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Long-Term Effects of Precommercial Thinning on the Stem Dimensions, Form and Branch Characteristics of Red Spruce and Balsam Fir Crop Trees in Maine, USA

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The effects of precommercial thinning (PCT) on stem dimensions, form, volume, and branch attributes of red spruce [*Picea rubens* Sarg.] and balsam fir [*Abies balsamea* (L.) Mill.] crop trees were assessed 25 years after treatment in an even-aged northern conifer stand. Treatments were a uniform 2.4 × 2.4-m spacing and a control (no PCT). The PCT treatment significantly increased individual tree diameter at breast height (DBH), height growth, crown ratio, and crown width, while it reduced the tree height to DBH ratio. PCT also significantly increased stem taper and consequently, regional volume equations overpredicted observed stem volume by 2 to 15%, particularly for the spaced trees. PCT also increased the number and maximum size of branches on the lower bole. The sizes of knots on half of the sampled spruce crop trees in the spaced plots precluded them from being used as select structural lumber; there were no other effects on log grade. Our findings indicate that PCT can have a long-term influence on the structural attributes of individual trees, and that improved stem-volume prediction equations are needed in the Acadian region of North America.

Keywords growth and yield, Acadian Forest, *Abies balsamea*, *Picea rubens*, precommercial thinning
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1 Introduction

Precommercial thinning (PCT) or early spacing is frequently applied to improve species composition and accelerate growth of selected trees in even-aged stands in the Acadian Forest of U.S. New England and adjacent Canada. Densely stocked immature stands became common throughout this region as a result of widespread overstory removals during and after the 1970s and 1980s spruce budworm [*Choristoneura fumiferana* (Clemens)] infestations, which resulted in prolific regeneration of balsam fir [*Abies balsamea* (L.)] and associated northern conifers (Seymour 1995). Similar conditions also result from more recent heavy partial cutting. For example, in Maine, 45% of reported harvests in 2006 were shelterwood cuts (Maine Department of Conservation 2007) and 40% of the spruce-fir type is in the sapling stage of development (McWilliams et al. 2003). This suggests that PCT will continue to be an important silvicultural treatment in this region.

In these dense stands of saplings, PCT has been shown to be an effective means of reducing stand density, accelerating crop tree growth, enhancing future understory structural development, and maintaining desired species composition (Brissette et al. 1999, Pothier 2002, Pitt and Lanteigne 2008). In addition, PCT can increase windthrow resistance (Achim et al. 2005), wood uniformity (Shinya et al. 2002), nutrient availability (Thibodeau et al. 2000), and spruce budworm resistance (Lamontagne et al. 2002) of the treated stand. PCT can also have a positive long-term impact on revenues; the simulated internal rate of return at peak net present value for PCT in a typical spruce-fir stand in Maine has been estimated to be 6.9 to 14.1% (Saunders et al. 2007). Consequently, a significant number of acres are treated each year with PCT, particularly in the spruce-fir forest cover type.

In North America, PCT treatments vary significantly by region, species, and site quality. In the Acadian region, optimal thinning regimes have residual density targets near 2500 stems ha^{-1}, and are followed by commercial thinning when dominant tree height is slightly above 12 m (Saunders et al. 2007). Depending on site quality, PCT may be applied between 5 and 20 years after clearcutting or overstory removal and pre-treatment densities can often exceed 20 000 stems ha^{-1} (Brissette et al. 1999). Based on simulations with a regional growth and yield model, Saunders et al. (2007) suggested that wider PCT spacings (i.e. 2.4 m or about 1700 stems ha^{-1}) are favorable in very productive areas (site index > 20 m at breast-height age 50) where balsam fir composition is high (> 80% of initial basal area). Numerous PCT trials have been established in the Acadian region, but very few have been maintained long enough to verify long-term model predictions. For example, the Green River thinning trials in northwestern New Brunswick were installed between 1959 to 1961 and recently remeasured (Pitt and Lanteigne 2008). However, the site index of the Green River stand is quite high for the region (> 20 m at breast height age 50), it was heavily dominated by balsam fir (> 90% of initial basal area), and volunteer growth was removed for 11 to 13 years after PCT treatment. Therefore, their findings may not be broadly representative of stand response to PCT in the Acadian region and further information on the long-term response of individual trees to PCT is needed.

PCT also has the potential to negatively impact stem form and branchiness. Weiskittel et al. (2006) found that PCT increased the mean maximum branch diameter for a given tree size in precommercially thinned Douglas-fir [*Pseudotsuga menziesii* var. *menziesii* (Mirb.) Franco] plantations relative to unthinned plantations, though relative stem form was not affected. In Scots pine [*Pinus sylvestris* (L.)], Ulvcrona et al. (2007) found that timing and intensity of PCT significantly influenced both branch size and stem form. To our knowledge, a similar assessment of the long-term influence of PCT on balsam fir and red spruce [*Picea rubens* Sarg.] branch size and stem form in the Acadian Forest region has yet to be performed. Knowledge on the extent to which PCT influences stem form and branchiness is important to consider in deciding whether or not to implement PCT, and in designing effective PCT treatments.

Potential changes in stem form as a result of PCT are important with regard to volume and product recovery prediction. Regional volume equations are often applied to trees regardless of their silvicultural history. In the Acadian Forest region, Honer's (1967) volume equations are the most widely used. Though these equations were parameterized with data from eastern and central Canada, a recent report from a long-term PCT study in eastern Canada suggested that they underestimated balsam fir stem volume by almost 12%, particularly in thinned stands (Pitt and Lanteigne 2008). The performance of Honer's (1967) volume equation in Maine and the influence of silvicultural treatments such as PCT on its accuracy have yet to be tested. Additional volume equations exist in the region (Reams and Brann 1981, Lemin and Briggs 1993), but have also not been fully verified on an independent dataset.

The goal of this study was to use a long-term replicated experiment to evaluate the influence of PCT on key structural attributes of balsam fir and red spruce crop trees 25 years after treatment. Specific objectives were to: 1) quantify long-term changes in key tree-level attributes (e.g. diameter, height, and crown ratio); 2) test for differences in stem form between treatments and species; 3) evaluate the efficacy of several regional volume equations; and 4) determine differences in branchiness between treatments and their potential effect on wood quality.

2 Methods

2.1 Study Area

The 1540-ha Penobscot Experimental Forest (PEF) is located in the towns of Bradley and Eddington in Penobscot County, Maine at 44º52'N, 68º38'W. The PEF is included in the Acadian Forest (Halliday 1937, Braun 1950), which is a transition zone between boreal forests to the north and broadleaf forests to the south. Conifers with an admixture of hardwoods dominate the study area and include: balsam fir, red spruce, white spruce [*Picea glauca* (Moench) Voss.], white pine [*Pinus strobus* L.], eastern hemlock [*Tsuga canadensis* (L.) Carr.], and northern white-cedar [*Thuja occidentalis* L.]. Hardwoods commonly found in the area include: red maple [*Acer rubrum* L.], paper birch [*Betula papyrifera* Marsh.], gray birch [*Betula populifolia* Marsh.], yellow birch [*Betula alleghaniensis* Britt.], quaking aspen [*Populus tremuloides* Michx.], and bigtooth aspen [*Populus grandidentata* Michx]. Soil types on the PEF range from well-drained loams and sandy loams to poorly drained loams and silt loams with parent material primarily consisting of glacial till. The soil series on the study area is a Monarda-Burnham stony fine sandy loam on a 0 to 8% slope, developed in a deep till parent material. Several long-term silvicultural experiments are located on the PEF (Sendak et al. 2003).

2.2 Experimental Design

A PCT study (called Study 58) was established by the U.S. Forest Service, Northern Research Station on the PEF in 1976. The purpose of this study was to investigate the effects of different PCT regimes and fertilizer applications on species composition and the growth and yield of crop trees selected at the time of treatment. The PCT study was conducted in an even-aged stand regenerated with a two-stage shelterwood method between July 1957 and October 1967. In 1957, 46% of the overstory was removed in an establishment harvest with the remaining merchantable overstory removed in 1967. In 1976, all residual trees >12.7 cm or estimated to be >20 years old were removed from the stand. Prior to PCT, densities of the experimental units ranged from approximately 27 500 to 79 000 trees ha^{-1} with an overall mean of 42 736 trees ha^{-1} (Brissette et al. 1999). Species composition was predominantly balsam fir (47%) and red spruce (35%) with some white spruce (16%) and other species (2%).

The experimental design was a completely random replicated arrangement. The PCT treatment was applied between April and August of 1976 and included: 1) unspaced (i.e. no PCT) and 2) wide uniform spacing of selected crop trees (i.e. 2.4 × 2.4 m or 8 × 8 ft). The treatment was applied to 24 × 24-m experimental units and 19.5 × 19.5-m measurement plots were established within each experimental unit (Brissette et al. 1999). Crop trees were selected from the largest and fastest growing stems > 1.37 m tall, favoring (in order of priority) spruce species, balsam fir, eastern white pine, quality hardwoods, and eastern hemlock. A minimum of 0.6 m separated the crowns of adjacent crop trees. All woody and competing vegetation within 1.2 m of each crop tree was mechanically removed both at the time of the initial treatment and three years later. At the start of the study, the average number of crop trees per plot was 64. Due to tree mortality and stem breakage, plots currently have 48 crop trees on average, with a range of 38 to 62. A total of 9 experimental units were utilized for the present study; samples were taken from four of the 2.4 × 2.4-m spaced plots and 5 of the unspaced plots. Two of the unspaced plots selected were initially fertilized, but fertilization had been previously found to have no significant effects on crop tree growth (Brissette et al. 1999) and preliminary analysis confirmed that finding for the most recent remeasurement.

2.3 Data Collection

The U.S. Forest Service remeasured crop tree diameter at breast height (DBH, 1.37 m), total tree height (HT), crown length (CL), crown width (CW), and stump diameter (SD) on the study plots 8 times since the start of the PCT experiment with the last inventory in 2001. Data from all trees in the spaced and unspaced plots were used to quantify and compare DBH, crown ratio (CR = CL / HT), height growth ($HT_{2001} - HT_{1976}$), and ratio of height to diameter (H / D = HT / DBH) (Table 1).

Also in the summer of 2001, 80 crop trees were selected for additional sampling (Table 2). The sample consisted of 37 trees (21 balsam fir and 16 red spruce) in the unspaced plots and 43 trees (20 balsam fir and 23 red spruce) in the spaced plots. The subsample of crop trees were randomly selected, but had to meet several predetermined criteria, namely be: 1) 12.7 cm DBH or larger; 2) growing in the upper level of the canopy, (i.e. dominant (D) or codominant (CD)); and 3) free of any obvious defects. However, to obtain the intended sample size of 80 crop trees, it was necessary to choose some intermediate (I) trees and/or smaller diameter trees. The overall sample consisted of 56 CD, 2 D, and 22 I trees. Most of the intermediate trees were red spruce, due to the fact that there were more balsam fir than red spruce trees in upper canopy positions. The distribution of intermediate trees was equally divided between the spaced and unspaced plots so there is no confounding impact of tree canopy class in this analysis.

Each crop tree was climbed using tree climbing ladders and/or climbing gear to make stem form measurements; the heights up the tree bole were measured with a logger's tape. Measurements on each tree included: DBH; diameter 1.0 m below breast height (BH); and diameter at 1.0-m intervals above BH to the crown base. All of these were measured to 0.1 cm with a diameter tape. If a 1.0-m interval fell on a branch whorl, then diameter was measured 0.1 m directly above or below, whichever had a clearer bole area. Bark thickness for each of the bole sections was estimated using a model developed from red spruce and balsam fir trees as described in the next section. Height to the lowest live branch and height to the crown base (defined as at least 3 live branches extending halfway around the bole) were measured to

Table 1. Mean ± standard deviation for the crop trees in 1976 and 2001 by species and treatment.

Attribute	Unspaced balsam fir	Spaced balsam fir	Unspaced red spruce	Spaced red spruce
N_{1976}	242	130	178	230
N_{2001}	174	100	84	134
DBH_{1976} (cm)	2.30 ± 1.05	1.96 ± 0.93	1.62 ± 0.94	1.37 ± 0.93
DBH_{2001} (cm)	8.39 ± 3.13	15.84 ± 2.95	7.83 ± 3.54	14.27 ± 2.99
HT_{1976} (m)	2.45 ± 0.62	2.27 ± 0.58	2.14 ± 0.49	2.06 ± 0.53
HT_{2001} (m)	9.76 ± 2.21	13.13 ± 1.272	8.56 ± 2.51	10.75 ± 1.31
HCB_{1976} (m)	0.40 ± 0.25	0.47 ± 0.25	0.25 ± 0.17	0.33 ± 0.17
HCB_{2001} (m)	5.53 ±1.14	4.34 ± 0.94	4.62 ± 1.18	4.29 ± 0.97
CW_{1976} (m)	1.09 ± 0.31	1.14 ± 0.30	1.00 ± 0.29	1.08 ± 0.31
CW_{2001} (m) [a)]	0.84 ± 0.39	1.53 ± 0.32	0.93 ± 0.38	1.95 ± 0.43

[a)] A subsample of approximately 25% of the crop trees was measured for CW in 2001.

Table 2. Attributes of the subsample trees by species and treatment.

Attribute	Mean	Standard deviation	Minimum	Maximum
Spaced balsam fir (n = 20)				
DBH (cm)	17.23	1.82	13.9	21.1
HT (m)	13.32	0.77	11.34	14.78
HCB (m)	3.99	0.90	2.22	5.48
Unspaced balsam fir (n = 21)				
DBH (cm)	12.89	2.23	9.2	18.2
HT (m)	12.73	1.06	10.73	14.8
HCB (m)	6.31	1.15	3.17	7.67
Spaced red spruce (n = 23)				
DBH (cm)	15.02	2.09	11.4	20.9
HT (m)	10.92	1.12	8.99	13.07
HCB (m)	3.77	0.94	2.33	5.29
Unspaced red spruce (n = 16)				
DBH (cm)	12.27	2.84	7.5	18.9
HT (m)	11.27	1.59	8.81	15.09
HCB (m)	5.08	1.08	2.57	7.24

the nearest 0.01 m. Crown class was recorded and total height of each tree was measured to 0.1 m using a Vertex III hypsometer, made by Haglöf. The diameters of each branch (live and dead) between 1.0 and 2.0 meters above BH (i.e. between 2.37 and 3.37 m) were measured to the nearest 1.0 mm using a caliper. Branch diameters were measured just far enough from the bole of the tree to avoid the branch collar.

2.4 Data Analysis

2.4.1 Stem Dimensions

A linear mixed-model analysis of covariance was used to assess the influence of PCT on individual stem dimensions and growth. Although there were no statistically significant initial mean differences between plots, the measurement in 1976 was used as the primary covariate to account for differences in initial conditions between individual trees. The influences of species and PCT were assessed by indicator variables. A random effect for each tree within a plot was estimated to account for factors other than initial size, species, and the PCT treatment that might have influenced growth.

2.4.2 Stem form

Since bark thickness was not measured in the present study, regression equations between diameter inside bark (dib) and diameter outside bark (dob) were developed with the Maguire et al. (1998) red spruce (n = 65) and Gilmore's et al. (1996) balsam fir (n = 39) datasets. All data for their studies were collected from stands on the PEF and the University of Maine Dwight B. Demeritt Forest in Old Town, Maine (44°55´N, 68°40´W); both are in close proximity to the area used in the present study. The equations were of the following form:

$$\text{dib} = \beta_0 \, \text{dob}^{\beta_1} \quad (1)$$

For red spruce, β_0 and β_1 were 0.8761 (SE 0.0072) and 1.0208 (SE 0.0019), respectively. For balsam fir, β_0 was 0.9098 (SE 0.0058) and β_1 was 1.0126 (SE 0.0022). To test the influence of species and PCT treatment on relative stem form, a modified Kozak (1988) variable exponent taper equation was fit to the data. This model form was chosen because it is flexible and able to accommodate additional covariates for testing parameter significance (e.g. Muhairwe et al. 1994). The initial model was of the following form:

$$\text{dib} = \beta_0 \text{DBH}^{\beta_1} \cdot X^{\left(\beta_2 Z^4 + \beta_3 \exp(\frac{\text{DBH}}{\text{HT}}) + \beta_4 X^{0.1} + \beta_5 \text{CR} + \beta_6 \text{SP} + \beta_7 \text{PCT} + \beta_8 (Z \cdot \text{PCT})\right)} \quad (2)$$

where Z is relative height in the stem, X is $(1-Z^{(1/3)})/(1-p^{(1/3)})$, p is 1.37/HT, CR is crown ratio, SP is an indicator for species (1 for balsam fir, 0 otherwise), PCT is an indicator variable for spacing (1 if PCT, 0 otherwise), and β_i's are parameters to be estimated from the data. Stem taper has a nested data structure and consequently, violates the assumption of independence. To properly test covariates, it was necessary to fit Eq. (2) as a multi-level mixed effects model with a first-order continuous autorgressive regressive (CAR1) error term (e.g. Garber and Maguire 2003). The random effects were estimated on β_4 at the plot and tree levels because this parameter showed the most significant variation between nesting levels. In addition, the equation was weighted by a power variance function of relative height on the stem to correct for heteroscedasticity. Since the trees were climbed and relatively few upper stem diameter measurements were made because of safety concerns, the taper data were supplemented with the Maguire et al. (1998) red spruce and Gilmore et al. (1996) balsam fir datasets to ensure a more robust equation. Variables were deemed significant at $\alpha = 0.05$.

2.4.3 Tree Volume

Individual tree volume inside bark was estimated by summing the volumes of each section defined by the 1-m intervals using Smalian's formula. The Honer (1967) volume functions were also used to estimate individual tree volume:

$$\text{VIB} = \text{DBH}^2 / (\beta_0 + \beta_1 \cdot (1/\text{HT}) \quad (3)$$

where VIB is volume inside bark (m^3). In addition, the performance of two other regional equations, Lemin and Briggs (1993) and Reams and Brann (1981), was also assessed. These equations are linear functions of tree diameter squared times total tree height. The relationship between predicted and actual tree volume was compared using a simultaneous F-test. In addition, mean bias (observed minus predicted), mean percent bias, and mean absolute error were calculated by species and PCT treatment.

2.4.4 Branch Attributes

Although the numbers and sizes of branches were only recorded between 1.0 and 2.0 meters above BH, previous research has indicated that branch attributes at this height correlate well with branch attributes observed for the entire first log (e.g. Briggs et al. 2007). The number of branches and maximum branch size were compared between species and treatment using a mixed-effect covariance analysis with DBH as the primary covariate.

3 Results

3.1 Tree and Crown Dimensions

After accounting for initial DBH, tree DBH did not differ by species in 2001, but was 7.5 cm greater ($p < 0.0001$), on average, in the spaced plots than in the unspaced plots, which translates into 136.1% increase in diameter growth rate over 25 years. The PCT influence on height growth was dependent upon species ($p < 0.0001$). PCT increased red spruce and balsam fir 25-year height growth relative to unspaced trees by 37.8 and 51.5%, respectively, for a given initial tree height. Consequently, the H/D value of crop trees in the spaced plots was also dependent on species ($p = 0.0181$). The H/D value for spaced trees was 40.0 and 31.1% lower for red spruce and balsam fir, respectively, when compared to an unspaced tree at a given initial tree size. For a given initial tree size, PCT also significantly increased ($p < 0.0001$) the mean crown ratio by 43.2 and 58.1% for red spruce and balsam fir crop trees, respectively. The significant increase in crown ratio was a result of both greater height growth and reduced crown recession as height to crown base was 8.3 and 37.1% lower in the red spruce and balsam fir crop trees, respectively. Finally,

Table 3. Parameter estimates and standard errors for the stem taper equation.

Parameter	Estimate	Standard error
β_0	0.9555	0.0352
β_1	0.9931	0.0111
β_2	0.4957	0.0125
β_3	0.0130	0.0038
β_4	0.1903	0.0283
β_5	0.2583	0.0375
β_6	–0.0492	0.0184
β_7	–0.0891	0.0391
β_8	0.2663	0.1013

PCT significantly increased ($p<0.0001$) the mean crown width by 95.7 and 75.1% for red spruce and balsam fir crop trees, respectively.

3.2 Stem Form

After accounting for tree and crown size, species ($p=0.0078$) and PCT ($p=0.0070$) both had a significant influence on relative stem form (Table 3). However, the influence of PCT was dependent on relative height on the stem ($p=0.0087$). There was no significant interaction between species and treatment. Although statistically different, there was relatively little difference in stem form between balsam fir and red spruce at a given tree and crown size (Fig. 1); PCT significantly increased taper in both species, particularly in the upper-portion of the stem.

3.3 Tree Volume

At the individual tree level, spruce trees had 4.0% more volume than balsam fir trees for a given DBH and crown ratio. Mean percent bias of the Honer (1967) volume equation for red spruce and balsam fir was –11.1% ± 7.6 and –4.4% ± 7.7, respectively, though most points fell within the 95% confidence interval provided by Honer for his predictions. In general, predicted volumes in the unspaced plots were less biased than those in the PCT plots (Table 4; Fig. 2). The Honer

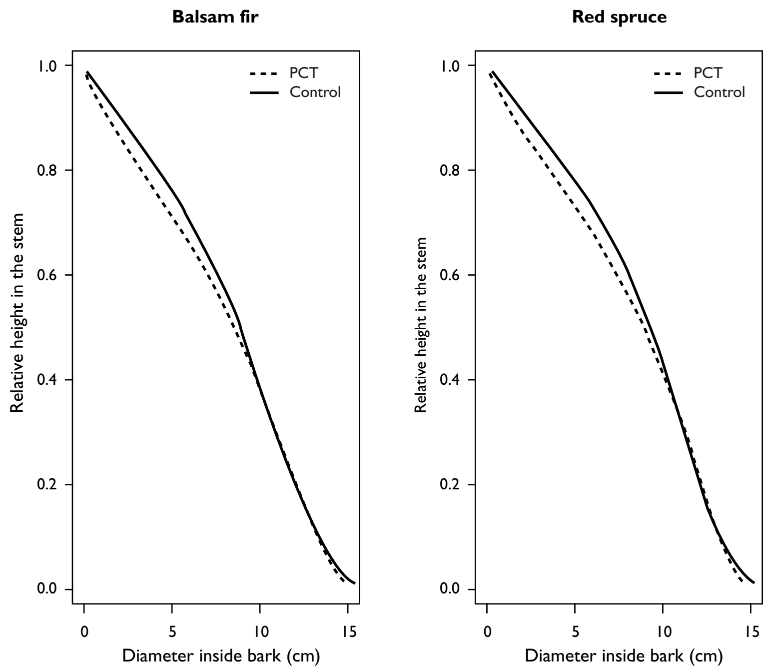

Fig. 1. Profile of diameter inside bark for the PCT and control mean tree in this study (DBH=14 cm, HT=12 m, HCB = 4 m) by species.

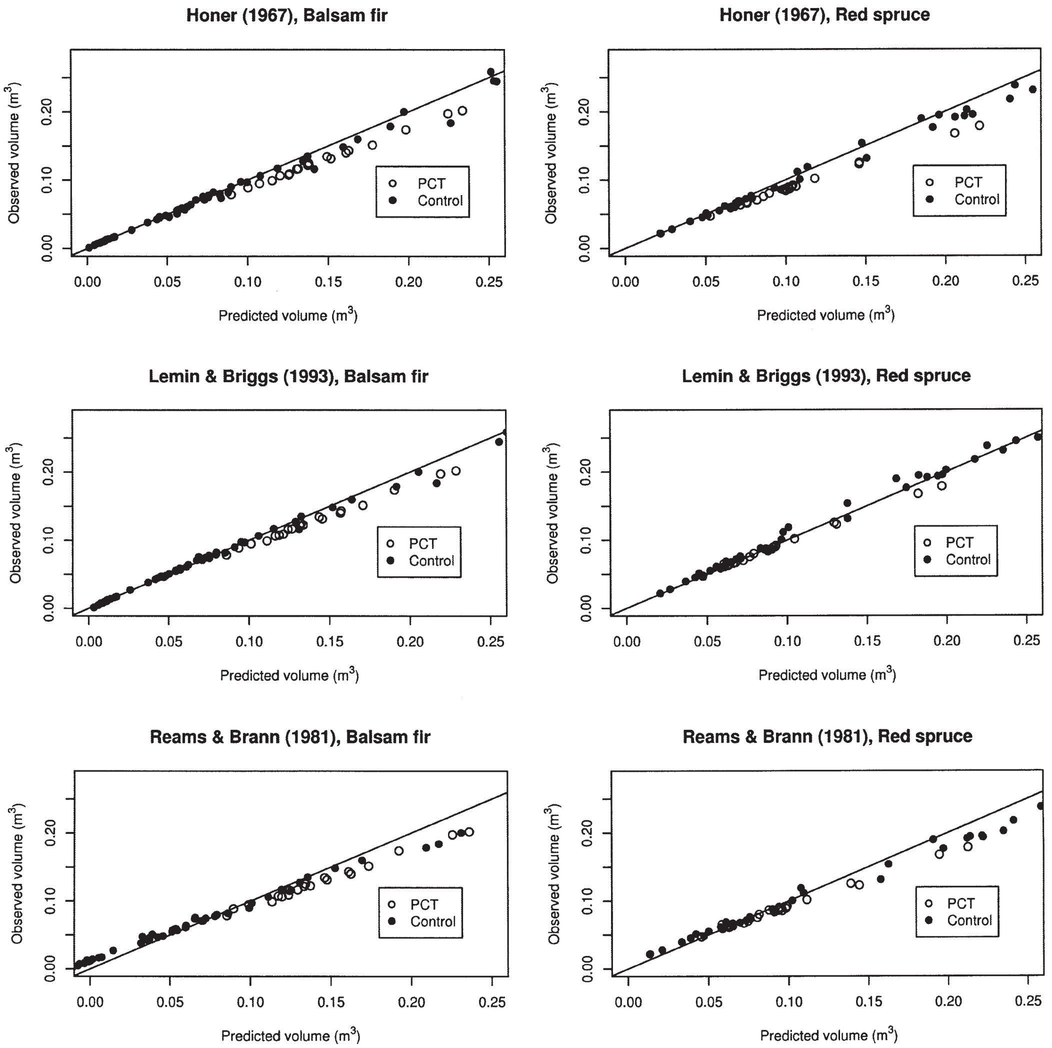

Fig. 2. Relationship between observed and predicted volume (m^3) for PCT and control trees by species. Volume was predicted using the Honer (1967), Lemin and Briggs (1993), and Reams and Brann (1981) equations.

(1967) equation was equally biased across the range of stem size classes in this study. Likewise mean percent bias of the Lemin and Briggs (1993) equation ranged from –1.8 to –9.5%; the Reams and Brann (1981) equation had mean percent bias between –2.8 and –9.0%.

3.4 Branch characteristics

After accounting for initial tree size, PCT increased maximum branch size ($p=0.0021$), but the increase was dependent on species ($p=0.0086$; Fig. 3). For a given tree size, maximum branch size was increased by 19.7% for spruce, but PCT had no effect on balsam fir. PCT also increased the number of branches between 1.0 and 2.0 m above BH ($p=0.0077$). The number of branches did not differ between species and PCT crop trees had 10.9% more branches than unspaced trees for a given crown size.

Based on the frequency and size of the branches,

Table 4. Mean percent bias ± standard deviation ((observed – predicted) / predicted) of Honer (1967), Lemin and Briggs (1993), and Reams and Brann (1981) volume equations by species and treatment.

Species	Spaced	Unspaced
	Honer (1967)	
Balsam fir	–13.95 ± 1.83	–2.66 ± 7.07
Red spruce	–14.97 ± 3.59	–10.25 ± 7.78
	Lemin and Briggs (1993)	
Balsam fir	–9.51 ± 2.20	–3.49 ± 12.61
Red spruce	–1.77 ± 3.26	–2.91 ± 8.73
	Reams and Brann (1981)	
Balsam fir	–8.99 ± 2.75	–2.83 ± 8.36
Red spruce	–8.96 ± 3.70	–4.81 ± 5.97

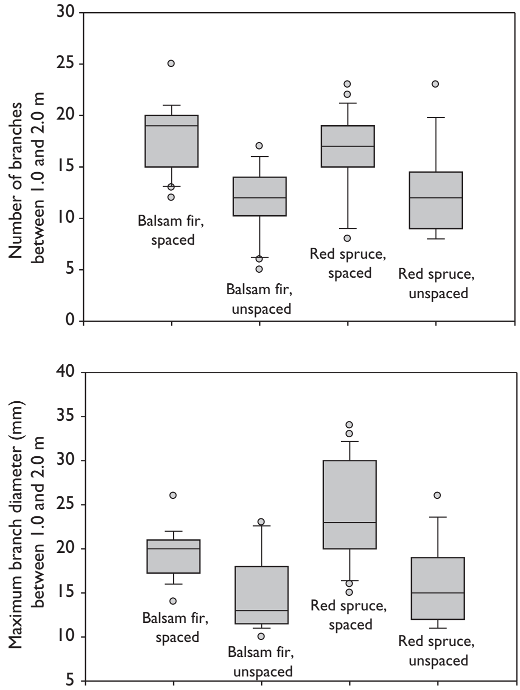

Fig. 3. Boxplots of the number of branches and maximum branch diameter (mm) between 1.0 and 2.0 m by species and treatment.

all of the crop trees in both PCT and unspaced plots in this study met the log grades of all categories, except for select structural grade. Less than 10% of the sampled balsam fir crop trees did not meet the select structural log grade and this result was not influenced by the treatment. For red spruce, PCT did have an influence on log grade; 52% of the sampled red spruce crop trees in the PCT treatment would not achieve the select structural log grade.

4 Discussion

PCT is an important silvicultural treatment in the Acadian Forest, but information on the long-term response to PCT in this region is relatively limited (e.g. Brissette et al. 1999, Pothier 2002). For example, PCT did not significantly increase diameter growth over the entire 20-year observation period in Pothier (2002), but the stand was severely defoliated by a spruce budworm outbreak during a portion of the study. In Pitt and Lanteigne (2008), individual growth rate observations were not reported.

The present study indicates that PCT can have a long-term influence (> 25 years) on individual crop tree dimensions and crown structure, particularly the ratio of tree height to diameter, crown ratio, stem taper, and the number and size of individual branches. In addition, the widely used Honer (1967) volume equation was found to be significantly biased, particularly for spaced trees. Investments in PCT are not trivial and accurate assessment of its benefits are critical. Thus, these results have important implications for designing effective PCT strategies in the spruce-fir forest type of Maine and for estimating stand volume.

In the present study, both stem taper and crown size increased due to PCT, while the ratio of height to diameter decreased. Consistent with our findings, Barbour et al. (1992) found red spruce trees in PCT treatments had, on average, longer crowns and greater stem taper. Other studies have also found that trees subjected to heavy thinnings had greater stem taper than those in unthinned or lightly thinned stands (Pape 1999, Karlsson 2000). Weiskittel et al. (2006) found that commercial thinning had a significant influence on Douglas-fir relative stem profile, but PCT did not have a significant influence. However, the PCT had only occurred six years prior to measurement in Weiskittel et al. (2006). Thinning influenced stem taper on the spaced crop trees because of greater allocation of growth lower on the tree stem due to the longer crowns. In addition, increased wind velocity in less dense (spaced) stands can also result in increased stem taper (Jacobs 1954, Larson 1965).

Vigorously growing trees with longer live crowns, such as the spaced crop trees in the present study, have a greater proportion of breast height diameter to height growth and therefore have a more pronounced diameter decrease up the tree bole relative to trees in lower crown classes or in denser stands (Larson 1963). The H/D ratio of a tree is also an expression of stability under wind and snow pressures with higher values indicating less stability, and lower values indicating increased stability. The spaced trees in this study had a lower H/D ratio, indicating they had greater stability than trees in the unspaced plots. H/D ratios above 0.8 have been identified as an indication of potential instability (e.g. Wonn and O'Hara 2001). Stand mean H/D ratios for both the unspaced spruce and fir crop trees in the present study were well above 0.8, while the spaced plots are just below this threshold value. This indicates that the both the spaced and unspaced plots may be susceptible to wind and snow damage, though additional thinning may increase stability.

Several studies have found no significant height differences between spaced and unspaced plots (Kerr 1987, Piene and Anderson 1987). However, other studies have found that crop trees in spaced plots were taller than unthinned trees (Lavigne and Donnelly 1989, Barbour et al. 1992). Brissette et al. (1999) found that the crop trees in the spaced plots used in the present study were 32% taller than crop trees in the unthinned plots 18 years after treatment. Similarly, it was found that the PCT treatment significantly increased the 25-year height growth of both balsam fir and red spruce, though the fir was much more responsive. This resulted in trees that were 27.9 to 39.2% taller in the PCT treatment when compared to the unspaced treatment. However, it should be noted that the PCT treatment favored balsam fir over red spruce unless the spruce was at least one-half the height of the fir, so there were relatively few dominant and co-dominant spruce crop trees. The result illustrates the sensitivity of balsam fir growth to spacing, which might be attributed to its ability to exploit available belowground resources. Tian (2002) found that most of the belowground variables examined in his study (e.g. total biomass, rooting length, and root radial growth) increased significantly in the spaced balsam fir plots used in the present analysis, while red spruce did not show any belowground treatment effects.

The Honer (1967) volume equation is widely used in the Acadian region. Similar to the present study, Pitt and Lanteigne (2008) recently found the Honer's (1967) equation to be significantly biased, particularly in the PCT stands. In their study, the Honer (1967) volume equation underestimated balsam fir stem volume by an average of 11.7%. A similar level of bias was found in the present study in the opposite direction; the Honer (1967) equation tended to overestimate individual tree volume, particularly for spaced trees. Though most of the predicted volumes fell within Honer's (1967) confidence intervals, the level of bias was as much as 0.05 m^3 for some of our largest trees. The Honer (1967) equation was developed with data from unthinned, natural stands in Ontario, so its application to thinned plots in Maine is questionable given the different stand histories and geographic locations. The other regional equations examined in this study performed slightly better than the Honer (1967) equation, but also showed a significant bias of 2 to 10%. The better performance of these equations was expected because they were developed with data from small-diameter trees from Maine similar to the size of the trees in the present study. Moreover, the Lemin and Briggs (1993) dataset included both spaced and unspaced trees, though they found no difference between species or treatments after accounting for breast height diameter and tree height. The relatively poor predictive performance of all the stem volume equations assessed in the present study was likely driven by their reliance on tree diameter and height and not crown size, which has been shown to improve volume predictions in other species (Walters and Hann 1986, Leites and Robinson 2004). Thus, development of a new stem taper and volume equation for both species using data from Maine, and accounting for differences in crown size, seems to be warranted by the present study.

PCT was found to increase both the number and size of branches in the 1.0 m above BH on individual trees in this study. This is because PCT increases both the amount of space available for crown expansion and the amount of light reaching the lower crown, resulting in larger branches and longer branch retention (Weiskittel et al. 2007). Maguire (1983) also found that PCT increased the number of buds formed. Since all of the crop trees had live crowns well below breast height at the time of PCT in the present study, the observed response is likely attributed to both differential branch survival and increased branch bud initiation.

The size and frequency of branches on a tree have a marked effect on wood quality and are key factors in determining log and lumber grades. In loblolly pine [*Pinus taeda* L.], Baldwin et al. (2000) found a significant increase in the number and size of branches with heavier thinnings. In contrast, several studies have found the number of branches to not be influenced by spacing (DeBell et al. 1994, Mäkinen and Hein 2006). DeBell et al. (1994) found an increase in branch size as spacing increased over a range of PCT intensities in young western hemlock [*Tsuga heterophylla* (Raf.) Sarg.] stands. Even at the widest spacing (6.6 m) in that study, the largest hemlock branch diameter did not exceed 5.1 cm (DeBell et al. 1994). This did not affect the log grade to be achieved with the size logs produced at the particular rotation age. In the present study, the largest branch diameter did not exceed 3.4 cm, with an average branch size in the spaced plots of 1.5 cm. Although the potential impacts of these knot sizes on log grade are minimal, over half of the spaced red spruce crop trees had knot sizes that precluded them from being in the select structural grade. However, the gains in log volume due to PCT likely outweigh the slight loss in log value for this species.

5 Conclusions

We found significant differences between the structural attributes of crop trees in plots treated with PCT and controls; DBH, crown ratio, and stem taper were greater and the H/D value was lower. Also, a significant difference between Honer's (1967) volume estimation and actual measured volumes was observed in this study, particularly for PCT crop trees. The mean percent bias was also high for two other regional volume equations (2 to 10%) and suggests that a new volume equation for the spruce-fir forest type is needed in the region. Additionally, the size of the knots on half of the sampled red spruce crop trees in PCT plots of this study precluded them from being used as select structural lumber. Implications of this study will enable managers to make better decisions about the appropriateness of PCT with regard to crop tree growth and stem quality, particularly branchiness and stem taper.

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