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Precommercial Thinning of *Picea mariana* and *Pinus banksiana*: Impact of Treatment Timing and Competitors on Growth Response

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Early successional competition among boreal forest tree and shrub species and its effects on growth of commercial tree species have been a major source of uncertainty in establishing efficient precommercial thinning and brushing prescriptions. We examined the effect of prethinning competitor density, postthinning competitor regrowth density, prethinning stem diameter, and the timing of thinning operations on the growth response of black spruce (*Picea mariana* [Mill.] BSP) and jack pine (*Pinus banksiana* Lamb.). In addition, we examined the mortality rate of hardwoods after thinning and the number of new shoots produced per surviving thinned stem. For jack pine, growth response was greatest when thinning occurred between 4 and 9 years after establishment, whereas for black spruce we observed no significant relationship between growth response and the timing of treatment. For jack pine, growth response was significantly affected by pretreatment competitor density, posttreatment competitor regrowth density, and pretreatment stem diameter. For black spruce, no significant relationship was observed between growth response and any variables. Mortality rates and production of new shoots in hardwoods varied significantly between species. Considering the high regrowth potential of willow (*Salix* spp.) and alder (*Alnus* spp.), we recommend that stands exhibiting low densities of these species should be left unthinned. Our results help foresters identify stands that require precommercial thinning and call for modification of currently used thinning strategies.

Keywords: precommercial thinning, treatment timing, *Picea mariana*, *Pinus banksiana*, competition density, growth response, hardwood regrowth

Early successional competition among boreal forest tree and shrub species and its effect on commercial tree growth and yield have been a major source of uncertainty in establishing efficient intensive management strategies, including precommercial thinning and brushing programs (Ontario Ministry of Natural Resources [OMNR] 1998b, Thompson and Pitt 2003). Precommercial thinning and brushing reduce tree and shrub density, and in boreal forest stands are typically applied during the first 30 years of a stand's lifespan (Smith 1986, Cole et al. 2010). Thinning increases growing space and the amount of light and nutrients available for residual trees and therefore improves both radial and vertical growth rates (Smith 1986), thereby reducing rotation age (Fleming 1994). Precommercial thinning is less costly and more efficient in young than in older stands because of the relatively smaller diameters of stems (Riley 1973, Smith et al. 1986) and results in a stronger growth response of residual trees in younger stands (Vassov and Baker 1988). Indeed, in thinning trials of jack pine (*Pinus banksiana* Lamb.), treatment costs were lowest in the youngest age class tested (9 years) (Riley 1973, Smith 1984, Smith et al. 1986).

Cleaning and brushing may result in the regrowth of cut trees and shrubs that can potentially offset any short-term gains in growth of

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residual trees by increasing competition density in the long term beyond what was observed before the treatment. These stands may then require additional thinning and cleaning treatments (Smith 1986, OMNR 1998b, Thompson and Pitt 2003). For example, willow (*Salix* spp.) and speckled alder (*Alnus rugosa* [DuRoi] Sprengel.) are able to quickly regenerate after cutting to a greater density than existed before the treatment (Richardson 1979, Habgood 1983, Haeussler and Coates 1986, Bell 1991). The positive effect of cleaning and brushing on hardwood density can be further exacerbated if these treatments occur during the dormant period (Bell 1991, Thompson and Pitt 2003). Conversely, regrowth of young paper birch (*Betula papyrifera* Marsh.) may be greater after cutting during the growing season (Bell 1991). In addition, heavy thinning can lead to overthinning, making residual trees susceptible to wind, ice, snow, temperature stress, sunscald, and photoinhibition and thereby decreasing their growth rates (Janas and Brand 1988, Krishka and Towill 1989, Bell 1991, Aussenac 2000).

A good understanding of the optimal time to employ precommercial thinning and brushing operations, growth response to removal of competition at various densities, and the regeneration potential of hardwood trees and shrubs after precommercial thinning can aid foresters in the identification of stands in need of this type of intervention. Changes in the current practices may help maximize growth response of residual trees and minimize treatment costs, e.g., by limiting subsequent interventions.

This study examined seven tree and shrub species commonly found in the boreal forest of North America. These species have been earlier shown to influence regeneration and growth of conifers (Bell 1991). Black spruce (*Picea mariana* [Mill.] BSP) and jack pine are the most common and most harvested conifers in the boreal forest. They are well adapted to fire and regenerate through the use of aerial seedbanks after this disturbance (Greene et al. 1999). Trembling aspen (*Populus tremuloides* Michx.) and paper birch are two common hardwood tree species that regenerate after disturbance by basal sprouting and, in the case of the former, through root suckering as well (Bell 1991, Greene et al. 1999, Thompson and Pitt 2003) but are not considered commercial tree species in the region studied. Pin cherry (*Prunus pensylvanica* L.), willows (*Salix* spp.), and alders (*Alnus* spp.) are common small hardwood trees and shrubs and generally reproduce by suckering and basal sprouting when cut (Brown and Hansen 1954, Fulton 1974, Haeussler and Coates 1986, Rudolph and Laidly 1990, Viereck and Johnston 1990, Wendel 1990, Thompson and Pitt 2003). Because these major competitors can all obtain substantial stature and their stems are similar (or greater) in size to the preferred conifer stems, the term "thinning" is hereafter used to denote the reduction in density of all competing species.

Objectives

The objective of this study was to examine the response of both conifers (black spruce and jack pine) and competing hardwoods to early precommercial thinning in planted and naturally regenerated burned areas. We specifically aimed to evaluate (1) the effect of the timing of precommercial thinning on the growth response of black spruce and jack pine, (2) the effect of competitor density (both deciduous and coniferous) on the growth response of these two species, (3) the average number of new shoots produced per cut stem across competing hardwood species, and (4) the mortality rates of thinned hardwood species.

Methods

Study Area

Our study area was located in the western part of the managed continuous boreal forest of Quebec (Canada). A subpolar, subhumid continental climate dominates the western portion of the spruce-moss bioclimatic domain, with total annual precipitation between 800 and 1,000 mm and an average annual temperature of 0° C at the southern limit. The length of the growing season is approximately 5 months (Bergeron et al. 1998). The landscape is dominated by glaciolacustrine clays and sands, Cochrane tills, glacial tills, glacio-fluvial complexes, and organic surficial deposits (Bergeron et al. 1998, Blouin and Berger 2005). We examined sites affected by three forest fires occurring between 1995 and 1998 (Figure 1), situated along the boundary between the southern limit of the western spruce-moss and northern limit of the western balsam fir-white birch bioclimatic domains (Bergeron et al. 1998, Blouin and Berger 2005).

The Wedding fire was located in northwestern Quebec, 37 km north of the town of Lebel-sur-Quevillon (49°17.789′ N, 76°52.446′ W). Ignited accidentally on May 16, 1998, it burned 4,130 ha of forest before it was extinguished by rain on June 16. The Cuvillier fire was located in northwestern Quebec, 40 km southeast of the town of Lebel-sur-Quevillon (48°49.513′ N, 76°37.224′ W). Ignited accidentally on Aug. 16, 1995, it burned 47,709 ha of forest before it was extinguished by rain on Oct. 20. The Closse fire was located in northwestern Quebec, 100 km southeast of the town of Lebel-sur-Quevillon (48°41.242′ N, 75°58.793′ W). Ignited accidentally on Aug. 20, 1995, it burned 6,925 ha of forest before it was extinguished by rain on Oct. 20.

In the summers of 2011 and 2012, we sampled a total of 21 thinned and easily accessible stands within these three burned areas, established on mesic and xeric sites after wildfires that caused 100% tree mortality. All stands were salvage logged. We limited our sampling to those dominated by black spruce ($n = 8$), jack pine ($n = 12$), or a combination of both ($n = 1$). All black spruce stands were planted, whereas only four jack pine stands were planted. Planting occurred within 3 years after fire, at a density of approximately 2,750 stems/ha. Thinning dates were identified using data provided by government authorities and forest companies responsible for treatment application. All stands were thinned manually using motor-manual brush saws.

In each of these stands, 10 circular 4-m^2 plots spaced 10 m apart along a single transect (randomly located) were sampled to calculate natural and planted (where applicable) tree density at both the stand and plot level. Plots were centered on the closest dominant black spruce or jack pine tree (depending on site). Within each plot all stems of black spruce, jack pine, aspen, birch, pin cherry, willow, and alder were counted, and the state of each tree (alive, dead, and/or thinned) was recorded. The height, dbh (measured at 1.3 m), and diameter at stump height (measured directly above the rootcollar) of the dominant tree were also recorded. Stems that were cut but regrew were measured to a radius of 2 m (12.56 m^2) from the dominant tree; for each individual, we measured the number of cut stumps and the density of regrown stems emerging from the aboveground tissue of said stumps. Surficial deposit was identified by digging five pits (every second plot) per stand. The surficial deposit and indicator plant species were used to determine site drainage, which was grouped into two categories: xeric and mesic.

We dated trees and estimated growth rates using stem disks from five dominant trees per site, with one dominant tree sampled in

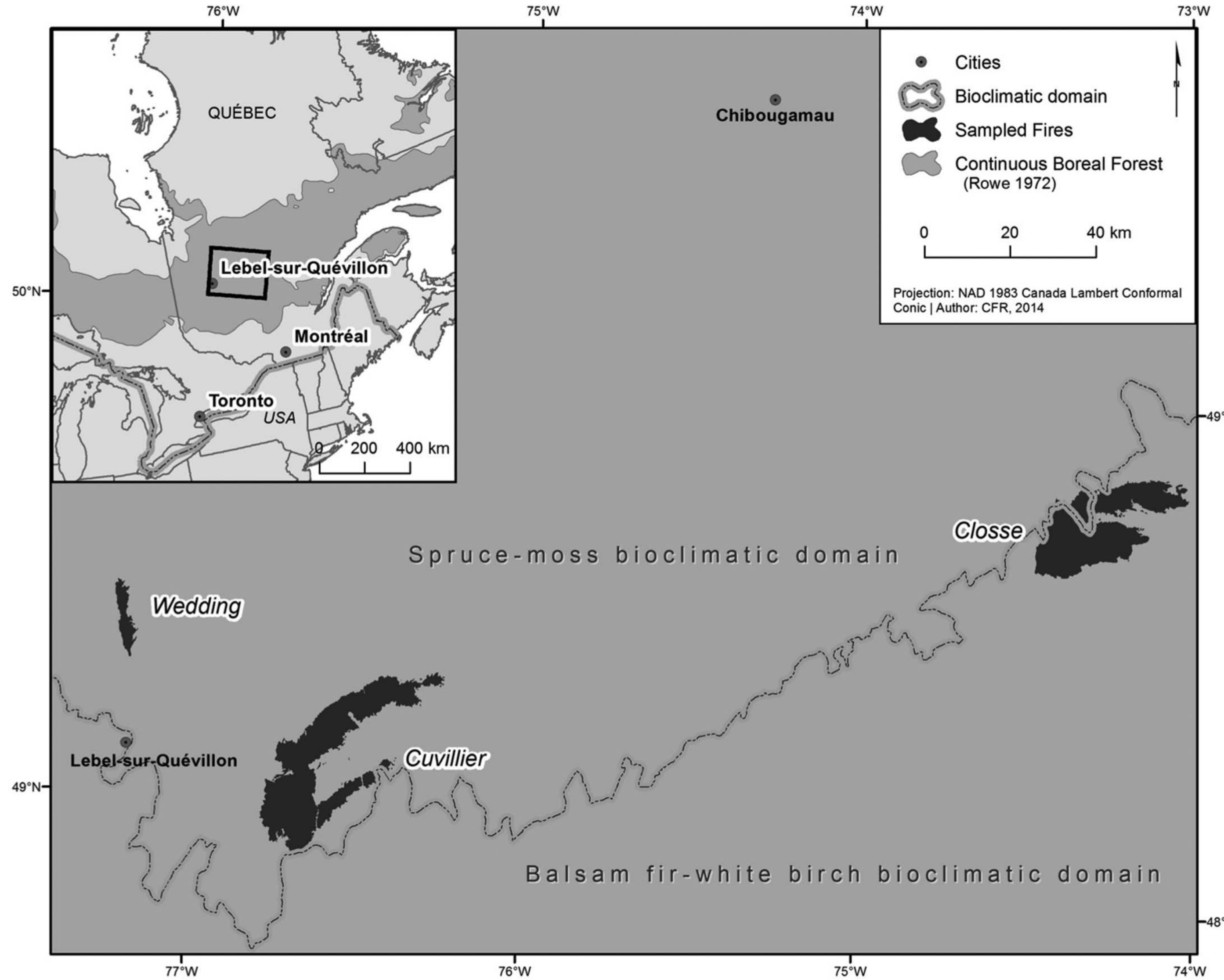

Figure 1. Location of the 3 fires sampled in this study.

every second 4-m^2 plot. Stem diameter at the end of the last dormant period preceding thinning operations was measured using a caliper. Age was determined based on the year the individual germinated. Trees displaying injuries to the terminal shoot were excluded from the analyses. Disks used in the age and growth analysis were cut just above the rootcollars. We used ring measurements to evaluate response to competition, as well as the pre- and postthinning competitor density (number of stems) around each dominant individual within a single plot. We sanded disks with up to 400-grit sandpaper and dated them under a binocular microscope.

Disks were scanned at 2,400 dpi, and tree rings were measured in CooRecorder (Larsson 2010) along three radii at 0, 120, and 240° from the north direction. If problems were encountered with the disk (branch whorls, cracks), the lines were moved by 30° in the clockwise fashion from their original position. If the problem persisted, the radii were once again moved by 30° in the opposite direction. If the problem persisted further, the process was repeated in increasing angular increments by 10°. Tree-ring data for each tree were averaged in CDendro (Larsson 2010). We obtained a tree-level estimate of growth response to thinning by averaging three radii.

Statistical Analyses

To provide a proxy of tree response to thinning we developed an index based on a ratio of the cumulative basal area increment (BAI) before and after the thinning. Because the sampled trees were young (<17 years), they exhibited a positive relationship between their age and BAI; i.e., BAI increases with age. Therefore, a simple ratio of pre- and postthinning increments would underestimate growth response by assuming no age-related difference in growth rates between periods. To address the age trend (in this case an increase of BAI with time), we first defined and estimated a linear function relating age and BAI, parameterized using the prethinning period for each tree analyzed. The basal area increment was calculated as the difference in the areas of two circles representing the growth in years t and $t + 1$:

$$\mathrm{BAI}_t = BA_{t+1} - BA_t = \pi \cdot (R_{t+1}^2 - R_t^2) \quad (1)$$

where BA is the basal area and R is the radius in the respective year.

Such a linear function explained, on average, 0.89 ($R^2_{\min} = 0.43$, $R^2_{\max} = 0.99$) of variability in tree-specific regression equations. The $R^2_{\min} = 0.43$ is somewhat of an outlier; the next nearest value is 0.63, with the vast majority (89%) of all R^2 values $\geq$0.80. Each tree's

Table 1. Summary of growth response to precommercial thinning for black spruce and jack pine.

Species	Mean	SD	Minimum	Maximum	n
	. . . .	. (%) .	. . . .		
Black spruce	240.47	123.16	95.85	570.53	45
Jack pine	211.36	132.94	56.15	649.50	64

growth rate was then projected for the posttreatment period using its own growth equation. The projections were extended to 2011, the most recent year for which we had the growth chronologies from all sampled trees. This protocol allowed us to project BAI as if the trees were growing at the same rate both before and after the treatment. The ratio between the observed and the projected cumulative growth (expressed as a percentage), which we refer to as "growth response" later in the text, was then used as a dependent variable in subsequent analyses. A positive growth response was defined as any growth response value greater than 100%. The period length used with that ratio varied between stands as thinning operations took place in different years over 2002–2009.

We used R package *nlme* (Pinheiro et al. 2014) to run a linear mixed effects analysis of variance (ANOVA) model with growth response of jack pine or black spruce as the dependent variable and age of thinning and site drainage category as independent factors. We then used R package *AICcmodavg* (Mazerolle 2014) to select the most parsimonious model from the initial pool of candidate models including both interactive and noninteractive effects. Because of low variability in the competitor density (due to treatment uniformity and the fact that it was an operational rather than experimental set of treatments), we could not use ANOVA to test for their specific effects on growth response for either the dominant black spruce or jack pine individuals examined. Instead, we considered the coniferous and deciduous competitors together.

To evaluate the extent to which factors other than age at treatment could affect the growth response, we then performed a multiple regression independently for both the black spruce and jack pine data sets. Growth response was the dependent variable, and total competitor density (i.e., total number of competing stems) removed by thinning, total regrowth density (i.e., total number of regrown stems), age at thinning, and stem diameter at the end of the last dormant period preceding thinning operations were considered independent variables. The model that accounted for the most variance and the greatest number of significant independent variables was then selected.

To examine the mean number of new shoots produced by hardwoods based on the number of cut stems (per individual) after thinning, we used a mixed-effects ANOVA with factors *species* (fixed) and *site* (random); a post hoc Tukey's honest significant difference (HSD) test was used to determine where the differences occurred. The response variable was the ratio of new shoots produced after cutting to the number of stems before cutting. Variables were log-transformed to comply with assumptions of normality and homoscedasticity.

To compare the mortality rates among hardwood species after thinning, we used a χ^2 test. An α value of 0.05 was used for all statistical analyses.

Results

Black Spruce and Jack Pine Growth Response after Thinning

Thinning resulted in a positive growth response in the majority of sampled trees (95.56% for black spruce and 75% for jack pine). Details on the distribution of growth response data by species can be found in Table 1.

Growth Response versus Timing of Thinning Operations

No significant relationship was identified between the growth response (%) and age at thinning (years since establishment) for black spruce (Figure 2A); however, individuals thinned at 6 years of age showed the lowest growth response. Although also not significant, site drainage was a better predictor of growth than age at thinning. For jack pine, individuals thinned between 4 and 9 years after establishment had a significantly greater growth response than those thinned 10+ years after establishment (Figure 2B). Detailed results of the analyses can be found in Table 2.

Growth Response versus Stem Diameter, Competitor Density Removed, Competitor Regrowth Density, and Timing of Thinning

For black spruce, multiple regressions showed no significant relationship between growth response and competitor density removed, competitor regrowth density, treatment age, or stem diameter at the end of the last dormant period preceding thinning operations although this last variable was close to being significant ($R^2 = 0.08$, $P = 0.0684$) (Table 3). For jack pine, significant effects

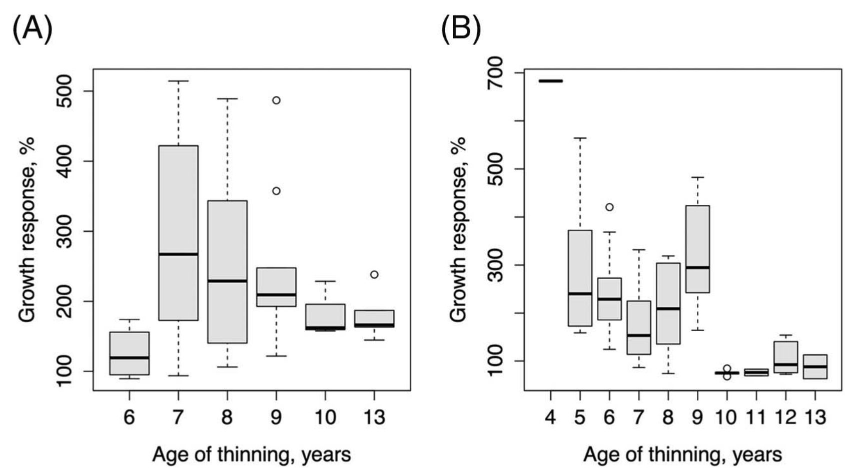

Figure 2. Boxplot of growth response as a function of thinning age for black spruce (A) and jack pine (B). Sample size for individual age classes (from youngest to oldest) were as follows: for black spruce, 4, 8, 14, 10, 4, 5; for jack pine, 1, 6, 15, 16, 6, 5, 5, 2, 6, 2.

Table 2. Best mixed-effects ANOVA models for release (growth response) of black spruce and jack pine after precommercial thinning.

Species	Model	Coefficient	SE	*df*	*t*-value	*P* value	Correlation
Black spruce	Drainage	39.52	57.31	7	0.69	0.51	−0.67
	Intercept	210.86	38.21	31	5.52	0.00	
Jack pine	Thinning age	−24.57	10.30	37	−2.39	0.02*	−0.95
	Intercept	398.60	84.30	37	4.73	0.00	

Only the best predictive model is presented for each species.
* Significant at $p < 0.05$.

were observed for all independent variables except treatment age ($R^2 = 0.36$, $P < 0.0001$) (Table 3); stem diameter at the time of thinning exhibited the highest significance, followed by competitor density removed and competitor regrowth density.

To determine whether prethinning stem diameter was related to treatment age, we then performed multiple regressions examining the effect of treatment age and competition density removed on stem diameter of dominant trees. For black spruce, stem diameter was significantly affected by treatment age but not by competitor density ($R^2 = 0.30$, $P = 0.0005$); for jack pine, stem diameter was significantly affected by both independent variables, with treatment age exhibiting the highest significance, followed by competitor density removed ($R^2 = 0.52$, $P < 0.0001$) (Table 4).

Mortality Frequency and Mean Number of New Shoots Per Thinned Stem by Hardwood Species

The abundance of hardwood species varied across the study sites, with aspen and pin cherry being the most frequently observed, followed by willow spp., paper birch, and alder spp. (Table 5).

We observed that the mortality of competitors after thinning varied significantly among species. Figure 3 illustrates the results of the χ^2 test. Trembling aspen exhibited the highest mortality (40%) among the five hardwoods, followed by pin cherry (35%) and paper birch (29%), with willow spp. (3%) and alder spp. (2%) exhibiting the lowest mortality rate.

Mixed-model ANOVA indicated that the after/before ratio of shoots produced by cutting varied significantly among hardwood species ($P < 0.0001$) (Figure 4). Alder spp. produced significantly more shoots per stump than willow spp., paper birch, pin cherry, and trembling aspen (Tukey's HSD) (Table 6).

Discussion

Black Spruce and Jack Pine Growth Response after Thinning

Thinning resulted in an overall positive growth response in both black spruce and jack pine. By increasing growing space, light, and nutrient availability for residual trees, thinning increases radial growth rates (Smith 1986, Vassov and Baker 1988, OMNR 1998a, 1998b). However, some residual trees experienced a decline in growth rates after thinning (4.4% of sampled black spruce and 25% of sampled jack pine trees). This may be due to overthinning (excessive spacing), which could leave residual trees susceptible to wind, ice, snow, temperature stress, sunscald, and photoinhibition (Janas and Brand 1988, Krishka and Towill 1989, Bell 1991, Aussenac 2000), damage to the trees as a direct result of the thinning operation itself (Vassov and Baker 1988), or crown closure of planted stands beginning at or around the time of thinning. We believe that crown closure occurred or was close to occurring in two of the sampled jack pine stands (sites 18 and 20 in the annex) at the time of thinning application; all sampled trees within these stands exhibited a negative growth response after thinning (representing 10 trees of the 16 jack pine trees exhibiting a negative growth response). These two sites were thinned relatively late (11–12 years after fire), had the highest stem diameters at the time of thinning when compared to all other sampled jack pine stands, and exhibited high lateral branch mortality at the time of sampling.

Timing of Precommercial Thinning Operations

Our results indicate that for jack pine, a significantly greater growth response was observed in individuals that were thinned between 4 and 9 years after disturbance (stands were thinned between 6 and 13 years after fire [see Table A1 in the Appendix]; this should not be confused with the age at which individual trees were thinned within their respective stands, which was based on germination year and not the year of fire occurrence). Because of increasing competition for nutrients, space, and light, precommercial thinning operations in jack pine stands generally coincide with the onset of the self-thinning phase, between 6 to 12 years after stand establishment (Vassov and Baker 1988). It is also cheaper to thin stands at a younger age because less time and energy are required because trees exhibit relatively smaller diameters (Riley 1973, Smith et al. 1986). Thinning stands early also leaves residual trees less vulnerable to stress and may improve stand stability (Aussenac 2000), making them less susceptible to overthinning. Our results are in line with these observations. Vassov and Baker (1988) found that 10 year-old jack pine stands typically exhibit a greater response to thinning than older age stands; in addition, the 9-year age class was identified as the most

Table 3. Multiple regression results for black spruce and jack pine growth responses to precommercial thinning.

Species	Model	Coefficient	*t*-value	*P*-value
Black spruce	Stem diameter	−27.59	−1.87	0.0684
	Intercept	333.86	6.29	<0.0001*
Jack pine	Stem diameter	−26.94	−3.19	0.0022*
	Competitor density	2.70	2.16	0.0344*
	Regrowth density	−6.54	−2.08	0.0422*
	Treatment age	−6.26	−0.75	0.4585
	Intercept	366.98	6.95	<0.0001*

Only the best predictive model is presented for each species.
* Significant at $p < 0.05$.

Table 4. Multiple regression results for black spruce and jack pine stem diameter preceding precommercial thinning.

Species	Model	Coefficient	*t*-value	*P* value
Black spruce	Treatment age	0.35	4.30	<0.0001*
	Intercept	0.35	0.48	0.6355
Jack pine	Treatment age	0.67	7.25	<0.0001*
	Competitor density	−0.05	−3.87	0.0003*
	Intercept	−0.26	−0.33	0.7410

Only the best predictive model is presented for each species.
* Significant at $p < 0.05$.

Table 5. Presence of hardwood species out of total sites sampled (n = 21) and sample size (number of saplings) by species for both the mortality and regrowth study after precommercial thinning.

Species	Sites present	n for mortality	n for stem regrowth
Trembling aspen	16	497	526
Pin cherry	16	222	204
Paper birch	8	75	88
Willow spp.	13	143	193
Alder spp.	7	53	87

economical one to thin (Riley 1973). Smith (1984), however, suggests that jack pine stands be thinned between 10 and 15 years after establishment. It is important to mention that the studies conducted by both Riley (1973) and Smith (1984) examined 9-, 22-, and 33-year-old age classes, whereas our youngest jack pine individual examined was thinned 4 years after fire.

No significant difference among thinning years was observed for black spruce, although trees thinned at 6 years of age showed the lowest growth response. This may be due in part to black spruce's slow growth rate and its greater shade tolerance than jack pine (Sims et al. 1990, Viereck and Johnston 1990); at the time of thinning, the canopy would have not yet closed, so intense competition would have not yet begun, thereby minimizing growth response.

We suggest that thinning operations in jack pine stands not be used beyond 9 years after fire, as is currently often the case. Indeed in our study area, we observed black spruce and jack pine stands being thinned up to 16 years after fire. Based on our results, we are hesitant to provide a thinning schedule for black spruce, but given its slow growth rate and the fact that it appeared to exhibit the strongest growth response 7 and 8 years after establishment (Figure 2), we suggest that thinning in black spruce stands should occur no earlier than 7 years after fire.

Growth Response versus Stem Diameter, Competitor Density Removed, Competitor Regrowth Density, and Timing of Thinning

The growth response of jack pine after thinning operations was significantly affected by pretreatment stem diameter (i.e., smaller diameters resulted in a greater response) and the density of competitors removed by thinning operations, as well as posttreatment competitor regrowth density. This supports Vassov and Baker's (1988) suggestion that smaller trees (diameter) may exhibit higher postthinning relative growth rates.

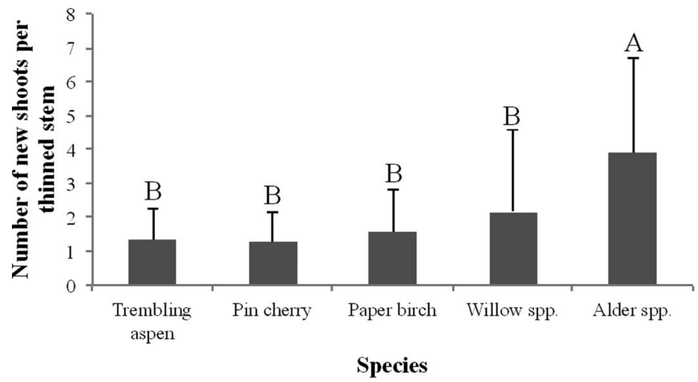

Figure 4. Adjusted mean number of new shoots per cut stem by species after precommercial thinning. ANOVA P < 0.0001. Error bars represent SD, and letters illustrate significant differences in new shoot production between species.

This analysis suggested that treatment age did not significantly affect growth response, contrary to what was concluded from the mixed-model ANOVA approach (Figure 2); instead, pretreatment stem diameter exhibited the highest significance (Table 3). We hypothesized, however, that pretreatment stem diameter would be dependent on both treatment age and competitor density removed, so an additional multiple regression analysis was performed. The results supported this hypothesis (Table 4). So, although treatment age did not appear to significantly affect growth response when we considered other variables, it is directly linked to the most highly significant variable.

Jack pine is highly shade intolerant (Reich et al. 1998). In addition, hardwood species such as cherry, willow, and alder compete heavily with jack pine and black spruce for light, nutrients, and especially water (Bell 1991). It is therefore not surprising that the greater the competition density removed, the greater the growth response. Indeed, Bell (1991) suggests that all overhead competition should be removed within 1 year after planting of jack pine.

With respect to competitor regrowth, the surviving root system of hardwood vegetation that regrows after thinning continues to use resources such as nutrients and water, and regrown stems may once

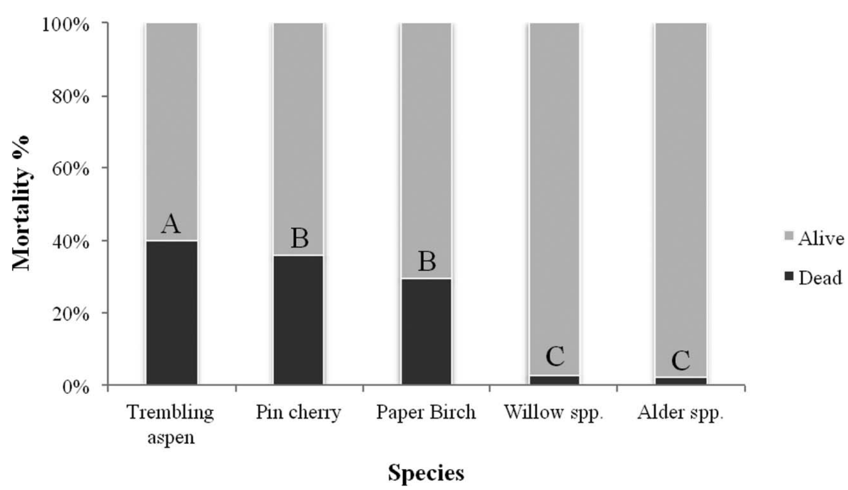

Figure 3. Percent stem mortality by species ($P > \chi^2 < 0.0001$) after precommercial thinning. Letters illustrate significant differences in mortality between species.

Table 6. Adjusted and observed mean shoot production, upper and lower 95% confidence limits, and minimum and maximum value per cut stem by species after precommercial thinning.

Species	Adjusted mean	Observed mean	95% confidence limit Upper	Lower	Minimum	Maximum
Trembling aspen	1.20	1.32	1.41	1.24	0.33	10
Paper birch	1.23	1.55	1.82	1.27	0.25	7
Pin cherry	1.15	1.27	1.39	1.15	0.33	8
Willow spp.	1.52	2.17	2.51	1.82	0.20	20
Alder spp.	2.82	3.91	4.49	3.32	0.33	19

again begin competing for light with residual trees if their growth rates are rapid. Indeed, trembling aspen root suckers and paper birch sprouts exhibit rapid growth after cutting, with the former growing up to 2 m in its first year due to the availability of resources in parent roots (Frey et al. 2003). In addition, if competing jack pine stems are cut above the first living branch whorl, there is a significant chance of regrowth (Splawinski et al. 2014).

There was no significant relationship between black spruce growth response after thinning and competitor density removed, competitor regrowth density, treatment age, or pretreatment stem diameter; however, stem diameter was close to significant ($P = 0.0684$). All sampled stands were dominated by black spruce before the fire, and because of poor conifer recruitment, were planted after salvage operations. We believe that the resulting low variation in competition density and composition (almost all hardwood) in the stands, as well as the slow growth rate and greater shade tolerance of black spruce (Reich et al. 1998), explains this lack of relationship.

Hardwood Mortality and Regrowth

Both willow and alder species can reproduce quickly and vigorously after cutting (Bell et al. 2011). For example, although highly variable, individual stems of willow spp. that have been cut can produce up to 50–60 new sprouts (Haeussler and Coates 1986). Unless treated chemically, alder is not removed by cutting; indeed, stem density may increase by approximately 63% depending on cutting season (Stoeckeler and Heinselman 1950).

Observed mortality rates varied significantly by species (here mortality refers to the death of the stem and does not take into account the production of root suckers). Of the species that exhibited the highest mortality rates after precommercial thinning (trembling aspen, paper birch, and pin cherry), those that regrew displayed the lowest shoot production per cut stem. Conversely, those that exhibited the lowest mortality rates (willow spp., 2%; alder spp., 3%) displayed the highest shoot production per cut stem (a maximum of 20 for willow spp. and 19 for alder spp.). If the density of these species is relatively low (especially willow and alder), it may be beneficial to avoid thinning. For example, the presence of alder may enhance conifer reproduction and growth, especially in black spruce, by increasing available nitrogen and preventing grass growth (Stoeckeler and Heinselman 1950, Bell 1991), which has been identified as detrimental to early conifer establishment and growth (Bell et al. 2000). The presence of birch and aspen may also improve nutrient cycling (Haeussler and Coates 1986, Bell 1991). This may improve growth rates and survival as well as provide some protection, especially in the case of black spruce (Bell 1991). For example, Légaré et al. (2004) observed that black spruce dbh was enhanced when aspen occupied between 0 and 41% of total stand basal area.

Study Limitations and Future Research

In addition to the relative lack of variation in competition density in the sampled black spruce stands, we identify three factors that may explain some of the variability that was not accounted for by our statistical models. First, we did not examine root suckering after precommercial thinning; however, this is a common reproduction strategy in trembling aspen (Frey et al. 2003), pin cherry (Fulton 1974), and speckled alder (Brown and Hansen 1954). We observed, to varying degrees, this type of regeneration in almost all thinned stands where these species were present; in some cases the density (post- versus pretreatment) increased at the stand level. Second, residual tree spacing after precommercial thinning was not measured; however, it is known to affect growth response (Smith 1984). Third, we did not examine the effect of ericaceous species presence on conifer growth. Numerous studies indicate that ericaceous shrubs can negatively affect conifer regeneration and growth (Mallik 2003). This may include allelopathy, soil nutrient deficiency, and imbalance due to phenolic compounds, direct competition, soil acidification, poor ectomycorrhization, changes in conifer mycorrhizae activities, site degradation, and water use (Inderjit and Mallik 1996a, 1996b, 2002, Mallik 2003). Given that cutting aboveground parts of these species stimulates the emergence of new shoots (e.g., Mallik 1993), precommercial thinning has the potential to increase their density and inhibition effects on conifer growth.

A drawback of our approach is that we examined an operational rather than an experimental set of treatments; therefore, we were not able to use control (untreated) plots to compare treatments. However, the use of treewise analyses of changes in growth dynamics helped avoid the effect of differences in site conditions between treated and eventual control sites.

Future research should focus on examining the effects of the pretreatment density of individual hardwood species on the growth response of black spruce and jack pine after precommercial thinning to identify their relative competiveness, and if and at what limit hardwood retention would be beneficial. To date, hardwood retention in Quebec has focused primarily on benefits for fauna and biodiversity (Legris and Couture 1999, Cimon and Labbé 2006) and not on maximizing crop-tree growth. High competitor density has a negative effect on the growth of black spruce and especially the shade-intolerant jack pine (Bell et al. 2000). However, companion species may improve nutrient cycling (e.g., nitrogen fixation), which can result in an overall positive effect of their presence in natural stands and commercial plantations if their densities are below threshold levels for competition impacts to become important. For example, in the absence of thinning, jack pine had a greater average dbh and volume when mixed with paper birch than pure jack pine and mixed aspen stands (Longpré et al. 1994). Similarly, a positive effect of aspen presence on black spruce dbh and height growth has been reported (Bell 1991, Légaré et al. 2004). We know of only one study, that of Bell et al. (2000), which examined the relative competiveness of woody and herbaceous species on growth of planted seedlings of black spruce and jack pine; however; it focused on the first 4 years after planting and not beyond.

This study focused on stands subjected to precommercial thinning only as a means for controlling density. Future research should aim to develop comprehensive intensive stand management regimes by examining the combined use of silvicultural approaches. This includes the above-mentioned hardwood retention strategy, chemical treatment (Bell 1991), timing of thinning (Riley 1973, Vassov and Baker 1988), thinning intensity (spacing) (Smith 1984, Vassov

Table A1. Site details.

Site no.	Species	Drainage	Fire	Yr since fire (thinning timing)	Yr since thinning	DSH before thinning (cm)	SD	Mean height (cm)	Height: minimum–maximum (cm)	Mean growth response (%)	SD	Mean competitor density (stems/ha)	SD	Mean competitor regrowth density (stems/ha)	SD	Hardwood species present
1	BS	M	Cl	7	9	2.82	0.34	502	425–630	121.18	34.66	1,500	2,236	500	1,118	C, W
2	BS	M	Cu	9	7	3.84	0.96	548	491–625	196.01	56.46	26,000	27,928	22,000	22,804	A, C, W
3	BS	M	Cu	13	2	4.80	1.91	432	202–598	228.91	52.86	32,000	19,316	22,500	19,764	A, B, C, W
4	BS	M	We	7	5	3.24	0.32	407	369–458	378.56	80.99	5,000	1,768	4,500	2,092	A, B, C, W
5	BS	M	We	7	5	3.46	0.93	360	222–515	194.95	80.70	3,000	2,739	3,000	2,739	B, C, W
6	BS	X	Cl	8	8	2.64	0.63	520	471–557	397.84	157.6	20,000	17,589	18,000	15,350	A, B, C, W
7a	BS	X	Cl	8	8	3.00	1.26	529	377–652	160.85	69.63	15,000	5,863	10,000	8,478	A, C
8	BS	X	Cu	9	6	4.26	1.43	515	344–650	189.39	43.13	8,500	4,873	7,000	4,472	A, C
9	BS	X	Cu	8	8	2.40	0.74	424	355–514	296.55	148.8	25,500	16,808	12,000	2,739	A, C, W
10	JP	M	Cl	8	8	3.44	0.98	516	448–619	120.45	70.86	12,000	8,551	4,000	2,850	A, W
11	JP	M	Cu	9	6	2.40	0.82	397	235–507	243.64	83.97	67,500	66,685	23,000	19,072	C, W
12	JP	M	Cu	13	3	4.08	1.06	399	257–473	200.08	108.5	44,500	27,295	9,500	6,471	A, B, C, Al
13	JP	M	We	7	5	3.94	0.89	508	458–552	280.35	110.7	4,500	5,123	3,500	4,873	Al
14	JP	M	We	7	5	3.96	0.77	557	503–620	199.65	36.46	18,000	6,225	7,000	5,701	A, C, W, Al
15	JP	M	We	7	5	4.14	1.20	462	370–590	238.25	66.42	6,000	4,183	2,000	3,260	A
16	JP	X	Cl	6	9	1.96	0.48	614	492–664	436.04	152.90	24,500	10,216	16,500	8,404	A, B, C, W
17	JP	X	Cl	6	10	2.46	0.22	671	602–725	192.51	37.98	98,500	47,355	35,000	25,981	A, W
7b	JP	X	Cl	8	8	5.25	0.19	783	720–836	193.67	108	22,500	14,860	7,500	6,770	A, C
18	JP	X	Cu	12	3	9.52	0.70	736	680–780	63.57	6.56	2,000	4,472	2,000	4,472	W
19	JP	X	Cu	8	7	2.18	1.10	345	186–470	136.74	52.16	53,000	34,884	26,500	37,022	
20	JP	X	Cu	11	5	8.50	1.21	766	700–890	65.22	6.17	28,500	7,202	7,500	5,863	A, B, C
21	JP	X	Cu	9	7	3.56	0.89	634	541–690	373.93	153.30	116,000	52,933	24,000	16,826	A, B, C, Al

and Baker 1988), thinning height (Splawinski et al. 2014), pretreatment stand density (OMNR 1998b), disease and insect susceptibility (Vassov and Baker 1988), the possibility of multiple thinning treatments (Smith 1986, OMNR 1998b), and economic factors such as desired end-products (OMNR 1998b), current and future market value of products, and operational costs (OMNR 1998a).

Conclusion

Results of this study indicate the following: the timing of precommercial thinning has a significant effect on the growth response of jack pine and should be employed between 4 and 9 years after fire; jack pine growth response after thinning is significantly affected by pretreatment competitor density, posttreatment competitor regrowth density, and pretreatment stem diameter; and mortality rates and new shoot production vary significantly by hardwood species. Because of the high and dense regrowth potential of willow and alder, we recommend that stands exhibiting low densities of these species be left unthinned.

Appendix

Site details including dominant species (BS, black spruce; JP, jack pine), drainage (M, mesic; X, xeric), site location within a specific fire (Cl, Closse; Cu, Cuvillier; We, Wedding), years since fire, years since thinning, mean diameter at stump height (DSH) before thinning with SD, mean height, minimum and maximum height, mean growth response (%) after thinning with SD, mean competitor density before thinning with SD, mean competitor regrowth density after thinning with SD, and hardwood species present (A, aspen; B, birch; C, cherry; W, willow spp.; Al, alder spp.) are shown in Table A1.

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