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Long-term influence of commercial thinning on stand structure and yield with/without pre-commercial thinning of spruce-fir in northern Maine, USA

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ABSTRACT

Pre-commercial (PCT) and commercial thinning (CT) are important silvicultural tools applied to spruce-fir (*Picea-Abies*) forests, a key forest type in the northeastern portion of North America. However, the long-term influences of CT, particularly when combined with PCT, are relatively unknown, except for a few specific locations in the region. Utilizing the repeated measurements from replicated experimental research sites (n = 15) initiated in the early 2000s throughout Maine, we quantified the influence of contrasting thinning treatments on spruce-fir stands with prior PCT and without a prior PCT (NoPCT). Thinning treatments at the nine sites with a prior PCT were a combination of multiple entry timings (immediate, 5-, and 10-year delay) and removal intensities (0, 33, and 50 % relative density reduction). At the six NoPCT sites, the CT treatments were a combination of thinning methods (dominant, crown, and low) and removal intensities (0, 33, and 50 %). The most effective CT in terms of large tree response, sawlog volume, and stand value were immediate CT rather than delayed treatments after PCT, and low thinning in NoPCT stands. Dominant thinning in NoPCT showed detrimental effects on residual stand conditions leading to the lowest yield and generated product values. In general, the earlier CT entry in PCT stands led to greater long-term benefits of the treatment in terms of tree size, merchantable volume, and financial value of the stand. No thinning treatment significantly enhanced cumulative total volume or merchantable volume or financial value compared to unthinned controls because even though thinning enhanced sawlog production, unthinned stands produced more pulpwood and studwood. Although we did not find significant economic benefits of CT in stands with or without PCT, light low thinning in NoPCT, and light crown thinning without delay in PCT could be an optimal strategy to maximize the average merchantable stem size without compromising the total stand value, while providing additional benefits to stand composition and generating mid-rotation revenue. Overall, the findings highlight some complexities and challenges with effective thinning regimes in highly shade-tolerant conifer species.

1. Introduction

The actual growth of a tree is largely determined by its local environmental factors; of these, water, nutrients, and light intensity are the most easily manipulated (USDA, 1985). Tree thinning is a widely used yet varied silvicultural practice applied worldwide to manipulate those environmental factors within forest stands (Zhou et al., 2016). Thinning increases the growth of residual trees by decreasing competition for light, water, and nutrients (Zeide, 2001; Cañellas et al., 2004; Bose et al., 2018b). However, numerous long-term studies have shown contrasting responses of different species to thinning, which can make developing general recommendations difficult (e.g. Bose et al., 2018b). Nevertheless, several studies have shown that while thinning may increase the diameter and volume for individual trees, it does not neces-

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sarily increase total production relative to unthinned stands (Curtis et al., 1997; Zeide, 2001; Cañellas et al., 2004; Mäkinen & Isomäki, 2004a, 2004b). Instead, total yield obtained during a rotation may be considerably reduced after heavy thinning that leaves stands understocked or if thinning is applied too late and trees respond slowly after losing crown size and vigor (Nyland, 2002). In general, it can be expected that individual tree volumes are greater at lower stand density, whereas stand volume is greater in stands with higher density (Ashton & Kelty, 2018; Gauthier & Tremblay, 2019; Postma et al., 2021). Thinning can also affect the value of residual trees by distributing and concentrating the total stand production on fewer stems with greater growth potential and desirable stem forms and characteristics. Consequently, the size, quality, and financial value per unit volume of wood in thinned stands may increase (Curtis et al., 1997; Kuehne et al., 2018).

One of the key aspects of thinning in relation to long-term volume production is the ability to alter typical stand dynamic patterns and shift competitive processes. For example, potential volume loss due to competition-induced mortality can be avoided by thinning to capture that volume before it is lost (Powers et al., 2010; Tappeiner et al., 2015). Therefore, a slight growth reduction may be acceptable when it is compensated by the production of valuable larger stem diameters and earlier income from thinnings (Mäkinen & Isomäki, 2004a). However, different silvicultural treatments have contrasting effects on the residual stands and can be difficult to generalize or predict, particularly in regions with mixed species compositions or highly varied site conditions (Kizha et al., 2021). The response of both individual trees and stands to thinning can vary with several complex yet highly interactive factors including thinning type, intensity, time since the last thinning, stand structure or age, and site conditions (Bose et al., 2018a). In particular, shade-tolerant conifers can have a more complex and varied response to thinning when compared to shade-intolerant species (Bose et al., 2018a). Consequently, long-term monitoring of replicated experimental designs in forest types composed of species with differing resource requirements is essential to generate a broader understanding of the influence of thinning on tree growth and stand yield (Gauthier & Tremblay, 2019).

The spruce-fir (*Picea-Abies*) forest, also known as northern coniferous forest, is distributed throughout the Acadian forest (Loo & Ives, 2003), which covers much of Northeastern United States and the Canadian Maritimes, including 2.4 million ha in the state of Maine, USA (Clune, 2013; USDA, 2019). The spruce-fir forest has a unique ecological and human history with more of its area under commercial timber management for sawlogs and pulpwood production than any other forest type in North America (Ferguson & Longwood, 1960; Seymour & Hunter, 1992). However, no consensus has been reached about issues such as thinning methods and timing, residual stocking level, or even if pre-commercial (PCT) and commercial thinning (CT) are desirable in spruce-fir stands (Sendak et al., 2003; Hiesl et al., 2015; Kuehne et al., 2016).

PCT is often conducted as an investment with the objective of improving the health and accelerating the growth of remaining trees by shifting species composition and lowering within stand competition for resources, thereby shortening the rotation age (Tappeiner et al., 2015; Ashton & Kelty, 2018; Reicis et al., 2020). This practice is commonly applied in spruce-fir forests and several studies have reported it as being effective in increasing timber value (Tong et al., 2005; Pitt & Lanteigne, 2008; Bataineh et al., 2013) and also maintaining desired species composition (Weiskittel et al., 2011b). Pitt et al. (2013a) assessed the effects of PCT on roundwood production and stumpage value in naturally regenerated balsam fir (*Abies balsamea* (L.) Mill.) dominated stands in New Brunswick. They observed production of more merchantable volume in PCT stands resulting in increased stumpage revenues by as much as 23 % compared to unthinned stands by the stand-age of 50 years (Pitt et al., 2013a). However, net present value (NPV) estimated at age of maximum sawlog production was similar between the PCT and unthinned stands (Pitt et al., 2013b). Thirty-two years after PCT in spruce-fir stands in central Maine, Weiskittel et al. (2011b) evaluated effects of PCT treatments on diameter distribution and species composition. They found more large trees and fewer small trees; and, more conifers and less hardwoods in treated plots than the control (Weiskittel et al., 2011b), which was similar to the findings of Bataineh et al. (2013). However, the generality of these prior long-term studies across the broader region remains relatively unassessed.

Given the widespread use of thinning in the northeastern US and Canada, there are relatively few studies assessing the effect of CT on tree and stand growth of spruce-fir forests in this region. Unlike harvesting of small saplings and poles in PCT, CT involves removal of larger trees that can also generate immediate revenue. There are a variety of CT methods available, which are primarily based on the crown or social position of the trees to be removed and retained. Generally, there are three distinct types of thinning based on tree social position: low, crown, and dominant (Ashton & Kelty, 2018). Pelletier and Pitt (2008) evaluated the influence of two methods of CT (low and crown) along with single, delayed single and double entries in white (*Picea glauca* (Moench) Voss) and red spruce (*Picea rubens* Sarg.) plantations in New Brunswick. They observed no overall gross total or gross merchantable volume gains or losses associated with any of the thinning treatments relative to the unthinned plantations. However, their study was conducted in intensively managed plantations, which are likely to respond differently than natural spruce-fir stands. Soucy et al. (2012) evaluated CT in naturally- regenerated black spruce (*Picea mariana* (Mill.) B.S.P.) stands in Quebec, Canada and observed less mortality and higher growth rates in thinned plots leading to 33 % more merchantable volume in heavily thinned plots (50 % basal area removal) than in unthinned control for the period covering 34–40 years after CT. More quantitative information across a broader array of site conditions is needed on how CT affects long-term outcomes in spruce-fir.

The long-term influences of PCT, particularly when combined with CT, are relatively unknown and commonly based on growth model projections (e.g. Saunders et al., 2008; Hiesl et al., 2017a). The University of Maine Cooperative Forestry Research Unit (CFRU) established the Commercial Thinning Research Network (CTRN) in 2000 to study the effects of CT in stands that had/had not received PCT (NoPCT) throughout the spruce-fir forest in Maine (Seymour et al., 2014; Kuehne et al., 2018). Saunders et al. (2008) analyzed the early data from the CTRN study and the Green River study in New Brunswick to assess the influence of various PCT and CT regimes in spruce-fir forests of the northeastern United States and eastern Canada. They found early CTs were more beneficial independent of whether the stand had received PCT or not. However, their study was based on the growth model projections across typical initial conditions for stands in the region. After 10 years since treatment application in CTRN study, Clune (2013) observed low and crown thinning being effective in producing larger stems, higher sawlog to pulpwood ratio, and greater financial value per unit volume than the control and dominant thinning in NoPCT stands. Clune (2013) also reported light thinning (33 % density reduction) without delay in treatment application was the most effective treatment in terms of tree-level diameter growth, and enhanced stand structure and financial value. Hiesl et al. (2017a; 2017b) projected future stand conditions and evaluated effect of CT on net present value (NPV), but did not find substantial economic benefit of CTs compared to unthinned control. However, Hiesl et al. (2017a; 2017b) assessments were constrained by the lack of growth response data, particularly for the delayed treatments. Now, with the full application of all treatments, and multi-year data measuring response, results of this study represent a longer-term assessment of a wider range of treatments across a broad geographic region. In addition, there are now markets for small-diameter logs named studwood, which can be sawn into dimensional lumber (but, unlike sawlogs, may not be suitable for production of boards). Studwood is less valuable than sawlog grades, but more valuable than pulpwood (Maine Forest Service, 2002).

The goal of our study was to assess the influence of thinning treatment type, intensity and timing on key stand-level key attributes. Specific objectives were to compare: (1) tree size, stand density, and diameter distributions among the treatments; (2) how treatments and time since treatment affect the availability of different products (sawlog, studwood, and pulpwood) and financial value of stands receiving CT and/or PCT; and (3) provide specific recommendations for future PCT and CT prescriptions based on the long-term findings. We expected that CT would result in greater tree size and production of higher value log grades.

2. Materials and methods

2.1. Study area and experimental design

We used long-term data from 15 study sites of the University of Maine's Commercial Thinning Research Network (CTRN). Located across diverse geographic regions around northern Maine (Fig. 1), these sites are within the Acadian forest, a conifer-dominated mixed-wood ecosystem that covers much of Maine and the Canadian Maritimes (Clune, 2013). The stands are dominated by red spruce (*Picea rubens* Sarg.) and balsam fir (*Abies balsamea* (L.) Mill.) where white spruce (*Picea glauca* (Moench) Voss), eastern white pine (*Pinus strobus* L.), black spruce (*Picea mariana* (Mill.) Britton, Sterns & Poggenb.), eastern hemlock (*Tsuga canadensis* (L.) Carrière) and northern white-cedar (*Thuja occidentalis* L.) are among conifer species. Hardwood species in the stands include red maple (*Acer rubrum* L.), yellow birch (*Betula alleghaniensis* Britton), paper birch (*Betula papyrifera* Marshall), and quaking aspen (*Populus tremuloides* Michx.). Drainage classes range from poorly to well-drained with common soils being podzols with glacial till and alluvium as parent material. Similarly, the elevations are between 44 and 652 m; mean annual temperature and precipitation range from 2.8 to 5.0 °C and 1046 to 1185 mm, respectively (Kuehne et al., 2018; Pekol, 2011).

The CTRN consists of two types of experiments: (1) thinning experiment on the stands that had received PCT (9 sites), and (2) on the stand that had no history of PCT (6 sites) (Fig. 1). The PCT stands were naturally regenerated either after shelterwood removal cutting or salvage clearcutting following the eastern spruce budworm (*Choristoneura fumiferana*) outbreak in 1970s-1980s. Released with herbicide, these stands received PCT to approximately 2–2.5 m spacing between the early 1980s to early 1990s. The NoPCT stands were primarily missed by the 1970s-1980s spruce budworm outbreak; thus, were much older. Stand age at the time of installation in NoPCT sites ranged from 33 to 73 years (mean = 55 year), whereas it was from 21 to 40 years (mean = 28 year) in PCT sites. Similarly, the site index in NoPCT sites ranged from 12.7 to 17.6 m (mean = 14 m), while it was from 16.2 to 22.2 m (mean = 19.2 m) in PCT sites. At the last measurement of each plot, the leaf area index (LAI) was 3.35 ± 1.37 with a range of 0.25 to 6.40 (Bhattarai et al., 2022).

Both PCT and NoPCT experiments were initially replicated in six sites each and three new sites were added in 2010 in the PCT experiment to provide a more continuous range of site quality throughout the experimental network. Experiments consist of 3 by 2 factorial combinations of treatments as each site had seven plots: six treated and one untreated (Table 1). Treatments in NoPCT were a combination of thinning methods (dominant, crown, and low) and intensities; whereas they were a combination of thinning timing (immediate, delayed 5 years, and delayed 10 years) and intensities in PCT. The thinning intensities were the levels of relative density reduction (RD) (33 or 50 %) based on the density management diagram of Wilson et al. (1999). The CT method on each plot of the PCT sites sought to retain an even spacing with the best possible residual trees while meeting the RD targets. Generally, spruce trees were retained over fir unless they were of poor quality, and all hardwoods were removed.

The low and dominant thinning treatments were defined as the removal of trees beginning at the lower or upper end of the diameter distribution, respectively, until the target reduction in relative density was achieved. In the crown thinning treatment, crop trees were selected at approximately-one third average tree height apart, followed by harvesting dominant and co-dominant competitors around each crop tree until desired residual density was reached (Kuehne et al., 2018). PCT sites

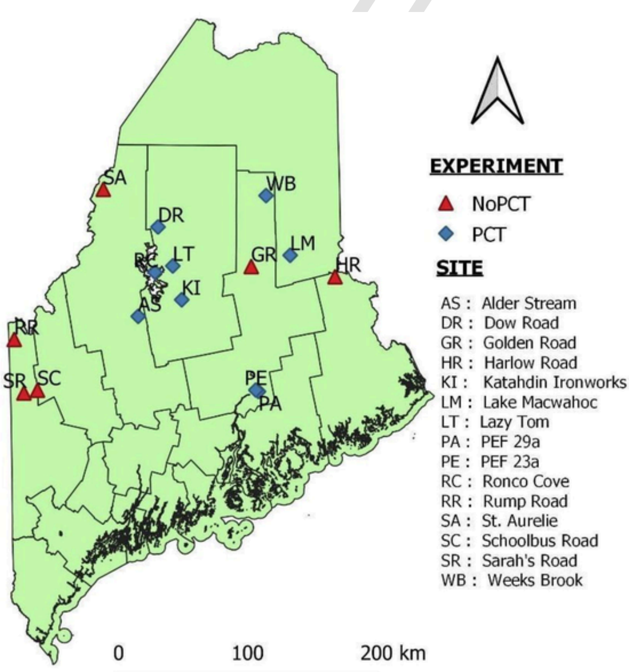

Fig. 1. Location of study sites.

Table 1
Description of treatments and actual removal intensity (% of total basal area) by study for the pre-commercially thinned (PCT) and not pre-commercially thinned (NoPCT) stands.

Treatments	Description	Actual removal (% of total BA): Mean ± SD (range)
(A) NoPCT		
LOW.33	Low thinning with 33 % RD reduction	20.8 ± 12.8 (2.5; 35.2)
LOW.50	Low thinning with 50 % RD reduction	40.5 ± 8.3 (30.0; 50.3)
CRN.33	Crown thinning with 33 % RD reduction	41.8 ± 8.7 (28.0; 52.3)
CRN.50	Crown thinning with 50 % RD reduction	55.4 ± 5.5 (49.5; 63.3)
DOM.33	Dominant thinning with 33 % RD reduction	45.7 ± 8.1 (37.1; 56.2)
DOM.50	Dominant thinning with 50 % RD reduction	59.3 ± 5.1 (51.8; 67.0)
Control	Unthinned	0.0 ± 0.0 (0.0; 0.0)
(B) PCT		
0YR.33	RD reduced by 33 % in 2001–2002	34.0 ± 8.2 (15.4; 43.6)
0YR.50	RD reduced by 50 % in 2001–2002	47.5 ± 3.2 (40.5; 51.3)
5YR.33	RD reduced by 33 % in 2006–2007	38.4 ± 4.1 (32.8; 45.4)
5YR.50	RD reduced by 50 % in 2006–2007	51.9 ± 5.2 (45.4; 60.0)
10YR.33	RD reduced by 33 % in 2011–2012	35.3 ± 2.8 (30.2; 38.0)
10YR.50	RD reduced by 50 % in 2011–2012	49.8 ± 2.4 (46.2; 53.0)
Control	Unthinned	0.0 ± 0.0 (0.0; 0.0)

In three most recent PCT sites, 0YR and 5YR treatments were conducted in 2010 and 2015, respectively. Actual removal was based on trees with diameter at breast height (DBH) ≥ 10.2 cm. RD = relative density; SD = standard deviation; BA = basal area.

were chosen based on stands ready for CT in either 2001–02 or 2009–2010, a well-stocked and single-cohort stand structure with relative density > 0.25 (Wilson et al., 1999) based on trees with DBH > 6.3 cm, and a good to excellent site quality (Hiesl et al., 2017a). The timing of CTs applied in the six initial PCT stands in either 2001–02, 2006–07, or 2011–12 were defined as immediate (0YR), delayed 5 years (5YR), and delayed 10 years (10YR) treatments, respectively (Seymour et al., 2014); and for the three new sites included in the study in 2010, the thinning timings for 0YR and 5YR treatments were 2010 and 2015, respectively. The 10 year delay treatments had not been applied in those three new sites until the last measurements of this study in 2018. Treatments in each PCT site were assigned based on plot ranking of initial RD. The plot with the median RD was selected as untreated control. Plots with first, second and third highest RD were assigned 33 % thinning of 0YR, 5YR and 10YR treatments, respectively. Similarly, plots ranked fifth, sixth and seventh received 50 % thinning of 0YR, 5YR and 10YR treatments, respectively.

Treatments were applied in square plots of 3716 m^2 and a measurement plot of 809 m^2 was nested at the center of each treatment plot that included a forwarder trail through the middle of it. Before the treatment, species and DBH of all trees > 10.2 cm DBH were recorded. Height and height to crown base (lowest live branch) were also measured for sub-samples representing all diameter classes. Missing heights were predicted using these measurements. Pretreatment measurements were made in 2000 and 2001 in the initial 12 sites and in 2009 for the three sites included in 2010 in PCT experiments. All sample plots were measured for DBH, total height, and crown height in the first season after thinning and each residual tree was tagged and numbered. In NoPCT, measurements were taken annually or semi-annually until 2013 and the last measurements in all sites was made in 2018. The initial six sites of PCT experiment were measured annually until 2013, while only one site (PEF 23a) was measured in 2016 and final measurement in all sites was done in 2018. Similarly, for the three most recent sites of PCT, measurements were made annually or semi-annually until the last measurement in 2018. In addition to DBH and status (alive, dead, and so on) of every tree, those regular inventories generated tree height and height to crown base (HCB) of a varying, randomly selected subsample (61 % on average) of trees at different years (Kuehne et al., 2016). Summary of stand information at the time of CT, just after CT and in 2018 have been presented in Supplemental Materials S1, S2, and S3, respectively.

2.2. Analysis

In order to predict and impute the missing heights, DBH and total height were fitted to a power equation (Equation 1) using mixed effects modeling with DBH as a fixed predictor and species, tree status, site, and plot as random effects.

$$H = b_0 D^{b_1}. \quad (1)$$

where H = total height (m), D = DBH (cm), b_0 and b_1 are regression coefficients. Quadratic mean diameter (QMD) for each plot was calculated as square root of mean squared diameter; average height of the 100 largest trees (by DBH) per ha was calculated as top height. We used a summation method to calculate stand density index (SDI) where the SDI represented by each tree was calculated from Equation 2 (Reineke, 1933; Shaw, 2000).

$$SDI = \left(\frac{DBH}{25.4}\right)^{1.605} \quad (2)$$

Similarly, we used 1425 as the maximum SDI (SDI_{max}) to estimate relative density, which is the ratio between SDI and SDI_{max} (Bose et al., 2018a; Wilson et al., 1999). Individual tree DBH and height were used to calculate the total and merchantable stem volumes using a Kozak (2004) taper function for the region (Li et al., 2012). We divided each tree into 100 sections and diameters were predicted at each section height, and then volume for each section was calculated using the Smalian's formula (Kershaw et al., 2017). Total volume for an individual tree was obtained by summing each section. For sawlogs, minimum DBH and top diameter were 22.9 cm and 19.3 cm, respectively; for studwood 12.7 cm and 10.2 cm, respectively; and for pulpwood 12.7 cm and 7.6 cm, respectively. For a tree that had DBH ≥ 22.9 cm, volume up to 19.3 cm top diameter was considered as sawlog; that in between the top diameters 19.3 cm and 10.2 cm was studwood and the volume in between 10.2 and 7.6 cm top diameters was pulpwood. Likewise, for the trees having DBH in between 12.7 cm and 22.9 cm, entire volume up to 10.2 cm and in between 10.2 cm and 7.6 cm top diameter were accounted as studwood and pulpwood, respectively. The stand's diameter distribution was determined using three-parameter Weibull distribution directly fitted with maximum likelihood with estimates of the scale and shape parameters based on each plot. Modeling diameter distributions in a forest stand with the Weibull function has been extensively used because of its flexibility and simplicity where the shape parameter controls slope of line and the scale parameter makes the curve wider or narrower (Cao, 2004).

Tree level data was summarized at the plot level and then expanded to per ha basis. Basal area and volume of different products removed from thinning were estimated by taking differences between pre- and post-treatment values. Removed volume was added to each year's measurement to get cumulative volumes for the respective years. Stand value was estimated using the average price of all years between 2001 and 2018 in Maine for sawlog (\$28.3 m^{-3}), studwood (\$21.5 m^{-3}) and pulpwood (\$9.2 m^{-3}) (Maine Forest Service, 2002). Conversion from \$ ton^{-1} to \$ m^{-3} was done using a conversion factor of 0.87 ton m^{-3} (Hiesl et al., 2017b).

A linear mixed-model analysis of covariance (ANCOVA) on the last measurement was used to evaluate the influence of treatments on the stand level attributes. Time since treatment (TST) and basal area prior to treatment were included as covariates to account for unequal post-treatment time and initial stand condition (basal area). Random effects for sites were included to account for variation from unknown sources that may have an effect on the dependent variables. Pairwise comparison tests among the treatments of the NoPCT experiment were performed using Tukey's method of multiple comparisons at 5 % level of significance ($p < 0.05$). Since treatments in PCT were applied in different years, the same TST for immediate (0YR), 5 year (5YR), and 10 year (10YR) delay was represented by different times. Therefore, mean values were adjusted for 16, 11, and 6 years TST (TST in 2018) and average basal area of 0YR, 5YR, and 10YR delay treatments, respectively.

For some comparisons due to reduced sample sizes, 95 % confidence intervals (CI) of mean ± the standard error (mean ± 2 × SE) were used to assess a difference between the treatments in the PCT experiment. In order to evaluate the effects of CT on stand-level attributes and different products over the period, mixed-effect analysis of linear regression was performed using measurements across all years. Performance of various model forms with and without interactions of the treatment, basal area prior to treatment (PreBA) and TST (Table 2)

Table 2
Model considered for the analysis of stand level attributes over the period.

Model form	Designation
$Y_{ij} = Trt_{ij} * TST_{ij} * PreBA_{ij} + u_i + u_{ij}$	M1
$Y_{ij} = Trt_{ij} * TST_{ij} + PreBA_{ij} + u_i + u_{ij}$	M2
$Y_{ij} = Trt_{ij} * PreBA_{ij} + TST_{ij} + u_i + u_{ij}$	M3
$Y_{ij} = Trt_{ij} * TST_{ij} + PreBA_{ij} + u_i + u_{ij}$	M4
$Y_{ij} = Trt_{ij} + TST_{ij} + PreBA_{ij} + u_i + u_{ij}$	M5

Y_{ij} = response variable, Trt_{ij} = Treatment, TST_{ij} = time since treatment, $PreBA_{ij}$ = basal area prior to treatment, u_i = random effects of i^{th} site; u_{ij} = random effects of j^{th} plot in i^{th} site.

were assessed with plot nested within site as random effects. Best models based on fit statistics: AIC, R^2, mean bias (MB), mean absolute bias (MAB), and percentage mean absolute bias (% MAB) for each stand attribute were selected for further interpretation. Homogeneity of variance and normality were verified for all analyses using residual plots. Square root or log transformations were used on some of the variables to meet homogeneity of variance and normality assumptions (Supplementary Materials S4 and S5). All analyses were implemented in R version 4.0.4 (R Core Team, 2021), using nlme (Pinheiro et al., 2021), multcompView (Spencer et al., 2019) and lsmeans (Lenth, 2016) libraries.

3. Results

3.1. Stand structure

Analysis of covariance (ANCOVA) indicated that the thinning treatments had significant effects on the stand structure attributes for both NoPCT and PCT stands. Average tree size varied among the treatments where heavy low and heavy crown thinnings resulted in stands with significantly higher QMD compared to unthinned stands and both of the dominant thinings ($p < 0.05$, Table 3). The greatest top height in LOW.50 was significantly different with dominant thinning. Heavy dominant thinning resulted in the lowest top height. Basal area per ha (BAPH) and relative density (RD) were significantly higher in control compared to all other treatments, except light low thinning. RD in the light low thinning was significantly higher than that of all other treatments except control. Within the same category of removal intensity, the BAPH and RD followed a consistent pattern of highest in low thinning followed by crown and dominant thinning. All treatments had significantly lower stem density than the control ($p < 0.05$). The commercial thinning treatments also had a significant effect on the diameter distribution of NoPCT stands. Scale parameters of the Weibull distribution for control and heavy dominant thinning were significantly smaller than that of both low and both crown thinning treatments. Shape parameters of heavy dominant thinning differed with both treatments of crown thinning and control.

Table 3
Adjusted mean of stand structure attributes by experiment and treatment.

Treatment	QMD (cm)	Top height (m)	Basal area (m^2/ha)	Relative density	Stem density (trees ha^{-1})	Weibull scale	Weibull shape
(A) NoPCT							
LOW.33	20.2bc	18.6c	35.2 cd	0.53 cd	1107b	21.4bc	4.7abc
LOW.50	22.8c	19.0c	24.6bc	0.35bc	604ab	24.2c	5.4bc
CRN.33	20.1bc	18.4c	23.8bc	0.35bc	759ab	21.4bc	3.5a
CRN.50	21.5c	18.0bc	19.4ab	0.28ab	546a	22.9c	4.0ab
DOM.33	17.7ab	16.8ab	20.7ab	0.33ab	850ab	18.8ab	5.5bc
DOM.50	17.6ab	16.1a	11.8a	0.19a	502a	18.6a	5.6c
Control	17.3a	18.8c	44.6d	0.70d	1895c	18.4a	4.1ab
(B) PCT							
0YR.33	23.3b	18.4a	31.7b	0.45b	714c	24.7 cd	5.5b
0YR.50	24.9b	18.5a	29.6b	0.41ab	596abc	26.4d	6.2b
5YR.33	21.7ab	17.9a	27.3ab	0.40ab	701c	23.0abc	5.6b
5YR.50	23.0b	17.7a	23.3ab	0.33ab	545ab	24.4bcd	5.5b
10YR.33	20.8ab	17.4a	24.6ab	0.37ab	712c	22.0ab	6.3b
10YR.50	22.6ab	17.6a	19.2a	0.28a	490a	23.9abcd	6.9c
Control	20.3a	18.7a	40.7c	0.61c	1335d	21.6a	4.6a

*a, b, c, d indicate adjusted means followed by the same letter(s) within a column were not significantly different ($p < 0.05$) using Tukey's multiple comparison test in case of NoPCT; and for the PCT, values followed by the same letters were not different, as indicated by overlaps between the confidence interval (mean $\pm$ 2 $\times$ SE) of their estimates.

Average tree size in PCT varied between treatments where the highest and lowest QMDs were in 0YR.50 and control, respectively (Table 3). Top height was greatest in unthinned control, however, the difference was very small and confidence intervals of all treatments overlapped. Unthinned stands had higher basal area, stem numbers, and, therefore, relative density than all of the commercially thinned PCT stands. All delayed treatments had overlapping CIs, whereas the CI of the lowest basal area in 10YR.50 did not overlap with 0YR treatments. The CT applied in the PCT stands also affected their diameter distribution. Both scale and shape parameters of the Weibull distribution were higher in treated stands compared to control.

Differences in QMD among the treatments were dependent on TST, removal intensity, and type or timing of thinning. For example, dominant thinning needed approximately 13 (for light removal) to 15 years (for heavy removal) of post-treatment growth to have a greater QMD than that of unthinned control (Fig. 2A). QMD in light crown thinning, which initially was well below the light low thinning, became approximately equal to the latter in about 15 years since treatment. In the PCT stands, QMD in different treatments also increased differently over the period (Fig. 2F). Both heavy removals of immediate and 5 years delay showed a rapid increase in QMD than that of other treatments. Over the period, trees were shifted to larger diameter classes with the shift more pronounced in crown and low thinning than in control and dominant thinning of NoPCT experiment (Fig. 3A). Similarly, CTs in PCT experiment shifted trees to larger diameter classes than in the unthinned control (Fig. 3B). The top height, basal area, and relative density increased, whereas number of trees decreased linearly in all thinned and unthinned stands for both NoPCT (Fig. 2B-2E) and PCT (Fig. 2G-2J) experiments over time. All models selected to describe the effect of treatments over the period on the stand structure attributes of NoPCT stands had generalized R^2 of the fixed effects above 0.63 and a R^2 above 0.90 and up to 0.98 when including the random effects of plot and site (Supplementary Materials S4). Similarly, models of all stand structure variables, except the Weibull shape parameter for PCT, had generalized R^2 of the fixed effects above 0.54 and a R^2 above 0.91 and up to 0.98 when including the random effects of plot and site. Mean absolute bias expressed as a percentage of measured value varied between 1.4 % (QMD & Weibull scale) and 9.6 % (stand density) in NoPCT and between 1.4 % (Weibull scale) and 5.5 % (basal area) in PCT (Supplementary Materials S4).

3.2. Volume and merchantability

In stands without prior PCT, both growing stock and cumulative volume of all products, except sawlogs, were highest for unthinned stands (Table 4). Multiple comparison tests indicated that growing stock total, merchantable, and studwood volumes in unthinned stands were significantly higher than that of all other treatments except light low thinning. Growing stock sawlog volumes (GSSV) in the NoPCT experiment were ranked as low thinning > crown thinning > control > dominant thinning, where the lowest volume in DOM.50 was significantly different than all other treatments. Crown and dominant thinning resulted in stands with higher GSSV in light removal than that of heavy removal of the same thinning, whereas the opposite occurred with low thinning. Cumulative sawlog volume (CSV) was highest in LOW.50, followed by CRN.33 and the lowest in DOM.50. The cumulative total and merchantable volumes were highest in control, but not significantly different compared to LOW.33, LOW.50, and CRN.33. Cumulative volume of studwood was highest in control, which was also statistically different with all treatments except LOW.33 and both of dominant thinnings. The highest cumulative volume of pulpwood in control was significantly different than all CTs in the NoPCT stands.

In PCT stands, the growing stock total and merchantable volumes were found to be highest in the unthinned control followed by 0YR.33 and the lowest in 10YR.50. Within the same category of removal inten-

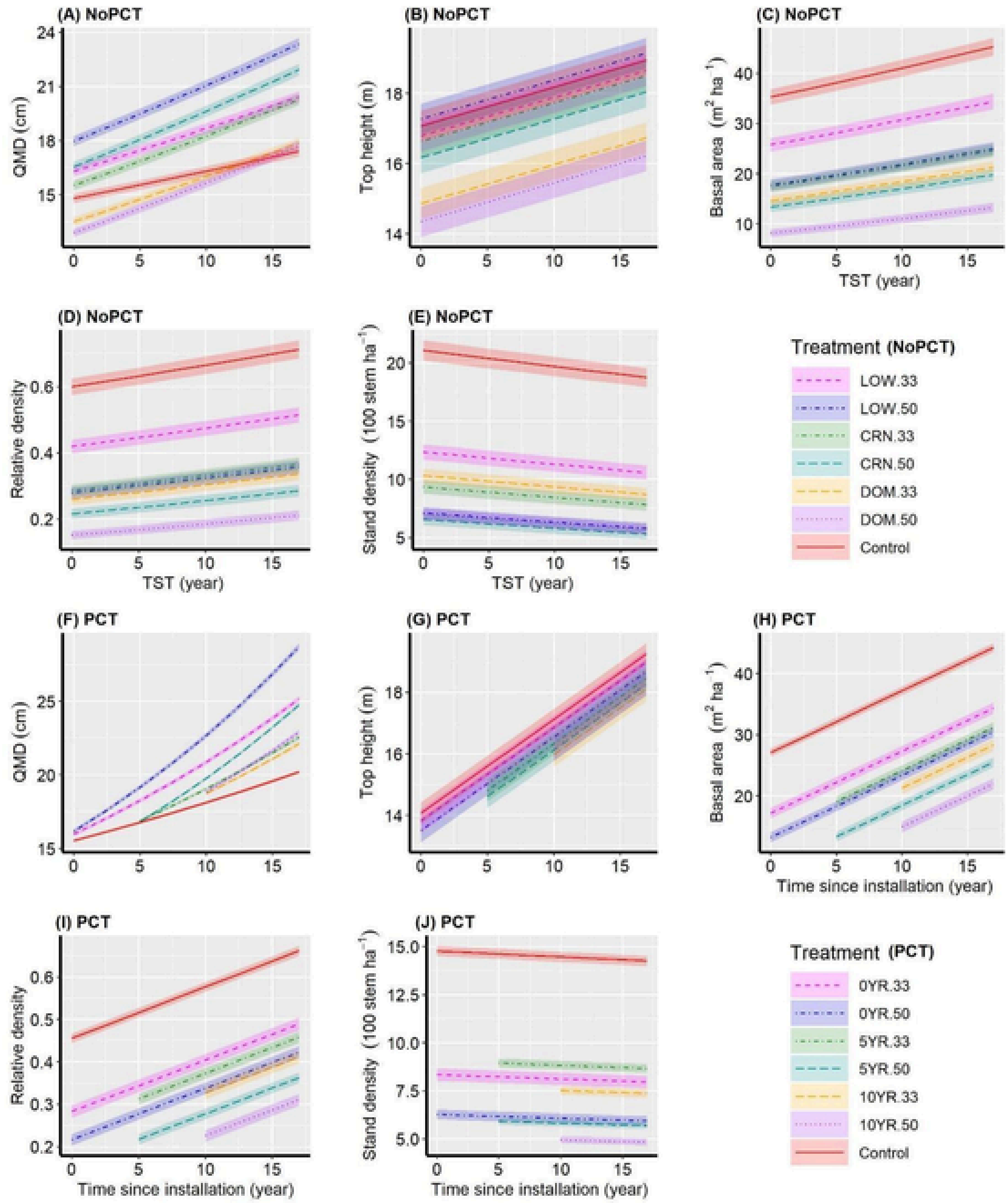

Fig. 2. Treatment wise predicted stand structure attributes for different TST and mean basal area prior to treatment (33 m^2/ha for NoPCT; and 24.6, 31.4, 35.5 m^2/ha for 0YR and control, 5YR, and 10YR treatments, respectively for PCT). Shaded areas correspond to ± 1SE calculated from the fixed effects of the respective models. The x-axis (time since installation) for PCT was equivalent to time since treatment (TST) for 0YR treatment.

sity, earlier thinning resulted in higher total, merchantable, and sawlog standing volumes. Similarly, GSSV was higher after earlier thinning regardless of the removal intensity. Immediate (0YR) treatments resulted in more GSSV than that of 10YR treatments. Within the same timings, GSSV was higher after heavy thinning. Studwood and pulpwood were highest in unthinned stands and lowest in 10YR.50. When removed volumes were added to the growing stock volumes, the difference in cumulative volumes of total, merchantable, and pulpwood between the treatments were quite small. Differences in volume of different products among the treatments were dependent on time since treatment, removal intensity, and type or timing of thinning. All treatments of both PCT and NoPCT experiments showed a steady increase in total (Fig. 4A and 4F) and merchantable volume (Fig. 4B, 4G); and decline in pulpwood volume over the period (Fig. 4E and 4J). Studwood volume also increased steadily for all treatments of NoPCT over the period, whereas it exhibited a trend of increasing for control and 0YR treatment, more or less constant for 5YR and decreasing for 10YR treatments (Fig. 4I).

In both PCT and NoPCT experiments, total, merchantable, and studwood volumes in control remained well above all treatments, whereas the sawlog volume changed more dramatically over the period. For example, sawlog in all four treatments of the low and crown thinning in NoPCT increased more rapidly and remained above the control approximately 5 years following CTs (Fig. 4C). The sawlog volume in both of the dominant thinning treatments remained well below all other treatments, including control through the period. In PCT, post-treatment growth of approximately 5 years for immediate, 8 and 10 years for light and heavy thinning of 5 year delay, respectively, was needed to generate sawlog volumes approaching those in the unthinned

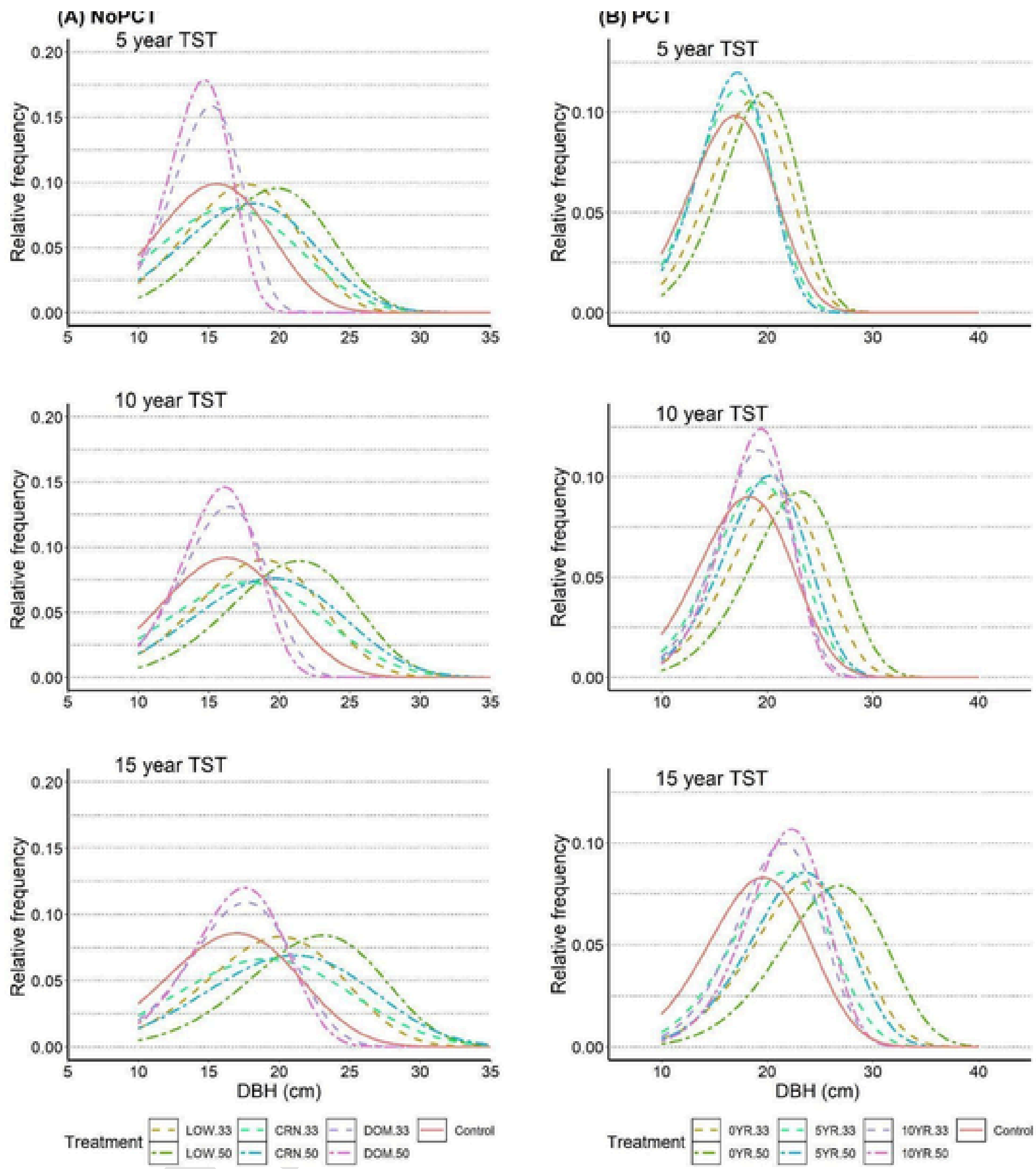

Fig. 3. Predicted Weibull curves of diameter distribution by experiment and treatment: column 'A' NoPCT and column 'B' PCT for 5, 10, and 15 years post thinning from top to bottom, respectively. For PCT, TST for all treatments were in reference to 0YR treatment. For example: interpretation for "15YR TST" of the bottom right figure should be "15 year Time Since Treatment" for 0YR, "10 year TST" for 5YR and "5 year TST" for 10YR treatments; all three figures of PCT should be interpreted in this way.

control (Fig. 4H). Models selected to describe the effect of treatments on the volume of different products including total and merchantable volume of NoPCT experiment over the study period had generalized R^2 of the fixed effects of 0.71 to 0.77 and a R^2 between 0.91 and 0.97 when including the random effects of plot and site. Similarly, generalized R^2 of fixed effects of the models selected for different products of PCT experiment ranged between 0.57 & 0.85 and a R^2 between 0.87 & 0.96 when including the random effects (Supplementary Materials S5).

3.3. Stand value

In the absence of prior PCT, heavy commercial thinning resulted in lower, but not significantly different growing stock stand value (GSSTV) compared to light thinning of the same thinning type. When revenue from CT was added to the GSSTV, the cumulative stand value (CSTV) was also highest in control, but it was not significantly different with all low and crown thinning treatments (Fig. 5B). Heavy dominant thinning gave lower CSTV than the control and light low thinning. Thus, the CSTV of the treatments in the NoPCT stands were ranked: Control > LOW.33 > LOW.50 > CRN.33 > CRN.50 > DOM.33 > DOM.50.

GSSTV in the PCT experiment was highest in the unthinned stands and both of the immediate thinning treatments (Fig. 5C). Light immediate CT had a higher (non-overlapping CI) stand value compared to both 10 year delay thinnings. Light thinning had higher, but overlapping CI of the GSSTV value compared to heavy thinning of the same timings. GSSTV was also higher when the earlier thinning treatments were applied, regardless of thinning intensity. However, all four delayed treatments did not indicate a clear difference in GSSTV. In contrast to GSSTV, CSTVs in immediate and 10 year delay were slightly higher in heavy thinning compared to light thinning of the respective timings (Fig. 5D). The CSTVs were also higher in earlier treatments than the delayed treatments. However, their CI did not indicate differences in the cumulative stand values between any treatments of the PCT stands.

Table 4
Adjusted mean of growing stock and cumulative volume of different products for NoPCT (A), and PCT (B).

	Growing stock volume (m³ ha⁻¹)					Cumulative volume (m³ ha⁻¹)				
Treatment	Total	Merch.	Saw.	Stud.	Pulp.	Total	Merch.	Saw.	Stud.	Pulp.
(A) NoPCT										
LOW.33	276.7cd	258.6cd	76.5b	163.6bc	11.1a	329.5bc	305.8bc	78.5b	182.3bc	22.7b
LOW.50	202.4bc	190.2bc	85.9b	97.4a	4.4a	295.0bc	271.4abc	86.1b	143.3ab	22.6b
CRN.33	184.8bc	172.5bc	77.6b	85.3a	11.8a	286.8abc	265.4abc	85.8b	151.2ab	14.6ab
CRN.50	148.3ab	138.8b	72.6b	61.0a	6.9a	274.1ab	252.2ab	83.2b	132.4a	17.9b
DOM.33	150.9b	139.9b	15.5a	108.4ab	12.5a	267.6ab	252.7ab	48.3ab	170.6abc	13.4ab
DOM.50	82.2a	76.0a	4.0a	63.0a	6.9a	234.9a	220.5a	23.4a	163.6ab	8.6a
Control	350.9d	324.6d	59.6b	220.4c	34.9b	352.3c	325.8c	59.4ab	222.0c	36.4c
(B) PCT										
0YR.33	236.3b	221.3cd	118.0d	97.9a	5.7abc	282.2a	261.8a	123.0cd	122.2ab	11.0a
0YR.50	222.7b	208.9cd	127.9d	74.0a	4.3a	285.7a	265.1a	128.5d	113.8a	12.4a
5YR.33	201.3ab	188.1abc	71.4bc	100.4a	6.9c	269.9a	250.3a	82.9b	143.0abc	16.8a
5YR.50	170.6ab	159.7abc	74.9bc	69.5a	4.5ab	265.9a	246.3a	90.8bc	128.1abc	18.3a
10YR.33	172.6ab	161.1abc	45.2a	107.6a	6.4b	255.2a	236.1a	54.8a	158.9bc	18.9a
10YR.50	138.0a	129.1a	52.2ab	66.8a	3.9a	259.6a	241.1a	74.7ab	143.5abc	16.3a
Control	292.4c	271.1d	80.0c	163.6b	16.5d	292.8a	271.3a	76.3ab	163.3c	17.3a

Merch. = merchantable volume; Saw. = sawlog volume; Stud. = studwood volume; Pulp. = pulpwood volume. Letters a, b, c, d in adjusted means indicate values followed by the same letter(s) within same column were not significantly different ($p < 0.05$) using Tukey's multiple comparison test in case of NoPCT; and for the PCT, values followed by the same letters were not different as indicated by overlaps of the confidence intervals (mean ± 2 × SE) of their estimates.

4. Discussion

CT in spruce-fir stands with or without a prior PCT influenced stand structure, volume, and log grades, but did not enhance cumulative value of the harvested and standing volume when compared to unthinned control. Older spruce-fir stands that had not received PCT prior to CT responded positively to low thinning, whereas substantial reduction in tree size, total and merchantable volumes, and total stand value were the consequences of dominant thinning in these stands. Delaying CT after prior PCT in younger spruce-fir stands did not show any benefit in terms of tree size, increased merchantable volume, and stand value when compared to unthinned control. There were similarities and differences in the stand level response to CT between our study and prior studies are further outlined below.

4.1. Stand structure

Effects of CT on different stand attributes may be varied yet are also dependent on various factors including the amount of growing stock before and immediately after thinning, type of thinning, stand age, the time since thinning, and productivity of the site (Weiskittel et al., 2011a). Our results indicated that 16–18 years after CT, the QMDs following low and crown thinning treatments were 24 and 20 % higher than in the unthinned control, respectively. Similarly, the QMDs following 0YR, 5YR, and 10YR delay thinning treatments were on an average 19, 10, and 7 %, higher compared to the control, respectively. This increase in mean diameter was related to the diameter distribution being shifted towards larger diameters over time. Low and crown thinning shifted the trees to larger diameter classes more rapidly than the unthinned control, while dominant thinning was less responsive in terms of shifting trees to larger size classes. Similarly, earlier thinning treatments in PCT stands were more effective than delayed ones in terms of producing larger trees. Within the same type and/or timings, heavy thinning shifted a greater proportion of trees into larger size classes compared to light thinning.

In general, these results are consistent with prior studies in the region. For example, 35 years after PCT with two different intensities in balsam fir stands, Zhang et al. (2009) observed average diameter in heavy and light thinning treatments increased by 41.1 and 15.8 %, respectively compared to control. Thirty-two years after PCT in spruce-fir stands in central Maine, Weiskittel et al. (2011b) also found that treated stands had more large trees and fewer small trees than the unthinned stands. Similarly, production of larger trees in heavily thinned stands compared to less-heavily thinned or unthinned stands have been confirmed by several studies including Gauthier & Tremblay (2019) in a jack pine (*Pinus banksiana* Lam.) stand in Quebec, Canada and Mäkinen & Isomäki (2004a), in Norway spruce (*Picea abies* (L.) Karst.) in Finland.

Ten years after CT in the spruce-fir experiment used in the present study, Clune (2013) observed an increase in QMD of 23 % over the control in NoPCT stands, while it was 17 % higher after PCT and CT. Pelletier & Pitt (2008) observed QMD 10 % greater than the controls 16–17 years after CT in white spruce (*Picea glauca* (Moench) Voss) plantation. However, it should also be noted that depending upon the type of thinning, QMD of the stand after CT could increase, decrease or remain the same (Weiskittel et al., 2011a). After low thinning treatments, higher QMD resulted in part from removal of small trees during CT and in part from accelerated growth. Similarly, dominant thinning had the lowest QMD since the largest trees were removed. Thinning treatments altering size distributions of trees not only affect stand structure but may also affect stand value following thinning (Clune, 2013; Hu et al., 2020).

The diameter growth of residual trees can be drastically increased by thinning, while there is typically little effect on height growth (Ashton & Kelty, 2018). Our result showed top heights after dominant thinning were reduced on average by 14 % compared to the control. However, the top heights between both intensities of both low and crown thinning were not significantly different than that of the unthinned control. Stem density remained consistently lower than unthinned controls following all CT treatments.

4.2. Volume, merchantability, and stand value

After 16–18 years of response to CT with and without prior PCT, we observed lower total and merchantable growing stock volumes in all CT stands compared to the control. Stand yield is strongly related to plant population density and/or stocking level of the stand (Curtis, 2006; Repola et al., 2006; Soucy et al., 2012; Moreau et al., 2020; Postma et al., 2021). Increasing stand density generally increases total, but decreases per tree volume (Postma et al., 2021). After heavier thinning, the growing space remains unoccupied for a long period leading to reduction in total yield of the stand (Ashton & Kelty, 2018). In coastal Douglas-fir (*Pseudotsuga menziesii* var *menziesii* (Mirb.) Franco) stands with eight different levels of growing stock after thinning, Curtis (2006) observed highest volume growth and yield in the highest stocking lev-

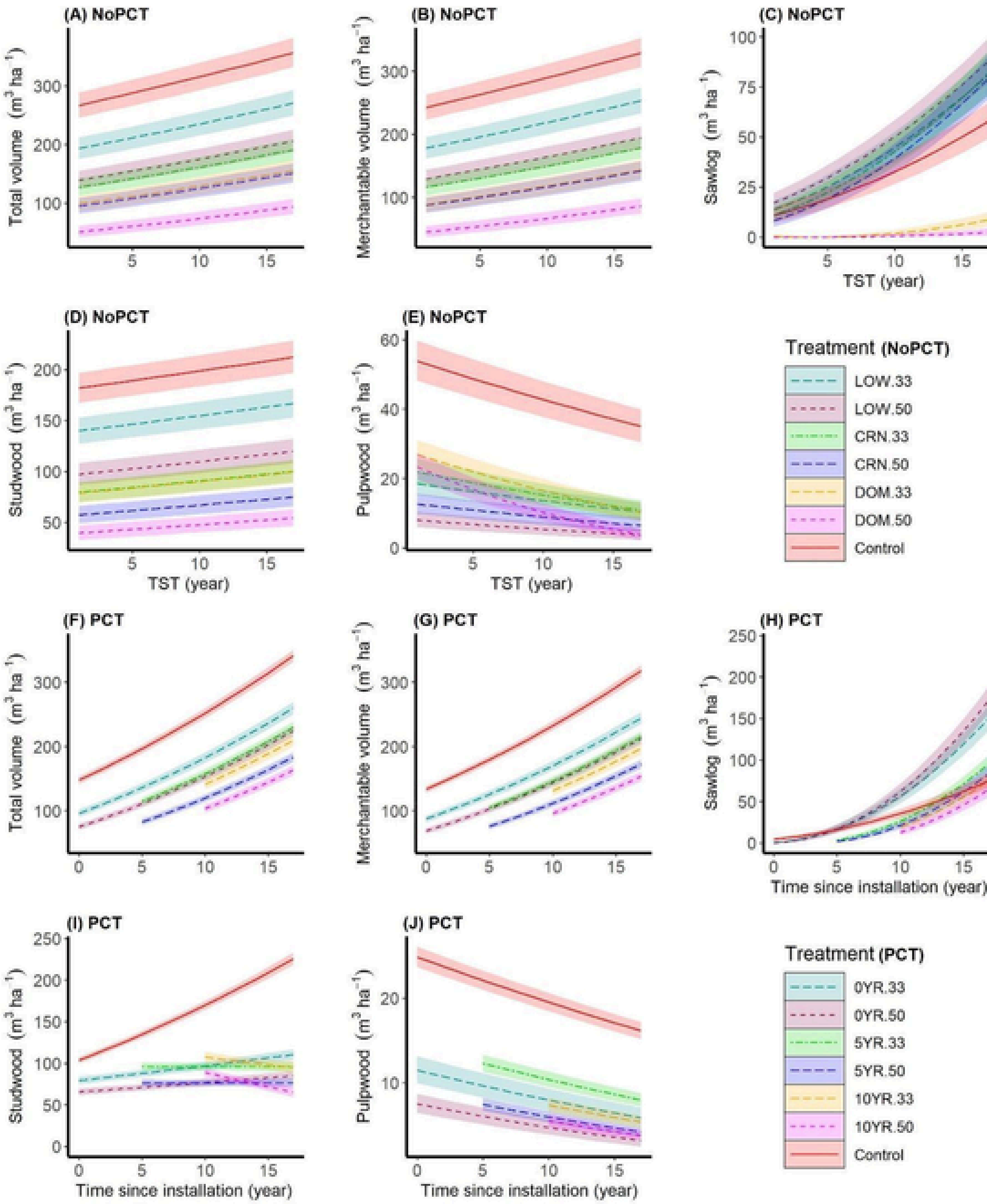

Fig. 4. Treatment wise predicted growing stock volumes of different products for different TST and mean basal area prior to treatment (33 m^2/ha for NoPCT; and 24.6, 31.4, 35.5 m^2/ha for 0YR and control, 5YR and 10YR treatments, respectively for PCT). Shaded areas correspond to ± 1 SE calculated from the fixed effects of the respective models. The x-axis (time since installation) for PCT was equivalent to time since treatment (TST) for 0YR treatment.

els. Similar results were reported from different parts of the world, for example, jack pine (*Pinus bankisiana* Lamb.) in Quebec, Canada (Gauthier & Tremblay, 2019), Scots pine (*Pinus sylvestris* L.) (Mäkinen & Isomäki, 2004a) and Norway spruce (*Picea abies* (L.) Karst.) (Mäkinen & Isomäki, 2004b) in Finland and Japanese cedar (*Cryptomeria japonica*) in Japan (Negishi et al., 2020).

When removed volumes were added to the standing volume, cumulative total volume (CTV) in the unthinned control of the NoPCT experiment was still significantly higher compared to both dominant and heavy crown thinnings. We expected that dominant thinning would result in less stocked stands compared to other thinning types, even though our dominant species had high shade tolerance and possibly greater ability of smaller trees to respond well to thinning. The low yield (both growing stock and cumulative) from the dominant thinned stands might be associated with the higher post-CT mortality (mainly blowdown) observed in some of these stands compared to unthinned and low thinning treatments, as observed by Pekol (2011). In a Douglas-fir stand, Emmingham et al. (2007) also found low thinning performing better in terms of maximizing stand growth and minimizing mortality loss compared to a thinning treatment that involved the removal of dominant and co-dominant trees. Compared to low thinning, Powers et al. (2010) also observed a higher mortality in red pine (*Pinus resinosa* Ait.) stands that received dominant thinning. Despite the shade-tolerance of red spruce and balsam fir, our findings are consistent with responses of less tolerant species (Pekol, 2011; Emmingham et al., 2007).

Despite total volume being highest in the unthinned control, the CTs generally resulted in stands with higher sawlog volumes in both NoPCT

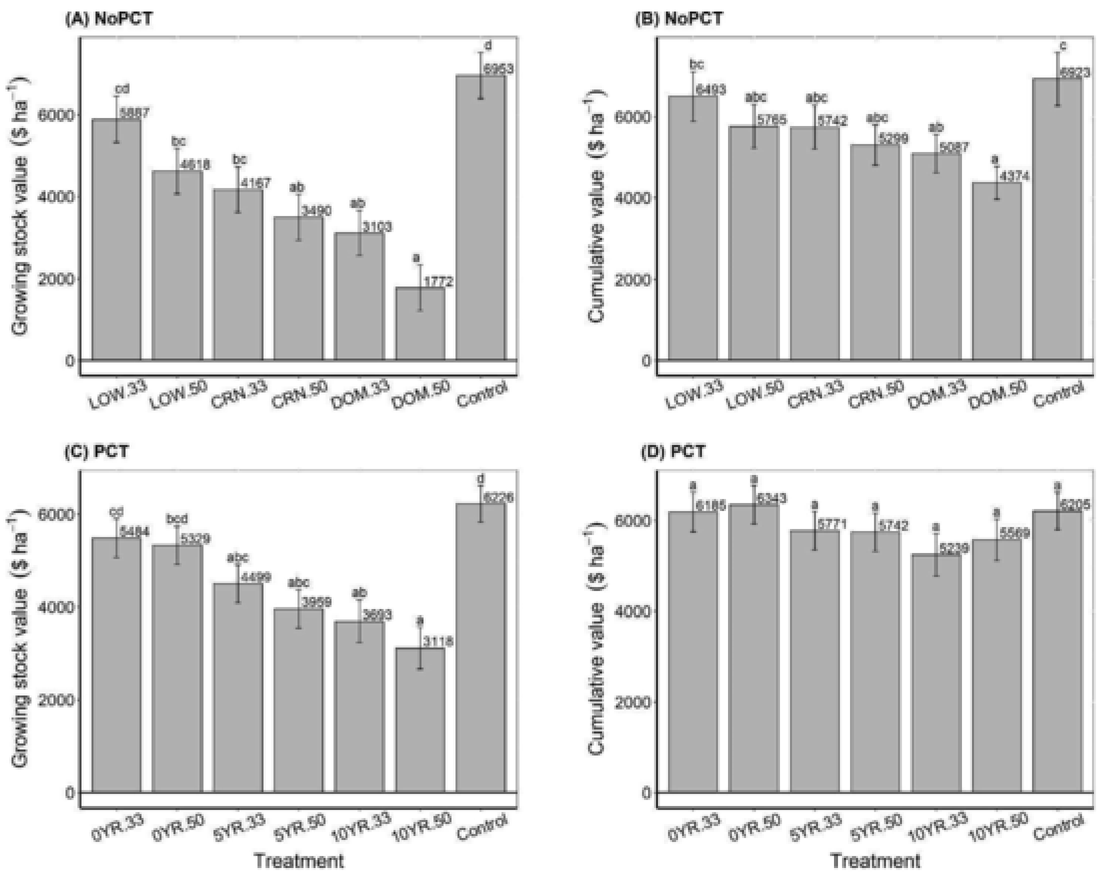

Fig. 5. Growing stock and cumulative stand value ($ ha-1) for all treatments and control including error bars (±1 standard error). Same letters above the error bar indicate significantly different ($P < 0.05$) values using Tukey's multiple comparison test in case of NoPCT; and for the PCT, values followed by the same letters were not different as indicated by overlaps of the confidence intervals (mean ± 2 × SE) of their estimates.

and PCT experiments. Heavy low thinning in NoPCT and immediate heavy thinning in PCT stands were most effective in terms of shifting stand growth towards sawlog production in spruce-fir stands. This is consistent with Soucy et al. (2012) who found 33 % more merchantable volume after heavy thinning compared to unthinned plots 34–40 years after CT in upland black spruce in Quebec, Canada. In their study, the difference was associated with both higher growth rates in thinned plots and much larger wind losses in unthinned controls (Soucy et al., 2012). Similarly, 47 years after PCT in balsam fir stands in New Brunswick, Pitt et al. (2013a) observed production of 26 % more merchantable volume and 28 % more sawlog volume in PCT stands compared to unthinned stands. High volume production in unthinned control stands at high relative densities may be desirable, but also may bring elevated risk of forest health problems (Veteli et al., 2006) and produces lesser log grades due to the smaller average tree size. Heavy thinning might have consequences of decreased wood quality or sawmill recovery by decreasing slenderness (Mäkinen & Isomäki, 2004b; Zhang et al., 2009).

When sawlog volume removed in CTs was added to the standing sawlog volume, average cumulative sawlog volume of low and crown thinning treatments were on average 40 and 133 % higher compared to control and dominant thinning, respectively. We observed both growing stock and cumulative volume of studwood (the next most valuable product after sawlog) highest in unthinned controls for both NoPCT and PCT stands. Similarly, both growing stock (PV) and cumulative pulpwood (CPV) volumes in NoPCT and PV in PCT were higher in unthinned control than the thinned treatments, whereas we did not observe clear effect of CT treatments on CPV in the PCT stand. These results suggested that CT treatments, except those that involved removal of dominant trees of NoPCT and 10 year delay of PCT, were effective in producing larger trees that can be utilized as sawlogs, probably the product most preferred by any manager due to its higher price compared to other products. Conversely, total merchantable volumes including studwood and pulpwood can be maximized without CT. Therefore, there is a trade-off between sawlog and total merchantable volume production under these CT treatments.

In order to evaluate the overall effects of CTs, we estimated a specific financial value of each product and then summed those to obtain both growing stock as well as cumulative stand value. Our results indicated that the highest growing stock stand value (GSSTV) in the control of NoPCT stands was significantly different from all treatments, except the light low thinning. The next highest GSSTV was present in the light low thinning treatment, which was 18 % lower than in control. Lowest growing stock value in heavy dominant thinning was significantly different than both treatments of low thinning and light crown thinning ($p < 0.05$). When revenue from the removals of CTs were added to the growing stock value, the differences in cumulative stand values (CSTV) between the treatments were greatly reduced. However, the intermediate revenue was not sufficient to compensate for the reduced stand value in thinned stands yet the highest CSTV in unthinned stands was not significantly different from all thinned stands except that received dominant thinning. Pitt et al. (2013a) observed increased stand value in balsam fir stands that received PCT by as much as 23 % compared to unthinned stands by the stand-age of 50 years. However, another study on these stands estimated similar net present value (NPV) from both thinned and unthinned stands at the ages when mean annual increments (MAIs) of sawlogs were maximized (Pitt et al., 2013b). Clune (2013) analyzed data from the same stands that we used for our analysis, separately for 5 and 10 years following CT and found that total stand value in all treatments, including control were not significantly different to each other at 5 years since CT, whereas 10 years after CT, the stand value in DOM.50 was significantly lower compared to control, LOW.33 and CRN.33. Among six CT treatments, Hiesl et al. (2017b) also reported that the low-thinning was best in terms of projected maximum net present value (NPV) which could also be obtained earlier compared to other treatments. However, the maximum projected NPV for light low thinning was 10 % lower compared to unthinned control. Our study along with the previous studies (Clune, 2013; Hiesl, 2017b) suggest that light low thinning could be an optimal strategy of producing large sized valuable logs from the naturally regenerated spruce-fir stands in Maine that have not received PCT, whereas dominant thinning in these stands has a detrimental effect on the total yield and stand value.

After PCT in spruce-fir stands, managers have the choice of CT or waiting until final harvest with little impact on overall growing stock value or cumulative stand values. Based on the timing of common CT prescription (i.e., favor spruce, even spacing) uniformly applied across all plots and sites in the PCT experiment, growing stock values were ranked: 0YR > 5YR > 10YR. However, there was no clear difference in GSSTV between all delayed CTs. When revenue from the removals of CTs were added to the growing stock value, the differences in cumulative stand values (CSTV) between the treatments were greatly reduced with overlapping CI of all treatments including control. Using 10 years of data gathered after implementing the same CT experiment, Clune (2013) found that treatment 0YR.33 had the highest total stand value which was not significantly different from the unthinned control and other treatments except the heavy delayed CT. Hiesl et al. (2017a) projected future stand conditions from the measurements taken in 2012 for 35 years and analyzed the effects of CTs on NPV each year. There was no benefit of delaying CT or removing more volumes in CTs in terms of maximizing NPV for these stands (Hiesl et al., 2017a). In our study of CT after PCT, the choice of thinning method favoring spruce by removal of fir may have influenced results. For example, preferentially cutting fir trees that were generally larger than spruce leaves a residual stand with smaller growing stock that may respond more slowly but is expected to live longer and produce more valuable sawlogs at rotation (Seymour & Hunter, 1992; Meng & Seymour, 1992).

It is important to note that the product specifications in our study and previous studies in these stands were not consistent. Stand values in all three of the previous studies in these stands (Clune, 2013; Hiesl et al., 2017a, 2017b) were based on quantity of sawlog and pulpwood, but they used different rules for product specifications. Clune (2013) considered volume until 10.2 cm top diameter as sawlog and until 5.1 cm top diameter as pulpwood, whereas it was 19.1 cm and 10.2 cm, respectively for the sawlog and pulpwood in Hiesl et al. (2017a, 2017b). Sawlog specification in our study was similar to Hiesl et al. (2017a, 2017b), which was also consistent with the merchantability specification of the prevalent growth and yield model for the region, the Forest Vegetation Simulator (FVS; Dixon, 2002). Since mills in Maine are also accepting small timbers as studwood at a far better price compared to pulpwood, we defined volume in between 19.3 and 10.2 cm top diameters as studwood and the volume in between 10.2 and 7.6 cm top diameters as pulpwood. Due to the high difference in the stumpage rates of these products, merchantability specification greatly affects the total stand value. Per unit price of sawlog volume in our estimates was 1.3 and 3.1 times of studwood and pulpwood, respectively. Similarly, the unit price of studwood was 2.3 times of the pulpwood. In addition, there was also a high variation in the stumpage rates over the period and we used the mean of the all years between 2001 and 2018. Inter-product price variations over the period was also not consistent; for example, average of last five years (2014 to 2018) stumpage prices for sawlog and studwood were 21 and 10 % higher, respectively, whereas that of pulpwood was 20 % lower than the average of all years between 2001 and 2018. Since detailed financial analysis was outside the scope of this study, we did not adjust the stand value neither for management cost, including that occurred during CTs and nor for the early income from CTs. Further assessment of the factors affecting price of these products will help make management decisions on when to harvest these stands with maximum return.

Our study covered a wide range of stand ages and site quality throughout northern Maine, therefore, our results have a broad geographic scope of inference. However, PCT sites tended to be on higher quality sites and these stands were younger at the time of CT. Therefore, we do not recommend comparing results of PCT and NoPCT analysis. Variability among and between sites in terms of initial stocking resulted in inconsistency in the removal rate as well as the residual stand condition even within the same treatment type, which might have increased uncertainty in our results. Incorporating removal as a continuous variable and measures of site quality in the analysis might be helpful to further improve the understanding of treatment response of these stands.

5. Conclusion

Our primary finding is that after 16–18 years of CT in both PCT and NoPCT stands, those treatments have resulted in reduced stand density (stem number, basal area, and relative density), total volume, and merchantable volume. While low and crown CT treatments are beneficial in terms of increased tree size and sawlog volume production, dominant thinning has substantial negative impacts both on stand structure and yield of the older spruce-fir stands that were not PCT. Delaying CT does not have any benefit in terms of tree size, increased merchantable volume, and stand value of the relatively young PCT spruce-fir stands.

Regardless, there is an important trade-off between sawlog and total as well as merchantable volume production under these CT treatments. Despite reduced volume of valuable sawlogs in the stands without CT, yield of small-wood is highest in the unthinned stands. The contribution of sawlogs to the total stand value of thinned stands is not enough to compensate for the reduced value due to lower quantity of studwood and pulpwood in these stands. Assuming that market conditions, merchantability specifications, and relative prices of the products (sawlog, studwood, and pulpwood) do not change dramatically, the economic benefits of CT over unthinned stands are not realized until 16–18 years after treatment. However, the technical rotation age, where an objective is to attain a threshold minimum tree size can substantially be shortened by low or crown thinning treatments. In addition, CT not only reduces rotation age, but it also increases the abundance of spruce/fir advance reproduction, which may increase the probability of regenerating a spruce-fir stand (Olson et al., 2014). Most importantly, the decision on whether or not to implement CT depends on the landowner's objectives to prioritize the production of larger stems for sawlogs or maximize the total merchantable volume regardless of tree size. This is particularly important to consider if long-term carbon sequestration and value are also considered (e.g. Puhlick et al. 2020,). Overall, the findings showcase the complexity and diversity of response of shade-tolerant species to both PCT and CT.

Uncited references

Puhlick et al. (2022), USDA (2019).

CRediT authorship contribution statement

Bishnu Hari Wagle : Conceptualization, Methodology, Formal analysis, Visualization, Writing – original draft. **Aaron R. Weiskittel :** Conceptualization, Funding acquisition, Methodology, Supervision, Writing – review & editing. **Anil R. Kizha :** Funding acquisition, Methodology, Supervision, Writing – review & editing. **John-Pascal Berrill :** Methodology, Writing – review & editing. **Anthony W. D'Amato :** Writing – review & editing. **David Marshall :** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2022.120453.

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