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# Influence of Stem Taper on the Yield of Black Spruce Stands and Trees Following Commercial Thinning<sup>†</sup>

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**Abstract:** In this work, we examine the effects of commercial thinning on stand volume and individual stem form in nine naturally regenerated black spruce (*Picea mariana* (Mill.) B.S.P.) stands. We compared these study sites with controls in the commercial boreal forest of northern Quebec, Canada. At stand level, dendrochronological data provided insight into changes in stand volume ten years after thinning. Analysis of a subsample of six individual trees from each commercially thinned stand and three individual trees from the controls illustrated the role of thinning on stem shape development. Although average volume increased for residual stems in thinned stands slightly more than in the controls (110% versus 106%), the treatment effect stand-level volume increment or stand-level total volume harvested (ten years after treatment) was not statistically significant. Moreover, at tree level, thinning did not significantly affect stem volume increment. However, radial growth increment significantly increased after treatment. Trees from commercially thinned stands showed a significantly higher growth increment along the lower first two-thirds of the stem. Response to thinning at tree level correlated strongly with the size and number of harvested competitors around a residual stem. We conclude that commercial thinning modified wood allocation rather than wood volume and did not affect taper and stem shape. These patterns of post-cutting growth are explained by wood allocation following thinning. After commercial thinning, growth increment is favored at the expense of height growth. As the treatment effect was found at the stem scale rather than at the stand scale, further research is needed in regard to commercial thinning treatments to investigate how to increase productivity at the stand scale.

**Keywords:** *Picea mariana*; black spruce; boreal forest; commercial thinning; taper; volume increment

## 1. Introduction

Black spruce (*Picea mariana* (Mill.) B.S.P.) is an important commercial and reforested species in Eastern Canada [1,2]. The traditional harvesting method used in black spruce stands is clear-cutting; however, forest management practices in the boreal forest have evolved, and in Quebec, ecosystem-based management is now applied to respond to concerns about sustainability [3]. Intermediate stand management activities (e.g., thinning) achieve numerous resource management objectives, including the improvement and maintenance of wildlife habitats, wildfire hazard reduction, ecosystem restoration, and timber production [4]. The Canadian Forest Service defines partial cutting as “any cutting in

which only part of the stand is harvested”; however, they specify no minimum level of retention. Commercial thinning is one type of partial cutting treatment. Many studies examining the boreal ecosystem response to partial cutting have focused on biodiversity and how various levels of cutting affect forest ecology, including regeneration [5], biodiversity protection [6], and cover retention [7]. The issue of timber production rates in partial cuts, however, has received less attention [8–10], specifically in naturally regenerated, unmanaged black spruce stands. Timber production yield can be evaluated at different scales as it depends on a range of factors. Yields can be expressed according to the produced stand volume and also by volume increment of individual trees. At the individual scale, predicting wood volume and lumber yield requires information regarding stem shape [11–13] and lumber yield [14,15]. Two stems having the same volume but that differ in terms of taper will produce two different lumber volumes. In natural, unmanaged stands, given the high stand density before treatment, we may assume substantial changes in stem form after a canopy opening; for example, wind-induced bending events increase linearly with increased spacing between trees [16,17].

In this study, we focus on fire-origin black spruce stands that had undergone commercial thinning at least ten years before sampling. Using measurements collected at two scales—stand and stem levels—this study aimed to examine changes in wood volume within thinned black spruce stands and take into consideration stand and treatment characteristics. At the stem level, we evaluated variations in stem taper and shape after treatment to better explain our stand-scale observations. We hypothesized that thinning led to an increased individual volume caused by availability of light and nutrients. Stand-level volume may increase several years after treatment. Thinning should also induce changes in radial growth along the stem. Indeed, wind entrance within stands—in response to the opening of the canopy—should affect the pattern of wood deposition along the stem and modify stem taper as demonstrated by Lemay et al. [11].

## 2. Material and Methods

### 2.1. Study Area

We studied nine commercially thinned stands and their controls from 2006 to 2008 in a portion of the boreal forest of Quebec, Canada. We used two main criteria to select our sites: (1) thinning which had occurred in the naturally regenerated, unmanaged natural black spruce stands and (2) that this treatment happened at least ten years prior to our sampling. Stands also had to be accessible by truck and be located close to trails to allow us to carry field material and samples on foot. As this was a recent silvicultural treatment in the boreal forest of Canada, information about commercial thinning, with regard to type and technical details, is not available.

Whenever possible, we selected a nearby unmanaged natural black spruce stand which had similar characteristics to the treatment stand to be a control (Table 1). In two instances, when multiple stands shared similar environmental characteristics, the same control stand was used to compare more than one nearby partially thinned stand. Study plots covered an area 47.9° N to 49° N and 70.5° W to 72.7° W. Elevations of the study sites ranged between 210 to 671 m above sea-level. The region is characterized by cold winter temperatures and a short vegetative period. The average minimum temperature is  $-18.3^{\circ}\text{C}$  during the coldest month and  $17.9^{\circ}\text{C}$  during the warmest month. Average annual precipitation varies from 920 cm to 1187 cm in the studied stands [18]. All relevant stand characteristics are presented in Table 1.

**Table 1.** Summary statistics of studied sites.

Site	Location	Annual Precipitation (mm)	Temperature (Min/Max, °C)	Year of Thinning	Age <sub>init</sub>	DBH <sub>init</sub> (cm)	G <sub>init</sub> (Residuals and Harvested, m <sup>2</sup> ha <sup>-1</sup> )	G <sub>harvested</sub> (%)
HEB95	N47.887 W71.464	992.9	-12.1/17.9	1995	48.4 (10)	13.0 (3.7)	29.16	19.6
HEB96-1	N48.315 W71.679	992.9	-12.1/17.9	1996	58.7 (9)	15.4 (4.1)	23.76	9.7
HEB96-2	N48.279 W71.683	992.9	-12.1/17.9	1996	53.2 (8)	16.6 (4)	41.05	31.8
HEB C	N48.145 W71.589	992.9	-12.1/17.9		51.3 (9)	15.8 (5.2)	48.27	
LB95	N48.033 W72.33	1012.7	-16.8/17.3	1995	81.9 (27)	14.7 (3.2)	33.08	13.1
LB C	N48.032 W72.334	1012.7	-16.8/17.3		67.1 (23)	14.6 (4.4)	17.15	
LC96	N48.143 W71.879	1036.7	-11.7/19.3	1996	56.3 (6)	15.1 (1.8)	44.85	39.6
LC C	N48.143 W71.878	1036.7	-11.7/19.3		54.9 (13)	20.7 (4.8)	35.24	
LJ96	N48.983 W72.738	919.8	-18.4/17.6	1996	46.8 (6)	13.6 (2.5)	42.30	52.5
LJ C	N48.983 W72.741	919.8	-18.4/17.6		53.1 (7)	12.3 (2.5)	48.87	
MV95	N48.794 W70.544	1187.3	-16.1/17.5	1995	60.9 (11)	14.1 (3.1)	40.04	39.7
MV96	N48.76 W70.551	1187.3	-16.1/17.5	1996	59.5 (8)	12.9 (2.4)	32.98	30.8
MV C	N48.764 W70.55	1187.3	-16.1/17.5		52.8 (12)	14.6 (3.8)	49.82	
SL97	N48.874 W71.747	1061.4	-11.7/18.2	1997	57.1 (7)	17.1 (2.4)	40.10	37.4
SL C	N48.874 W71.475	1061.4	-11.7/18.2		50.2 (7)	15.5 (5.6)	33.99	
Mean for harvested stands					58	14.7	38.5	30.5
Mean for controls					55	15.6	38.9	

Legend: C, controls; G, basal area; init, year of partial cutting; DBH, diameter at breast height. Mean values are followed by their standard deviation in parentheses.

## 2.2. Stand Measurements

In each stand, we established a 20 × 20 m quadrat (400 m<sup>2</sup>) comprising at least 35 black spruce (diameter at breast height (DBH) > 9 cm). At one control site, LJ C, we selected only 25 trees because of environmental constraints. For each tree in the quadrat, we determined total tree height (H), DBH, and diameter at stump height (DSH). In thinned stands, stump circumference was also recorded.

To determine tree age and variations in stand-level radial growth after thinning, we recovered an increment core from each living tree at 25 cm above the ground; the core was aligned along a N–S axis. Initial merchantable basal area (G<sub>init</sub>, m<sup>2</sup> ha<sup>-1</sup>) and the resulting percentage basal area harvested (G<sub>harvested</sub>, %) were calculated according to Perron et al. [19] (Equation (1), Table 1), i.e.,

$$G = \frac{\pi \times factor}{40000} \times \sum_{i=1}^n DBH_i^2 \quad (1)$$

where G is the basal area, factor is the conversion factor for correcting obtained values to a value in ha, and n represents the number of trees in the quadrat. The conversion factor also considers the nature of the measurement variability. For harvested trees, G<sub>init</sub> was calculated using DSH corrected using the DBH/DSH ratio. Harvested tree height was assessed using the stumps of residual stems of similar diameter within or close to the quadrat [20,21].

We calculated stem volume from volume tables for black spruce as a function of stem DBH and H [22]. Based on this information, we determined at stand level the average volume by stem (AVS, m<sup>3</sup>) and stand volume (V, m<sup>3</sup> ha<sup>-1</sup>) for the year of thinning and for the sampling year (AVS<sub>init</sub>, AVS<sub>f</sub>, V<sub>init</sub>, and V<sub>f</sub>, respectively). The total volume harvested was also calculated (Table 2). For our analysis, we considered stands ready for final felling in the year of sampling.

**Table 2.** Stand volume (V) and stand-level average volume by stem (AVS) at the year of harvest (init) and ten years after treatment (f).

Stands	V <sub>init</sub> (m <sup>3</sup> ha <sup>-1</sup> )	V <sub>f</sub> (m <sup>3</sup> ha <sup>-1</sup> )	V <sub>tot</sub> (Partial and Final Harvest)	AVS <sub>init</sub> (m <sup>3</sup> )	AVS <sub>f</sub> (m <sup>3</sup> )	Stand Volume Increment (%) (RES Stems Only)
HEB95	83.82	69.46	88.78	0.073	0.104	107.69
HEB96-1	219.16	204.29	225.50	0.195	0.215	103.20
HEB96-2	248.14	182.18	263.63	0.140	0.152	109.30
HEB C	285.64	306.04	306.04	0.127	0.136	107.14
LB95	204.48	187.85	216.97	0.134	0.163	107.12
LB C	96.40	110.41	110.41	0.101	0.116	114.54
LC96	272.16	180.16	294.35	0.125	0.185	114.05
LC C	229.39	237.41	237.41	0.255	0.264	103.50
LJ96	239.99	124.97	259.03	0.084	0.076	117.97
LJ C	283.74	298.07	298.07	0.073	0.076	105.05
MV95	190.80	124.75	201.48	0.079	0.111	109.36
MV96	157.27	120.41	172.11	0.068	0.102	114.05
MV C	268.48	280.42	280.42	0.098	0.102	104.45
SL97	263.55	183.81	278.52	0.162	0.223	108.86
SL C	218.27	225.40	225.40	0.140	0.145	103.27
Mean						
Harvested stands	208.82	153.10	222.26	0.118	0.148	110.18
Controls	230.32	242.96	242.96	0.132	0.140	106.33

Legend: C, controls; RES stems only, residual stems only.

### 2.3. Selected Tree Measurements

#### 2.3.1. Selected Tree Neighborhood

We randomly selected and felled, among dominant and codominant trees, six black spruce in each thinned stand and three black spruce in the control stands. A total of 71 trees were harvested for stem analysis. We recorded the neighborhood conditions of sampled trees to interpret stand response (Table 3).

**Table 3.** Summary statistics of the selected trees and their competitors.

Sites	Number of Selected Trees	Mean DBH (cm)	Mean H (m)	Number of Living Competitors	Mean DBH of Living Competitors (cm)	Number of Stumps of Competitors	Mean DBH of Stumps of Competitors (cm)
HEB95	6	17.1 (3.4)	12.5 (1.4)	1.5 (1.5)	13.4 (1.8)	1.3 (1.0)	11.6 (3.7)
HEB96-1	6	17.2 (3.1)	14.4 (2.1)	2.2 (1.0)	19.7 (2.7)	0.7 (1.2)	18.8 (2.5)
HEB96-2	6	19.4 (3.2)	16.3 (2.3)	2.7 (0.8)	15.2 (2.1)	0.8 (0.4)	18.3 (6.2)
HEB C	3	18.9 (4.5)	16.0 (2.3)	3.3 (1.2)	14.4 (3.2)	N/A	N/A
LB95	6	16.7 (2.9)	16.1 (2.6)	3.0 (2.5)	17.5 (1.1)	1.7 (1.2)	18 (4.6)
LB C	3	16.9 (6.1)	14.1 (3.6)	2.7 (0.6)	16.5 (0.8)	N/A	N/A
LC96	6	22.5 (5.6)	18.2 (1.9)	1.8 (0.8)	19.2 (2.2)	2.5 (2.2)	11.2 (0.7)
LC C	3	17.9 (3.4)	16.6 (0.6)	2.3 (1.2)	23.4 (2.0)	N/A	N/A
LJ96	6	12.3(2.0)	13.2 (0.9)	2.2 (0.8)	13.2 (0.8)	1.7 (1.2)	12.8 (2.9)
LJ C	3	12.2 (2.4)	14.0 (1.6)	6.0 (1.7)	11.1 (0.6)	N/A	N/A
MV95	6	15.1 (3.6)	13.0 (1.7)	2.5 (1.6)	15.8 (1.0)	0.7 (0.8)	12.7 (1.2)
MV96	5	14.4 (1.6)	12.7 (0.7)	2.0 (1.6)	15.0 (1.1)	1.6 (1.8)	9.8 (0.2)
MV C	3	16.2 (1.6)	12.7 (0.7)	2.3 (2.1)	12.1 (1.3)	N/A	N/A
SL97	6	17.0 (3.2)	16.0 (1.5)	1.8 (1.0)	25.2 (7.3)	0.8 (1.3)	15 (1.7)
SL C	3	14.4 (3.5)	13.9 (2.7)	3.7 (2.1)	11.5 (2.4)	N/A	N/A
Mean							
Harvested stands	6	16.9 (1.2)	14.7 (0.5)	2.2 (0.6)	17.2 (2.0)	1.3 (0.5)	14.2 (1.9)
Controls	3	16.1 (3.6)	14.5 (1.9)	3.4 (1.5)	14.8 (1.7)	N/A	N/A

Legend: C, controls; H, height; N/A, not applicable. Mean values are followed by their standard deviation in parentheses.

Based on these data, we calculated a competition index (CI) for each selected tree using Hegyi's diameter–distance CI [23] (Equation (2)), i.e.,

$$CI_i = \sum_{j=1}^n \left( \frac{DBH_j}{DBH_i} \times \frac{1}{DIST_{ij}} \right) \quad (2)$$

where  $CI_i$  is the competition index of the subject tree  $i$ ,  $j$  is the competitor tree located within 4 m of the subject tree ( $3.5 \times$  mean crown radius of canopy trees), and  $DIST_{ij}$  is the distance between the subject and competitor trees. We considered a tree a potential competitor when its DBH was greater or equal to two-thirds of the DBH of the subject tree [23,24].

We calculated two Hegyi indices: (1) the stump competition index ( $CI_s$ ) and (2) the competition index for the year of treatment ( $CI_{init}$ ).  $CI_s$  characterizes the influence of the harvested tree on the growth of the selected trees, whereas  $CI_{init}$  characterizes the competition among the remaining trees after treatment.

### 2.3.2. Growth Measurement

Once felled, we removed a 5 cm disc at each meter of the stem, starting at ground level and moving up to the crown. Each sample disc was dried and sanded. We measured tree-ring widths from four perpendicular radii using Henson and WinDendro software [25]. We then cross-dated the rings [26,27]. Tree-ring dating was verified using the COFECHA program [28]. We obtained the radii for each year and for the top and bottom of each section by summing the ring widths up to that year.

To compare trees of differing height and size, we expressed height and tree-level growth values relatively, following Assman's method [21]. We calculated the relative height (RH) of all selected trees as the ratio between disc height and  $H$ .

Tree-level decennial relative growth was calculated;  $\alpha$  was expressed based on RH for the ten years prior to (Equation (3)) and the ten years post-treatment (Equation (4)), i.e.,

$$\alpha_{\text{before}} = \frac{\sum_{t=-9}^{t=0} \alpha_{RH}}{\sum_{t=-9}^0 \alpha_{1.3/H}} \quad (3)$$

$$\alpha_{\text{after}} = \frac{\sum_{t=1}^{t=10} \alpha_{RH}}{\sum_{t=-9}^{t=0} \alpha_{1.3/H}} \quad (4)$$

where  $t$  is time (in years, with  $t = 0$  the year of treatment), and  $\alpha$  is the tree-level radial growth increment. We measured  $\alpha$  for each disc taken along the stem.

For statistical analyses, the tree-level relative growth increment (GrowthInc) was calculated as the ratio between  $\alpha_{\text{after}}$  and  $\alpha_{\text{before}}$ .

### 2.3.3. Stem Shape

A common approach for studying stem shape is to assume that a tree is composed of three segments with its form constant within a segment and differing between segments. Each segment is described by a "power function", a continuous function which has an exponent. The limit between segments is commonly called the inflection point. Various studies have suggested that the inflection point ranges from 20% to 25% of the total height from the ground [29,30] and that the relative height is fairly constant within a species, regardless of tree size [13]. Thus, to calculate shape characteristics of the middle segment of the stem, we recorded the diameter at two relative positions along the stem, namely, at 0.2 and 0.7 of total stem height [31]. We determined the positions using the tree height at harvest time.

Stem shape was calculated using the equation of Forslund [32] (Equation (5)), i.e.,

$$A_{SEC} = ln \quad (5)$$

where an  $A_{SEC}$  equal to 2 represents a parabola and an  $A_{SEC}$  value of 1 represents a cone [31].

Taper was calculated by determining the stem diameter change divided by the stem length between the two diameter measurements [32] (Equation (6)), i.e.,

$$T = \frac{D_{RH=0.2} - D_{RH=0.7}}{L} \quad (6)$$

where  $D_{RH}$  is the diameter at relative height RH and  $L$  is the length between the two relative heights. Profile shape was defined as the geometric shape of the stem profile between the two diameter measurements and it was quantified by the exponent  $A_{SEC}$  in the power function.

We determined taper and stem shape ( $A_{SEC}$ ) for the five-year average, for ten years prior to treatment, and for the mean five to ten years after treatment.

### 2.3.4. Statistical Analysis

Statistical analyses were performed using R software run with the *nlme* package and the *lme* function using a confidence level of 95 per cent [33]. Linear mixed-effect models were built to investigate variations in the variables of interest (V, GrowthInc, taper, and  $A_{SEC}$ ) with treatment (thinned/control). For all analyses, treatment was the main effect. Models were run using restricted maximum likelihood (REML) to estimate the final parameters. Before our analyses, we calculated Pearson correlations to investigate possible autocorrelation between explanatory variables. We verified the model's assumptions using graphical diagnostics (i.e., residual versus predicted, Cook's distances and hat values, and distribution of observed values) initially with a general linear model without random effects but with all explanatory variables integrated into it, as well as for the final model. After these analyses, we used the natural log transformations of GrowthInc (lnGrowthInc) and taper (lnTaper) in the models.

At stand level, to study variations in stand volume increment (stand volume increment and  $V_{tot}$  harvested) with treatment and stand characteristics, we built a seven-block unbalanced split-plot design. Initial density ( $G_{init}$ ) was added as a covariate for each site within a block. Blocks were randomized factors. To evaluate stem volume increment ( $AVS_f/AVS_{init}$ ) variations with treatment, we built a mixed model which had trees nested within a block as random effects and  $G_{init}$  as a covariate. Then, for partially harvested stands only, we ran a linear model with  $G_{init}$  and percentage of basal area harvested ( $G_{harvested}$ ) as explanatory variables.

To evaluate the treatment effect on tree-level radial growth allocation (GrowthInc), we developed a mixed-effect model which had discs nested within selected trees, which were nested within a block as random factor effects. Relative height was included in the model as a factor effect and DBH,  $G_{init}$ , tree slenderness (slenderness, H/DBH),  $CI_s$ , and  $CI_{init}$  were included as covariates. As H and DBH were correlated, H was not included in the models. To evaluate growth increment variation with RH, we computed orthogonal contrasts. First-level RH (RH = 0) was compared with all superior levels and then RH = 0.1 was compared with RH > 0.1, and so on.

To evaluate the treatment effect on stem shape and taper, we built a mixed-effect model having two repeated measures (time = before/after) for each tree nested within a block as random factor effects. Again, DBH,  $G_{init}$ , slenderness,  $CI_s$ , and  $CI_{init}$  were included as covariates.

## 3. Results

The mean age of the stands varied from 48 to 82 years (Table 1). Stand density before thinning varied between 800 and 3900 trees ha<sup>-1</sup>. At the year of harvest, the thinned stands had a mean age of

58 years while control stands had an average age of 55 years. Based on  $G_{init}$ ,  $G_{harvested}$  varied from 9.7% to 52.5%; this percentage can be classified as light to heavy thinning.

### 3.1. Variations in Volume

The  $V_{tot}$  of thinned stands was less than that of the control stands ( $222.3 \text{ m}^3 \text{ ha}^{-1}$  versus  $243.0 \text{ m}^3 \text{ ha}^{-1}$ , Table 2). In terms of residual stems only, stand-level increment after thinning was slightly higher than in the control stands (110.2% versus 106.3%, Table 2). After thinning, merchantable stand-level increment was higher for seven of the nine thinned stands relative to their controls. Stand-level increment, however, was not significantly affected by either treatment or  $G_{init}$  (Table 4). The  $V_{init}$  affected significantly  $V_{tot}$  at ten years post-treatment; however, treatment did not have a significant effect (Table 4).

By stand, the average stand-level increment ( $AVS_f/AVS_{init}$ ) varied from 90.5% (a reduction of average volume increment) to 150.0% with a mean of 118.7% (Table 2). Thinned stands presented an average stand-level increment at the final harvest of 125.6%; the value for the controls was 105.7%. Treatment did not significantly affect stand-level increment; this lack of effect was mainly due to between-tree variations. Calculated on the intercept model only, the variance component showed that the fraction of total variance due to tree was about 99%, whereas the fraction of total variance due to block was about 0.1% (data not shown).  $G_{harvested}$  did not significantly affect stand-level increment in the thinned stand ( $p = 0.34$ , data not shown).

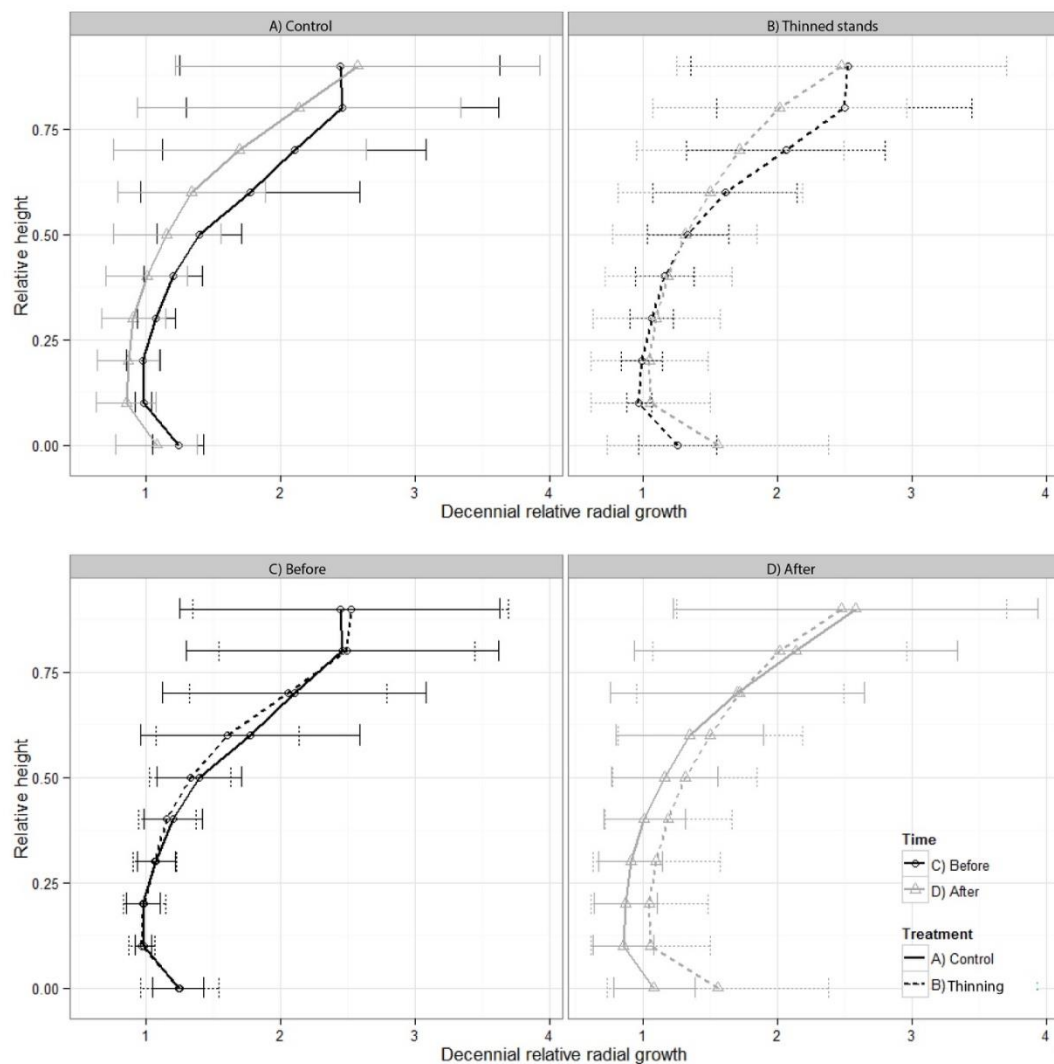
**Table 4.** ANOVA for fixed effects for (a) stand-level increment, (b)  $V_{tot}$  harvested, and (c) stand-level increment.

Variable	Effect	Num DF	Den DF	F Value	p Value
(a) Stand volume increment	Intercept	1	7	19.655	<0.0001
	Treatment	1	7	1.583	0.139
	$G_{init}$	1	7	−0.057	0.956
(b) $V_{tot}$ harvested	Intercept	1	7	0.593	0.564
	Treatment	1	7	0.670	0.516
	$V_{init}$	1	7	50.815	<0.0001
(c) Stem volume increment	Intercept	1	928	0.659	0.510
	Treatment	1	928	−0.182	0.856
	$G_{init}$	1	928	0.561	0.575

### 3.2. Radial Growth Response in Relation to Taper and Stem Shape

The DBH of trees selected for stem analysis from the thinned stands varied from 9.1 cm to 28.5 cm, with a mean of 16.9 cm. The DBH of trees selected for stem analysis from the control stands varied from 9.5 cm to 23.5 cm, with a mean of 16.1 cm. Selected trees from thinned stands averaged approximately 2.2 competitors with a DBH between 11.2 and 33.2 cm and a mean DBH of 17.2 cm. Selected trees from the control stands averaged approximately 3.4 competitors, having a DBH of 8.8 to 25.7 cm with a mean DBH of 15 cm (Table 2). Trees selected from the thinned stands had an average of 1.3 stumps around them; the number of stumps varied from 0 to 6. Mean stump diameter was 17.1 cm, ranging from 8.3 cm to 35 cm in diameter.

To evaluate wood allocation, we studied tree-level decennial relative radial growth along the stem ( $\alpha$ ) before ( $\alpha_{before}$ ) and after ( $\alpha_{after}$ ) treatment. Figure 1a,b shows that  $\alpha$  at the base of the tree increased slightly after thinning while  $\alpha_{after}$  was lower than  $\alpha_{before}$  in control stands. We observed that the  $\alpha_{before}$  along the stem was similar for both thinned and control stands; however,  $\alpha_{after}$  was higher in the lower two-thirds of tree height in thinned stands than in controls (Figure 1c,d).



**Figure 1.** Mean relative radial tree-level growth ten years before (black) and ten years after (grey) treatment along the bole for thinned (dashed line) and control (solid line) stands: Data are unitless. Decennial relative radial tree-level growth (A) for control stands before and after treatment; (B) for thinned stands before and after treatment; (C) for both stand types; and (D) after treatment for both stand types.

DBH, slenderness, and  $CI_{10m}$  (reflecting the number of competitor trees, their diameter, and their distance from the selected tree before treatment) did not significantly affect relative  $Growth_{Inc}$ . They were excluded from the final model (Table 5a).

At tree level, thinning led to a significant increase of  $Growth_{Inc}$  ( $p = 0.0007$ , Table 5a).  $Growth_{Inc}$  decreased with relative height. More specifically, the treatment effect on  $Growth_{Inc}$  varied significantly with relative height ( $p < 0.0001$ , Table 5a). Based on orthogonal contrasts, for the first two-thirds of tree height,  $Growth_{Inc}$  was significantly higher in thinned stands than for control trees; at the top of the tree,  $Growth_{Inc}$  was significantly higher for the control trees (Figure 2). Eventually, at the stem level, only  $CI_{10m}$  (representing the number of stumps and their distance from the selected sampled tree) had a positive significant effect on  $Growth_{Inc}$ .

Treatment and time significantly affected  $A_{SEC}$ , although the interaction treatment  $\times$  time was not significant (Table 5b).

We observed similar results for taper variations (Table 5c). Logically, slenderness influenced taper significantly, and selected trees from the thinned stands had a significantly lower taper.



**Table 5.** ANOVA for fixed effects for (a) lnGrowthInc, (b) A<sub>SEC</sub>, and (c) lnTaper. Only significant effects are presented in the table.

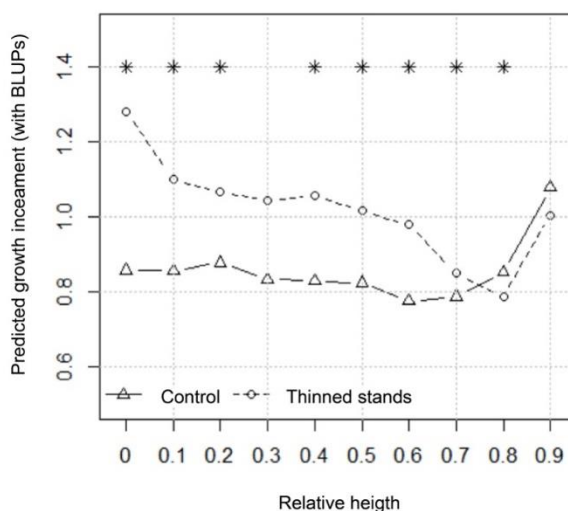
Variable	Effect	Num DF	Den DF	F Value	p Value
(a) lnGrowthInc <sup>1</sup>	Intercept	1	621	433.040	<0.0001
(a) lnGrowthInc <sup>1</sup>	Treatment	1	63	433.040	<0.0001
	Relative height (RH)	9	621	12.7516	<0.0001
	CI <sub>s</sub>	9	621	23.61948	<0.0001
	Treatment × RH	1	63	16.948	<0.0001
	Treatment × CI <sub>s</sub>	9	621	7.810	<0.0001
(b) A <sub>SEC</sub> <sup>2</sup>	Intercept	1	70	286.119	<0.0001
(b) A <sub>SEC</sub> <sup>2</sup>	Treatment	1	70	286.119	<0.0001
	Time	1	63	8.55034	<0.0001
	CI <sub>s</sub>	1	70	211.583	<0.0001
	Time × CI <sub>s</sub>	1	63	4.3794	<0.0001
(c) lnTaper <sup>3</sup>	Intercept	1	63	4.367546	<0.0001
(c) lnTaper <sup>3</sup>	Treatment	1	70	367.465	<0.0001
	Time	1	63	4.65913	<0.0001
	Slenderness	1	70	35.23072	<0.0001
	Time × Slenderness	1	63	23.072	<0.0001

<sup>1</sup>lnGrowthInc = log(GrowthInc); <sup>2</sup>A<sub>SEC</sub> = Stem shape; <sup>3</sup>lnTaper = log(Taper). Legend: GrowthInc, growth increment; CI<sub>s</sub>, stump competition index.

#### 4. Discussion

##### 4.1. Thinning Effect on Stand Attributes

Based on our study sites, stand-level volume growth increment from thinned stands, ten years after treatment, was not sufficient to recover the control stand volume. We observed no significant change of stand volume increment after thinning. Contrasting results are found in the literature with regard to partial harvesting and its effects on stand volume increment. Stinson [33], studying stands of second-growth Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), found that low thinning from below led to an increase in total harvest volume with extended rotations. By contrast, Mäkinen et al. [34] observed a decrease in annual volume increment per unit area 8–10 years after intensive thinning in a study of Scots pine (*Pinus silvestris* L.). Their results, however, suggested that when coupled with a fertilization treatment, this harvesting method would enable a shorter rotation period. Similar results have been reported for stands of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) [35].



**Figure 22.** The level of mean growth increment for each relative height from estimates of the control and thinned stands BLUPs. BLUPs as a unbiased prediction. Significant differences between growth increments between treatments at various relative heights.

In black spruce stands 15 years after treatment, stand volume of a heavily thinned stand was about 75% of the control stand volume. However, when a spruce budworm (*Choristoneura fumiferana* Clemens) outbreak occurred in the stand, the thinned stand was not affected relative to the control sites, and stand volume eventually reached the same volume as the control, 33 years after harvesting [9].

We may argue that different types of thinning (from above, from below, thinning intensity, species, and sites, etc.) serve different purposes and thus produce different results. One of the earliest studies focusing on the effect of partial harvesting on black spruce stands demonstrated that light thinning (25%) had little impact on the growth of individual trees within a 65-year-old stand; a 50% thinning increased the basal area growth rate by 30% 15 years after treatment [36]. In this study, however, thinning intensity did not significantly affect stand or average stem volume variation and the inter-block variation was negligible. Moreover,  $G_{init}$  did not affect stand-level increment. This lack of effect could be related to stand productivity. For example, in a Norway spruce (*Picea abies* (L.) Karst) stand, Lundqvist et al. [37] found that standing volume had a significant effect on growth increment after thinning. However, this effect was apparent only in the southern site (no effect was observed in the study's northern site).

#### 4.2. Wood Allocation and Stem Shape Variations Following Treatment

At tree level, growth increment was significantly higher for selected trees from thinned stands than the control stands. Similar observations have been noted for jack pine (*Pinus banksiana* Lamb.) [38], Douglas fir [39], black spruce [24], and Norway spruce [40,41]. More specifically, growth increment was affected strongly by  $CI_S$  (the number and the size of harvested competitors). The lack of effect of treatment on average stem volume increment by stand may thus not be the result of an ineffective treatment but rather the heterogeneous response at the stem scale depending on a tree's neighborhood. At the stand level, the characteristics of harvested trees (size, number) are related to partial harvest type (from above, from below, or single-tree selection system, etc.) rather than intensity. In uneven-aged Norway spruce stands, thinning from above (removing the larger trees) has been found to lead to a consistent increase of volume increment compared to thinning from below [37]. In the same type of stand, the system of single-tree selection has also been found to induce a higher growth volume increment compared to low thinning and dimension cutting [42]; more marked differences were observed in a planted Norway spruce stand in Sweden [40].

We also observed a specific pattern of wood deposition for selected trees from thinned stands. Contrary to control stands, where tree-level growth increment was located at the top of the tree, selected trees from thinned stands demonstrated a growth allocation along the first two-thirds of the stem. Neither taper nor stem shape ( $A_{SEC}$ ) were affected significantly by thinning. The significant effect of treatment on both  $A_{SEC}$  and taper reflects a between-site difference (control versus thinned) rather than a real effect of the treatment. With regard to Figure 2, this result is logical according to the inflection point position selected for  $A_{SEC}$  and taper calculation. Both 0.2 and 0.7 RH are included in the growth increment zone for selected trees from thinned stands. These results agree with Goudiaby et al. [43], who observed that the vertical distribution of specific volume increment was constant in black spruce stems after thinning. This led to no modifications of the stem taper. In a similar sense, Sharma and Parton [44] observed that the stand density effect on taper was more pronounced in jack pine than in black spruce.

Ever since theories related to stem form were first proposed [45], foresters have concurred that silvicultural practices favoring growth increment also produce changes in stem shape. Various authors have suggested that the patterns of wood deposition along the stem are affected by variations in crown size, which in turn are affected by tree characteristics and stand conditions (particularly stand density) [46–49]. This hypothesis has been verified for some species, including Douglas fir and Sitka spruce (*Picea sitchensis*), for which Mitchell [17] found that basal allocation temporarily increased after thinning, suggesting a period of acclimatized growth during which trees re-equilibrate with post-thinning wind loads. In Jack pine stands (*Pinus banksiana* Lamb.), Goudiaby et al. [43] also detected

a positive correlation between stem volume growth, growth efficiency (stem to foliage biomass ratio), and foliage biomass at mid-crown. However, for shade-tolerant species such as black spruce, opening the canopy may not necessarily affect branch development, taper, or stem shape in the same way [49]. Thus, Goudiaby et al. [43] again observed no change in growth efficiency, foliage biomass, or biomass density after thinning. Despite these observations, the model suggested that  $A_{SEC}$  decreased when  $CI_5$  increased; therefore, the stem would become more conical when the number and the size of direct competitors harvested are important.

By contrast, our control trees showed a tree-level growth increment located at the top of the tree, a higher position than for trees selected from thinned stands. This variation in tree-level growth allocation may contribute to the relative success of thinning in regard to volume increment. Mitchell [17] has suggested that a temporary reduction in height increment, increased radial increment, and increased basal allocation after thinning may contribute to reducing the height-diameter ratio. In studies of Douglas fir and Sitka spruce, this reduction was more pronounced in trees that were initially slenderer. These results are in accordance with the negative slenderness effect observed for changes in taper.

As we had anticipated an increase in stand volume increment ten years after treatment, our observations in commercially thinned stands did not meet our expected results. However, this result is attenuated by wood allocation being located along the merchantable portion of the stem. As treatment did not affect taper stem shape, economic loss during sawmilling can be avoided [15].

## 5. Conclusions

Depending on the purpose of thinning and other partial harvest—simplifying stand structure, converting even-aged stand to uneven-aged stands, increasing stand productivity, or decreasing or extending rotation—our results show that in natural black spruce stands, the thinning effect is greater at the individual scale than the stand scale. After treatment, growth increment along the main part of the stem is favored to the detriment of growth at the top of the tree.

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