Canadian Journal of Forest Research
Revue canadienne de recherche forestière

**EVALUATING THE LONG-TERM INFLUENCE OF ALTERNATIVE
COMMERCIAL THINNING REGIMES AND HARVESTING
SYSTEMS ON PROJECTED NET PRESENT VALUE OF
PRECOMMERCIALLY THINNED SPRUCE-FIR STANDS IN
NORTHERN MAINE**

Journal:	<i>Canadian Journal of Forest Research</i>
Manuscript ID	cjfr-2016-0228.R2
Manuscript Type:	Article
Date Submitted by the Author:	24-Oct-2016
Complete List of Authors:	Hiesl, Patrick; Clemson University, Department of Forestry and Environmental Conservation Crandall, Mindy; University of Maine, School of Forest Resources Weiskittel, Aaron; University of Maine Benjamin, Jeffery; University of Maine, School of Forest Resources Wagner, Robert; University of Maine
Keyword:	Commercial thinning, New England, Net Present Value, Harvesting System, Spruce/Fir

SCHOLARONE™
Manuscripts

**EVALUATING THE LONG-TERM INFLUENCE OF ALTERNATIVE COMMERCIAL THINNING
REGIMES AND HARVESTING SYSTEMS ON PROJECTED NET PRESENT VALUE OF
PRECOMMERCIALLY THINNED SPRUCE-FIR
STANDS IN NORTHERN MAINE**

Patrick Hiesl^{1a}, Mindy S. Crandall¹, Aaron Weiskittel¹,
Jeffrey G. Benjamin¹, and Robert G. Wagner¹

¹ University of Maine, School of Forest Resources, 5755 Nutting Hall, Orono, ME 04469

Email addresses:

PH (phiesl@clermson.edu), MSC (mindy.crandall@maine.edu), AW
(aaron.weiskittel@maine.edu), JGB (jeffrey.g.benjamin@maine.edu), RGW
(robert.wagner@maine.edu)

Corresponding Author:

Patrick Hiesl
Clemson University
Department of Forestry and Environmental Conservation
261 Lehotsky Hall
Clemson, SC 29634

Phone: 864-656-7293
phiesl@clermson.edu

^a Assistant Professor of Forest Operations, Clemson University, Department of Forestry and Environmental Conservation, 261 Lehotsky Hall, Clemson, SC 29634, Phone: (864) 656-7293, phiesl@clermson.edu

ABSTRACT

Commercial thinning (CT) is an important silvicultural practice in the northeastern US. Relatively little is known, however, about the interaction of harvest system and treatment (removal intensity or timing of entry) on the overall profitability of CT. To address this question, ten-year measurements from a controlled CT experiment across six sites in Maine were used to project the long-term effect of removal intensity (33% and 50% relative density reduction) and timing of entry (no-delay, 5-year delay, 10-year delay) on: (1) maximum net present value (NPV), (2) timing of maximum NPV, and (3) the effect of three harvesting systems (cut-to-length, whole-tree, hybrid system) on maximum NPV. A regional growth and yield model was used to project individual-tree growth and mortality into the future. Harvest costs for the harvesting systems were estimated using regional cycle-time equations. No difference was found in maximum NPV between the CT and non-CT areas, or the timing of CT entry. Stand age at time of maximum NPV differed between delays but not between the two removal intensities. Our results indicate that there is no economic benefit in delaying a CT nor removing more volume at the time of thinning for the range of stand conditions evaluated.

Keywords: Commercial Thinning; New England; Net Present Value; Harvesting System; Spruce/Fir

INTRODUCTION

The management of forests for timber production generally includes a series of treatments aimed at improving stand growth and yield. Herbicide application, precommercial thinning (PCT), and commercial thinning (CT) are often used to manage conifer forests in North America and Europe (e.g. Hiesl et al. 2015; Bataineh et al. 2013; Zhang et al. 2009; Zeide 2001). The use of herbicides has been shown to reduce competition from early successional vegetation and increase softwood stand growth (Wagner et al. 2006), whereas PCT is a common and widely applied tool for density management (Nyland 2002; Smith 1986). PCT is also applied to control species composition (Weiskittel et al. 2011), accelerate growth (Prévost and Gauthier 2012), reduce time to merchantability (Pitt et al. 2013a; Pitt and Lanteigne 2008), improve commercial operability, reduce harvesting and processing costs (Plamondon and Pitt 2013), and increase landowner stumpage revenues (Pitt et al. 2013a). A CT treatment is often prescribed years after PCT to maintain or increase residual tree growth (Clune 2013; Reukema and Bruce 1977) and decrease mortality (Pekol 2011; Mäkinen and Isomäki 2004a,b).

The benefits of CT on spruce-fir (*Picea* spp. / *Abies balsamea* (L.) Mill.) stand stability and growth in Maine have been shown by Clune (2013), whose results indicate a positive influence from early, light thinning on short-term growth and yield. Pelletier and Pitt (2008) showed an increase in growth and yield as a response to CT in stands dominated by balsam fir in Canada, and noted a shorter time to grow merchantable trees. However, the long-term effects of combined PCT and CT in spruce-fir stands is limited, with the exception of the Green River Study in northwestern New Brunswick, Canada (Pitt and Lanteigne 2008; Baskerville 1959), the Austin Pond Study in west-central Maine, USA (Newton et al. 1992a,b), and the Commercial Thinning Research Network (CTRN) across the state of Maine (Wagner et al. 2001; Wagner and Seymour 2000).

Spruce and fir are the most harvested timber species in Maine (Maine Forest Service 2014) and contribute significantly to the state's annual 8 billion dollar forest-based economy (Maine Forest Products Council 2013). Herbicide application, PCT, and CT are common tools used in the management of spruce-fir stands, however, long-term results of tree growth and studies of the financial returns of these treatments in Maine are limited. Hiesl et al. (2015) investigated the differences in harvest cost and profits of three different CT intensities in a spruce-fir stand in central Maine. Their results indicated that there was no difference in unit cost between the different removal intensities. They further reported no difference in unit profit between treatment areas with and without a previous PCT treatment. However, two different harvesting systems were used in their study, thus results might not be easily comparable. Bataineh et al. (2013) also investigated the long-term financial response of spruce-fir stands in Maine to herbicide and PCT treatments and found that at a 2% interest rate, herbicide and PCT treated stands resulted in up to 140% higher net present value (NPV) than only herbicide treated stands approximately 60 years post clearcut. Their study, however, did not include subsequent CT treatments. Using a 4% discount rate, Pitt et al. (2013b) analyzed the NPV of vegetation management and PCT in fir dominated stands in New Brunswick, Canada, and found that both treatments offered a similar NPV at a stand age that maximizes sawlog production. Finally, Saunders et al. (2008) simulated stand growth of spruce-fir stands in the Northeastern US and Eastern Canada and found that the NPV of CT stands culminated earlier and at a higher value than unthinned stands. They also found that early CT added approximately \$370 United States Dollar (USD)/ha (\$150 USD/ac) to the maximum NPV that could be achieved without CT on the lowest quality sites.

Forest managers in Maine are often faced with the challenge of managing forestland that was inherited by company acquisitions or other ownership changes. Such forestland often

already received a herbicide or PCT treatment and may be passed the time of first merchantability of trees for a CT treatment. The question for the forest managers is whether further delaying CT from this point results in a higher economic benefit. Clearly, tree size has an impact on the time consumption and profitability of harvesting equipment (Hiesl and Benjamin 2015; Hiesl and Benjamin 2013a; Kluender et al. 1998), and thus a delayed CT may be to the financial advantage of a forest manager. In Maine, two fully mechanized harvesting systems are predominantly used for timber harvesting: whole-tree (tracked feller-buncher, grapple skidder, stroke delimber) and cut-to-length (harvester, forwarder) (Leon and Benjamin 2012). In addition, some companies use a combination (hybrid) of the two systems. The use of such different harvesting systems adds another dimension to the question of the economic benefit of a delayed CT as each system has a different cost and productivity associated with it.

We used ten-year measurements and a 35 years growth projection from a controlled experiment across six sites in Maine, to examine the long-term effect of CT removal intensity and timing of CT application on maximum NPV. We expected that an early and heavy CT would produce a higher maximum NPV due to early financial returns and increased merchantable volume at the time of final harvest. We also expected to see the highest maximum NPV in harvests conducted with a whole-tree harvesting system, due to its prevalence as the most common harvesting system in Maine.

METHODS

Study Area

All sites are part of the University of Maine's Commercial Thinning Research Network (CTRN), had been naturally regenerated, and previously received herbicide and PCT treatments

(Wagner et al. 2001). Spruce-fir stand composition and structure are influenced by climatic zone. Briggs and Lemin (1992) found that Maine is divided into nine climatic zones, and the CTRN study sites represent three of the climatic zones of the north. Parent material of soils was glacial till and alluvium (Ferwerda et al. 1997). All study sites were within the Acadian forest, a conifer-dominated mixedwood ecosystem that covers much of Maine and the Canadian Maritimes. Red spruce (*Picea rubens* Sarg.) and balsam fir (*Abies balsamea* (L.) Mill.) are the most dominant tree species in these stands. Other conifer species include white spruce (*Picea glauca* (Moench) Voss), eastern white pine (*Pinus strobus* L.), black spruce (*Picea mariana* (Mill.) Britton, Sterns and Poggenburg), eastern hemlock (*Tsuga Canadensis* (L.) Carrière), and northern white-cedar (*Thuja occidentalis* L.). Common hardwood species include red maple (*Acer rubrum* L.), yellow birch (*Betula alleghaniensis* Britt.), paper birch (*Betula papyrifera* Marshall), and quaking aspen (*Populus tremuloides* Michx.).

Study Sites

All sites are located in central and northern Maine (Figure 1) and received a PCT treatment between 1983 and 1985, were dominated by balsam fir, and consisted of good to excellent site quality (16 – 21 m at 50 years breast-height) (Seymour et al. 2014; Clune 2013; Wagner et al. 2001). Each site consisted of one control plot and six treatment plots including two different removal intensities (33% and 50% relative density removal) and three different timings of entry (no-delay, 5-year delay, 10-year delay; Table 1) (McConville et al. 2003; Wagner and Seymour 2000). Rectangular permanent plots, 809 m² in size, were fully inventoried on an annual or semi-annual basis between 2002 and 2012, and diameter at breast height (DBH) and total tree height were recorded for each tree greater than 5 cm DBH. Stand density in 2012 ranged from 384 to 2,046 trees per ha, quadratic mean diameter (QMD) ranged

140 from 15.4 to 23.3 cm, basal area ranged from 12.2 to 46.4 m²·ha⁻¹, and average tree height
141 ranged from 12.1 to 16.6 m (Table 2).

142 The CTRN study was established in 2000 and 2001, but CT treatments were not applied
143 until 2002 (Wagner et al. 2002). All study sites in the CTRN were chosen based on a stand age
144 ready for a CT, a well-stocked and single-cohort stand structure with a relative density of greater
145 than 0.25 (Wilson et al. 1999) based on trees with a DBH larger than 6.3 cm, and a good to
146 excellent site quality (Briggs site class 1, 2, or 2/3; Briggs 1994) (Wagner et al. 2001).
147 Therefore, individual trees were (1) in need of thinning due to high competition levels, (2) large
148 enough to generate enough revenue to pay for the thinning, and (3) had the ability to respond
149 favorably to thinning (e.g. strong vigor, low windthrow susceptibility, acceptable live-crown ratio).
150 However, stand age may have been past the initial timing of first merchantability. Due to the
151 varying degrees of site quality, the age of these stands at the beginning of the experiment in
152 2000 ranged from 23 to 42 years, a range of age that was commonly encountered by forest
153 managers due to the clear cuts following the spruce budworm outbreak in the 1970s and 1980s
154 (Seymour 1992; Irland et al. 1988). The delayed treatments were used to evaluate the effect of
155 a delayed timing of entry on tree growth and NPV compared to a normal thinning close to the
156 time of first merchantability of a stand.

157 The seven plots in each site varied in their initial plot conditions. To ensure that the two
158 different removal intensities did not create thinned plots of similar conditions each plot was
159 ranked based on initial relative density. Plots with first and fifth highest relative density were
160 assigned a 33% and 50% relative density removal in the initial year of the study (2002),
161 respectively. The plot with the median relative density was selected as the untreated control plot
162 and the remaining plots were left unthinned during the first cutting cycle and were assigned
163 treatments for the 5 and 10 year delay based on the initial ranking (Wagner et al. 2001). The

target relative density ($\pm 1\%$) in each plot was calculated using a laptop computer during leave tree selection, which was based on the goal to retain most spruce and removal of all hardwoods, balsam fir greater than 21.5 cm DBH, and any poor quality trees. The aim of the thinning method was to represent a crown thinning. Following leave tree selection all remaining trees greater than 11.3 cm DBH were marked for removal. Additional information about the experimental design can be found in Clune (2013) and Wagner et al. (2001).

Growth and Yield

Growth and yield for each plot was projected from plot measurements taken in 2012 (Table 2) for 35 years using the Acadian Variant of the Forest Vegetation Simulator (FVS-ACD) (Weiskittel et al. 2012). This variant projects the growth and mortality of individual trees on an annual basis using species-specific equations developed for the Acadian Region. In addition to using FVS-ACD, we also included newly developed diameter, height, and height to crown base increment and mortality modifiers for balsam fir and red spruce that adjust predicted growth and mortality of individual trees based on information from the last commercial thinning measurements (Kuehne et al. 2016; Weiskittel et al. 2015). These growth and mortality modifiers rely on time since commercial thinning, % basal area removed, and the ratio of QMD post- and pre-thinning. We also used observed plot data measured in 2002, 2007, and 2012 to calculate net present values for all treatments.

Product Merchandising

For every year in the projection we merchandised individual trees by using an R (R Core Team 2015) based product merchandiser developed by Hutchinson (2014). This merchandiser estimates merchantable sawlog and pulpwood volume based on regional taper and volume

equations (Weiskittel and Li 2012; Li et al. 2012). Biomass volume was not estimated or included in this study. Minimum top diameter for pulpwood for all relevant species was 10.2 cm with a minimum DBH of 12.7 cm. For sawlogs the minimum top diameters were 19.3 and 24.4 cm with a minimum DBH of 22.9 and 27.9 cm for softwood and hardwood species, respectively. These values are consistent with the merchantability specifications of the FVS Northeast variant.

Harvest Cost and Revenue

The costs for CT were estimated using the approach outlined by Saunders et al. (2008). They used a simplified version of the model of Randolph et al. (2001), who estimated CT harvesting costs using PPHARVST harvest cost simulator (Fight et al. 1999). The thinning system chosen by these authors was a cut-to-length (CTL) system with a machine rate of \$74.56 USD per productive machine hour (PMH) for a harvester, and \$51.88 USD·PMH⁻¹ for a forwarder. As the majority of study sites were thinned using a CTL system (Wagner et al. 2001), we believe that this method represented a good approximation of the real thinning costs. At the time of thinning, harvest costs and volume removal were not recorded for all treatments and sites, and thus for consistency throughout the projection, all removal costs and volumes were estimated. Volume removal for each CT was estimated by using average piece size before the thinning and the number of trees removed during the thinning (Table 3) in an equation provided by Saunders et al. (2008). The average piece size was estimated by inserting QMD and stand density before the thinning into an equation provided by Wilson et al. (1999) that was solved for piece size. Saunders et al. (2008) also reported a mill delivered product value for pulpwood (\$147.23 USD·m⁻³) that was used for revenue calculation of the CT. This product value is from Maine in the early 2000s and does not reflect current product values for pulpwood, which are

between \$40 and \$50 USD·m⁻³. To allow for the same effect of CT cost on NPV, the value used by Saunders et al. (2008) was used in all CT estimations. Detailed information before and after CT for all treatments can be found in Table 3.

To estimate final stand harvest costs, lists of trees created by the growth and yield projection were expanded to represent a one-hectare harvest block for each plot. The growth and yield projection returned such a list of trees for every year for 35 years. Each year's projection was based on the previous year's tree list, starting with measured data from 2012. In this projection, final stand harvest costs were estimated for every year following the CT, and there was no definition of the final stand in terms of age. Harvest time for three harvesting systems was estimated using regional cycle time equations for harvesting equipment (Hiesl and Benjamin 2015; Hiesl 2013; Hiesl and Benjamin 2013a,b). A cut-to-length (CTL) system consists of a harvester (\$160 USD·PMH⁻¹ (productive machine hour)) and forwarder (\$110 USD·PMH⁻¹), a whole-tree (WT) system consists of a feller-buncher (\$140 USD·PMH⁻¹), grapple skidder (\$100 USD·PMH⁻¹), and stroke delimber (\$130 USD·PMH⁻¹), and a hybrid (HYB) system consists of a feller-buncher, processor (\$160 USD·PMH⁻¹), and forwarder (all machine rates represent averages estimated as part of an early commercial thinning study in Maine (Benjamin et al. 2013)). These systems were chosen as they represent harvesting equipment that is commonly used in this region. A processor in a HYB system does not have to fell trees and therefore uses less time to process individual trees. Processor cycle time of the HYB system was estimated using 70% of the estimated harvester cycle time of a CTL system. Research by Simões et al. (2008) suggests that a harvester spends approximately 30% of its time felling trees. Time consumption for a loader/crane to load one truck was assumed to be 25 min. We used an average skidding and forwarding distance of 300 m, a forwarder payload of 10 m³, and a bunch size of 3 m³, which are consistent with regional values.

Harvest costs were calculated using the estimated time consumption for each machine multiplied with the appropriate machine rate (see previous paragraph). The machine rate for a loader was assumed to be \$40 USD·PMH⁻¹. Cost of delivering roundwood to the mill at a round-trip distance of 160 km and a cost of \$1.67 USD·km⁻¹ were also included. This distance was chosen as it represents a common trucking distance in Maine. Payload for one truck was assumed to be 28 m³, to ensure that the truck and the load are within state specifications of gross weight. Revenue was estimated for every year using the projected merchandised sawlog and pulpwood volume from each plot and multiplying it with average mill delivered product values of \$72 USD·m⁻³ for sawlogs and \$42 USD·m⁻³ for pulpwood. All product values are based on information from the forest industry in Maine in 2014. We did not adjust product value for possible changes in the future.

Net present value (NPV) is the sum of all cash flows, positive or negative, discounted or compounded to a base year (= 2002). In this study there were two cash flows: CT costs and revenue, and final harvest costs and revenue (Eqn. 1). Other management costs of the stand, such as PCT before 2002, reforestation, and future values past the final harvest were not included.

$$(Eqn. 1) \quad NPV(\$ \cdot ha^{-1}) = \frac{CT_{gross} - HC_{CT}}{(1+i)^{t_1-t}} + \frac{FH_{gross} - HC_{FH}}{(1+i)^{t_2-t}}$$

CT_{gross} and FH_{gross} are gross revenues from the CT and final harvest, respectively, whereas HC_{CT} and HC_{FH} are the harvest costs associated with these treatments. The years of CT, and final harvest are described by t_1 , and t_2 , respectively. The base year, t , is 2002, the

year of the decision making of whether to thin immediately or delay CT. We used a 4% discount rate, i , based on the adopted recommendation of the US Forest Service in long-term resource planning (Row et al. 1981). NPV was calculated for every potential final harvest year of the projection.

Analytical Approach

To assess the influence of treatment on the value and timing of maximum NPV, we developed two linear mixed-effect analysis of variance (ANOVA) models. Since the sites were previously thinned by a CTL system (Wagner et al. 2001), we used a CTL system as our baseline for NPV calculations. For the assessment of the influence of harvesting system and treatment on maximum NPV, we developed an additional ANOVA model using NPV data from all three harvesting systems simulated in this study. Random effects for plots nested within site were estimated to account for variation from factors that have not been identified and may have influenced the dependent variables. Pairwise comparison tests among thinning treatments and controls were performed using Tukey's method of multiple comparisons at a significance level of 0.05. For the analysis of influence of harvesting system and treatment on maximum NPV we conducted paired comparisons between all sites. All analyses were implemented in R (R Core Team 2015) using the nlme (Pinheiro et al. 2015), multcomp (Hothorn et al. 2008), and lsmeans (Lenth and Herve 2015) packages.

A sensitivity analysis for six major input variables (skidding distance, trucking distance, trucking costs, pulpwood and sawlog value, and machine rates for the harvesting system) was conducted by changing one input variable by $\pm 20\%$ while holding all other input variables constant. The percent change in maximum NPV for each change in input variable values was

then calculated. The values described in this methods section for the projection of maximum NPV were used as baseline values representing a 0% change in input variable and a 0% change in maximum NPV.

RESULTS

Five variables were used to describe the response of spruce-fir stands to the various CT treatments. Responses were measured and projected from the time of CT and included merchantable volume (Figure 2a), merchantable volume mean annual increment (MAI; Figure 2b), average merchantable stem size (Figure 2c), net present value (NPV; Figure 2d), and NPV differences from the control (Figure 2e). Merchantable volume reached its peak between 29 and 40 years after thinning for both the light (treatments A-C) and heavy thinning (treatments D-F), regardless of the delay (Figure 2a). At its peak, merchantable volume ranged from 296 to 372 $\text{m}^3 \cdot \text{ha}^{-1}$ for light thinning, and from 212 to 246 $\text{m}^3 \cdot \text{ha}^{-1}$ for heavy thinning. For both thinning intensities the 10-year delay in thinning (treatments C and F) produced the highest merchantable volume. The untreated control plot reached its highest value of 437 $\text{m}^3 \cdot \text{ha}^{-1}$ at 49 years after site establishment, but due to the limited projection time may not have reached its peak yet. Merchantable volume MAI for all thinning treatments peaked 14 to 15 years after thinning (Figure 2b). MAI for the control plot peaked 23 years after site establishment. Light thinning (treatments A-C) had a larger peak MAI (5.1 to 5.6 $\text{m}^3 \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$) than heavy thinning (treatments D-F; 3.6 to 4.2 $\text{m}^3 \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$). The control plot had the highest peak MAI with 6.4 $\text{m}^3 \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$. The average merchantable stem size in all treatments and the control plot increased over time (Figure 2c). At the time of maximum NPV the average merchantable stem size was 0.33 m^3 for treatment A, 0.36 m^3 for treatment B, 0.40 m^3 for treatments C, D, and E,

and 0.46 m³ for treatment F. The average merchantable stem size for the control was much smaller at 0.22 m³.

Maximum NPV over the projected life of a stand for light and heavy thinning was reached 14 to 15 years after thinning (Figure 2d). For control plots the maximum NPV occurred 14 years after CTRN establishment. The average maximum NPV differed in magnitude between light and heavy thinning by up to 29%. For light thinning, this NPV ranged from \$6,067 to \$6,337 USD·ha⁻¹, and from \$4,931 to \$5,709 USD·ha⁻¹ for heavy thinning. On average, the maximum NPV for control plots was \$4,889 USD·ha⁻¹.

Treatment Effect on maximum NPV

The ANOVA results suggested that treatment had a significant effect on maximum NPV ($p_{\text{treatment}}=0.01$; Table 4a), however, pairwise comparison's indicated that there was no statistical difference (Table 5). Across all treatments and final harvest years, the maximum NPV ranged from \$3,611 to \$8,172 USD·ha⁻¹ (Table 5). Ninety-one percent of the random variation in maximum NPV were accounted for differences at the site and plot-level within the individual study sites (Table 4a).

Treatment Effect on Stand Age of maximum NPV

The ANOVA results showed that treatment had a significant effect ($p<0.001$; Table 4b) on the stand age of maximum NPV. The average rotation length to reach maximum NPV across all CT treatments ranged from 49 to 59 years (Table 5). Light and heavy thinning's resulted in a rotation length of between 40 and 67 years, while control plots reached economic maturity, as defined by reaching maximum NPV, at a rotation length between 39 and 59 years. Pairwise comparison indicated that there were no differences between treatments A and D, B and E, and

C and F (Table 5). This result indicates that there are no differences between the different removal intensities in the stand age to reach maximum NPV. Since all treatments reached maximum NPV at the same time after thinning it is not surprising that when NPV is plotted over rotation age the maximum NPV for the delayed thinning occurred 5 (treatments B and E) or 10 years (treatments C and F) later than a CT with no delay (treatments A and D). Approximately 99% of the random variation can be explained by differences on the site and plot-level within the individual sites (Table 4b).

Harvesting System Effect on maximum NPV

The ANOVA results indicated that treatment ($p=0.01$), harvesting system ($p<0.001$), and their interaction ($p<0.001$) had significant effects on maximum NPV (Table 4c). Maximum NPV for all CT treatments ranged from \$3,611 to \$8,172 USD·ha⁻¹ when using a CTL system, from \$3,269 to \$8,031 USD·ha⁻¹ when using a HYB system, and from \$3,393 to \$7,783 USD·ha⁻¹ when using a WT system. Pairwise comparisons within each individual CT treatments and control plots indicated that using a CTL system resulted in a higher maximum NPV than using a HYB system or a WT system, with the exception of control plots (Figure 3). In the control, there was no significant difference in maximum NPV between a HYB and WT system. The differences in maximum NPV among thinning treatments between using a CTL and WT system ranged from \$215 to \$322 USD·ha⁻¹, and from \$83 to \$189 USD·ha⁻¹ when comparing a CTL to a HYB system. In the control, the average difference between CTL and WT was \$298 and \$334 USD·ha⁻¹ when comparing CTL to HYB. Thus, a final harvest using a CTL system returned a maximum NPV that was between 4.5% and 6.3% higher than that of a WT system, and between 1.7% and 7.1% higher than that of a HYB system. All of the random variation in the data was captured by site and plot-level differences between the sites (Table 4c).

Differences between harvesting systems were influenced by the unit cost of production based on average stem diameter (Figure 4). The CTL system consistently had a lower unit cost of production than either the WT or HYB system, regardless of average merchantable stem size. For merchantable stem sizes ranging from approximately 0.15 to 0.25 m³ the WT system had a lower unit cost of production than a HYB system, however, outside of this range, a WT system had the highest unit cost of production of all three harvesting systems (Figure 4). Average merchantable stem size in 2002 was approximately 0.15 m³ for all treatments, indicating that in comparison with the unit cost in Figure 4, the CTL system was the best choice for CT at the time of study begin.

Sensitivity of maximum NPV

To understand the robustness of our analysis we conducted a sensitivity analysis of the major input variables (skid distance, trucking distance, trucking costs, pulpwood value, sawlog value, machine rate) that affect unit cost of production. Results for treatment A showed that a change in mill delivered value of sawlogs had the greatest impact on maximum NPV (Figure 5). For example, a 20% decrease in sawlog value resulted in an 18% decrease in maximum NPV. Pulpwood value had the second largest impact on maximum NPV, with a 20% decrease in pulpwood value resulting in an 8% decrease in maximum NPV. A 20% decrease in the machine rate for all equipment in a harvesting system resulted in a 6% increase of maximum NPV. Trucking cost, trucking distance, and skidding distance affected maximum NPV by less than 5% for a 20% change in the respective input variable. For all other treatments (B-F) the relationship was approximately the same, however, an increase in the sensitivity to pulpwood value was noted in treatments C and F. For control plots, the sensitivity to changes in pulpwood value was the greatest (Figure 5). For a 20% decrease in pulpwood value the maximum NPV decreased

by 20%. A 20% decrease in sawlog value would result in an 18% decrease in maximum NPV. Changes in machine rate when operating in control plots had a higher impact on maximum NPV than for any treatment. A 20% reduction in machine rate resulted in a 10% increase in maximum NPV. Trucking cost and trucking distance had a greater effect on maximum NPV in the control than it had in any other treatment. In light and heavy thinning treatments, the effect of trucking cost and trucking distance on maximum NPV is generally less than 5%, whereas in control plots the effect is closer to 7.5% for a 20% change in the respective input variable. Skidding distance had a slightly larger impact on maximum NPV in the control than in any thinning treatment. However, the difference in maximum NPV between control and thinning treatments is only 1% for a 20% change in skidding distance.

DISCUSSION

Commercial Thinning Effects

Our results indicated that there was no difference in maximum NPV among the CT treatments and control plots. Thus, delaying CT, or increasing removal intensity, did not result in a higher maximum NPV. However, a delayed and light CT (treatments B and C) resulted in the highest maximum standing merchantable volume among thinned stands.

A previous study of the same sites with data until 2010 indicated that treatment B produced the highest average of standing total volume across the first 5 years post thinning (Clune 2013). At the time of that study, treatment C was not yet conducted and therefore was not included by Clune (2013). Our analysis showed that treatment C returned the highest merchantable volume. Clune (2013) also reported that the merchantable volume for treatments A to C was higher than for treatments D to F. Our results showed the same trend; however, the

additional volume was not enough to cause a significantly higher maximum NPV. This finding can be attributed to the fact that treatments D to F resulted in a greater sawlog percentage at the time of final harvest, which are valued at a higher price.

Effect of Delaying Commercial Thinning

Delaying the first CT by 5 or 10 years had no effect on maximum NPV for the delayed treatments. Consequently, it was possible to achieve a similar profit whether or not a CT was delayed from the point a stand was ready for thinning, regardless of the actual time past first merchantability in this study. Thus, there is a window of opportunity of 10 years to conduct a CT without an economic loss. However, the time when maximum NPV was achieved is of importance, as this can have implications on the rotation length of a stand. For all treatments, the time to reach maximum NPV after a CT was not significantly different between them. However, this time did not include the additional 5 or 10 years that trees were growing before they were thinned, and thus the rotation time is significantly different between the three timings of entry for the light and heavy thinning's. When including this additional growing time, the 10-year delay in thinning resulted in the longest rotation time to reach maximum NPV, regardless of removal intensity.

A CT is used to reduce stand density and focus diameter growth on a smaller number of trees (Smith 1986; Nyland 2002). Research in Maine and the surrounding area confirms that CT generally increases stem diameter and volume growth on a reduced number of trees in spruce plantations (Pelletier and Pitt 2008). However, research on Norway spruce (*Picea abies* L.) stands in Finland showed that a delayed thinning reduced basal area increment when compared with CT at a normal time or with intensive CT (Jaakkola et al. 2006). Saunders et al. (2008)

reported that unthinned controls were not able to “catch up” with PCT stands within the same rotation length. They also showed that the NPV of control plots was lower and culminated later. Similar findings were also reported by Bataineh et al. (2013) when using a 2% discount rate. In our study, however, the NPV of the control was no different than any of the CT treatments, and did culminate at the same time as treatments that were thinned with no delay.

Choice of Harvesting System

We also evaluated the use of three different harvesting systems. Since a WT harvesting system is the most commonly used system in Maine (Leon and Benjamin 2012) we aimed to investigate whether alternative systems would be economically feasible. The results showed that a CTL harvesting system resulted in the highest NPV across all three harvesting systems tested. This is a surprising result, as approximately 80% of Maine’s timber volume is processed by WT harvesting systems (Leon and Benjamin 2012). With a significant difference of several hundred dollars per ha, greater use of CTL systems would be expected. One of the reasons for the high percentage of timber processed by WT systems might be the initially higher costs for CTL equipment, and the greater complexity to operate such equipment. Harvesters and forwarders can be several hundred thousand dollars more expensive than other machines (Rankin 2015). Another factor that affect harvest costs is stem size (Kluender et al. 1998; Adebayo et al. 2007; Lageson 1997). The unit cost of production generally decreases with increasing stem size. Our results showed that stem size had a major effect on unit cost of production and that a CTL system consistently had lower costs than the WT or HYB system. However, at small stem sizes the WT system produced at a lower cost than a HYB system, which may be due to the larger number of stems per feller-buncher accumulation (Hiesl and

Benjamin 2013a) when thinning a small diameter stand. The fact that the average merchantable stem size at the age of maximum NPV in the control was around 0.22 m³, a value for which unit cost of production is similar between WT and HYB systems, may explain the similar maximum NPV between the two systems.

Our results also indicated that a HYB system consisting of a feller-buncher, processor, and forwarder returned a lower maximum NPV than a CTL system for CT treatments. This result was unexpected because the HYB system is considered to be less expensive than a CTL system, mainly due to the high productivity of the feller-buncher and the concentrated processing of trees. One of the major reasons for this result may be the fact that the forwarder cycle time equation used did not account for spacing between logs but was developed based on commonly encountered conditions during thinnings. The conditions commonly encountered include a varying log spacing that was not measured but is known to be much farther than what actually would be present on site when using a HYB system. Log concentration at a harvest site has been shown to influence forwarder productivity (Manner et al. 2013) and therefore the actual forwarder productivity for a HYB system might be higher, due to fewer stops and a larger payload per stop. Currently, however, there are no forwarder equations available for this state that would include log spacing as a determining factor.

One of the limitations of this simulation was that we did not include any costs associated with moving harvesting equipment to the harvest site, or any administrative or road building/maintenance costs. Including these costs is difficult as they are highly variable and depend on factors such as a distance from a logging contractor and road conditions, but also affect NPV differently with increasing harvest tract size. It is therefore important to highlight that the NPVs presented here are likely rather optimistic projections, and will probably be smaller due to additional costs that were not included in this simulation. In addition, we did not include future

forest values in our analysis and limited our study to only one rotation. By including future forest values into these calculations, the maximum NPV would typically be reached earlier.

Influence of Study Design

The study design of the CTRN (Wagner et al. 2001) may have a significant influence on our results. Treatments were assigned based on relative density to avoid treatments with a low removal intensity to produce a similar residual stand as high removal intensity treatments. Thus, heavy removal intensities (treatments D-F) were always associated with a higher initial relative density as compared to light removal intensities (treatments A-C). This stratification may limit the ability to predict results for different management scenarios such as a light thinning in a dense stand. Emmingham et al. (2007) found that in natural Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) stands the growth rates of residual stands depended on the amount of residual growing stock. Their results indicated that dominant and codominant trees provided the majority of net volume growth. In our study, a crown thinning was performed (Wagner et al. 2001), which may remove a greater number of dominant and codominant trees, and thus reduce the potential net volume growth, as compared to a low thinning like evaluated in Emmingham et al. (2007).

In addition, the study in the CTRN may have started past the time of first merchantability of stands, as may be indicated by the various stand ages at time of study establishment (Wagner et al. 2001). Harvest costs are strongly influenced by stem size, with a higher stem size reducing the overall unit cost of production (Kluender et al. 1998; Lageson 1997). Larger stem size, however, also results in a higher value of the individual tree. Both factors strongly affect NPV calculations and thus, stand conditions at the beginning of the study need to be considered when applying our results to other areas. However, due to the clear cuts occurring during and after the spruce budworm outbreak in the 1970s and 1980s (Griffith and Alerich

1996; Seymour 1992; Irland et al. 1988), the stand conditions represented in the CTRN study were commonly encountered by foresters in northern Maine. In addition, the change of ownership from forest industry to Timber Investment Management Organizations (TIMO) and Real Estate Investment Trusts (REIT) in the 1990s (Jin and Sader 2006; McWilliams et al. 2005) often forced forest managers to deal with stands that were past the first time of merchantability.

Influence of Models and Assumptions

For our projection, we assumed that the machine rate and product values remained constant over a 35-year period; however, there may be significant changes in these values over time. Further, the model used for growth projection has been parameterized with growth and mortality CTRN data over a 10 year period post-treatment (Kuehne et al. 2016), and thus extrapolations beyond 10 years post-treatment may have significant effects on the results. It is therefore crucial to acknowledge that the costs and revenues of the final harvest might be different from the presented results. This difference in harvest costs can easily negate the benefit of CT in terms of maximum NPV. Our sensitivity analysis indicated that changes in product value and machine rate had the largest impact on maximum NPV. In particular, the influence of pulpwood value was the largest in the control, which can be attributed to smaller stem sizes and thus a higher volume of pulpwood as compared to other treatments. The control also showed a higher sensitivity to machine rate, which may be attributed to a lower productivity when cutting small diameter stems. It is important to note that for all CT treatments a financial return was provided during the CT, whereas the control plots did not yield any financial return until final harvest. This is an important consideration for forest managers that require an early financial return.

The assumptions made in this projection were important factors that can influence the long-term financial returns from CT (e.g. product values at time of CT and at final harvest). We used average skidding distances and bunch sizes for softwood stands in Maine, based on published and unpublished information from research by Hiesl (2013) and Hiesl et al. (2015). Stand and site conditions, harvesting equipment, and extracting distances are just a few factors that influence machine productivity and vary greatly among states and countries (Hiesl and Benjamin 2013c). Thus, the assumptions used for the simulation may not be appropriate for some neighboring jurisdictions. For example, the maximum skidding distance in Maine is approximately 800 m, while a common skidding distance in the state of New York can easily exceed 1,600 m (personal communication with Dr. Steve Bick, principal consultant, Northeast Forests, LLC., Thendara, NY).

Depending on the distance to a mill, average tree diameter, and other factors, the stumpage rate for a given parcel of land can fluctuate substantially. For example, the stumpage rate for spruce/fir pulpwood used by Bataineh et al. (2013) was \$11 USD·ton⁻¹, which was the average stumpage rate reported by the Maine Forest Service in 2010 (Maine Forest Service 2011). The reported range of 2010 stumpage rates for pulpwood in Maine Forest Service (2011), however, was from \$0.22 up to \$40 USD·ton⁻¹. These stumpage rates are self-reported annually by loggers, landowners, and foresters, and represent a wide range of stand and site conditions. Therefore, using the average stumpage rate for any parcel might not be representative at all.

CONCLUSION

With the limitations of our experimental design, model outcomes, and assumptions as a caution, we conclude that there is a margin for CT of approximately 10 years where there will be no reduction in maximum NPV. However, due to the different stand ages and level of merchantability at the beginning of the study we do not know whether or not a CT starting at first merchantability would have resulted in a different maximum NPV. With a scope of 10 years past study initiation, we also do not know whether a thinning with a greater delay would have resulted in any change in maximum NPV. Thus, our results provide initial information for decision makers, but further research is needed to fully understand the implications of delays and thinning intensity on NPV and subsequently on the decision making process of forest managers. The results also highlight the complexities associated with developing effective CT strategies given variation in available markets, stumpage rates, and harvesting systems.

ACKNOWLEDGEMENTS

We would like to thank the Cooperative Forestry Research Unit (CFRU) at the University of Maine for providing stand and plot level data for this project. In addition, Clemson University is acknowledged for the generous allotment of computation time on the Palmetto cluster. Funding for this project was provided by the University of Maine – School of Forest Resources. Thanks to two anonymous reviewers and Associate Editor who helped to significantly improve previous versions of this manuscript.

REFERENCES

- Adebayo, A.B., Han, H.-S. and Johnson, L. 2007. Productivity and Cost of Cut-to-length and Whole-tree Harvesting in a Mixed-conifer Stand. *For. Prod. J.* **57**(6): 59–69.
- Baskerville, G.L. 1959. Establishment Report - Cleaning and Thinning Young Fir. Department of Northern Affairs and National Resources, Forestry Branch, Maritimes District. Technical Report Project M-443-59.
- Bataineh, M.M., Wagner, R.G. and Weiskittel, A.R. 2013. Long-term Response of Spruce–fir Stands to Herbicide and Precommercial Thinning: Observed and Projected Growth, Yield, and Financial Returns in Central Maine, USA. *Can. J. For. Res.* **43**(4): 385–395. Available from: <http://www.nrcresearchpress.com/doi/abs/10.1139/cjfr-2012-0343> [accessed 31 July 2013].
- Benjamin, J.G., Seymour, R.S., Meacham, E. and Wilson, J.S. 2013. Impact of Whole-tree and Cut-to-length Harvesting on Postharvest Condition and Logging Costs for Early Commercial Thinning in Maine. *North. J. Appl. For.* **30**(4): 149–155.
- Briggs, R.D. 1994. Site Classification. Maine Agricultural and Forest Experiment Station.
- Briggs, R.D. and Lemin, R.C. 1992. Delineation of Climatic Regions in Maine. *Can. J. For. Res.* **22**(6): 801–811.
- Clune, P.M. 2013. Growth and Development of Maine Spruce-fir Forests Following Commercial Thinning. M.Sc. thesis, School of Forest Resources, University of Maine.
- Emmingham, W., Fletcher, R., Fitzgerald, S. and Bennett, M. 2007. Comparing Tree and Stand Volume Growth Response to Low and Crown Thinning in Young Natural Douglas-fir Stands. *West. J. Appl. For.* **22**(2): 124–133.
- Ferwerda, J.A., LaFlamme, J.K.J., N.R. Kalloch, J. and Rourke, R.V. 1997. The Soils of Maine. Maine Agricultural and Forest Experiment Station. MAFES Miscellaneous Report 402.
- Fight, R.D., Gicqueau, A. and Hartsough, B.R. 1999. Harvesting Costs for Management Planning for Ponderosa Pine Plantations. U.S. Department of Agriculture Forest Service, Pacific Northwest Research Station. General Technical Report PNW-GTR-467.
- Griffith, D.M. and Alerich, C.L. 1996. Forest Statistics for Maine, 1995. Forest Inventory and Analysis Unit, Northeastern Forest Experiment Station, USDA Forest Service. Resource Bulletin NE-135.
- Hiesl, P. 2013. Productivity Standards for Whole-tree and Cut-to-length Harvesting Systems in Maine. M.Sc. thesis, School of Forest Resources, University of Maine.
- Hiesl, P. and Benjamin, J.G. 2013a. A Multi-stem Feller-buncher Cycle-time Model for Partial Harvest of Small Diameter Wood Stands. *Int. J. For. Eng.* **24**(2): 101–108. doi:<http://dx.doi.org/10.1080/14942119.2013.841626>.
- Hiesl, P. and Benjamin, J.G. 2013b. Harvesting Equipment Cycle Time and Productivity Guide for Logging Operations in Maine. Maine Agricultural and Forest Experiment Station. Miscellaneous Publications 762.

- 595 Hiesl, P. and Benjamin, J.G. 2013c. Applicability of International Harvesting Equipment
596 Productivity Studies in Maine, USA: A Literature Review. *Forests* **4**(4): 898–921.
597 doi:10.3390/f4040898.
- 598 Hiesl, P. and Benjamin, J.G. 2015. Estimating Processing Times of Harvesters in Thinning
599 Operations in Maine. *For. Prod. J.* **65**(3/4): 180–186.
- 600 Hiesl, P., Benjamin, J.G. and Roth, B.E. 2015. Evaluating Harvest Costs and Profit of
601 Commercial Thinnings in Softwood Stands in West-central Maine: A Case Study. *For.*
602 *Chron.* **91**(2): 150–160.
- 603 Hothorn, T., Bretz, F. and Westfall, P. 2008. Simultaneous Inference in General Parametric
604 Models. *Biometrical J.* **50**(3): 346–363.
- 605 Hutchinson, S.F. 2014. Evaluating Variation in Commercial Timber and Land Value for Parcels
606 in the Northeast United States. M.Sc. thesis, School of Forest Resources, University of
607 Maine.
- 608 Irland, L.C., Dimon, J.B., Baum, E., Falk, J. and Stone, J.L. 1988. The Spruce Budworm
609 Outbreak in Maine in the 1970's - Assessment and Directions for the Future. Maine
610 Agricultural Experiment Station. Bulletin 819.
- 611 Jaakkola, T., Mäkinen, H. and Saranpää, P. 2006. Wood Density of Norway Spruce: Responses
612 to Timing and Intensity of First Commercial Thinning and Fertilisation. *For. Ecol. Manage.*
613 **237**(1–3): 513–521. doi:10.1016/j.foreco.2006.09.083.
- 614 Jin, S. and Sader, S.A. 2006. Effects of Forest Ownership and Change on Forest Harvest
615 Rates, Types and Trends in Northern Maine. *For. Ecol. Manage.* **228**(1–3): 177–186.
616 Available from: <http://linkinghub.elsevier.com/retrieve/pii/S0378112706001691> [accessed
617 15 December 2014].
- 618 Kluender, R., Lortz, D., McCoy, W., Stokes, B. and Klepac, J. 1998. Removal Intensity and Tree
619 Size Effects on Harvesting Cost and Profitability. *For. Prod. J.* **48**(1): 54–59.
- 620 Kuehne, C., Weiskittel, A.R., Wagner, R.G. and Roth, B.E. 2016. Development and Evaluation
621 of Individual Tree- and Stand-level Approaches for Predicting Spruce-fir Response to Pre-
622 and Commercial-thinning in Maine, USA. *For. Ecol. Manage.* **376**: 84–95. Available from:
623 <http://dx.doi.org/10.1016/j.foreco.2016.06.013>.
- 624 Lageson, H. 1997. Effects of Thinning Type on the Harvester Productivity and on the Residual
625 Stand. *J. For. Eng.* **8**(2): 7–14.
- 626 Lenth, R. V and Herve, M. 2015. Ismeans: Least-Squares Means. R package version 2.16.
627 Available from: <http://cran.r-project.org/package=Ismeans>.
- 628 Leon, B. and Benjamin, J.G. 2012. A Survey of Business Attributes, Harvest Capacity and
629 Equipment Infrastructure of Logging Businesses in the Northern Forest. University of
630 Maine. The Northern Forest Logging Industry Assessment.
- 631 Li, R., Weiskittel, A., Dick, A.R., Jr, J.A.K. and Seymour, R.S. 2012. Regional Stem Taper
632 Equations for Eleven Conifer Species in the Acadian Region of North America:
633 Development and Assessment. *North. J. Appl. For.* **29**(1): 5–14.

- 634 Maine Forest Products Council. 2013. Maine ' s Forest Economy. Maine Forest Products
635 Council. Available from: [http://maineforest.org/wp-content/uploads/2014/04/Maines-Forest-](http://maineforest.org/wp-content/uploads/2014/04/Maines-Forest-Economy.pdf)
636 [Economy.pdf](http://maineforest.org/wp-content/uploads/2014/04/Maines-Forest-Economy.pdf).
- 637 Maine Forest Service. 2011. 2010 Stumpage Prices. Department of Conservation, Maine Forest
638 Service, Forest Policy and Management Division. Annual Report.
- 639 Maine Forest Service. 2014. 2012 Wood Processor Report. Department of Agriculture,
640 Conservation and Forestry - Maine Forest Service - Forest Policy and Management
641 Division. Annual Report [Updated March 12, 2014].
- 642 Mäkinen, H. and Isomäki, A. 2004a. Thinning Intensity and Growth of Norway Spruce Stands in
643 Finland. *Forestry* **77**(4): 349–364. doi:10.1093/forestry/77.4.349.
- 644 Mäkinen, H. and Isomäki, A. 2004b. Thinning Intensity and Growth of Scots Pine Stands in
645 Finland. *For. Ecol. Manage.* **201**(2–3): 311–325. Available from:
646 <http://linkinghub.elsevier.com/retrieve/pii/S0378112704005328>.
- 647 Manner, J., Nordfjell, T. and Lindroos, O. 2013. Effects of the Number of Assortments and Log
648 Concentration on Time Consumption for Forwarding. *Silva Fenn.* **47**(4): 1–19.
- 649 McConville, D.J., Wagner, R.G. and Seymour, R.S. 2003. Study Site Establishment and
650 Measurement of the Commercial Thinning Research Network. *In* Cooperative Forestry
651 Research Unit 2003 Annual Report. *Edited by* D.J. McConville. University of Maine, Orono,
652 ME, USA. pp. 24–25.
- 653 McWilliams, W.H., Butler B.J., Griffith, D.M., Hoppus, M.L., Lister, A.J., Lister, T.W., Morin, R.S.,
654 Stewart, L.B. and Westfall, J.A. 2005. The Forests of Maine: 2003. U.S. Department of
655 Agriculture Forest Service, Northeastern Research Station. Resource Bulletin NE-164.
- 656 Newton, M., Cole, E.C., McCormack, M.L. and White, D.E. 1992a. Young Spruce-Fir Forests
657 Released by Herbicides II. Conifer Response to Residual Hardwoods and Overstocking.
658 *North. J. Appl. For.* **9**(4): 130–135.
- 659 Newton, M., Cole, E.C., White, D.E. and McCormack, M.L. 1992b. Young Spruce-Fir Forests
660 Released by Herbicides I . Response of Hardwoods and Shrubs. *North. J. Appl. For.* **9**(4):
661 126–130.
- 662 Nyland, R.D. 2002. *Silviculture: Concepts and Applications*. 2nd ed. McGraw-Hill, New York,
663 NY, USA. pp. 682.
- 664 Pekol, J.R. 2011. The Influence of Commercial Thinning on Stand- and Tree-level Mortality
665 Patterns of Balsam Fir (*Abies balsamea*) and Red Spruce (*Picea rubens*) Forests in Maine
666 That Have or Have not Received Precommercial Thinning. Master thesis.
- 667 Pelletier, G. and Pitt, D.G. 2008. Silvicultural Responses of Two Spruce Plantations to
668 Midrotation Commercial Thinning in New Brunswick. *Can. J. For. Res.* **38**(4): 851–867.
669 Available from: <http://www.nrcresearchpress.com/doi/abs/10.1139/X07-173> [accessed 9
670 September 2013].
- 671 Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D. and R Core Team. 2015. nlme: Linear and
672 Nonlinear Mixed Effects Models. R package version 3.1-120. Available from: <http://cran.r->

- 673 project.org/package=nlme.
- 674 Pitt, D.G. and Lanteigne, L. 2008. Long-term Outcome of Precommercial Thinning in
675 Northwestern New Brunswick: Growth and Yield of Balsam Fir and Red Spruce. *Can. J.*
676 *For. Res.* **38**(3): 592–610. Available from:
677 <http://www.nrcresearchpress.com/doi/abs/10.1139/X07-132> [accessed 13 August 2013].
- 678 Pitt, D.G., Lanteigne, L., Hoepting, M.K. and Plamondon, J. 2013a. Effects of Precommercial
679 Thinning on the Forest Value Chain in Northwestern New Brunswick : Part 1 – Roundwood
680 Production and Stumpage Value. *For. Chron.* **89**(4): 446–457.
- 681 Pitt, D.G., Lanteigne, L., Hoepting, M.K., Plamondon, J., Duchesne, I., Bicho, P. and Warren, G.
682 2013b. Effects of Precommercial Thinning on the Forest Value Chain in Northwestern New
683 Brunswick : Part 6 – Estimating the Economic Benefits. *For. Chron.* **89**(4): 502–511.
- 684 Plamondon, J. and Pitt, D.G. 2013. Effects of Precommercial Thinning on the Forest Value
685 Chain in Northwestern New Brunswick : Part 2 – Efficiency Gains in Cut-to-length
686 Harvesting. *For. Chron.* **89**(4): 458–463.
- 687 Prévost, M. and Gauthier, M.M. 2012. Precommercial Thinning Increases Growth of Overstory
688 Aspen and Understory Balsam Fir in a Boreal Mixedwood Stand. *For. Ecol. Manage.* **278**:
689 17–26. doi:10.1016/j.foreco.2012.05.005.
- 690 R Core Team. 2015. R: A Language and Environment for Statistical Computing. R Foundation
691 for Statistical Computing. Available from: <http://www.r-project.org/>.
- 692 Randolph, K.C., Seymour, R.S. and Wagner, R.G. 2001. ThinME: User's Guide. University of
693 Maine. Cooperative Forestry Research Unit Report 357. Available from:
694 <http://library.umaine.edu/cfru/pubs/CFRU357.pdf>.
- 695 Rankin, J. 2015. Mechanical harvesting - The Future is Here. *For. Maine's Futur.* Available from:
696 [http://www.forestsformainesfuture.org/fresh-from-the-woods-journal/mechanical-harvesting-](http://www.forestsformainesfuture.org/fresh-from-the-woods-journal/mechanical-harvesting-the-future-is-here.html)
697 [the-future-is-here.html](http://www.forestsformainesfuture.org/fresh-from-the-woods-journal/mechanical-harvesting-the-future-is-here.html) [accessed 1 January 2015].
- 698 Reukema, D.L. and Bruce, D. 1977. Effects of Thinning on Yield of Douglas-fir: Concepts and
699 Some Estimates Obtained by Simulation. U.S. Department of Agriculture Forest Service,
700 Pacific Northwest Research Station. General Technical Report PNW-GTR-58.
- 701 Row, C., Kaiser, H.F. and Sessions, J. 1981. Discount Rate for Long-Term Forest Service
702 Investments. *J. For.* **79**(6): 367–376.
- 703 Saunders, M.R., Wagner, R.G. and Seymour, R.S. 2008. Thinning Regimes for Spruce-Fir
704 Stands in the Northeastern United States and Eastern Canada. Cooperative Forestry
705 Research Unit.
- 706 Seymour, R.S. 1992. The Red Spruce-Balsam Fir Forest of Maine: Evolution of Silvicultural
707 Practice in Response to Stand Development Patterns and Disturbances. *In* The Ecology
708 and Silviculture of Mixed-species forests. A festschrift for David M. Smith. *Edited by* M.J.
709 Kelty, B.C. Larson, and C.D. Oliver. Kluwer Publishers, Norwell, MA. pp. 217–244.
- 710 Seymour, R.S., Meyer, S.R. and Wagner, R.G. 2014. The Cooperative Forestry Research Unit
711 Commercial Thinning Research Network: 9-year Results. *In* Penobscot Experimental

- 712 Forest: 60 years of research and demonstration in Maine, 1950-2010. GTR-NRS-P-123.
 713 *Edited by* L.S. Kenefic and J.C. Brissette. U.S. Department of Agriculture Forest Service,
 714 Northern Research Station, Newtown Square, PA. pp. 81–90.
- 715 Simões, D., Marcelino, F.A., Pletsch, T.A., De Faria, L.R. and Fenner, P.T. 2008. Technical and
 716 Economical Evaluation of Harvester Cut-to-length System in First Cut Eucalyptus Forest.
 717 Proceedings of CIGR International Conference of Agricultural Engineering. XXXVII
 718 Congresso Brasileiro De Engenharia Agricola – CONBEA.
- 719 Smith, D.M. 1986. The Practice of Silviculture. 8th ed. John Wiley & Sons, Inc, New York, NY.
 720 pp. 527.
- 721 Wagner, R.G. and Seymour, R.S. 2000. Commercial Thinning Research Network. *In*
 722 Cooperative Forestry Research Unit 2000 Annual Report. *Edited by* H.E. Griffin. University
 723 of Maine, Orono, ME, USA. pp. 21–27.
- 724 Wagner, R.G., Seymour, R.S. and McConville, D.J. 2001. Commercial Thinning Research
 725 Network. *In* Cooperative Forestry Research Unit 2001 Annual Report. *Edited by* H.E.
 726 Griffin. University of Maine, Orono, ME, USA. pp. 23–35.
- 727 Wagner, R.G., Seymour, R.S., McConville, D.J. and Opland, D.M. 2002. Commercial Thinning
 728 Research Network. *In* Cooperative Forestry Research Unit 2002 Annual Report. *Edited by*
 729 University of Maine, Orono, ME, USA. pp. 23–28.
- 730 Wagner, R.G., Little, K.M., Richardson, B. and McNabb, K. 2006. The Role of Vegetation
 731 Management for Enhancing Productivity of the World's Forests. *Forestry* **79**(1): 57–79.
 732 Available from: <http://forestry.oxfordjournals.org/cgi/doi/10.1093/forestry/cpi057> [accessed
 733 9 September 2013].
- 734 Weiskittel, A.R., Kenefic, L.S., Li, R. and Brissette, J. 2011. Stand Structure and Composition 32
 735 years after Precommercial Thinning Treatments in a Mixed Northern Conifer Stand in
 736 Central Maine. *North. J. Appl. For.* **28**(2): 92–96.
- 737 Weiskittel, A.R., Russell, M.B., Wagner, R.G. and Seymour, R.S. 2012. Refinement of the
 738 Forest Vegetation Simulator Northeast Variant Growth and Yield Model: Phase III. *In*
 739 Cooperative Forestry Research Unit 2011 Annual Report. *Edited by* B.E. Roth. University
 740 of Maine, Orono, ME, USA. pp. 85–93.
- 741 Weiskittel, A. and Li, R. 2012. Development of Regional Taper and Volume Equations:
 742 Hardwood Species. *In* Cooperative Forestry Research Unit 2011 Annual Report. *Edited by*
 743 B.E. Roth. University of Maine, Orono, ME, USA. pp. 87–95.
- 744 Weiskittel, A.R., Hennigar, C. and Kershaw, Jr., J.A. 2015. Extending the Acadian Variant of
 745 FVS to Managed Stands. *In* Cooperative Forestry Research Unit 2014 Annual Report.
 746 *Edited by* R.G. Wagner. University of Maine, Orono, ME, USA. pp. 47–51.
- 747 Wilson, D.S., Seymour, R.S. and Maguire, D.A. 1999. Density Management Diagram for
 748 Northeastern Red Spruce and Balsam Fir Forests. *North. J. Appl. For.* **16**(1): 48–56.
- 749 Zeide, B. 2001. Thinning and Growth: A Full Turnaround. *J. For.* **99**(1): 20–25. Available from:
 750 <http://www.ingentaconnect.com/content/saf/jof/2001/00000099/00000001/art00005> \nhttp://

751 search.ebscohost.com/login.aspx?direct=true&db=agr&AN=IND22086145&site=ehost-live.
752 Zhang, S., Chauret, G. and Tong, Q. 2009. Impact of Precommercial Thinning on Tree Growth,
753 Lumber Recovery and Lumber Quality in *Abies Balsamea*. *Scand. J. For. Res.* **24**(5): 425–
754 433. Available from: <http://www.tandfonline.com/doi/abs/10.1080/02827580903124392>
755 [accessed 4 February 2013].
756

Draft

Table 1: Description of all treatments and control plots.

Treatment	Description
A	33% relative density reduction with no-delay in thinning. Thinning was done in 2002. Average basal area removal was 40%.
B	33% relative density reduction with a 5-year delay in thinning. Thinning was done in 2007. Average basal area removal was 40%.
C	33% relative density reduction with a 10-year delay in thinning. Thinning was done in 2012. Average basal area removal was 37%.
D	50% relative density reduction with no-delay in thinning. Thinning was done in 2002. Average basal area removal was 53%.
E	50% relative density reduction with a 5-year delay in thinning. Thinning was done in 2007. Average basal area removal was 54%.
F	50% relative density reduction with a 10-year delay in thinning. Thinning was done in 2012. Average basal area removal was 52%.
Control	Unthinned control plot at each study site.

Table 2: Stand and site information for the six commercial thinning treatments and the control in 2012. Values shown are the means $\pm$ standard deviation across all six study sites with minimum and maximum in parentheses. TPH, QMD, BA, and Height are based on merchantable trees.

Treatment	Age (yrs)	Time since PCT (yrs)	TPH (# ha ⁻¹)	QMD (cm)	BA (m ² ·ha ⁻¹)	Height (m)
A	45 $\pm$ 7 (35; 54)	28 $\pm$ 1 (27;29)	901 $\pm$ 156 (694;1,141)	20.9 $\pm$ 1.3 (19.1;23.0)	30 $\pm$ 2 (28;33)	14.7 $\pm$ 1.5 (12.1;16.6)
B	45 $\pm$ 7 (35; 54)	28 $\pm$ 1 (27;29)	893 $\pm$ 170 (670;1,141)	19.5 $\pm$ 1.3 (18.4;21.8)	26 $\pm$ 5 (18;30)	15.0 $\pm$ 0.8 (14.0;16.5)
C	45 $\pm$ 7 (35; 54)	28 $\pm$ 1 (27;29)	984 $\pm$ 187 (756;1,290)	18.3 $\pm$ 1.7 (17.2;21.5)	25 $\pm$ 3 (21;30)	15.0 $\pm$ 1.3 (12.8;16.6)
D	45 $\pm$ 7 (35; 54)	28 $\pm$ 1 (27;29)	639 $\pm$ 83 (546;769)	22.2 $\pm$ 1.0 (20.8;23.3)	25 $\pm$ 4 (21;32)	14.4 $\pm$ 1.3 (13.2;16.5)
E	45 $\pm$ 7 (35; 54)	28 $\pm$ 1 (27;29)	544 $\pm$ 96 (446;670)	20.6 $\pm$ 1.7 (18.6;22.5)	18 $\pm$ 4 (12;23)	14.5 $\pm$ 0.7 (13.1;15.1)
F	45 $\pm$ 7 (35; 54)	28 $\pm$ 1 (27;29)	591 $\pm$ 132 (384;744)	19.1 $\pm$ 1.9 (16.5;21.7)	17 $\pm$ 2 (14;20)	14.8 $\pm$ 1.4 (12.9;16.4)
Control	45 $\pm$ 7 (35; 54)	28 $\pm$ 1 (27;29)	1,835 $\pm$ 200 (1,612;2,046)	17.3 $\pm$ 1.2 (15.4;18.7)	43 $\pm$ 4 (38;47)	14.6 $\pm$ 1.1 (13.1;16.5)

Notes: RD = relative density; TPH = trees per hectare; BA = basal area; QMD = quadratic mean diameter

Table 3: Stand information for the six commercial thinning treatments at the time of treatment. Values shown are the means $\pm$ standard deviation, and minimum and maximum in parentheses across all six study sites. TPH, BA, QMD, Piece size, Trees removed, and Vol. rem. are based on merchantable trees.

Treatment	Pre-harvest				Post-harvest	
	TPH	BA (m ² ·ha ⁻¹)	QMD (cm)	Piece size (m ³)	BA (m ² ·ha ⁻¹)	QMD (cm)
A	1,691 $\pm$ 252 (1,331;2,003)	32 $\pm$ 3 (30;38)	15.6 $\pm$ 1.3 (14.0;17.3)	0.12 $\pm$ 0.03 (0.09;0.17)	19 $\pm$ 1 (18;20)	17.4 $\pm$ 0.9 (16.3;18.8)
B	1,888 $\pm$ 203 (1,680;2,211)	36 $\pm$ 3 (32;39)	15.6 $\pm$ 0.8 (14.7;17.0)	0.13 $\pm$ 0.02 (0.11;0.16)	22 $\pm$ 2 (20;24)	16.9 $\pm$ 0.8 (16.3;18.5)
C	1,853 $\pm$ 300 (1,433;2,248)	40 $\pm$ 3 (35;44)	16.8 $\pm$ 1.6 (15.5;19.6)	0.16 $\pm$ 0.04 (0.13;0.24)	25 $\pm$ 3 (21;30)	18.3 $\pm$ 1.7 (17.2;21.5)
D	1,691 $\pm$ 252 (1,331;2,003)	27 $\pm$ 3 (22;30)	14.2 $\pm$ 0.7 (13.5;15.2)	0.09 $\pm$ 0.01 (0.08;0.11)	13 $\pm$ 1 (11;14)	16.0 $\pm$ 0.9 (15.0;17.3)
E	1,692 $\pm$ 313 (1,408;2,198)	31 $\pm$ 3 (26;34)	15.4 $\pm$ 1.4 (13.5;17.0)	0.12 $\pm$ 0.03 (0.08;0.15)	14 $\pm$ 2 (13;17)	17.3 $\pm$ 1.5 (15.5;19.1)
F	1,484 $\pm$ 397 (951;2,112)	34 $\pm$ 5 (30;42)	17.5 $\pm$ 2.0 (15.5;20.3)	0.17 $\pm$ 0.05 (0.12;0.24)	17 $\pm$ 2 (14;20)	19.1 $\pm$ 1.9 (16.5;21.7)

Treatment	Trees removed	BA removal (%)	Vol. rem. (m ³ ·ha ⁻¹)	Cost* (\$·ha ⁻¹)	Gross Revenue* (\$·ha ⁻¹)	Net Profit* (\$·ha ⁻¹)
A	703 $\pm$ 169 (380;823)	40 $\pm$ 5 (35;50)	85 $\pm$ 27 (55;135)	941 $\pm$ 203 (580;1,182)	2,170 $\pm$ 690 (1,396;3,424)	1,229 $\pm$ 531
B	924 $\pm$ 98 (803;1,050)	40 $\pm$ 4 (36;46)	119 $\pm$ 19 (98;154)	1,233 $\pm$ 121 (1,063;1,365)	3,029 $\pm$ 479 (2,484;3,918)	1,796 $\pm$ 388
C	836 $\pm$ 127 (679;963)	37 $\pm$ 3 (32;41)	133 $\pm$ 17 (119;163)	1,209 $\pm$ 87 (1,070;1,313)	3,370 $\pm$ 419 (3,025;4,155)	2,161 $\pm$ 420
D	1,084 $\pm$ 171 (882;1,287)	53 $\pm$ 3 (50;57)	99 $\pm$ 14 (82;121)	1,294 $\pm$ 173 (1,074;1,480)	2,526 $\pm$ 362 (2,094;3,064)	1,232 $\pm$ 251
E	1,083 $\pm$ 239 (877;1,507)	54 $\pm$ 4 (50;59)	125 $\pm$ 17 (93;142)	1,378 $\pm$ 206 (1,233;1,731)	3,164 $\pm$ 429 (2,369;3,621)	1,786 $\pm$ 399
F	865 $\pm$ 235 (531;1,223)	52 $\pm$ 2 (48;54)	140 $\pm$ 22 (112;166)	1,259 $\pm$ 222 (948;1,631)	3,569 $\pm$ 559 (2,837;4,223)	2,309 $\pm$ 458

Notes: CT = commercial thinning; TPH = trees per hectare; QMD = quadratic mean diameter; BA = basal area; * = at time of CT; Vol. rem. = volume removed during CT.

Table 4: ANOVA results for fixed and random effects on the effect of treatment on maximum NPV (a), stand age at time of maximum NPV (b), and the effect of harvesting system on maximum NPV (c).

(a) Maximum Net Present Value								
<i>Fixed effects</i>					<i>Random Effects</i>			
Treatment	n	DF	F-value	p-value	Variable	Std. Dev.	Variance	Percent Explained
Intercept	1	30	444.731	<0.001	SITE	572.430	327,676.21	32
Treatment	6	30	3.449	0.010	PLOT (in SITE)	776.732	603,312.60	59
					Residual	316.333	100,066.25	9
(b) Stand age at time of maximum Net Present Value								
<i>Fixed effects</i>					<i>Random Effects</i>			
Treatment	n	DF	F-value	p-value	Variable	Std. Dev.	Variance	Percent Explained
Intercept	1	30	377.225	<0.001	SITE	6.747	45.516	96
Treatment	6	30	65.975	<0.001	PLOT (in SITE)	1.104	1.218	3
					Residual	0.746	0.556	1
(c) Harvesting system effect on maximum Net Present								
<i>Fixed effects</i>					<i>Random Effects</i>			
Treatment	n	DF	F-value	p-value	Variable	Std. Dev.	Variance	Percent Explained
Intercept	1	70	440.0	<0.001	SITE	559.983	313,580	32
Treatment	6	30	3.476	0.01	PLOT (in SITE)	823.106	677,503.15	68
System	2	70	606.047	<0.001	Residual	36.747	1,350.355	0
Treatment:System	1	70	10.185	<0.001				

Table 5: Projected mean maximum NPV and stand age at time of maximum NPV $\pm$ standard deviation and minimum and maximum values in parentheses for all six treatments and control at final harvest. All values are based on a CTL harvesting system.

Treatment	Maximum Net Present Value	Stand age at time of maximum NPV
	(\$·ha ⁻¹)	(yrs)
A	6,311 $\pm$ 988 (5,244;7,838) ^a	49 $\pm$ 6 (40;57) ^a
B	6,346 $\pm$ 1,206 (4,607;8,172) ^a	54 $\pm$ 7 (45;63) ^b
C	6,081 $\pm$ 1,027 (5,075;7,991) ^a	59 $\pm$ 7 (50;67) ^c
D	5,731 $\pm$ 856 (4,994;7,154) ^a	50 $\pm$ 7 (40;58) ^a
E	5,007 $\pm$ 959 (3,654;6,046) ^a	54 $\pm$ 7 (44;63) ^b
F	4,956 $\pm$ 651 (4,254;5,910) ^a	60 $\pm$ 7 (49;68) ^c
Control	5,002 $\pm$ 1,287 (3,611;6,492) ^a	49 $\pm$ 7 (39;59) ^a

Note: different letters following maximum net present value and rotation length indicate statistical differences among treatments.

Figure 1: Study site location across the state of Maine with county boundaries. **Note:** AS = Alder Stream site, LT = Lazy Tom study site, LM = Lake Macwahoc study site, RC = Ronco Cove study site, PE = Penobscot Experimental Forest study site, WB = Weeks Brook study site

Figure 2: Response of merchantable volume (a), gross merchantable volume MAI (b), average merchantable stem size (c), net present value (d), and net present value difference from the control following a CT treatment (e). Data after 2012 is projected, whereas data until 2012 was measured. Data shown represents the average for each treatment across all six study sites.

Figure 3: Maximum net present value (NPV) and on standard error bars for six treatments and one control plot across six study sites, with three different harvesting systems. The letters above the individual bars show the statistical significance between systems within each treatment but do not compare across treatments. Products harvested by all systems included roundwood only and did not include biomass chips.

Figure 4: Unit cost of production of three harvesting systems from stump to landing.

Figure 5: Sensitivity of maximum NPV to changes in input variables based on a light thinning with no delay. A change of 0% in input variables represents the baseline conditions as outlined in this manuscript. The curves for a change in trucking distance and trucking costs overlay each other and are not distinct from each other. Letters in the top center of each figure represent the treatment.