximity of the 24 plots and the thinning treatment applied.

2.5 Thinning Treatment

The criteria for the thinning treatments were to select trees based on (1) target spacing (Table 1), (2) a target species composition of 60% amabilis fir and 40% western hemlock, and (3) leave trees with good form and vigour. All leave trees within the plot and buffer areas were selected and flagged by one person to maintain consistency among plots, and inter-tree distance was measured to verify spacing among trees within the plot and buffer area.

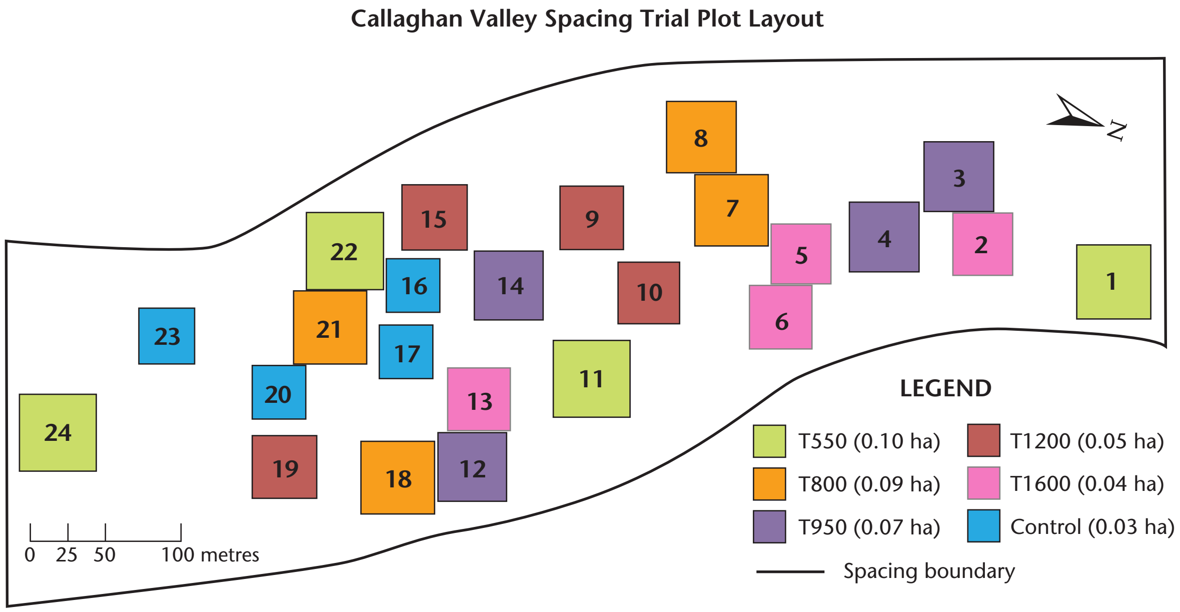

FIGURE 1 *Plot layout showing the relative size and proximity of the 24 plots and the pre-commercial thinning treatment.*

Flagged leave trees in all plots were tagged and measured immediately before PCT in the fall of 1998. The measurements that were taken and are relevant to this analysis were total height (ht [m]), diameter at breast height (dbh [cm]), height to live crown (hlc [m]), and crown radii (CW [m]) as measured by distance (m) from stem to outside edge of the crown in the north and east directions. After completion of the thinning treatment, any replacement trees (substituted for any leave trees that were accidentally cut) were tagged and measured. The plots were measured immediately following treatment and 2, 4, and 15 years post treatment.

Pre-commercial thinning operations were conducted during the fall of 1998 when the stand was 18 years old. After PCT, tree densities in the four plots in each treatment were summarized and were found to differ from the target densities. In the least dense plots, the number of leave trees was greater than expected, and in all other treatments, less than expected. A few marked leave trees, especially in the denser treatments, were inadvertently cut. To better reflect the actual thinning treatment, the treatments were renamed based on the average post-treatment density of the four original replications per treatment, rounded to the nearest 50 (i.e., T550, T800, T950, T1200, T1600, and control). Treatment codes and summary information are provided in Table 1.

2.6 Determination of Stand Age

Stand age by species was estimated in 1998 by randomly selecting additional reconnaissance plots and aging the trees in the plots by destructive sampling. The entire experimental area was stratified into six sections of 125-m widths, and all reconnaissance plots that were not within 25 m of the permanent plots were assumed to be available for sampling. Within each section, one 3.99-m radius plot was randomly selected for destructive sampling. All trees > 1.3 m in height within the selected plot were measured for height and dbh and then were felled. At each felled tree, a 1- to 3-cm thick disc was cut at the root collar, labelled, and stored in a burlap sack at 4° C until air-dried and sent to a laboratory for ring analyses and aging. In total, 339 trees were sampled. Where ring boundaries were difficult to distinguish, a 40× microscope and Velmex-type stage measurement system were employed for ring boundary verification.

2.7 Statistical Analysis

The density (sph) of each plot was calculated by dividing the number of trees in each plot by the plot size. The site index of each plot was determined by first averaging the heights of the largest dbh trees of each species in each plot to obtain site height, where m is the plot size (ha) multiplied by 100. This was done to roughly conform to the British Columbia standards for site tree selection (B.C. Ministry of Forests and Range 2009), which specify that site height is the height of the largest dbh tree in a 0.01-ha plot. Assuming a total age of 33 years, the species, site height, and age were used to obtain site index from the growth intercept models for western hemlock (Nigh 1999) and amabilis fir (Nigh 2009).

The stand-level response variables of interest were total volume (VOL [m^3/ha]), basal area (BA [m^2/ha]), quadratic mean diameter (QMD [cm]), average height (HT [m]), average height to live crown (HLC [m]), average crown width (CW [m]), and taper (T [cm/m]). These stand-level statistics were calculated for all trees and for the crop trees, where the crop trees were defined as the 250 largest dbh trees per hectare.

While height was measured on most trees, a few trees were missed, and for trees that were leaning, the height was measured vertically from the ground to the tip of the tree. Using this height to calculate volume for the leaning trees could lead to an underestimate of volume. Therefore, height–dbh models were developed to predict heights for trees with a missing height and/or lean. The Chapman-Richards function was chosen as the height–dbh model:

$$ht_i = 1.3 + a \times (1 - e^{b \times \mathrm{dbh}_i})^c + \varepsilon_i \qquad (1)$$

where *ht* and dbh are previously defined; *i* indexes tree; *a*, *b*, and *c* are model parameters that are estimated in the fitting process; and ε_i is the random error term for tree *i*, where the ε_i are assumed to meet the standard regression assumptions (independent and normally distributed with a mean of zero and a constant variance [Sen and Srivastava 1990]). This height model was fit to the available height–dbh data for both species at each measurement with procedure NLIN (nonlinear least squares regression) in SAS (SAS Institute Inc. 2011).

Total individual tree stem volume was calculated from tree dbh and height. A volume equation was developed for this purpose from taper data used to develop volume and taper equations (e.g., Kozak 1988). The form of the individual tree volume equation is:

$$\mathrm{vol}_i = (a + b \times \mathrm{dbh}_i + c \times ht_i) \times (\mathrm{dbh}_i^2 \times ht_i)^d + \varepsilon_i \qquad (2)$$

where vol, dbh, and *ht* are previously defined; *i* indexes tree; *a*, *b*, *c*, and *d* are model parameters that are estimated in the fitting process; and ε_i is the random error term for tree *i*, where the ε_i are assumed to meet the standard regressions assumptions. Individual tree volume equations were fit separately for both western hemlock and amabilis fir using the NLIN procedure in SAS (SAS Institute Inc. 2011).

Stand-level response variables were calculated from individual tree data, actual and predicted. VOL and BA were calculated by summing tree volume and basal area by plot, respectively, and dividing by the plot size. QMD is the square root of the average of dbh^2 by plot. HT, HLC, CW, and T are average tree height, height to the base of the live crown, crown width (sum of the two crown radii), and tree taper (dbh ÷ tree height), respectively, by plot.

These response variables were analyzed as a completely randomized design, as represented by the following model:

$$Y_{ij} = \mu + \alpha_i + \varepsilon_{ij} \tag{3}$$

where Y_{ij} is the response variable for treatment i and replicate j, μ is the overall mean, α_i is the treatment effect for treatment i, and ε_{ij} is the random error term for treatment i and replicate j, where the ε_{ij} are assumed to meet the standard regression assumptions. The response variables were analyzed for the first measurement at age 18 and for the last remeasurement at age 33. Procedure MIXED in SAS was used to analyze the model (SAS Institute Inc. 2011). The F-max test (Mason et al. 1989) was applied to test whether the assumption of constant variance across the treatments was tenable. If not, the treatments with similar variances were grouped, and the within-group variance was assumed to be constant. This was implemented via the group option in the repeated statement in procedure MIXED. In most instances, the F-max test indicated that the variance was constant across all treatments. All pairwise differences between the least-squares means for the treatments were tested with the Holm's adjustment to the Bonferroni procedure for multiple comparisons (Bretz et al. 2011).

The periodic annual increment (PAI) was calculated for response variables VOL (m^3/ha/yr), BA (m^2/ha/yr), QMD (cm/yr), and HT (m/yr) for each of the three remeasurements (period one = 1998–2000, period two = 2000–2002, period three = 2002–2013) by dividing the difference in the response variable between two remeasurements by the interval between the remeasurements. The PAIs were also calculated in the same way over the whole experiment (1998–2013). The PAI for VOL, BA, QMD, and HT for all trees and for just the crop trees was analyzed with Equation 3 to quantify the PAI response to the treatment. For these analyses, Y_{ij} is the PAI of the response variable for periods one, two, and three, and from 1998 to 2013.

Regression analyses were done on PAI for VOL and QMD for all trees and only for the crop trees to better detect the trends with respect to initial density in the response variables. Control plots were not included in these analyses because their initial density was so much larger than that of the treated plots that they obscured the trends in the data for the lower densities. A quadratic model was proposed:

$$Y_{ij} = \beta_0 + \beta_1 \times \text{SPH}_{ij} + \beta_2 \times \text{SPH}_{ij}^2 + \varepsilon_{ij} \tag{4}$$

where Y_{ij} is the response variable VOL or QMD for all trees or crop trees for treatment i and replicate j, SPH_{ij} is initial density (stems per hectare) for treatment i and replicate j, β_0, β_1, and β_2 are model parameters to be estimated, and ε_{ij} is the error term with the standard regression assumptions. If parameter β_1 and/or β_2 were not significantly different from 0 ($\alpha = 0.05$), then the term was dropped from the model and the reduced model was refitted.

3 RESULTS

3.1 Reconnaissance Survey and Age Sampling

Mean densities of regenerating trees sampled in the reconnaissance survey ranged from 0 to 80 400 sph, with a mean of 11 000 sph (Figure 2). Of the 217 sampled survey points, 1% of the plots had no trees. These apparent "holes" tended to occur on wet soils occupied by dense shrubs and herbs. The most commonly occurring shrub and herb species were salmonberry (*Rubus spectabilis*), huckleberry (*Vaccinium* spp.), fireweed (*Epilobium angustifolium*), lady fern (*Athyrium filix-femina*), devil's club (*Oplopanax horridus*), and bunchberry (*Cornus canadensis*). Other minor species included queen's cup (*Clintonia uniflora*), rosy twistedstalk (*Streptopus amplexifolius*), five-leaved bramble (*Rubus pedatus*), foam flower (*Tiarella trifoliata*), and red elderberry (*Sambucus racemosa*). The species composition did not vary much among plots.

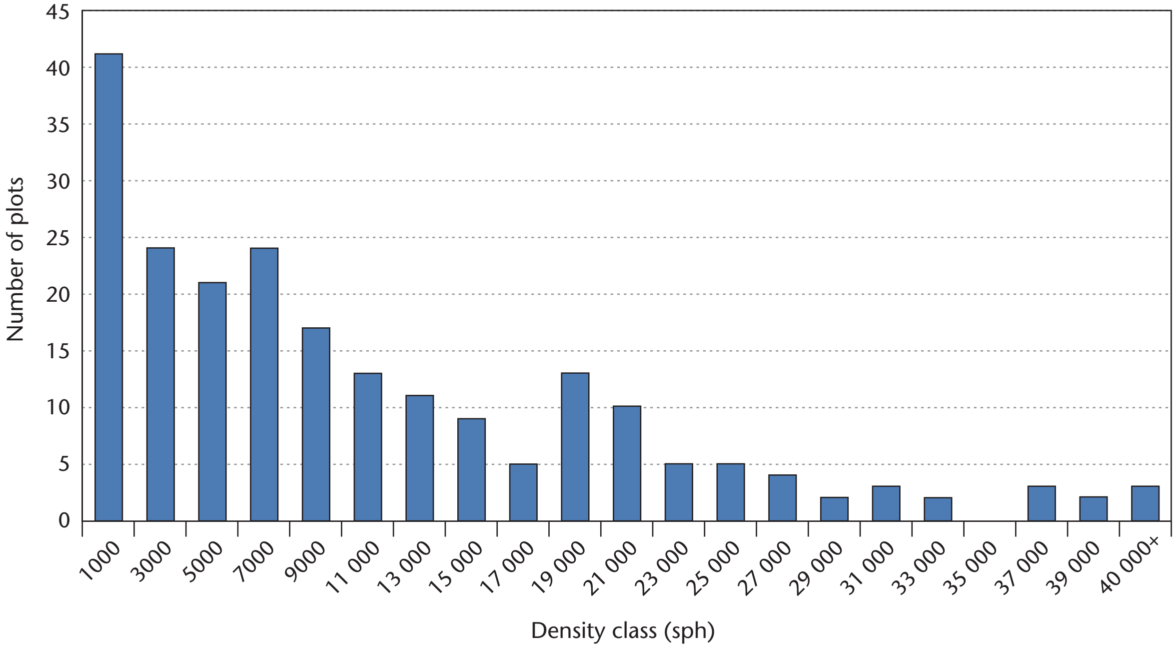

FIGURE 2 *Number of plots in density classes from the reconnaissance survey in 1997 (n = 217).*

About 7% of sampled survey points had tree densities < 800 sph, 59% had densities < 10 000 sph, 24% had densities of 10 000–20 000 sph, and 18% had densities > 20 000 sph.

On average across the entire treatment area, 58% of total stems were western hemlock and 42% were amabilis fir. The destructive sampling showed that the average age of amabilis fir was 30 years (ranging from 14 to 90 years), and 72% of the amabilis fir trees had regenerated before harvest. The average age of western hemlock was 17 years (ranging from 13 to 26 years), and 75% of the western hemlock trees had regenerated at or after harvest.

Despite the difference in ages between amabilis fir and western hemlock, the size of the amabilis fir trees (dbh ranging from 0.3 to 23.7 cm, with a mean of 5.0 cm) was not greatly different from that of the western hemlock (dbh ranging from 0.2 to 13.1 cm, with a mean of 3.7 cm) (Figure 3).

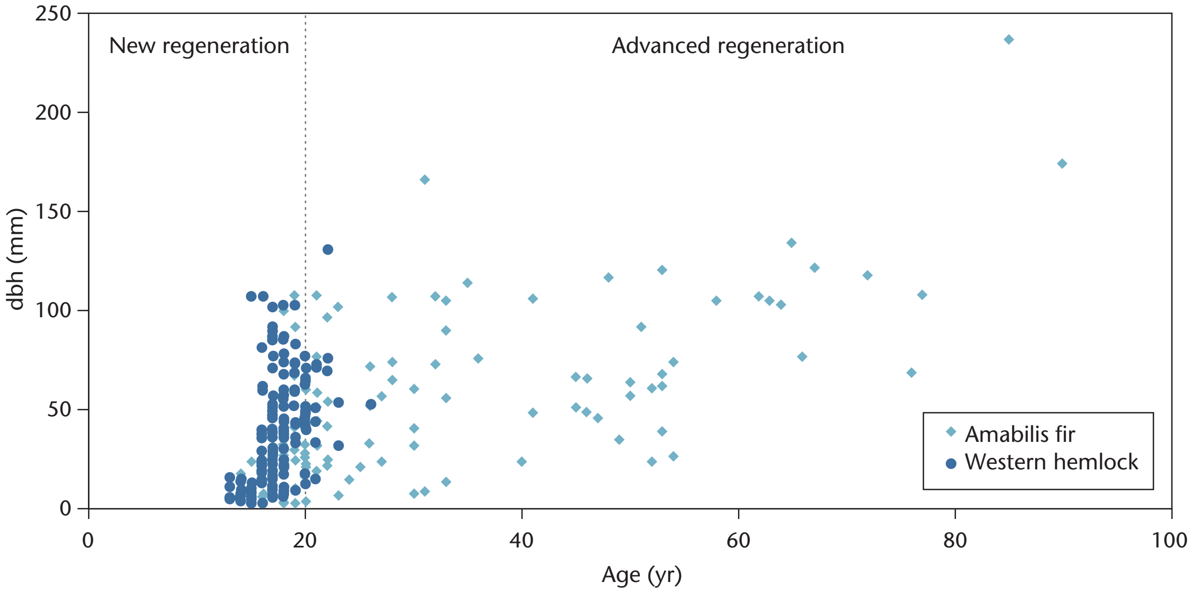

FIGURE 3 *Diameter at breast height (dbh) versus age of amabilis fir and western hemlock trees that were destructively sampled. The dotted vertical line indicates when the original stand was logged.*

3.2 Individual Tree Models

Individual tree height and volume models were used to calculate stand-level parameters. These models are supplementary to the main objectives of the study and are shown in Table 2.

TABLE 2 *Models used to predict tree height (ht [m]) from diameter at breast height (dbh [cm]) and total stem volume (vol [m^3]) from height and diameter at breast height*

Species	Measurement	Model
Amabilis fir	1	$ht = 1.3 + 9.9435 \times (1 - e^{-0.1293 \times dbh})^{1.3893}$
	2	$ht = 1.3 + 11.1076 \times (1 - e^{-0.1275 \times dbh})^{1.6086}$
	3	$ht = 1.3 + 12.5894 \times (1 - e^{-0.0873 \times dbh})^{1.2413}$
	4	$ht = 1.3 + 16.1124 \times (1 - e^{-0.1243 \times dbh})^{1.7693}$
	All	$vol = (0.3300 - 0.00114 \times dbh + 0.00246 \times ht) \times (dbh^2 \times ht)^{0.9541}$
Western hemlock	1	$ht = 1.3 + 8.9432 \times (1 - e^{-0.1455 \times dbh})^{1.2571}$
	2	$ht = 1.3 + 9.6701 \times (1 - e^{-0.1433 \times dbh})^{1.4136}$
	3	$ht = 1.3 + 11.3103 \times (1 - e^{-0.1023 \times dbh})^{1.1062}$
	4	$ht = 1.3 + 15.9050 \times (1 - e^{-0.1625 \times dbh})^{2.1002}$
	All	$vol = (0.3063 - 0.00088 \times dbh + 0.001656 \times ht) \times (dbh^2 \times ht)^{0.9701}$

3.3 Stand Conditions Immediately after Pre-commercial Thinning

Immediately after the PCT treatment, actual densities were 11–16% lower than the prescribed target densities (Table 1). Nevertheless, densities were significantly different among all treatments (Table 3). At the time of PCT, the control stands had a species composition of about 30% amabilis fir and 70% western hemlock (Table 1). The PCT treatment was to favour amabilis fir, with a target composition of 60% amabilis fir to 40% western hemlock; this preference for amabilis fir was achieved, although actual post-treatment proportions of

TABLE 3 *Least-squares means of post-treatment density, tree parameters, and mortality at measurement one (immediately following treatment) and measurement four (15 years post-treatment) summarized by treatment. Row-wise values with the same letter are not significantly different from each other ($\alpha = 0.05$).*

			Treatment					
Trees	**Parameter**	**Measurement**	**T550**	**T800**	**T950**	**T1200**	**T1600**	**Control**
All	Density (sph)	1	565a	789b	957c	1180d	1606e	22 008f
		4	620a	797ab	961bc	1120c	1569d	5 900e
	QMD[a] (cm)	1	10.9a	10.4a	10.1a	10.4a	9.2a	4.6b
		4	26.5a	25.3a	24.1a	25.0a	19.9b	13.3c
	Height (m)	1	7.4a	7.0ab	7.0ab	7.0ab	6.2b	3.9c
		4	14.6ab	14.7ab	15.1ab	15.7a	13.6bc	12.6c
	Basal area (m^2/ha)	1	5.3a	6.7a	7.8a	10.1a	11.0a	34.5b
		4	34.1a	40.0ab	43.9abc	54.6c	48.8bc	82.4d
	Volume (m^3/ha)	1	19.8a	24.4a	29.2a	37.7a	41.8a	104.8b
		4	224.3a	261.2a	294.7ab	376.0b	324.2ab	553.4c
	Height to live crown (m)	1	0.59a	0.63a	0.72a	0.66a	0.60a	0.89a
		4	1.7a	2.2ab	2.6abc	3.3c	3.0bc	7.1d
	Crown width (m)	1	2.4a	2.3a	2.3a	2.3a	2.1a	1.3b
		4	4.9a	4.6a	4.3a	4.5a	3.6b	2.8c
	Taper (cm)	1	1.4a	1.3a	1.3a	1.3a	1.2a	0.8b
		4	1.7a	1.6ab	1.5bc	1.5c	1.3d	0.9e
	Mortality rate	1 to 4	0.03a	0.05a	0.02a	0.06a	0.04a	0.73b
Crop	QMD (cm)	1	13.9a	14.5a	14.5a	15.7a	15.7a	14.1a
		4	32.2a	32.8a	30.9a	32.7a	29.8a	25.7b
	Height (m)	1	8.8a	8.8a	9.1a	9.2a	9.3a	9.0a
		4	17.0a	16.9a	17.2a	17.7a	17.4a	18.0a
	Basal area (m^2/ha)	1	3.8a	4.0a	4.1a	4.7a	5.0a	3.7a
		4	20.4a	20.6a	18.2a	20.2a	17.5a	12.1b
	Volume (m^3/ha)	1	15.1a	15.7a	16.8a	19.7a	21.0a	14.8a
		4	139.1a	138.2a	127.0ab	145.3a	125.2ab	92.6b
	Height to live crown (m)	1	0.59a	0.60a	0.80a	0.64a	0.72a	0.82a
		4	1.8a	2.4ab	2.6abc	3.5c	3.2bc	6.7d
	Crown width (m)	1	2.9a	3.1a	3.0a	3.1a	3.3a	2.9a
		4	5.8a	5.9a	5.3a	5.4a	5.0ab	4.2b
	Taper (cm)	1	1.6a	1.7a	1.6a	1.7a	1.7a	1.6a
		4	1.9ab	2.0a	1.8bc	1.8abc	1.7c	1.4d

[a] QMD: quadratic mean diameter.

amabilis fir varied from 65% (T1600) to 51% (T800). In comparing the PCT treatments with the unthinned control treatment (Table 3), stand densities were lower by 93–97%, BA by 68–85%, and total volume by 60–81%.

As expected, immediately after the PCT treatment, mean tree size in all PCT treatments was greater than in the unthinned controls (Table 3), which reflected the removal of a large number of small trees and the preference for retention of larger leave trees. For example, in comparison to the unthinned controls (Table 3), tree size in PCT treatments was larger for QMD by 100–137%, height by 47–59%, crown width by 62–85%, and taper by 31–89%. Although the trends showed that differences among the PCT treatments were related to the intensity of the PCT treatment, there were no significant differences in any individual tree parameter (except that height of T1600 was less than that of T550) or per-hectare parameter between any of the PCT treatments for all trees or crop trees.

Immediately after PCT, the densities of the two smallest dbh classes in the stands with PCT varied from 35 to 469 sph (5-cm dbh class) and from 255 to 600 sph (10-cm dbh class) compared to 16 817 and 4408 sph (5- and 10-cm dbh class, respectively) in the control (Table 4). In other words, the PCT stands had 97–99% and 86–94% fewer stems in the 5-cm and 10-cm dbh classes, respectively, compared to the untreated control. The removal of the large number of small stems resulted in 60–81% less total residual volume after the PCT (20–42 m³/ha) compared to the control (105 m³/ha).

TABLE 4 *Mean treatment density (sph) and volume (m^3/ha) by diameter class immediately after pre-commercial thinning (PCT) and after 15 years*

	Density (sph)						**Volume (m^3/ha)**					
Treatment	**550**	**800**	**950**	**1 200**	**1 600**	**Control**	**550**	**800**	**950**	**1 200**	**1 600**	**Control**
dbh class						**Immediately after PCT**						
5	35	111	114	150	469	16 817	0.99	1.46	2.12	2.66	4.16	42.07
10	255	331	489	560	600	4 408	7.27	9.36	11.30	12.75	14.26	44.48
15	205	264	254	330	388	750	9.42	10.86	11.98	14.15	14.39	18.28
20	70	81	100	120	138	33	2.16	2.74	3.83	7.10	7.02	0.00
25	0	0	0	20	6	0	0.00	0.00	0.00	1.08	0.00	0.00
30	0	0	0	0	6	0	0.00	0.00	0.00	0.00	2.00	0.00
35	0	0	0	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00
40	0	0	0	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00
45	0	0	0	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00
Total	565	789	957	1 180	1 606	22 008	19.83	24.42	29.23	37.74	41.84	104.83
dbh class						**15 years after PCT**						
5	30	11	11	10	25	300	0.33	0.29	0.12	0.11	0.61	11.50
10	35	53	21	40	181	2 158	0.49	1.86	1.36	2.29	11.07	95.48
15	23	64	71	70	350	1 908	2.10	5.64	11.07	13.92	40.59	166.98
20	40	89	179	195	356	908	14.90	25.56	50.33	57.98	74.05	139.83
25	100	211	289	290	344	483	39.23	65.77	92.89	95.99	97.84	123.14
30	210	164	257	270	206	142	99.66	90.40	99.79	113.05	67.95	16.51
35	133	158	118	205	81	0	62.25	62.63	39.17	83.90	25.37	0.00
40	50	44	14	40	19	0	5.36	9.06	0.00	8.77	6.68	0.00
45	0	0	0	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00
Total	620	797	961	1 120	1 569	5 900	224.32	261.21	294.73	376.01	324.17	553.44

The diameter distributions also showed that almost all treatment plots had some trees in the 20-cm diameter class, with the exception of the control. During a subsequent field inspection, the largest trees (> 20 cm) were cored and found to be the same age (33 years) as stand initiation. Therefore, size differences for these large trees were likely caused by favourable microsites such as beside small draws or on knolls, which would allow early snowmelt or greater room for crown expansion. The larger plot sizes likely provided a wider range of microsites that included these few larger trees than did the small control plots.

3.4 Stand Conditions 15 Years after Pre-commercial Thinning

Although all treatment densities were significantly different from each other immediately after treatment, the trends were not as clear after 15 years. For the widely spaced treatments (T550, T800, and T950), ingress (stem recruitment into the lowest dbh class) increased density by 12, 4, and 2%, respectively, while in the densely spaced treatments (T1200 and T1600), mortality reduced density by 5 and 2%, respectively (Table 3). Consequently, density differences were no longer significant between T550 and T800, T800 and T950, and T950 and T1200.

The rate of mortality over the 15-year period remained low in the thinned treatments (2–6%), and differences among treatments were not significant (Table 3). Although most of the mortality was in the smallest dbh class and presumably was density-dependent, there were also some large-dbh trees that died. The cause of mortality of the larger trees is unknown. Mortality in the unthinned control was very high (73%), which resulted in a reduction in density from about 22 000 to 5900 sph. Eighty percent of the trees that died were western hemlock in diameter classes < 10 cm.

The effects of PCT on stand growth as measured by the periodic annual increments for QMD, HT, BA, and VOL among treatments in the first two periods following PCT (1998–2000 and 2000–2002) were not significant (data not shown). The effects of PCT on growth after 15 years were, in general, similar to those in other thinning trials where significant differences developed between thinned and unthinned stands (Table 5): as density decreased, diameter growth tended to increase, but differences were not always significant. Over the 15-year treatment response period (Table 5), we found:

- no differences in height growth among any thinned stand treatment means for all trees and crop trees;
- no differences in QMD, basal area, and volume growth among more heavily thinned treatments T550, T800, and T950, but these treatments were significantly different from the control for all trees and crop trees;
- that basal area and volume growth for T1200 were significantly larger than that for treatments T550 and T800 for all trees but not for crop trees;
- that basal area growth for T1200 was not different from the control for all trees but was different from the control for the crop trees;

TABLE 5 *Least-squares means of periodic annual increments by treatment for all trees and crop trees. Row-wise values with the same letter are not significantly different from each other (α = 0.05).*

		Treatment					
Trees	**Parameter**	**T550**	**T800**	**T950**	**T1200**	**T1600**	**Control**
All	QMD[a] (cm/yr)	1.04a	0.99a	0.93a	0.97a	0.71b	0.59b
	Height (m/yr)	0.48a	0.51ab	0.54ab	0.57ab	0.49ab	0.58b
	Basal area (m^2/ha/yr)	1.9a	2.2a	2.4ab	3.0bc	2.5ab	3.2c
	Volume (m^3/ha/yr)	13.6a	15.8a	17.7ab	22.6b	18.8ab	29.9c
Crop	QMD (cm/yr)	1.22a	1.22a	1.09ab	1.13ab	0.94bc	0.77c
	Height (m/yr)	0.55a	0.54a	0.54a	0.57a	0.54a	0.60a
	Basal area (m^2/ha/yr)	1.10a	1.10a	0.94ab	1.03ab	0.84b	0.56c
	Volume (m^3/ha/yr)	11.3a	11.1a	10.0a	11.4a	9.5ab	7.1b

a QMD: quadratic mean diameter.

- that QMD growth for treatment T1600 was not different from the control for all trees or crop trees; and
- that volume growth of crop trees in T1600 was not different from the control. The differences in growth over 15 years led to differences in mean tree size (Table 3).

Mean treatment heights reflect the difference in density across the treatments, with denser treatments having more small trees and therefore smaller mean heights. For example, the mean height of all trees in treatments T550 to T1200 was taller than that of the control. More importantly, we found no significant differences in mean crop tree heights between the thinned treatments and the control or between any of the thinned treatments, which indicated, again, no site differences among treatments. The mean QMD of all trees ranged from 13.3 cm (unthinned control) to 26.5 cm for the most widely spaced (T550), and all the thinned treatments had larger mean QMDs than the controls. Within thinned treatments, mean QMDs between treatments T550 to T1200 were not different but were larger than for T1600. This difference was due largely to the larger number of smaller trees in T1600 because there was no treatment difference for the crop trees. Crop tree QMDs were different between the thinned treatments and the unthinned control. With no difference in heights and significant differences in QMDs, tree taper decreased with increasing tree density.

The dbh distribution within treatments 15 years after PCT (Table 4) shows, as expected, that PCT treatments with wider spacing had fewer trees in the smaller (≤15 cm) dbh classes and more trees in the larger (≥30 cm) dbh classes. Although the PCT stands had 32–59% less total volume compared to the control, the proportion of total volume from larger (≥30 cm) dbh classes was 32–59% greater in PCT stands. After 15 years, the control did not have stems larger than 30 cm dbh. This thinning effect is reflected in the mean QMDs (Table 3), where, after 15 years, all trees in the thinned treatments were similar from T550 to T1200 but were significantly smaller for T1600 and the unthinned control. For crop trees, all thinned treatments were significantly larger than the control but not from each other.

Differences in tree size and density among treatments resulted in differences in stand basal area and volume (Table 3). As expected, the unthinned control had significantly greater all-tree basal area but significantly less crop tree basal area than in thinned stands. All-tree volume was also greater in the unthinned control than in thinned treatments, but crop tree volume was not different between the unthinned control and treatments T1600 and T950. There were no differences in basal area or volume for crop trees in the thinned treatments.

The relationship between the 15-year volume (m^3/ha) of all trees and post-treatment density (sph) for the 20 thinned plots was significant, positive, and quadratic (Table 6; Figure 4); total volume increased with increasing density up to treatment T1200 and then decreased with treatment T1600. Pre-commercial thinning below T950 resulted in lower total volume. For crop trees, the relationship was not significant (Figure 5). The regression analysis on 15-year QMD growth also showed a significant linear relationship for all trees and crop trees (Table 6). The relationships between density and volume should not be extrapolated below 500 sph or above 1800 sph.

Branching and taper were affected by the PCT treatments. Trees growing in the more open-grown treatments (T550) had longer, wider crowns and greater taper than trees growing in denser treatments (T1200 and T1600) (Table 3).

TABLE 6 *Results of the regression of volume periodic annual increment (PAI) and quadratic mean diameter (QMD) PAI on initial density (Equation 4) for all trees and for the crop trees*

	Parameter				
Response variable	**Name**	**Estimate**	**SE**	R^2	**Root mean squared error**
Volume PAI, all trees (m^3/ha/yr)	β0	−3.44	6.140	0.54	3.090
	β1	0.04	0.120		
	β2	−0.0000159	0.00000520		
Volume PAI, crop trees (m^3/ha)	β0	10.65	0.710	0.27	1.080
	β1	−0.00169	0.000658		
QMD PAI, all trees (cm)	β0	1.16	0.070	0.53	0.100
	β1	−0.000280	0.0000623		
QMD, crop trees (cm)	β0	1.35	0.064	0.56	0.096
	β1	−0.000282	0.0000588		

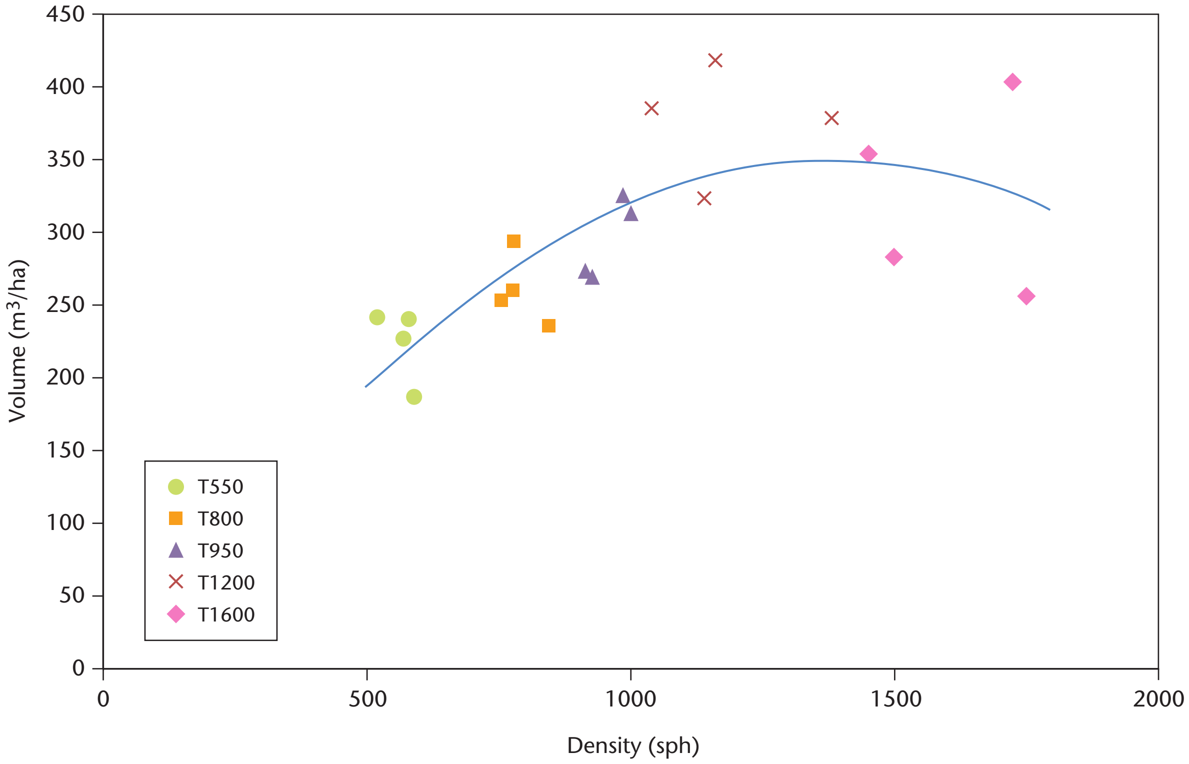

FIGURE 4 *All-tree volume versus initial post-treatment density of the 20 treatment plots (controls excluded).*

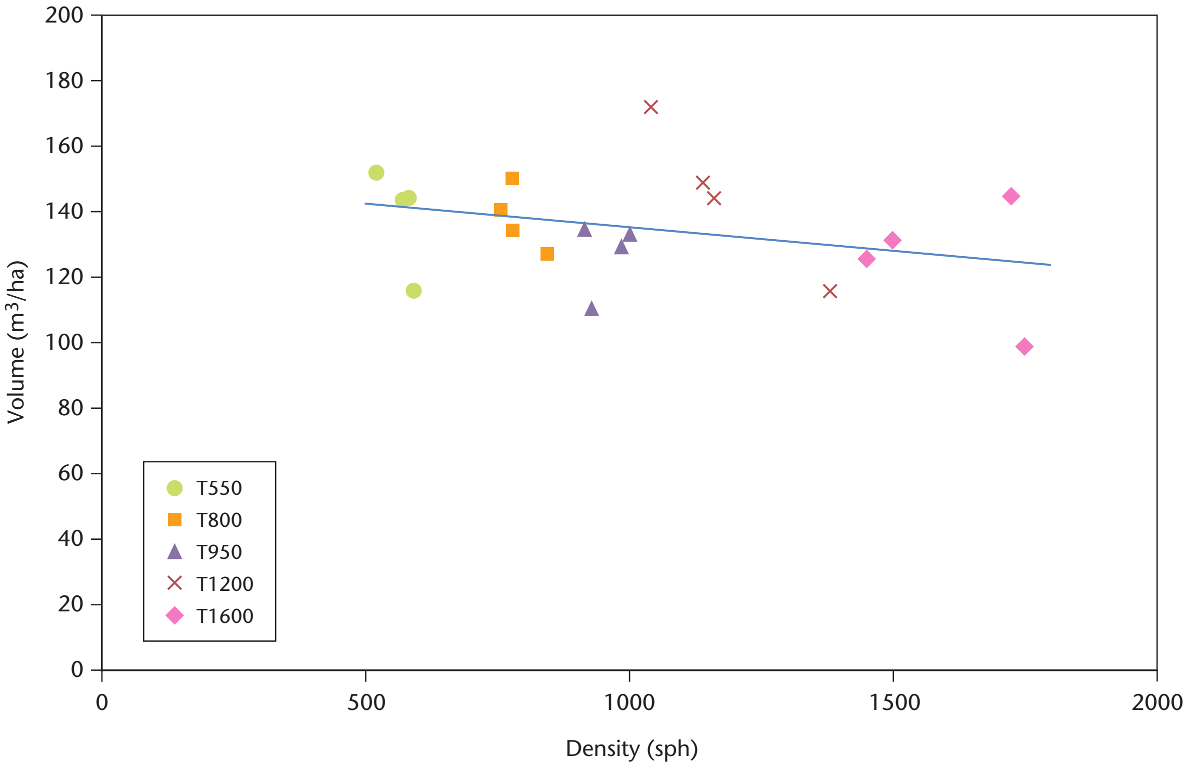

FIGURE 5 *Crop tree volume versus initial density of the 20 treatment plots (controls excluded).*

4 DISCUSSION

The clumpy nature of naturally regenerated mixed western hemlock and amabilis fir stands, as described by Klinka et al. (1992), was apparent from the reconnaissance survey, where we found that the density of regenerating trees in the surveyed sample points ranged from 0 to 80 400 sph, with a mean of 11 000 sph (Figure 2). The densest sample point of 80 400 sph was approaching the upper density limit of 100 000 trees modelled by de Montigny and Nigh (2007) for young, naturally regenerated western hemlock.

The species differences in density (proportion of total stems: 58% for western hemlock and 42% for amabilis fir) and average age (17 and 30 years for western hemlock and amabilis fir, respectively) reflect the regeneration strategies of the two species. Western hemlock is a prolific seed producer, and the small, light seed has high dissemination capacity and, in moist environments, a high germination rate, even under low-light conditions; however, the seeds do not germinate well where forest floors are covered in dense vegetation such as shrubs, ferns, or herbs; consequently, hemlock regeneration is most successful after harvesting (Fowells 1965). In contrast, amabilis fir seeds are relatively large, and although they seldom carry far from the parent, they can germinate and grow in moist conditions under heavy shade, where they grow very slowly; when canopy gaps are created, the trees are released from light and root competition and can respond with increased diameter and height growth (Fowells 1965). This difference in species ages was also found by Brett

(1997) for higher-elevation montane sites in coastal British Columbia, where amabilis fir accounted for 76% of naturally regenerated trees, very few advance regeneration trees were western hemlock, and only 20% of all trees and seedlings established more than 1 year after clearcut logging.

Immediately after the PCT treatment, target thinning densities were 11–16% lower than expected, despite the fact that leave trees were flagged after inter-tree distance was carefully considered. Curtis (2008) suggested that the lower-than-expected post-treatment densities in these stand types could be caused by the patchy nature of these stands and the difficulty in maintaining accurate inter-tree spacing while selecting leave trees; the differences would be greater at narrow spacing than at wider spacings. This patchy nature must be considered when developing PCT prescriptions that are based on inter-tree distance.

Pre-treatment measurements were not taken within treatment plots due to the high cost of measuring many small trees; consequently, differences in stand structures immediately after the PCT are important to consider. As expected, the PCT treatments removed many small trees. As a result, the density of stems in the smallest dbh classes (5 and 10 cm) was as much as 99% less than in the control (Table 4), and the total residual volume was 60–81% less than in the control. With the removal of these small trees, mean tree size in PCT treatments was significantly larger for QMD, height, crown width, and taper compared to the control. The immediate increase in average tree size due to the removal of smaller trees is known as the "chainsaw effect" and is well documented (B.C. Ministry of Forests 1999).

The diameter distributions also showed that PCT stands had some trees in the 20-cm diameter class, but the control did not. During a subsequent field inspection, the largest trees (> 20 cm) across the treatment plots were cored, and were found to be 33 years old and to have originated at the time of clearcut harvesting. Therefore, size differences for these large trees were not because they were older advance regeneration but likely because they grew on favourable microsites such as beside small draws or on knolls, which would allow early snowmelt or greater room for crown expansion.

Despite the differences in mean tree size, there were no significant differences in any individual tree parameter (except that height of T1600 was smaller than that of T550) or per-hectare parameter among any of the PCT treatments for all trees or crop trees. The lack of significant treatment differences in total height of crop trees and that of the control provides confidence that any possible differences in site quality did not confound the treatment effects. The lack of significance in mean QMD, and crop tree height to live crown, crown width, and taper among any of the treatments, including the control, indicates that, at the time of PCT, the stands had likely just reached crown closure, before which competition mortality would be expected to begin.

Fifteen years after the PCT treatments, the rate of mortality remained low in the thinned treatments (2–6%), and differences among treatments were not significant. Although most of the mortality was in the smallest dbh class and presumably was density-dependent, there was also a loss of some large-dbh trees. *Abies* species are susceptible to rot entering through logging injuries (Curtis 2013). Hoyer and Swanzy (1986) found that mortality in thinned treatments at one experimental site was not from competition but from armillaria root rot (*Armillaria mellea* (Vahl ex Fr.) Kummer) or animal damage. The cause of mortality of the larger trees in this study is unknown.

In contrast to the low mortality in PCT treatments, mortality in the unthinned control was very high (73%), which resulted in a reduction in density from about 22 000 to 5900 sph. Eighty percent of the trees that died were western hemlock in diameter classes < 10 cm (Table 4). The high mortality rate is consistent with the density frontiers for even-aged western hemlock (de Montigny and Nigh 2007), where a sigmoid-like pattern of mortality consisted of three phases: a period of very high juvenile mortality lasting up to about 10-m top height, a second period of high overtopping mortality lasting up to about 20-m top height, followed by a third period of lower small crown mortality. In our study, at the time of PCT, the top height was 9–10 m, which corresponds to the point when the stands were approaching the period of high overtopping mortality. Fifteen years after PCT, the top height was 17 m, still within the period of high overtopping mortality; thus, continued density-dependent mortality resulting from self-thinning is expected.

"Thinning (or spacing) shock" is a term used to describe a reduction in height increment after thinning, which has been suggested to occur after pre-commercial thinning of western hemlock stands (Griffith 1959; Shortried and Stewart 1978; Curtis 2008). Thinning shock was examined in this study by comparing the periodic annual increments for QMD, HT, BA, and VOL among treatments in the first 2-year periods following PCT with the unthinned controls. No evidence of a thinning shock was found.

The effects of PCT on growth after 15 years were, in general, similar to those in other PCT trials where significant differences developed between thinned and unthinned stands (Table 5): as density decreased, diameter growth tended to increase (Hoyer and Swanzy 1986; Curtis 2008, 2013), while basal area and volume growth tended to decrease (Dilworth 1980; Hoyer and Swanzy 1986; Curtis 2008, 2013; Newton and Cole 2012). In our study, we found these same trends, but differences were not always significant between contiguous density treatments. For example, mean QMD growth of all trees and crop trees in treatments T550–T1200 were not different, which indicates that the trees were growing without crown competition, even after 15 years. As indicated, at the time of PCT, the stands had likely just reached canopy closure, but the thinning treatments reduced stand density to more open-grown conditions.

The most widely spaced PCT treatments (550 and 800 sph) had ingress after 15 years, which indicates that stand conditions were conducive to allowing natural regeneration. Hoyer and Swanzy (1986) also found high ingress in their most widely spaced treatments (21.3- and 17.6-foot spacing, equivalent to 237 and 347 sph, respectively). Curtis (2013) also found that wider spacings frequently had abundant ingrowth, and speculated that it was likely that the widest spacings (16.4- and 20.9-foot spacing, equivalent to 400 and 246 sph, respectively) would develop into two-storeyed stands, a characteristic that may be of importance from a wildlife and visual quality standpoint.

The most widely spaced treatments (T500 and T800) had lower total volume and growth than the T1200 treatment, which had the largest total volume and growth. Denser treatments T950 and T1600 did not have total volume growth as high as T1200, but the differences were not significant (Table 4). This was confirmed by a significant quadratic relationship (Table 6; Figure 4) between the 15-year volume (m^3/ha) of all trees and post-treatment density (sph) that indicated total volume increased with increasing density up to treatment T1200 and then decreased for treatment T1600. The widest PCT treatment (T550) had a target inter-tree spacing of 4.5 m, but the crown width after 15 years had reached just 4.9 m, which indicates that crown closure had likely just started. Although the volume increment of thinned stands was reduced in the first 15 years after PCT, the expectation is that, as crown closure is reached, the rate of volume growth will increase as stands achieve full site occupancy and are able to maximize the timber-producing capacity of the site.

Other studies have shown that denser spacing of western hemlock stands is more optimal for volume production than is wider spacing. Curtis (2013) found that, 20 years after PCT, western hemlock basal area increment in thinned plots increased as the number of leave trees increased, up to 430 trees per acre (1062 sph), but there was little difference among the 430–700 trees per acre treatments (1062–1730 sph), and there was no gain in production by retaining more than about 400 trees per acre (988 sph).

One reason why some landowners favour PCT of these high-density stands is the expectation that thinning will reduce the time for the stand to reach a minimum harvestable size (i.e., 25 cm), and thereby reduce the rotation age. We found that, 15 years after PCT at age 33 years, treatments T550–T1200 had reached a mean QMD of about 25 cm (24.1–26.5 cm), while T1600 (19.9 cm) and the unthinned control (13.3 cm) had not (Table 3). However, the average diameter of all trees does not adequately assess response to density management. For example, if we were to harvest each of the thinned stands that had reached the minimum mean QMD, the volume of stems > 25 cm would be 207, 228, 232, and 302 m^3/ha for treatments T550, T800, T950, and T1200, respectively (Table 4). The T1200 treatment would provide 21–31% more volume in diameter classes > 25 cm than would the more widely spaced stands. Given the relatively low volumes and the cost of treatment, an economic analysis would be advisable before choosing to harvest at this young age. An economic analysis of this study is under way to verify this.

Silviculture decisions affect not just tree and stand parameters, they also affect log quality characteristics, including log diameter, branch diameter and distribution, and stem taper and straightness (B.C. Ministry of Forests 1999). We found that volumes in thinned stands were concentrated in diameter classes > 25 cm, which resulted in larger log sizes than in the unthinned control (Table 4). Although the proportion of total stand volume from these larger-diameter classes increased with decreasing density from 61% in T1600 to 92% in the T550 treatments, the T1200 treatment had more volume in these larger-diameter classes than did the other thinned treatments.

Thinning to very wide spacings affected stem quality by reducing height to live crown and increasing taper and crown width. The resulting more heavily branched trees with larger taper may affect log quality. This should be considered when deciding the target density to thin. Hoyer and Swanzy (1986) found that western hemlock that were widely spaced to 16 feet (420 sph) or more were essentially free-growing. Middleton and Munro (2001) compared 90-year-old western hemlock stands, one with a density of 580 sph and two with densities of 930 sph, and found that (1) the 580-sph stand contained larger-diameter trees that had more taper, larger crown ratios, and more frequent and larger branches, (2) logs from the 580-sph stand had the highest mean knot frequencies and the largest mean and maximum knot sizes, and (3) greater taper in the more open-grown stand resulted in lower lumber recovery.

Mixed western hemlock and amabilis fir stands are often found at mid-elevations on steep slopes, where tree stem straightness and, subsequently, wood quality can be affected. Western hemlock is shallow rooted, and when growing on steep slopes is prone to windthrow or snow creep, which results in stems with a sweep (gradual bending in the stem of the tree) or lean (a deviation of the stem of the tree from the vertical) (Middleton and Munro 2001). To straighten the stem, compression wood forms on the side of the stem that is under compression from leaning. Middleton and Munro (2001) found that sweep and lean were recorded in 30% and 12%, respectively, of the western hemlock trees sampled in three 90-year-old stands. Compression wood has a higher proportion of lignin and a lower proportion of cellulose, and is usually undesirable because the mechanical and structural properties of the wood are altered. In examining the stem cores from the destructively sampled trees, we found that 30% of all trees sampled had compression wood.

5 MANAGEMENT IMPLICATIONS

Management objectives for naturally regenerated mixed western hemlock and amabilis fir stands that maximize timber volume, biomass, or carbon sequestration may be achieved without PCT. Over the 15-year period of our study, the unthinned, very high-density stands naturally self-thinned and about 75% of small-diameter stems succumbed to competition-induced mortality, with total density decreasing from 22 000 sph at plot establishment to 5900 sph after 15 years (Table 3). Continued competition-induced mortality can be expected to further reduce stand density.

It is important to note that the clumpy nature of these stands can result in actual densities that are lower than target densities. Pre-commercial thinning prescriptions should compensate for this clumpy nature by targeting an inter-tree spacing that is closer than would be needed to achieve similar residual densities in more homogeneous stands.

After 15 years, the resulting unthinned stands had significantly higher basal area (82.4 m^2/ha) and volume (553 m^3/ha) than the thinned stands (Table 3). Although much of this volume was in small-diameter classes, 25% of the total volume (140 m^3/ha) was in dbh classes > 25 cm, and this proportion will increase over time as density-dependent mortality removes smaller-diameter trees (Table 4). The stems of the unthinned relative to the thinned stands had significantly smaller taper and crown width and significantly higher height to live crown (Table 3), which will likely result in high-quality logs in the future.

Where management objectives are to reduce density to develop larger log sizes at an earlier rotation age, PCT can be an effective tool. We found that at the time of PCT treatments, total stand densities were 89–91% less than that of the unthinned control, with most of the volume removed (82–92%) coming from the diameter classes < 10 cm (Table 4). The immediate result was a significant increase in mean tree size (QMDs) in the PCT stands compared to the control stands, which indicates the absence of many small trees used in the calculation of mean tree size. However, individual tree or stand parameters of the crop trees (largest 250 sph) did not differ between PCT treatments or the unthinned control (Table 3), which indicates that: PCT treatments did not immediately affect the size or distribution of the larger trees, that the stands had not yet reached crown closure and the start of crown competition, and that potential site quality differences did not confound the treatment effects.

Pre-commercial thinning treatments led to a loss in productive growing capacity of the site, as indicated by lower volumes in more heavily thinned treatments (Figure 4). This loss in productive capacity is expected to continue until the thinned stands reach crown closure, at which time volume growth will increase to that of other closed canopy stands. Of the PCT treatments, we found no difference in tree size among treatment densities from T550 to T1200, but treatment T1200 had the largest volume, and this was significantly greater than that of treatments T550 and T800. We also found that for crop trees there was no difference in volume, basal area, and QMD among thinned treatments, which suggests that stands thinned to higher densities (950–1200 sph) offer the same gains in crop tree size as heavily thinned stands without as much loss in total tree volume. For the widest spacing (T550), the target spacing was 4.5 m; the crown width after 15 years had reached 4.9 m, which indicates that crown closure had likely begun.

Pre-commercial thinning to very wide spacings affected stem quality by reducing height to live crown and increasing taper and crown width. The resulting more heavily branched trees with larger taper may affect wood quality, and this should be considered when deciding the target density to space. Stands growing on steep slopes may also have reduced wood quality as a result of lean or sweep, which results in compression wood that is associated with undesirable mechanical and structural properties.

The results of this experiment provide information on the medium-term effects of PCT on growth and yield of mixed western hemlock and amabilis fir stands. It is important to continue to monitor this experiment over time to determine longer-term effects of PCT in meeting a variety of management objectives.

6 CONCLUSIONS

The western hemlock and amabilis fir stand in this study had regenerated naturally, and, at 18 years, was characteristically clumpy, with density ranging from 0 to 80 000 sph. Over the 15-year study period, competition-induced mortality reduced the density in the unthinned control by 73%, from 22 000 to 5900 sph, while mortality in the thinned stands remained low (2–6%). As expected, the mean QMD in the PCT stands was significantly larger (up to 100%) and total volume was significantly smaller (32–60%) than in the unthinned control. Of the PCT stands, the 1200-sph treatment had 30–40% more total volume and 23–32% more volume in diameter classes > 25 cm than the more widely spaced stands (550–800 sph). Trees growing in the more open-grown treatments (550 sph) had longer, wider crowns and greater taper than trees growing in denser treatments (1200 and 1600 sph). Pre-commercial thinning between 950 to 1200 sph appears to provide the best trade-off between piece size and volume. It is important to continue to monitor this experiment over time to determine longer-term effects of PCT on growth and yield of these mixed western hemlock and amabilis fir stands.

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