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Stand dynamics and tree quality response to precommercial thinning in a northern hardwood forest of the Acadian forest region: 23 years of intermediate results

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ABSTRACT

In the late 1980s, large forest companies began precommercial thinning (PCT) operations in young northern hardwood cutovers in New Brunswick, Canada. To provide supporting growth and yield information, an industrial experiment was established at residual stand densities of 1300, 1600, 1900, and 2200 stems ha^{-1}. Stand responses were examined for measurements recorded at 0 (1987), 5 (1992), 10 (1997), 16 (2003), and 23 (2010) years after establishment. Average diameter at breast height, quadratic mean diameter, stand basal area, and stand total volume growth increased as stem density decreased from PCT. There were significant linear differences for many of these variables between treatments and time periods (year). No significant differences were detected in tree height between treatments. In 2010, the four PCT thinning treatments did not exhibit any differences in potential sawlogs at 2.4 m (8 ft) and 3.6 m (12 ft) lengths. Significant differences were observed for 4.9 m (16 ft) sawlogs that were produced at the least dense spacing (1300 stems ha^{-1}). Results from this study and recommendations from the European literature suggest that value-added timber products may be produced from more intense PCT treatments than are currently being practiced on sites dominated by yellow birch (*Betula alleghaniensis* Britt.).

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Introduction

Precommercial thinning (PCT, or spacing) in young northern hardwood stands originating from clearcuts is a common silvicultural prescription in the Maritime Provinces (Maritimes) of Canada (Lees 1978, 1987, 1995; Higgs 1981; Lifford 2001; Nicholson et al. 2010). The silvicultural prescription is achieved by manually removing trees and shrubs around the crop trees using motorized brush saws to produce a desired stand density and spacing between residual crop trees. Limited published knowledge exists on the effects of PCT to different residual densities on crown dynamics of young northern hardwood stands in Acadian forests of the Maritimes (Drinkwater 1960; Lees 1978, 1995; Lifford 2001). In Nova Scotia, Drinkwater (1960) reported on the effects of crown release treatments for 20-year-old sugar maple (*Acer saccharum* Marsh.). Lees (1995) and Lifford (2001) reported on the stand dynamics at 15 and 20 years after treatment, respectively, for a PCT study in a 10-year-old northern hardwood stand at Flat Top Mountain, west-central New Brunswick (NB). In addition, Lifford (2001) produced the first growth and yield curves for PCT thinned northern hardwood stands for forest management in NB from this study. Nicholson et al. (2010) provided summary information for stand dynamics and tree stem quality from a series of PCT experiments and studies across Nova Scotia.

Until recently, much of the research for northern hardwoods in the Maritimes has been conducted in Nova Scotia and Prince Edward Island. Although young northern hardwood stands between the ages of 8–15 years in Acadian forests are thinned (spaced) to 1000–3000 stems ha^{-1} following regional guidelines (PEIDEF 1987; NSDNR 1992, 1993; NBDNR 2004; McGrath 2007; McGrath et al. 2015), it is important to test these prescriptions experimentally from existing long-term studies before recommendations are provided for commercial high-value timber production. Heitzman and Nyland (1991), Sendak and Leak (2008), and Weiskittel et al. (2011) noted the scarcity of conclusive information from long-term studies for assessing (i) the impact of release cuttings on stand development and (ii) generation of potential products from northern hardwood forests of eastern North America. Given the need to inform the forest industry of the merits of different stand intervention methods on stand structure and development and potential production of value-added goods, this manuscript reports on intermediate-term results (1987–2010) acquired from an operational PCT study established in a northern hardwood forest in west-central NB. The industrial objectives of the PCT study were to: (1) increase stand growth production and decrease stand rotation (age of stand to operable harvest), and (2) increase the content of yellow birch (*Betula alleghaniensis* Britt.) and white birch (*B. papyrifera* Marsh.). The experiment was to

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provide research support what was then a new PCT silviculture program (Higgs 1981; Valley Forest Products Ltd. 1990). It was predicted that a desired uniform spacing of approximately 2500 stems ha^{-1} in 10-year-old clearcuts of northern hardwoods would result in a rotation age of 30–35 years (Higgs 1981; Valley Forest Products Ltd. 1990). At that time, these managed stands would have an anticipated volume of approximately 200 m^3 ha^{-1}, with an average stem diameter of 10–14 cm. Species preferences, in decreasing order, for these PCT prescriptions were: birch (yellow or white), white ash (*Fraxinus americana* L.), sugar maple, red maple (*Acer rubrum* L.), and aspen (trembling aspen (*Populus tremuloides* Michx.) and largetooth aspen (*P. grandidentata* Michx.)). American beech (*Fagus grandifolia* Ehrh.) was discriminated against in both harvesting and stand-tending operations because of reduced growth rate and increased mortality caused by beech scale disease [*Neonectria faginata* (Lohman, Watson & Ayers) Castl. & Rossman and *Neonectria ditissima* (Tul. Z & C. Tul.) Samuels & Ross.; Morin et al. 2007]. Such stand structures would have been suitable for full-tree chip clearcut harvest systems that were being developed and used at that time. These clearcut harvesting systems were primarily based on using Koehring feller-forwarders as the harvesting and extraction equipment (Chisholm & van Raalte 1980; Chisholm 1981; Lees 1987).

From a research perspective, the following new objectives were considered, namely to (1) determine the impact of PCT on the anticipated volume of approximately 200 m^3 ha^{-1} after 30–35 years; (2) determine the impact of PCT on potential value-added products, such as sawlogs and veneer; and (3) provide additional stand dynamics information and potential value-added product information concerning northern hardwood forests of the Acadian Forest Region of the Maritime Provinces.

Methods and materials

Study area

The study site is located in the Buttermilk Ecodistrict of the Valley Lowlands Ecoregion of the current forest site classification system (Figure 1, Ecological Classification Working Group 2007). Rowe (1972) also classifies the study area as part of the Upper Miramichi-Tobique Forest Section of the Acadian Forest Region. The medium-textured soils of the Ecodistrict are fertile and often support shade-tolerant hardwood stand associations of sugar maple–yellow birch–American beech (Zelazny et al. 1989; Ecological Classification Working Group 2007). Yellow birch-dominated stands, such as those residing on the study site, often occur on ridges. The soils of the study site are well drained. Average elevation for the Ecodistrict is 306 m above mean sea level (amsl). Average precipitation between May and September is 450–500 mm, with 1650–1750 annual degree days above 5°C (Ecological Classification Working Group 2007). Although most settlement has occurred along the major rivers and connecting roads, the ecodistrict has a long history of forestry use before and after the arrival of the Europeans.

In the winter of 1986–1987, an operational PCT study was established on NB Crown license of St. Anne-Nackawic Pulp and Paper Co. Ltd. (now AV Nackawic Inc.) to support and provide additional information for the PCT silviculture program inaugurated in 1979 (Figure 1, Valley Forest Products Ltd. 1990). The study site for this operational experiment originated from a 1975–1976 clearcut harvest of a northern hardwood stand near Napadogan, NB (46° 22′ N and 66° 58′ W). The experimental design consisted of six replicates as treatment blocks, with the following four uniform density treatments: (1) 2200 stems ha^{-1} (2.1 × 2.1 m); (2) 1900 stems ha^{-1} (2.3 × 2.3 m); (3) 1600 stems ha^{-1} (2.5 × 2.5 m); and (4) 1300 stems ha^{-1} (2.8 × 2.8 m; hereafter referred to as T2200, T1900, T1600, and T1300, respectively). A total of 24 treatment areas or experimental units were established in this randomized complete block design (Figure 1). In the center of each treatment block, a circular 0.05-ha permanent sample plot (PSP) was established. The T2200 spacing treatment is a common PCT prescription in eastern Canada for both young hardwood and softwood stands. This PCT prescription is presently the desired residual density target for hardwoods in NB. On Crown land, the target may range from 2000 to 3500 stems ha^{-1} (NBDNR 2004). From this initial density of 2200 trees ha^{-1}, the remaining treatment densities were produced by successive removals of 300 stems ha^{-1}, increasing spacing of 0.2 m (20 cm) or 0.3 m (30 cm) between remaining trees. Such a selection of density treatment produces a narrow range of possible treatments for this operational setting as an experiment. The PCT prescriptions followed the principle of a "thinning from below" by removing the smaller and lesser quality trees around the selected crop trees to achieve the desired uniform spacing (Lamson & Smith 1987). Lamson and Smith (1987) also used the term basal area thinning to describe the stand-tending treatment. Although yellow birch, white birch, and sugar maple were the desired crop trees, other tree species were left to avoid leaving gaps, to avoid excessive branchiness in desired crop trees, and to conform to the desired uniform distance between crop trees. In the spring of 1987, tree stumps left from the winter operation were cut near the root collars using circular brush saws. As the original operational objective was to examine the impact of growth and yield of the thinning treatment without considering the comparison of no PCT (statistical control), the present statistical examination of the data will follow the original experimental design with linear model analysis. However, information from the nearest four control plots of a "paired" plot PCT study in the region for similar northern hardwood stands provides descriptive conditions before the thinning treatments were applied (Table 1). The distance from the study site to the control plots ranges from approximately 2–30 km. The control plots from "paired plot" study were established either 12 or 13 years after the final clearcut harvest in 1988. As with this study, periodic stem diameter (cm) at 1.3 m (dbh) and total tree height (m) measurements were recorded for all crop trees periodically until 2011 in circular 0.05-ha plots. The dates for the tree measurements for this study were 0 (1988) years, 5 (1993), 10 (1998), and 23 (2011) years after initial establishment. The same tree identification method was used at each measurement period as in this study. Species composition based on stem density (stems ha^{-1}) that was weighted by basal area (m^2 ha^{-1}) in the study

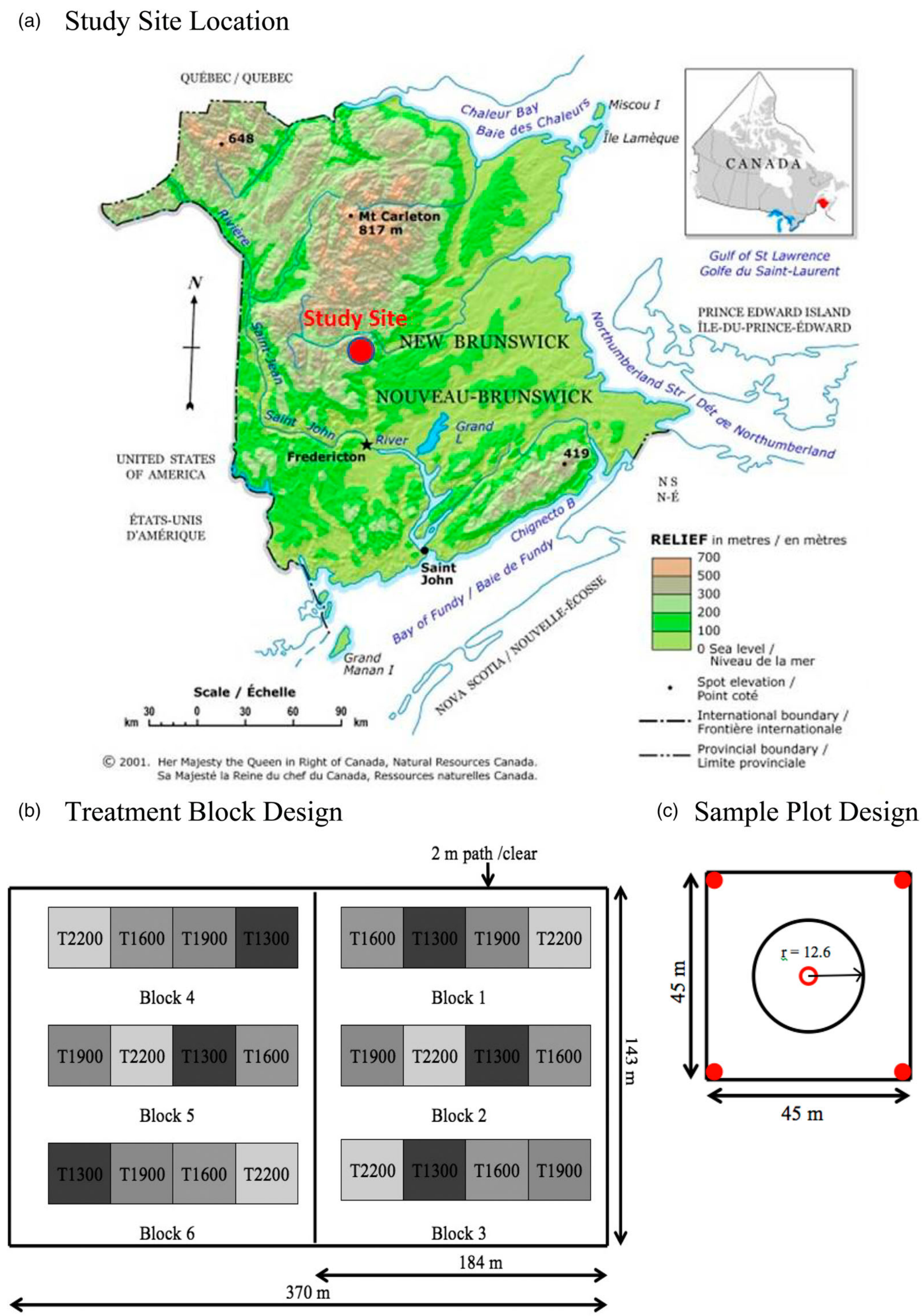

Figure 1. Design of the Napadogan precommercial thinning experiment in northern hardwoods of the Acadian Forest Region.

plots following treatment consisted of 60% yellow birch, 19% American beech, 12% sugar maple, 3% white birch, 5% trembling aspen, and 1% red maple. Identification of the tree species followed the convention according to Hinds et al. (2000).

Measurements

Stem diameter (cm) at 1.3 m (dbh) and total tree height (m) were recorded for all crop trees at 0 (1987), 5 (1992), 10 (1997), 16 (2003), and 23 (2010) years after the thinning treatments were established in the circular 0.05-ha plots. Trees in each plot were identified by number using spray paint at each measurement period. Because of the method used to number trees, the impact of ingrowth and tree mortality of previous trees cannot be separated without uncertainty and therefore must be considered together in the examination of changes in tree density through time. Very little ingrowth should have occurred because of the uniform PCT used in this study. Also any ingrowth should have been easily

Table 1. Initial stand conditions for surrounding unmanaged northern hardwood stands and for the precommercially thinned stands that have resulted from clearcut harvest operations.

	Stand variables										
Study site	Density (stems ha^{-1})	DBH (cm)	Height (m)	Basal area (m^2 ha^{-1})	Volume (m^3 ha^{-1})	Height: diameter ratio	yB % BA	sM % BA	Be % BA	tA % BA	Other % BA
18	15,800	3.3	6.0	20.1	76.6	232.9	38	0	0	30	32
20	22,220	2.6	4.5	14.8	40.3	218.7	28	5	1	54	12
21	18,100	3.1	5.5	17.8	55.3	204.4	47	6	1	39	6
22	12,700	4.0	6.0	21.5	80.0	179.1	40	0	1	10	49
Mean		3.3	4.5	18.6	63.1	208.7	38	3	1	33	25
T2200	2203	3.6	5.0	2.6	6.8	149.2	64	11	19	0.1	6
T1900	1907	3.6	5.2	2.3	6.4	152.2	62	13	18	6	1
T1600	1610	3.7	5.1	2.0	5.4	147.7	67	11	12	4	6
T1300	1297	3.6	4.9	1.5	3.9	147.0	59	11	16	3	11
Mean	–	3.6	5.0	2.1	5.6	149.0	63	12	16	3	6

Note: Species percentages for yellow birch (yB), sugar maple (sM), American beech (Be), and trembling aspen (tA) were derived from stand density and weighted by basal area.

detected as these trees would not have been painted with a tree number and dbh line. Regardless, without permanent tags on every tree, it proved impossible to obtain individual tree measurements through time and, thus, the analysis as given in this paper is based on aggregates of stand (plot) values rather than on individual tree measurements. Tree quality and potential tree quality product assessment were conducted on stand data acquired from the 2010 measurement period.

Calculations

Quadratic mean diameter was calculated by the following equation (Husch et al. 2003):

$$đ_Q = \mathrm{sqrt}\left(\sum_{i=1}^{n} di/n\right), \quad (1)$$

where, $đ_Q$ = quadratic mean square, d_i = dbh of the ith tree, and n = number of trees measured.

Total tree volume for each species was calculated using the following equations in Honer et al. (1983):

$$\text{Yellow birch} = \frac{0.0043891 \cdot D^2 \cdot (1 - 0.04365 \cdot 0.181)^2}{\left(0.1.449 + \left(0.3048 \times 334.754/H\right)\right)}, \quad (2)$$

$$\text{Sugar and red maple} = \frac{0.0043891 \cdot D^2 \cdot (1 - 0.04365 \cdot 0.145)^2}{\left(1.046 + \left(0.3048 \times 383.972/H\right)\right)}, \quad (3)$$

$$\text{American beech} = \frac{0.0043891 \cdot D^2 \cdot (1 - 0.04365 \cdot 0.145)^2}{\left(0.959 + \left(0.3048 \times 334.829/H\right)\right)}, \quad (4)$$

$$\text{White and gray birch} = \frac{0.0043891 \cdot D^2 \cdot (1 - 0.04365 \cdot 0.176)^2}{\left(2.222 + \left(0.3048 \times 300.373/H\right)\right)}, \quad (5)$$

$$\text{Trembling or largetooth aspen} = \frac{0.0043891 \cdot D^2 \cdot (1 - 0.04365 \cdot 0.145)^2}{\left(0.959 + \left(0.3048 \times 334.829/H\right)\right)}, \quad (6)$$

where D = diameter at breast height (cm) and H = total tree height (m).

The height:diameter ratio or slenderness factor was determined by dividing height by stem dbh, with both variables expressed in cm.

Predicted volume growth was first examined by modeling basal area (BA, m^2/ha^{-1}) as a function of stand age, with different thinning intensities, using the growth curve,

$$BA(t) = \frac{BA_m}{1 + \exp(-k(t - \alpha))}, \quad (7)$$

where t represents stand age (in years). The equation's three parameters include BA_m, the maximum basal area (33 m^2 ha^{-1}, based on NB PSPs, with a proportion of yellow birch >30%), and k and α are parameters related to thinning intensity and site quality.

Two steps were used in estimating k and α. First, k and α were estimated for each treatment block by fitting Equation (6) with constrained nonlinear regression (CNLR) using SPSS (IBM Corporation, Armonk, NY). Then, the estimated α for each block was modeled as a linear function of site index S, whereby:

$$\alpha = a_1 S + a_0. \quad (8)$$

Site index, S, is defined as the maximum tree height in a stand at reference age (30 years, in our case).

Stand volume was estimated according to stand basal area, based on Equation (8):

$$V(t) = V_k * (BA(t))^{K_v}. \quad (9)$$

Stand-level volume and basal area predictions were produced with the STELLA modeling software (Isee Systems Inc., Lebanon, NH).

Timber product quality assessment

McDonald (1999) classified hardwoods into the following three forest products: (1) veneer; (2) sawlogs; and (3) pulpwood based on the best 2.5 portion of the first 4.0 m of a tree. For a tree to be classified as a veneer product, the following criteria were used: (1) clear on all four faces; (2) no major defects; and (3) dbh > 24 cm. A sawlog tree required the following: (1) have no more than two minor defects on three clear faces; and (2) dbh > 24 cm. A pulpwood tree was identified as such when a tree did not meet the criteria for either veneer or sawlog. A potential forest product classification system followed the above criteria except the dbh could be <24 cm. If a tree did not meet the potential veneer and sawlog requirements, it was classified as pulpwood. Every live tree in the sample plots was classified for both current and future potential forest product at the last measurement period. Other tree grading systems exist in NB, but as Wiedenbeck et al. (2004) have pointed out for veneer quality trees the grade depends on the buyers and users of the material. The length of the potential sawlog was determined by selecting the best portion of the stem closest to the base of the tree. This is the same approach a harvest operator would use to select the best potential product from a tree stem. Sawlog lengths were either 2.4 m (8 ft), 3.6 m (12 ft), or 4.9 m (16 ft) that could be obtained anywhere on the tree stem.

Statistical analysis

Differences for average stem diameter (cm), tree height (m), height:diameter ratio, quadratic mean diameter (cm), stand density (stem ha^{-1}), basal area (m^2 ha^{-1}), total volume (m^3 ha^{-1}), average tree volume (m^3 stem^{-1}), and average tree basal area (m^2 stem^{-1}) at each measurement period were examined by linear models that were implemented with the GLM procedure in SAS (SAS Institute Inc., Cary, NC: version 9.2) or the lm-function in R (R Core Team 2013). The same statistical procedure was used to determine differences in sawlog potential and length of sawlog at the last measurement period. Independent factors examined were treatment (i.e. T2200, T1900, T1600, and T1300), treatment block (1–6), and year of measurement (Graybill 1961; Hocking 1985; Hicks & Turner 1999). Since one of the objects of this study is to estimate the treatment and age at which logs reach merchantable size, and since linearity is relevant to any such extrapolation attempt, sums of squares were partitioned into separate linear and nonlinear components in Table 2. The size of their sums of squares in Table A1 provides information on the practical significance (as opposed to the so called "statistical significance") of block, treatment, and time. As some measurements from T2200 in Treatment Block 4 were not available for 1992, an unbalanced linear ANOVA analysis was used to determine differences in quadratic mean diameter (cm), stand density (stems ha^{-1}), basal area (m^2 ha^{-1}), and total volume (m^3 ha^{-1}). Given adequate number of trees in the same plot, a balanced ANOVA analysis was able to be used in the examination of differences in average stem diameter (cm), tree height (m), and height: diameter ratio, average tree volume (m^3 stem^{-1}), and average tree

Table 2. ANOVA results of potential sawlogs frequency that include the stand variable, source of variation, degrees of freedom (df), sum of squares values (SS), and *p* values. *p* values <.10 are in bold print.

Potential sawlog	df	SS	*p*-Value
All blocks			
Block	5	1316.7	**0.0005**
Treatment linear	1	49.408	0.2244
Treatment_nonlinear	2	99.383	0.2316
Residuals	15	461.45	–
Block 5 removed			
Block	4	301.70	0.1193
Treatment linear	1	81.000	0.1426
Treatment_nonlinear	2	101.80	0.2524
Residuals	12	101.80	–

basal area (m^2 stem^{-1}). Independent variables used in the ANOVA analysis were stem density by diameter classes. A two-way ANOVA analysis for randomized complete block experimental design was used for the examination of height:diameter ratios for the first measurement period in 1987. Homogeneity of variances was checked for all variables and measurement periods during the ANOVA analyses. Tukey's Studentized Range Means Test was conducted at the 5% level (highly significant) and the 10% level (significant) among treatment means for diameter distribution, frequency of potential sawlogs, and sawlog length for the last measurement period, when significant differences occurred (Schlotzhauer & Littell 1987; Hicks & Turner 1999). This procedure of multiple comparisons was chosen to obtain a conservative evaluation of individual treatments and treatment blocks (Mize & Schultz 1985).

Results

Stem diameter

Although the *p* value in Table A1 in the Appendix for the slope at 5 years after treatment shows an initial delay in the response of stem diameters to the release treatments (Table A1), the consistency with other points in Figure 2 suggests that there was a significant treatment response. All four PCT treatments had initial average dbh of approximately 3.6 cm. The linear trend is statistically significant, whereas the nonlinear effects are not statistically significant (Table A1). The

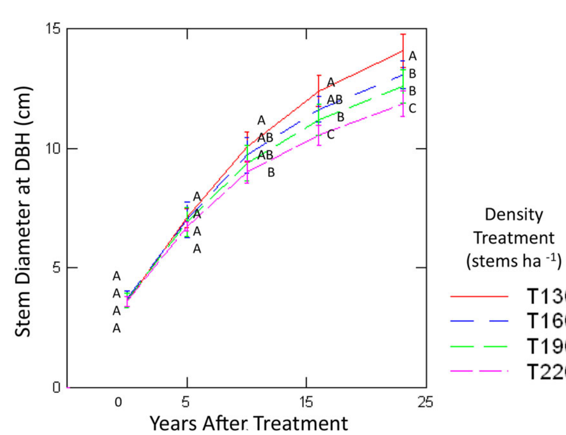

Figure 2. Stem diameter (cm) response at breast height (1.3 m) by precommercial thinning treatment.

slopes of the lines in Figure 2 show that there are significant linear differences in stem diameter between the four treatments starting 5 years (1992) after initial thinning (Table A1). These statistically significant differences between thinning treatments became more apparent between stem density extremes, T1300 and T2200, by the last two measurement periods. As the values at each measurement period were only slightly higher for quadratic mean diameters than average stem diameter growth, the graphs are not shown.

All four treatments exhibited an extremely skewed reversed J-shape or negative exponential diameter distribution curve at the initiation of the experiment (Figure 3). The J-shaped distribution curve is a very common feature of young stands (Leak 1970). Gradually the diameter distributions of the four treatments changed to a bell-shaped curve, which is becoming more flattened with time. The diameter classes are gradually shifting away from the lower classes toward larger classes. Because of their initial rapid growth and being well adapted to these sites, aspens are the main contributors to the larger diameter classes. The occasional small residual trees from the former stand now contribute to forming the larger-diameter-class trees. The largest diameter class at the last measurement period was 38 cm. Most of the stems were then in the 10–14 cm diameter classes for all treatments (Table A2 in Appendix) and were not significantly different between treatments (df = 3, SS = 29.833, p value = 0.9552). Slight significant linear differences (df = 3, SS = 602.33, p value = 0.0191) in the number of stems, expressed as a percentage of stand density, occur among the four treatments in the lower diameter classes of 2–8 cm (Table A2). The least dense treatment, T1300, had significantly more stems (23.5%) in the >16 cm diameter class (df = 3, SS = 525.12, p value = 0.0023; Table A2).

Height

At the start of the study, all tree heights were approximately the same at 5 m (Figure 4). Tree height showed no visible treatment effect or Treatment × Year interaction. (Table A1). Height growth has been steady for the last 23 years and shows no signs of culmination. According to Rytter (2013), height growth will accumulate earlier than stem diameter growth. Without treatment effect, there is no need to plot height vs treatment. At the last measurement period, the trees were on average 12.2 m tall, ranging from 12.1 to 12.3 m.

Basal area

As with stem diameter, there were no significant differences in basal area ($m^2\ ha^{-1}$) among treatments at the start of the study (Figure 5 and Table A1). All four PCT treatments produced initial basal areas averaging of 1.7 $m^2\ ha^{-1}$. Significant linear differences for basal area ($m^2\ ha^{-1}$) between the four PCT treatments became apparent 5 years after the treatments. Differences between the thinning treatments varied between the measurement periods but showed a strong linear relationship of increasing basal area from across least to most dense plots over time. Although the ANOVA analysis detects nonlinearity, the sum of squares indicates that this nonlinearity is not very large. At the last measurement period, the least dense treatment (i.e. T1300) had the lowest basal area (20.2

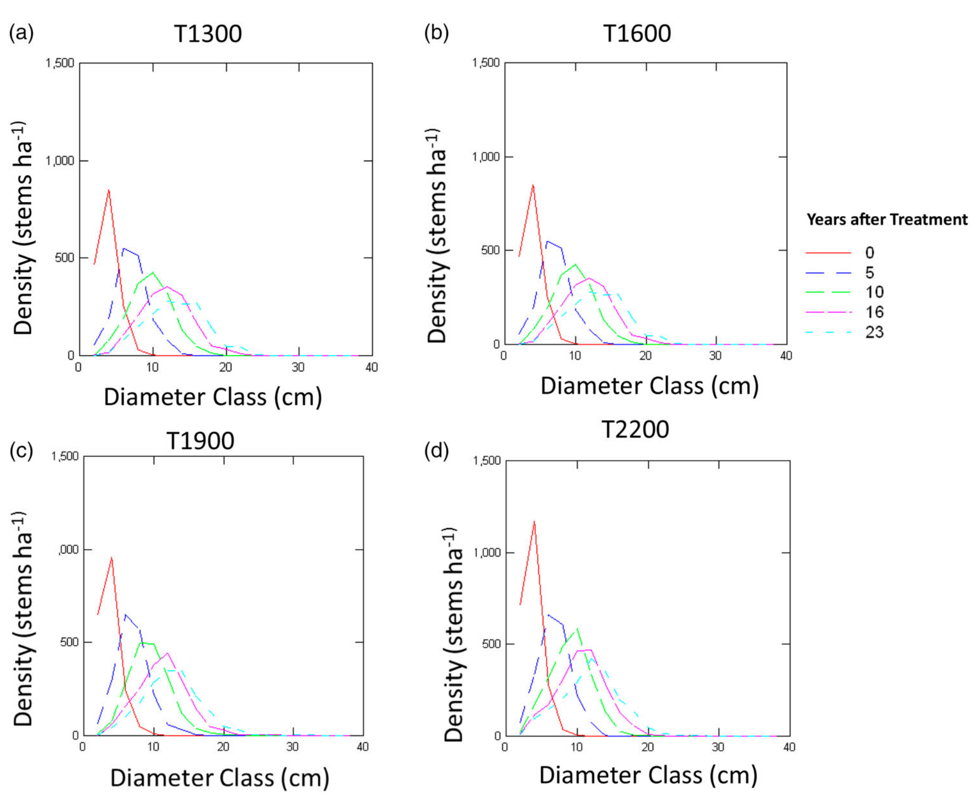

Figure 3. Diameter distributions over stand development by precommercial thinning treatments.

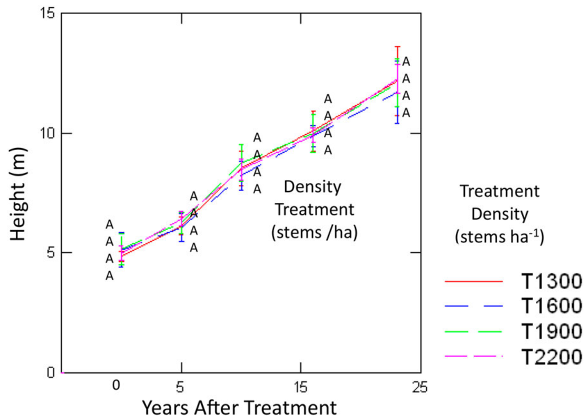

Figure 4. Height (m) response by precommercial thinning treatment.

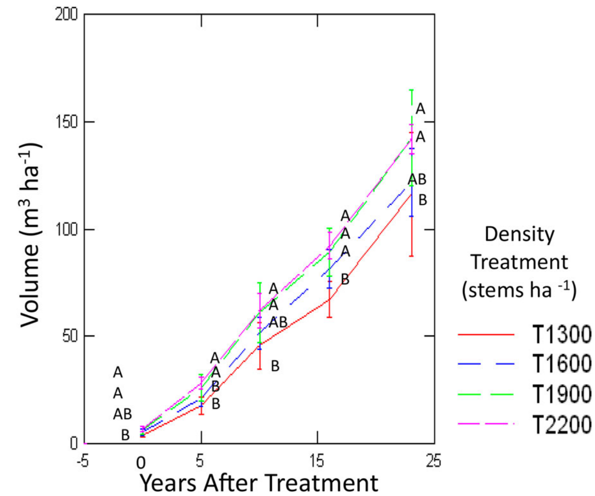

Figure 6. Total volume (m^3 ha^{-1}) response by precommercial thinning treatment.

m^2 ha^{-1}), but the range between treatments was not large (20.2 to 24.3 m^2 ha^{-1}).

Total volume

Unlike stem diameter and basal area, there were differences in total volume (m^3 ha^{-1}) between the PCT treatments at the start of the study (Figure 6, Table A1). Although the two least dense treatments (T1600 and T1300) had similar volumes at the start of the study, T1300 had significantly less than the two densest treatments (T1900 and T2200) then and for all subsequent measurement periods. Again, all relationships are strongly, significantly linear (Figure 6, Table A1). Differences between the thinning treatments for total volume became more apparent as the stands developed over time.

Height:Diameter ratio

All four PCT treatments produced higher height:diameter ratios at the beginning of the study than the over the four successive measurement periods (Figure 7). These higher height:diameter ratios ranged from 147 to 152 and were not significantly different from each other (df = 3, SS = 108.17, p = 0.5749). Treatment T2200 always had the highest height:diameter ratios over the five measurement periods. The magnitude of the height:diameter ratios decreased with decreasing targeted stand density. Significant differences between treatments became evident 5 years after the thinning treatment and varied at each measurement period (Table A1). Because of the large values for the initial height:diameter ratios (Figure 7), the linear ANOVA analysis was conducted on the last four measurement periods. At the end of the measurement periods, height:diameter ratios ranged from 92 to 113, increasing with treatment density. At the last measurement period, T2200 was beginning to show increase in height:diameter ratio.

Stand density

The average stand densities (stems ha^{-1}) were very close to the targeted densities at the start of the study, ranging from −0.2% to +0.6% of the targeted density value. This close range, <1% of the targeted stem density for each treatment, is not always achieved in stand density management studies. Significant differences (Table A1) between PCT treatments and stem density were maintained throughout the five measurement periods (Figure 8), regardless of changes in stand dynamics. At the final measurement period, the

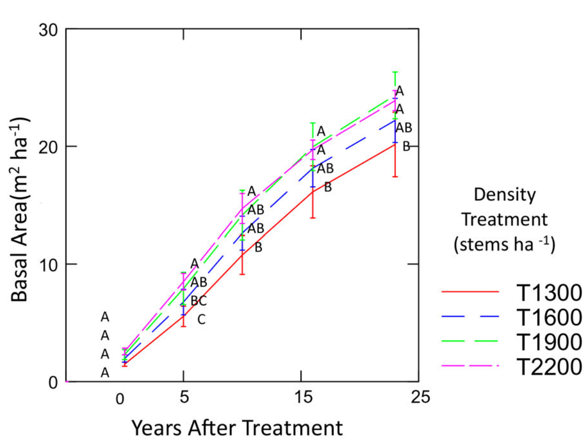

Figure 5. Basal area (m^2 ha^{-1}) response by precommercial thinning treatment.

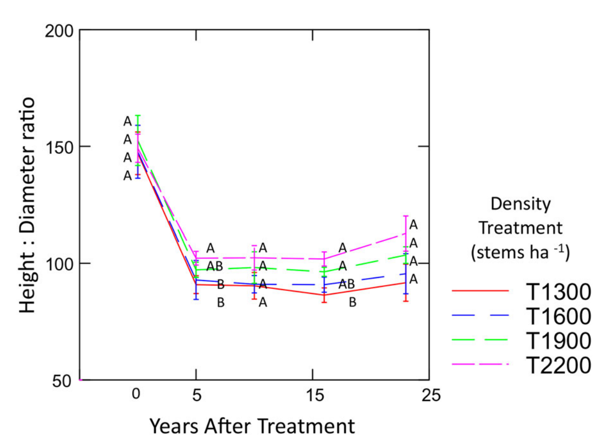

Figure 7. Height:diameter ratio response by precommercial thinning treatment.

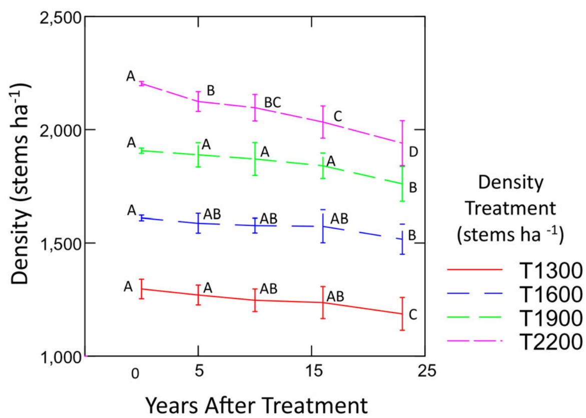

Figure 8. Density (stems ha^{-1}) response by precommercial thinning treatment.

densest treatment, T2200, exhibited the greatest decrease in density, followed by the remaining treatments in decreasing order of stand density. Unlike the previous variables, stand density showed both strong linear and nonlinear relationships between treatments and measurement periods (Table A1, Figure 8).

External tree quality

Under the tree product grading system of McDonald (1999), tree stem dbh needs to be at least 24 cm to qualify as veneer or sawlogs. Very few trees had reached this size at the present measurements recorded 23 years after treatment. Presently, most of the trees have the potential to become pulpwood or sawlogs, and only one tree has the quality to become a potential veneer product. Only one tree in the entire experiment has two potential sawlogs available; the rest of the trees of sawlog quality have one sawlog. Therefore the analysis was conducted on the potential quality, which excludes the required 24 cm at dbh. Results from ANOVA analysis for potential quality showed that there were no significant differences for pulpwood or sawlogs between treatments at 23 years after the initiation of the experiment (Table 2). Sawlogs ranged from 22% to 28% of the stand density among the four PCT treatments. However, there was great variation in the frequency of sawlogs between plots (7–43%, average 25%) and treatment blocks (10–35%), which was significant (Table 2). Treatment Block 5 had the lowest frequency of sawlogs (7–15%, average 10%), which was significantly different from the other treatment blocks (Table 2). The reason for this lower frequency is not apparent from species composition or other factors examined at this time. When Treatment Block 5 is removed from the ANOVA analysis, there are no significant differences between treatment blocks for potential sawlogs. Significant differences in frequency of all sawlog lengths existed between treatments 23 years after treatment (Table 3). Tukey's Studentized Range Test detected significant differences between the frequencies of the three sawlog lengths (2.4 m (8 ft), 3.6 m (12 ft), and 4.9 m (16 ft). The mean percent and standard deviations for the 2.4 m, 3.6 m, and 4.9 m sawlog lengths were, respectively, 54.1 ± 11.9 (standard error or deviation), 36.7 ± 12.1, and 9.1 ± 7.1%. No significant differences occurred between the four PCT treatments for the 2.4 m sawlog length (Table 3). At the 2.4 m sawlog length, the mean percent and standard deviations for T2200, T1900, T1600, and T1300 were, respectively, 54.4 ± 12.9, 62.2 ± 9.3, 48.8 ± 8.6, and 51.2 ± 14.9%. The mean percent and standard deviations for T2200, T1900, T1600, and T1300 at the 3.6 m sawlog length were, respectively: 40.2 ± 12.2%, 31.0 ± 6.3%, 43.2 ± .3%, and 32.4 ± 19.2%. For the 4.9 m length sawlogs, significant differences between the four PCT treatments were detected (Table 3). Tukey's Studentized Range Test detected no significant differences between T2200, T1900, and T1600. Likewise, no significant differences were detected between T1900, T1600, and T1300. The mean percent and standard deviations for T2200, T1900, T1600, and T1300 at the 4.9 m sawlog length were, respectively, 5.4 ± 4.1%, 6.8 ± 4.1%, 8.0 ± 7.3%, and 16.4 ± 7.7%.

Table 3. ANOVA results for sawlog lengths, which include the stand variable, source of variation, degrees of freedom (df), sum of square values (SS), and *p* values. *p* values <.10 are in bold print.

Stand variable	df	SS	*p*-Value
All sawlogs			
Block	5	0.05208	1.000
Length of sawlog	3	75616	**<0.0001**
Treatment linear	1	0.01875	0.9851
Treatment_nonlinear	2	0.01250	0.9999
Residuals	84	4514.87	-
Sawlogs at 2.4 m (8 ft)			
Block	5	433.33	**0.0049**
Treatment linear	1	20.833	0.2727
Treatment_nonlinear	2	34.167	0.3700
Residuals	15	241.00	-
Sawlogs 3.6 m (12 ft)			
Block	5	436.71	**0.0018**
Treatment linear	1	15.408	0.2944
Treatment_nonlinear	2	16.050	0.5538
Residuals	15	195.79	-
Sawlogs 4.9 m (16 ft)			
Block	5	6.6914	0.4594
Treatment	1	55.167	**0.0086**
Treatment_nonlinear	2	42.686	0.6760
Residuals	15	83.333	–

Discussion

In accordance with the vast amount of literature, stem dbh growth increased as stem density decreased (Sonderman 1985; Heitzman & Nyland 1991; Strong & Erdmann 2000; Rytter 2013). The four PCT treatments have achieved the main or most common objective of transferring the growth of undesired stems and of those that would potentially become lost to natural self-thinning mortality to the crop trees (Sjolte-Jørgensen 1967; Hilt & Dale 1982; Sonderman 1985; Lamson & Smith 1987; Simard et al. 2004; Hynynen et al. 2010). Increased response of stem diameter, quadratic mean diameter, basal area, and volume in the four treatments suggests that tree growth was transferred to the remaining crop trees (Figures 2–7). Stand density only affects height growth at the very low and very high levels and thus explains the nonsignificance obtained in this study. Such nonsignificant results for tree height between treatments is supported in the literature (Lamson 1983, 1988; Lamson & Smith 1987).The rapid decrease in stand density of the surrounding unmanaged

Table 4. Stand conditions for surrounding unmanaged northern hardwood stands and for the precommercially thinned stands 23 years after treatment that have resulted from clearcut harvest operations.

Study site	Stand variables: Density (stems ha^{-1})	DBH (cm)	Height (m)	Basal area (m^2 ha^{-1})	Volume (m^3 ha^{-1})	Height: diameter ratio	yB % BA	sM % BA	Be % BA	tA % BA	Other % BA
18	3360	9.7	11.9	31.9	209.8	141.9	55	9	2	25	11
20	4360	8.6	10.9	32.6	191.2	141.8	44	11	19	25	1
21	3840	9.5	10.5	33.1	179.8	122.4	74	5	1	15	5
22	2560	12.2	12.7	35.1	226.4	114.2	52	16	1	27	4
Mean	3530	10.0	11.5	33.2	201.8	130.1	56	8	6	23	5
T2200	1940	11.8	12.2	23.9	141.9	112.7	74	9	11	4	2
T1900	1760	12.6	12.1	24.3	142.2	103.5	66	12	11	7	4
T1600	1516	13.1	11.7	22.2	121.7	95.5	66	14	12	6	3
T1300	1187	14.1	12.2	20.1	116.3	91.7	63	10	10	13	4
Mean	–	12.9	12.0	22.6	130.5	100.8	68	11	11	7	3

Note: Species percentages for yellow birch (yB), sugar maple (sM), American beech (Be), and trembling aspen (tA) were derived from stand density and weighted by basal area.

northern hardwood stands between the first and last measurement periods suggests that part of the growth response was due to a reduction in natural self-thinning mortality in the thinned stands of this experiment (Tables 1 and 4). It is assumed that mortality was caused by natural self-thinning as no stand-replacing mortality, such as fire, weather event, or pest was observed. Natural self-thinning mortality rates decreased as the treatment densities decreased (Figure 8). As the stand canopy closed in, natural stand mortality increased within the four treatments. Both of the above observations are expected results in managed young or semimature northern hardwood stands. Regardless of the four treatments, the mortality rates are not as great as observed in the surrounding unmanaged stands and those reported in the literature for unmanaged stands (Marquis 1967; Leak 1970; Heitzman & Nyland 1991; Arthur et al. 1997) (Table 4).

Another objective of PCT prescriptions is to reduce the harvest rotation age (Sonderman 1985; Hynynen et al. 2010). As PCT disturbed stands have not reached the target 35th year since treatment, a final and conclusive examination cannot be provided, and neither can the anticipated volume of approximately 200 m^3 ha^{-1} be verified. However, volume model predictions suggest that 200 m^3 ha^{-1} should be obtained 27–32 years after treatment (Figure 9). The more dense stands (T2200 and T1900) should reach 200 m^3 ha^{-1} sooner than the least dense stands (T1600 and T1300). These results are in agreement with the stand density stocking diagram in Figure 10 and general consensus on stand development after thinning treatments (Sjolte-Jørgensen 1967). However, target volume levels resulting from PCT will occur later in the more intensely thinned stands; a trade-off between increased individual tree size (diameter and tree volume) vs. maximized stand total volume (Sjolte-Jørgensen 1967; Assmann 1970). Interestingly, the predicted total stand volume of 200 m^3 ha^{-1} is obtained earlier in T1900 than in T2200. The strong linear relationships exhibited with the growth variables examined in this study provide more confidence for the future volume and basal area predictions. Because a PCT treatment of 2500 stems ha^{-1} was not included in this experiment, we cannot determine when this treatment would reach 200 m^3 ha^{-1}. However, we suspect it would be sooner than T2200. Total stand basal area development is also provided in Figure 9 for comparison purposes and reader preference.

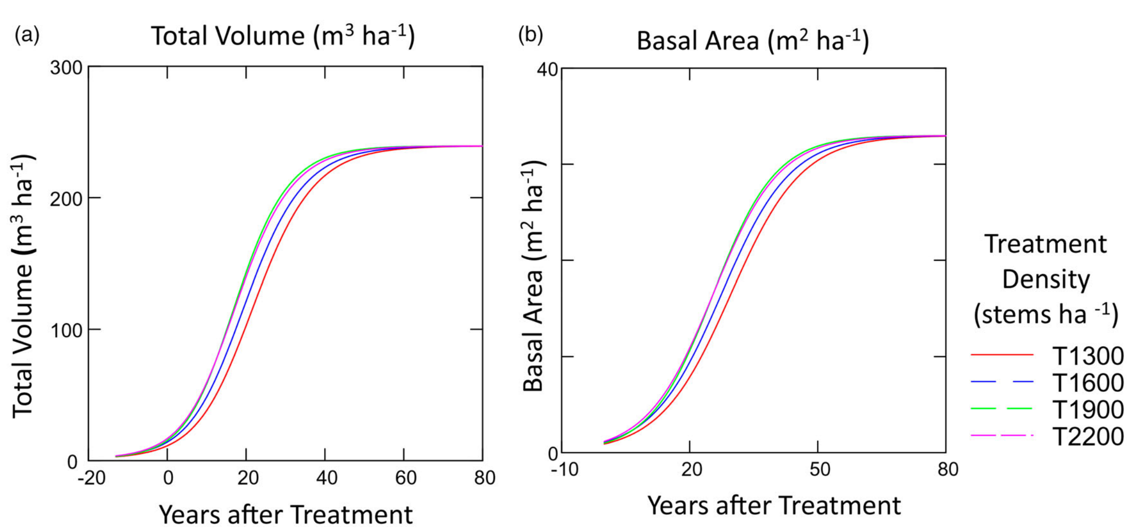

Figure 9. Predicted total stand volume (m^3 ha^{-1}) and basal area (m^2 ha^{-1}) development by thinning treatment: six replicates per line.

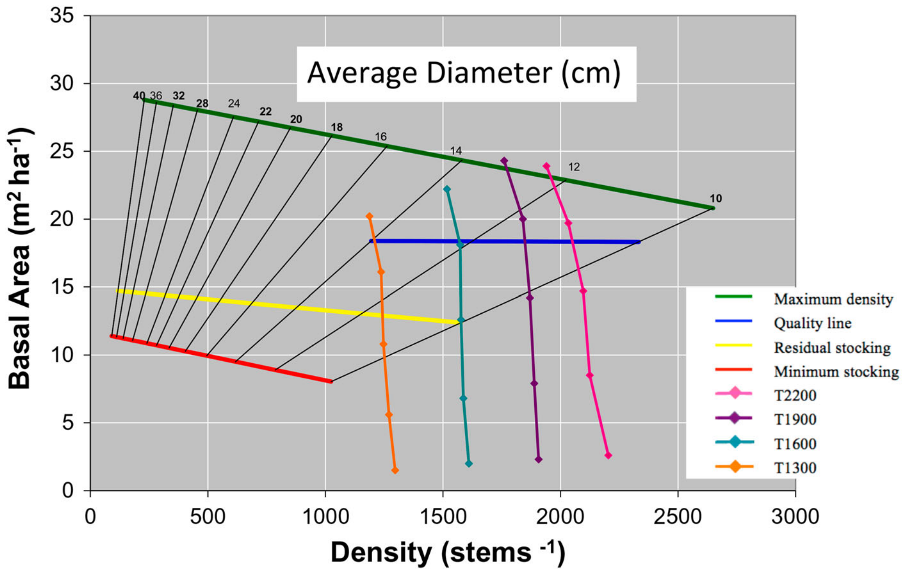

Figure 10. Average stand stocking development for the four thinning treatments: T2200, T1900, T1600, and T1300 (adapted from Leak et al. 1987).

At the time of establishment, Chisholm and van Raalte (1980) stated that marginal northern hardwood stands can be harvested more economically with a full-tree chip clearcut harvest system compared with conventional harvesting operation using chainsaws and skidders. Morey (1980) also advocated commercial thinning using a small feller-buncher shear and a small to medium-sized grapple skidder in such stand conditions. However, these harvesting systems are not currently used in the Maritime Provinces for clearcut and partial harvest operations and, therefore, the economic costs of present harvesting systems and new modified biomass-thinning harvesting systems must be considered for future partial harvests. Part of the economic restriction with current harvesting systems is that clearcut prescriptions used on the study area left few large residual trees. Although the four PCT treatments have reached the stand development stage at which a semicommercial or commercial thinning prescription could be applied (Figure 10), the total stand volume and average stem piece size restricts economic viability of such treatments with current harvesting systems. According to Figure 3 in Girard (2009), current average tree volume (T2200 = 0.0734 ± 0.0021 m^3 $stem^{-1}$, T1900 = 0.0812 ± 0.0054 m^3 $stem^{-1}$, T1600 = 0.0811 ± 0.0037 m^3 $stem^{-1}$, and T1300 = 0.0981 ± 0.0079 m^3 $stem^{-1}$) shows extremely low harvest machine productivity potential for partial removals.

As aspen is an early successional species on this site and is beginning to show signs of being overmature, regional semicommercial or commercial thinning prescriptions could be developed for this tree species. In the Great Lakes–St. Lawrence Forest Region, mixed stands of aspen and tolerant hardwoods tend to convert through natural succession processes to the northern hardwood types containing sugar maple, yellow birch, and American beech (Heeney et al. 1975). Forest management practices in Ontario generally recommend not keeping the shade-intolerant aspen species, but instead allowing the natural succession of northern hardwoods with the removal of aspen overstory (Heeney et al. 1975).

For even-aged northern hardwood stands such as those in this study, Leak et al. (1987) recommend leaving the stand for another 10 years until such time as current markets and harvest costs make the treatment of the stand more economically viable. Regional guidelines developed by Lees and Embree (1983) suggest that no thinning treatments are required for lightly stocked stands (<2500 stems ha^{-1}) with 70% of trees with a dbh <13 cm, but recommend removal of trees with a dbh >20 cm in stands of moderate to heavy stocking (>2500 stems ha^{-1}), where 70% of the trees are <13 cm. Field observations of current harvesting operations in northern hardwood stands in the region that have received early PCT suggest that commercial thinning or final harvest operations could be conducted in these stands in 5–10 years. Sendak and Leak (2008) state that a commercial thinning should be conducted between 45 and 56 years of age as determined from their hardwood study. These observations and recommendations from Leak et al. (1987) and Lees and Embree (1983) support later stand-tending prescriptions of commercial thinning and partial-harvesting treatments. Regardless, stands that have undergone past PCT are more desirable economically for current mechanized harvesting, because of stand uniformity, which tends to increase harvest productivity (Pitt & Lanteigne 2008; Girard 2009; Plamondon & Pitt 2013).

Clearcutting as conducted in this study is considered to be a satisfactory harvest method to regenerate northern hardwoods. The harvest method generally increases the proportion of pioneer (shade-intolerant) hardwoods species compared with what was present in the original stands. Lees (1987) considers the clearcut harvest method suitable for production of both pulpwood and timber products, especially for rehabilitating remnant hardwood stands, short-rotation pulpwood management, biomass production, and fuelwood production. The results of this study have shown that including early PCT treatments on former clearcuts in northern hardwood stands can increase the proportion of high-value timber products. The literature also suggests that semicommercial and commercial thinning treatments in these intensively managed stands should also help increase the proportion of high-value timber products. Because the initial treatment differences were small (removal increments of 300 stems ha^{-1}), it should not be surprising that potential saw timber production was not significantly different between treatments. However, the potential for high-value sawlogs (25%) in PCT plots is generally higher than in unmanaged stands (5–10%) in the area (McDonald 1999; Neil McCarthy, personal communication). Again, Sendak and Leak (2008) feel that commercial thinning is economically viable in northern hardwood stands that have received an earlier release treatment.

Although initial treatment differences were narrow compared with other studies, stand differences are becoming more pronounced and are having an impact on future stand-tending and harvesting options (Figure 10). Basal area decreases from densest (T2200) to the least dense treatment (T1300). In contrast, average stem diameter increases as stem density decreases. The densest treatments, T1900 and T2200, tend to reach a stocking level required for thinning for optimum growth sooner than the least dense treatments. However, these stocking levels may not be economically feasible with available harvesting systems. A stocking guide for northern hardwood stands for Prince Edward Island in PEIDEF (1987), not shown, shows similar relationships. Lees (1995) also notes that the PCT treatment produces the greatest increase in dbh, total volume, or basal area for crop trees may not be the desired silvicultural prescription, depending on the management objectives of the landowner. By knowing the potential stand structures that may develop as a result of PCT (Figures 4–10), a resource manager can plan and develop biocomplexity and biodiversity in second-growth stands for society's multiple values (Carey 2006; Jensen & Skovsgaard 2009). In Scots pine (*Pinus sylvestris* L.) stands, Husskonen and Hynynen (2006) demonstrated that merchantable volume at the first commercial thinning is influenced by both the timing and intensity of PCT and commercial thinning treatment. In Europe, heavy PCT treatments are prescribed in stands dominated by silver birch *(Betula pendula* Roth), followed by commercial thinning operations to produce high-value products such as saw timber or plywood (Hynynen et al. 2010); trees of lower quality are used for firewood and pulpwood. Because silver birch is a light-demanding species, intensive PCT (as conducted in this study) and commercial thinning are required for optimum tree growth, product development, and harvest cost concerns (Cameron et al. 1995; Cameron 1996; Hynynen et al. 2010). PCT of silver birch stands begins when the trees are between 5 and 7 m tall. Harvest rotations in silver birch stands tend to be longer for the production of high-value saw timber than for stands of poorer quality trees, and these stands are often subjected to more than one commercial thinning. Yellow birch dominates the study site because of tree species, site dynamics of the region, and PCT prescriptions. Although yellow birch is considered an intermediate shade-tolerant species that occurs in mixed stands, it responds well to heavy PCT and commercial thinning treatments (Erdmann 1990). Cameron (1996) considers that European birches have many similarities for forest management practices with those of yellow and white birch that occur in North America. Management recommendations for silver birch and research results with yellow birch suggest the need and opportunity to develop semicommercial and commercial thinning systems to promote high-value products from stands dominated by yellow birch. Stands on highly productive sites would provide both saw timber and pulpwood material, as suggested in an earlier hardwood thinning experiment in the Maritimes (Lees 1984). Poor quality sites tend not to provide the vigorous growth required for high quality saw timber (MacCauley & Marquis 1972; Carmean & Boyce 1974; Hynynen et al. 2010). Because yellow birch tends to occur in mixed-species stands, differences in stand developmental patterns between shade-intolerant and shade-tolerant tree species need to be considered for semicommercial and commercial partial harvest treatments. With proper planning and matching equipment capabilities with stand conditions, thinning northern hardwood stands can be an important management tool in the forest-product value chain (Winsauer & Mattson 1987).

Although hardwood stands tend to require fewer trees than conifers for adequate stocking (Hynynen et al. 2010), T1300 and T1600 are well below the recommendations from guidelines and research studies in the region (Lees 1978, 1995; Higgs 1981; PEIDEF 1987; NSDNR 1993; McGrath 2007; McGrath et al. 2015). Research studies outside of the Acadian Forest Region have reported that heavy thinning in young hardwood stands decreased the stem quality of potential crop trees (Erdmann et al. 1981; Dale & Sonderman 1984). Leak et al. (1969) recommend that early stand tending should not be undertaken until the stand reaches 20 years after the final harvest. Interestingly, there were no significant differences for potential sawlogs among the four PCT treatments in this study. Development of both the crown and the stem are known to be very sensitive to stand density in hardwoods (Sonderman 1985; Hynynen et al. 2010). Sonderman (1984) has reported that species and age of crop trees are important factors affecting potential stem quality in hardwoods, with the heavier thinning promoting greater stem defects. In another study, Sonderman (1986) observed that the number of live limbs and epicormic branches decreased as stand density increased; the usual assumed response from thinning studies. The results of Erdmann and Peterson (1985) and Sonderman (1985) have shown that defects were greater in the second 2.4 m (8 ft) sawlog than the first 2.4 m (8 ft) sawlog. Hence, as Hynynen et al. (2010) and Lamson (1988) have recommended, the production of high-value saw timber is best obtained on more productive sites that are specific to a tree species' requirements, where crown recession occurs at a faster rate to form clear stems sooner (Carmean & Boyce 1974). The difference between T1300 and the other treatments for production of 4.9 (16 ft) sawlogs may be explained by the study site being more favorable to yellow birch growth and reduction of light competition that promotes crown recession in clear stem formation. Carmean and Boyce (1974) also recommend that stand density be reduced to promote stem diameter growth, once a clear butt log has formed. Currently in NB, trees containing saw

Table 5. Description of existing potential sawlogs and number of treatment plots with a deficiency of potential sawlogs by treatment and targets of 250 and 300 stems ha^{-1} by treatment 23 years after treatment.

Density treatments (stems ha^{-1})	Minimal	Mean ± Std. err.	Maximum	Number of the six treatment plot with a deficient sawlogs	
				250 stems ha^{-1}	300 stems ha^{-1}
T2200	200	426 ± 121	520	1	1
T1900	260	457 ± 87	800	0	2
T1600	160	353 ± 49	520	1	1
T1300	80	333 ± 52	420	1	1

timber material measuring less than the former conventional length of 4.9 m (16 ft) are being utilized, thus formation time for a clear butt log may vary by local manufacturer. Results from a similar experiment established in a northern hardwood stand in 1978, showed that the widest spacing of 2.7 × 2.7 m (9 × 9 ft) did not produce excessive numbers of branches to reduce stem quality and resulted in the greatest increase in stem dbh and total volume for crop trees (Lees 1995). The results from Lees (1995) provided support for PCT in young northern hardwood stands under various federal and provincial funding programs, as do the results of this study. Lees (1990a, 1990b) also recommends wide spacing for establishing white ash and sugar maple plantations in the Maritimes. Presently in forest management, between 250 and 300 crop trees ha $^{-1}$ are desired at final harvest in some regions in eastern Canada. However, the amount of desired sawlogs varies in the literature and regional requirements. Based on the current density and assuming limited mortality of potential sawlogs, most of the thinned stands, regardless of thinning intensity, have an adequate number of potential sawlogs (Table 5). Hence, future commercial thinning treatments and partial harvest operations have the potential to increase the frequency of sawlogs to the point that these trees may become the dominant product at the end of a rotation.

Individual tree and stand height: diameter ratios are important indicators of stability for stand structures, especially for partial-removal treatments. Trees with lower ratios are generally less prone to snow and wind damage than those with higher ratios. Initial results from European studies suggest that conifer stands with a ratio of 80:1 or less are considered to be stable (Vospernik et al. 2010), and this value is being confirmed in North America (Powers & Oliver 1970; Wonn & O'Hara 2001). However, Nykänen et al. (1997) stated that a height:diameter ratio of 90:1 or less is required for stand stability. More is known with conifers than deciduous trees on the impact of height: diameter ratios (Nykänen et al. 1997; Vospernik et al. 2010). Stand stability as indicated by the ratio is often associated with past stand management and density (spacing between individual trees). Hence, spacing and thinning treatments produce variations in the height: diameter ratios, as past research has shown that increased distance between trees results in decreases in the ratios (Nykänen et al. 1997; Vospernik et al. 2010; Bošeľa et al. 2014). Best response for lower height:diameter ratios from spacing or thinning treatments is achieved early in stand development, as the ability to respond to density regulation decreases with stand age (Assmann 1970; Wonn & O'Hara 2001;Vospernik et al. 2010; Bošeľa et al. 2014), and PCT treatments tend to remove the lower crown classes. Bošeľa et al. (2014) reported that decreases in the height:diameter ratios are also associated with increasing crown length: a tree factor produced by PCT treatments. Co-dominant and medium-sized trees have higher diameter growth from partial-removal treatments (Assmann 1970; Cremer et al. 1982; Mäkinen & Isomäki 2004). The results from this study show that the four PCT treatments decreased the height:diameter ratios and, thus, increased stand stability once the residual trees exhibited increased diameter growth (Figures 2–7). Although significant differences in height:diameter ratios between treatments did not always occur (Table 2), the ratios generally increased with decreasing spacing between the trees. Lack of significant differences between the treatments can be attributed to the narrow ranges of PCT densities. The last measurement period is showing a slight increase in height:diameter ratios, but the long-term impact on stand structure is not known for young northern hardwood stands of the Acadian Forest Region. A standard, similar to the ratio of 80:1 for conifers, is currently not known for young northern hardwood stands. Regrettably, this study cannot help to resolve this limitation.

Observations from surrounding unmanaged stands, suggest that PCT has placed the stands in a more favorable status for future semicommercial and commercial thinning treatments and partial removals (Tables 1 and 3). To date, none of these stands show the impact of snow and ice storms that have occurred in the region on a frequent basis. The influences of species composition in these mixed young northern hardwood stands on height:diameter ratios need to be examined, as other research studies have shown differences between species (Nykänen et al. 1997; Rytter & Werner 2007; Rytter 2013). Although the literature is inconsistent with wind firmness between tree species, Nolet et al. (2012) state that yellow birch, sugar maple, and American beech are considered to be very wind-firm trees in northern hardwood forests. Nolet et al. (2012) also state that more research is required on factors that decrease wind damage in northern hardwood forests. As many studies on climate change suggest that climatic factors associated with natural disturbances, such as wind and ice damage, will increase in frequency and intensity (Park et al. 2014), a better understanding is required on the impact PCT treatments will have as an adaptation tool for these factors in northern hardwood stands. Furthermore, Park et al. (2014) state that forest management treatments and plans must consider that climate is not constant, and they must promote silvicultural treatments that reduce the effects of transient extreme weather events.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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Appendix

Table A1. ANOVAs results of stand variables, which include the stand variable, source of variation, degrees of freedom (df), sum of squares values (SS), and *p* values. *p* Values <0.10 are in bold print.

Variable	Source of variation	df	SS	*p* Value
Stem diameter (DBH)	Block	5	11.67	**2.4e−12**
	Year	4	1303.07	**<2.2e−16**
	Linear	1	1233.13	**<2.2e−16**
	Nonlinear	3	69.94	**<2.2e−16**
	Treatment	3	19.18	**<2.2e−16**
	Linear	1	19.09	**<2.2e−16**
	Nonlinear	2	0.08	0.731
	Year: Treatment	12	11.30	**4.3e−09**
	Linear	1	10.64	**2.6e−14**
	Nonlinear	11	0.65	0.929
	Residuals	95	12.56	–
Height	Block	5	10.81	2.17e−05
	Year	4	766.38	**< 2.2e−16**
	Linear	1	759.57	**< 2.2e−16**
	Nonlinear	3	6.81	**0.00255**
	Treatment	3	1.07	0.352
	Linear	1	0.24	0.391
	Nonlinear	2	0.83	0.282
	Year: Treatment	12	1.76	0.936
	Linear	1	0.03	0.765
	Nonlinear	11	1.73	0.907
	Residuals	95	30.65	–
Basal area	Block	5	66.3	**< 2.2e−16**
	Year	4	6605.1	**< 2.2e−16**
	Linear	1	6500.9	**< 2.2e−16**
	Nonlinear	3	104.2	**< 2.2e−16**
	Treatment	3	179.9	**< 2.2e−16**
	Linear	1	163.1	**< 2.2e−16**
	Nonlinear	2	16.8	**< 2.2e−16**
	Year: Treatment	12	27.8	0.0246
	Linear	1	14.1	**0.00060**
	Nonlinear	11	13.7	0.352
	Residuals	94	104.1	–
Total volume	Block	5	2618	**< 2.2e−16**
	Year	4	234808	**< 2.2e−16**
	Linear	1	232417	**< 2.2e−16**
	Nonlinear	3	2390	**< 2.2e−16**
	Treatment	3	5086	**3.7e−11**
	Linear	1	4742	**3.6e−12**
	Nonlinear	2	345	0.105
	Year: Treatment	12	1896	**0.022**
	Linear	1	1479	**< 2.2e−16**
	Nonlinear	11	417	0.893
	Residuals	94	7003	–
Height: Diameter ratio	Block	5	272.3	**0.0346**
	Year	3	660.8	**9.14e−06**
	Linear	1	262.8	**0.00763**
	Nonlinear	2	398.0	**0.00242**
	Treatment	3	3215.5	**< 2.2e−16**
	Linear	1	3136.5	**< 2.2e−16**
	Non-linear	2	79.0	0.164
	Year: Treatment	9	214.8	0.361
	Linear	1	177.9	**0.00508**
	Nonlinear	8	36.9	0.987
	Residuals	75	1600.5	–
Density	Block	5	5091	0.874
	Year	4	297965	**1.1e−14**
	Linear	1	276500	**3.0e−16**
	Nonlinear	3	21465	0.0614
	Treatment	3	11466329	**< 2.2e−16**
	Linear	1	11393251	**< 2.2e−16**
	Nonlinear	2	73079	**1.08e−05**
	Year: Treatment	12	66391	**0.0366**
	Linear	1	46523	**0.0001**
	Nonlinear	11	19868	0.790
	Residuals	95	265163	–

(Continued)

Table A1. Continued.

Variable	Source of variation	df	SS	*p* Value
Average volume Per tree	Block	5	0.001338	**5.0e−06**
	Year	4	0.098437	**<2.2e−16**
	Linear	1	0.097242	**<2.2e−16**
	Nonlinear	3	0.001195	**2.1e−06**
	Treatment	3	0.001223	**1.6e−06**
	Linear	1	0.001124	**1.71e−07**
	Nonlinear	2	0.000099	0.250
	Year: Treatment	12	0.001388	**0.00054**
	Linear	1	0.001104	**2.12e−07**
	Nonlinear	11	0.000284	0.706
	Residuals	95	0.003352	–

Table A2. Diameter distribution percentages based on stand density, standard deviations, and ANOVA results 23 years after treatment.

	Diameter distribution (cm)		
Treatments	2–8	10–14	>16
T2200	23.5 ± 6.3 A	65.3 ± 8.5 A	11.0 ± 3.2 A
T1900	18.3 ± 5.3 AB	67.0 ± 6.9 A	13.5 ± 4.2 A
T1600	16.7 ± 8.9 AB	67.7 ± 9.8 A	15.8 ± 2.5 A
T1300	9.5 ± 6.2 B	68.7 ± 12.5 A	23.5 ± 7.8 B

Note: Groups within the same diameter class having the same capital letter are not significantly different at $p < .10$ between treatments.