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Maximum Branch Diameter in Black Spruce Following Partial Cutting and Clearcutting

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Abstract: Branch diameter is an important aspect of wood quality, as lumber grades can be determined based on the maximum diameter of branches. Crown and branch development can be influenced by the environment surrounding the trees, and silvicultural interventions, which reduce stand density and increase the growth of residual trees, could therefore alter branch properties. We evaluated maximum branch diameter within the crown of residual black spruce (*Picea mariana* (Mill.) B.S.P.) subjected to five types of silvicultural intervention—three partial-cutting and two clearcutting treatments—as well as trees within unmanaged control stands. We sampled a total of 41 stands and 223 trees. We collected 15 whorls from the live crown of each tree and measured the diameters of the largest branches. For all treatments, we observed a curvilinear relationship between maximum branch diameter and distance from the stem apex, and the largest branches were located in the lower third of the live crown. DBH before treatment and treatment were the variables that best explained maximum branch diameter in the lowest portion of the crown. A generalized additive model showed that maximum branch diameter in black spruce following silvicultural treatment will not differ significantly from trees of unmanaged control stands. Therefore, the studied partial cutting and clearcutting treatments do not have adverse effects on maximum branch diameter when compared to unmanaged control stands. However, DBH prior to treatment must be considered before any treatment is applied in forest management operations if maximum branch diameter is an important wood quality factor at the time of the final harvest of the stands.

Keywords: *Picea mariana* (Mill.) B.S.P.; partial cutting; clearcutting; maximum branch diameter; silvicultural treatments; live crown

1. Introduction

Black spruce (*Picea mariana* (Mill.) B.S.P.) is a dominant species in the boreal forest of eastern North America. Due to its great abundance and wide distribution, black spruce is ecologically important in Canada. It is also valuable to the forest industry for timber production and pulp and paper due to the excellent quality of its fiber [1,2].

Wood quality can be defined as the wood characteristics and properties that make the wood valuable for a given end use [3,4]; hence, wood quality represents a multi-faceted assessment that depends on the intended use the wood. Given the multiple applications of wood, all its characteristics—chemical, anatomical, physical, and mechanical—can be considered as quality factors. Stem diameter and form, wood density, strength and stiffness, juvenile wood content, tracheid length, microfibril angle, and compression wood are some of the most important attributes for defining wood quality in general [3,5]. Other attributes associated with the live crown are also highly important for the study of wood quality; these properties include the number and size of branches and knots in the finished products. Branches, and in particular large-diameter branches, create a zone of weakness in the wood of the stem due to grain deviation, which can influence the strength and stiffness of the woody material, as well as the appearance of the finished products [3,5,6]. From a wood-quality standpoint, branch size is important for conifers of the boreal forest because timber quality and log grade can be determined according to the maximum diameter of branches [7].

In conifers, branch diameter generally increases downstem until the largest diameters are observed at the maximal lateral extension of the crown. Branch diameter then decreases slightly near the base of the crown [8–10]. Maximum branch diameter also has a curvilinear relationship with distance from the stem apex [8,11]. Crown and branch development in conifers can be influenced by the surrounding environment and by silvicultural interventions. The latter reduce stand density and increase the growth of residual trees, thereby affecting branch properties. For instance, thinning, which reduces competition and increases light availability for residual trees, can increase branch size in many conifer species [12,13], especially in the lower part of the crown that was previously shaded by competing neighbors [14,15]. However, the changes in environmental conditions are correlated with harvesting intensity [16]; therefore, residual trees in partial cutting or clearcutting stands may not be influenced in the same manner.

Traditionally, clearcutting was the dominant harvesting method used in the public forests of Quebec, Canada [17]. Careful logging around advanced growth (CLAAG, known as CPRS in Quebec) is probably the best-known clearcutting method. Clearcutting enables natural regeneration of even-aged stands by harvesting all merchantable trees to allow the establishment of regeneration in full light conditions [18,19]. In recent years, partial cutting has also been included in forest management practices in Quebec as an alternative to clearcutting. Partial cutting has been introduced to favor the implementation of more diverse silvicultural practices to address issues related to sustainable forest management in the boreal forest [20,21]. Partial cuttings are increasingly used in black spruce stands to maintain some of the structural attributes of the stands and preserve ecosystems in a more natural state [22–24].

In all cases, partial cutting and clearcutting reduce competition and increase the availability of light, water, and nutrients for the remaining trees; this leads to increased growth in the stem [25,26] and other parts of the tree, including roots and branches [13,27,28]. Increases in branch size due to a modified stand density (after thinning or partial cutting) can therefore result in bigger knots that could likely end in a marked downgrading of potential product recovery and quality. This decrease in quality has important implications for the final value of wood products from these treated stands [14].

This research aimed to evaluate maximum branch diameter within the crown of residual black spruce that were exposed to silvicultural treatments—partial cutting and clearcutting—and compare these results with control trees. More specifically, we wanted to determine the tree and branch characteristics that were most important in explaining maximum branch diameter. We also assessed whether maximum branch diameter within the live crown varied according to the imposed silvicultural treatment. Our hypotheses were that (1) the mean maximum branch diameter in black spruce trees would be higher following a silvicultural treatment relative to that of control trees; (2) the difference in branch diameter between the treated and control trees would be most pronounced in the lower portion of the crown; and (3) the type of silvicultural treatment (partial cutting or clearcutting) would influence maximum branch diameter.

2. Materials and Methods

2.1. Experimental Design and Sampling

We selected 41 black spruce stands in the Saguenay–Lac-Saint-Jean and North Shore (Côte Nord) regions of Quebec. These stands lie within the balsam fir-yellow birch, balsam fir-white birch, or spruce moss bioclimatic domains of Quebec's boreal forest (Figure 1). We assessed five silvicultural treatments of variable harvesting intensity and used unmanaged stands as controls. Of these five treatments, three represented forms of partial cutting and two were variants of clearcutting.

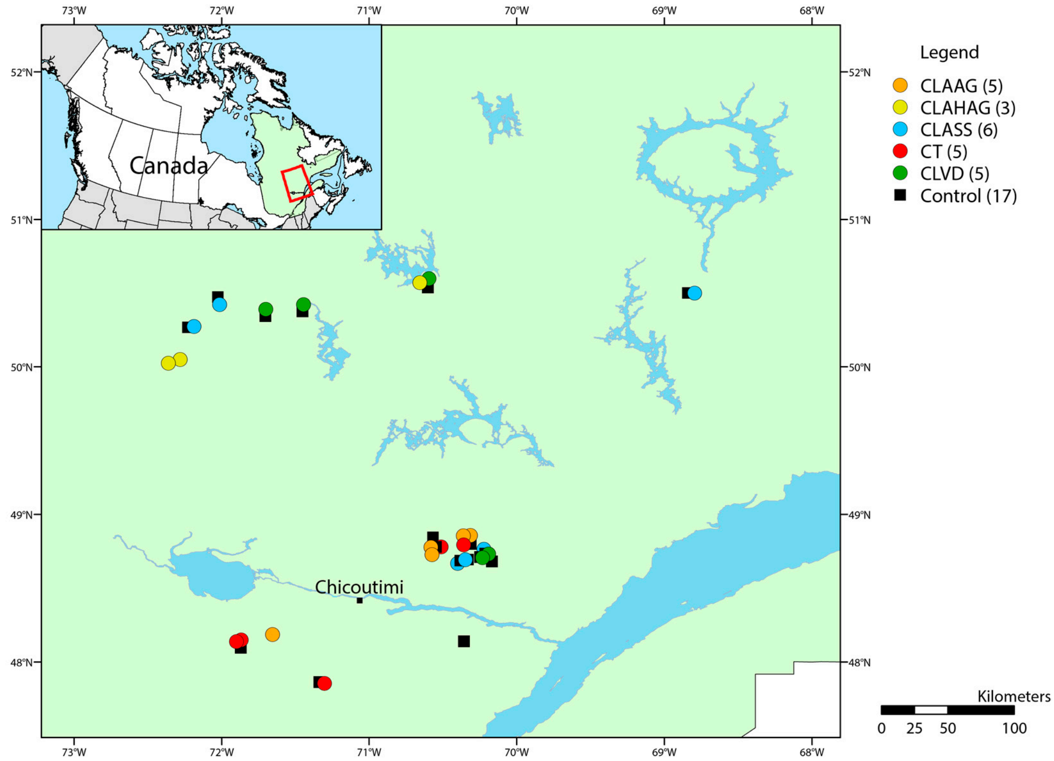

Figure 1. Location of the sampling sites in the Saguenay–Lac-Saint-Jean and North Shore regions of Quebec. The studied types of partial cutting are commercial thinning (CT), careful logging around small merchantable stems (CLASS), and careful logging around variable diameter stems (CLVD). Clearcutting variants are careful logging around advanced growth (CLAAG) and careful logging around high advanced growth (CLAHAG).

We assessed three types of partial cutting: commercial thinning (CT), careful logging around small merchantable stems (CLASS), and careful logging around variable diameter stems (CLVD). CT generally removes 30%–35% of the initial stand basal area and is applied to even-aged stands [18,29]. CLASS and CLVD are applied to uneven-aged and irregular forests, and harvested trees have a diameter at breast height (DBH) of ≥ 15 cm; this usually results in the removal of 70%–90% of the merchantable volume [20,30]. Further details on the characteristics and particularities of these partial cutting treatments are available in Pamerleau-Couture, Krause, Pothier, and Weiskittel [25].

We also assessed two clearcutting variants: careful logging around advanced growth (CLAAG) and careful logging around high advanced growth (CLAHAG). These two approaches differ in regard to regeneration, consisting mainly of seedlings for CLAAG, whereas CLAHAG includes a regeneration partly composed of ≥2 m high saplings [31,32]. For each treatment, we sampled three to six stands (Figure 1). The treated stands were selected using the forest maps from the Ministère des forêts, de la faune et des parcs du Québec (GIS, third inventory). We selected the stands based on the time elapsed since treatment application (at least 4 years post-treatment to observe the effect of time) and the post-harvest tree species composition (at least 50% of black spruce basal area) [25]. Both clearcutting and partial cutting treatments had been applied to these stands by the forest industry between 1989 and 2006; therefore, the time since treatment ranged between 4 and 18 years. We associated each treated stand to a nearby unmanaged control stand—located <1 km from a treated plot—having similar site conditions (tree composition, soil, and slope), initial stand structure, and age [25]. However, it was not always possible to find control stands sharing similar characteristics in the vicinity of our treated stands, particularly in the case of clearcutting treatments. As such, we sampled only 17 untreated control stands. We decided therefore to pool all control stands for our analyses. Mean characteristics of the stands (DBH, height, residual basal area, and residual stand density) for the five silvicultural treatments and for control stands are available in Table 1.

Table 1. Stand characteristics, residual basal area, and residual density of the control, and the five silvicultural treatments (A), and measured tree (B) and branch characteristics (C) of the control stand samples and samples from the five silvicultural treatments (mean ± standard deviation).

(A)		Partial Cutting			Clearcutting	
Mean Stand Characteristics	**Control**	**CT**	**CLASS**	**CLVD**	**CLAHAG**	**CLAAG**
N	17	5	6	5	3	5
DBH (cm)	12.3 ± 3.8	16.8 ± 3.4	10.6 ± 3.1	9.4 ± 4.6	8.4 ± 3.5	5.2 ± 2.1
Height (m)	10.1 ± 2.0	14.0 ± 2.3	7.6 ± 2.4	7.1 ± 3.3	6.8 ± 2.5	3.7 ± 1.0
Crown ratio (%)	58.1 ± 12.8	60.7 ± 15.6	67.1 ± 23.1	58.9 ± 16.0	58.7 ± 21.6	93.7 ± 6.2
Basal area (m^2 ha^{-1})	29.7 ± 9.9	29.0 ± 6.4	13.5 ± 3.3	11.2 ± 8.9	14.3 ± 6.2	5.4 ± 3.5
Stand density (trees ha^{-1})	2427 ± 317	1273 ± 201	1510 ± 388	1258 ± 494	2190 ± 800	2113 ± 396
Time since treatment (years)	-	9.2 ± 0.4	9.5 ± 1.8	4.3 ± 0.8	6.7 ± 1.5	15.7 ± 1.8
(B)						
Mean Tree Characteristics	**Control**	**CT**	**CLASS**	**CLVD**	**CLAHAG**	**CLAAG**
N	92	23	54	23	9	22
DBH (cm)	13.2 ± 3.7	17.4 ± 3.7	12.3 ± 3.0	10.1 ± 5.3	8.5 ± 2.0	5.5 ± 2.2
Height (m)	11.0 ± 3.2	14.5 ± 3.2	9.0 ± 2.4	7.7 ± 3.7	6.9 ± 2.2	4.0 ± 0.8
Crown ratio (%)	54.9 ± 12.8	59.7 ± 12.3	64.8 ± 12.4	68.1 ± 14.3	60.3 ± 19.4	92.0 ± 6.7
Age	107.3 ± 39.2	79.6 ± 19.0	110.7 ± 38.3	99.3 ± 29.5	105.3 ± 28.4	28.3 ± 11.7
(C)						
Mean Branch Characteristics	**Control**	**CT**	**CLASS**	**VD**	**CLAHAG**	**CLAAG**
N	2258	561	1348	534	204	550
Diameter (mm)	12.1 ± 4.8	15.6 ± 5.8	13.5 ± 5.1	10.9 ± 5.2	9.5 ± 3.4	9.5 ± 3.5
max	31.4	39.5	39.4	32.0	21.7	24.0
Estimated age	27.3 ± 20.6	25.2 ± 15.7	30.1 ± 21.1	22.2 ± 15.7	23.2 ± 15.8	6.1 ± 4.8
max	132	63	145	65	84	26

At each site, we randomly selected three to six trees in the dominant/codominant layer within a 400 m^2 plot. We recorded height, DBH, and height to crown base (first living branch) for each selected stem (Table 1).

2.2. Branch Diameter Measurements

We divided crown length into five sections, each having 20% of the total crown length, and we collected at least three whorls from each of these five sections, as in Lemay, Krause, and Achim [15]. The relative height of a branch in the live crown was determined as follows:

$$Relative\ branch\ height\ (\%) = \frac{Whorl\ height\ in\ the\ live\ crown\ (m)}{Live\ crown\ length\ (m)} \times 100 \quad (1)$$

For all branches present in a whorl, branch diameter (including bark) was measured at the base of the branch, just after the base swell [33]. We used the mean of the vertical and horizontal diameters to account for the branches not being perfectly circular. As it is mostly the largest branches that influence wood quality, for each tree we selected the five largest branches (maximum branch diameter) from each of the five crown sections to determine the diameter of the largest branches. Branch age was estimated as follows:

$$Branch\ age = Tree\ age - whorl\ age \quad (2)$$

where we determined tree age from ring counts of a disk recovered at the base of the tree and whorl age from the ring count of each whorl. Whorl area was calculated automatically by tracing its contour on a scanned image of the whorl using the WinDENDRO software (Regent Instruments Inc., Québec, QC, Canada, 2017). We sampled and measured a total of 5455 branches from 223 trees for this study.

2.3. Statistical Analysis

We used multiple linear regression to determine the most important explanatory variables that explained maximum branch diameter in each of the five sections of the live crown. Several models were tested, and we selected the model that had the lowest Akaike information criterion (AIC) [34]. We removed some explanatory variables from the final model as they were either not significant or showed marked collinearity (e.g., diameter at stump height, whorl diameter, and tree height). We confirmed the model assumptions for the normality of residuals and heteroscedasticity, and we verified for the non-independence of errors and multicollinearity. Using the R package relaimpo [35], we assessed the relative importance (R^2 contribution) of each explanatory variable by taking a hierarchical approach, in which all orders of variables were considered [36].

The most important variables for explaining maximum branch diameter—as determined by the multiple regression—were then used as covariates in a generalized additive model (GAM). This GAM evaluated trends in maximum branch diameter within the tree crown for the various silvicultural treatments and controls. The additive model incorporated smoothing functions of these covariates to model the non-linear relationships between these covariates and the response variable (maximum branch diameter). This produced a model having the form:

$$\begin{aligned} y = \quad & \alpha + Treatment + s(RelHeight) + s(DBHbt) + s(TST) + s(CrownRatio) \\ & + s(TreeAge) + s(BranchAge) + s(WhorlArea) + s(Site) + s(Tree) + \varepsilon \end{aligned} \tag{3}$$

where y is the vector of the maximum branch diameter, Treatment is one of the six studied treatments (including the control), RelHeight is the vector of the position of the branch in the crown, DBHbt is the vector of the tree diameter at breast height before treatment, TST is the vector of the time since treatment, CrownRatio is the vector of the crown length relative to the total tree height, TreeAge is the vector of the tree age, BranchAge is the vector of the estimated age of the branch, WhorlArea is the vector for the stem area at branch height, α is the intercept, s is an unspecified smoothing function, and ε is the error term. Vectors for the site and tree, set as random effects, were also added to the model. The model was fitted to the branch diameter using the R mgcv package [37]. The model estimated a distinct smoothing function for each level of the factor Treatment using the by- argument of the smoothing function to allow an easier visualization of the differences between treatments. We set the unmanaged control trees as a reference and verified the difference in smoothing functions between the maximum branch diameter in control trees and each of the different treatments. To visualize the model's output, we ran the R package visreg [38] to produce a conditional plot of branch diameter as a function of the relative position within the live crown (with all other explanatory variables held fixed at their median value). Data were log-transformed to meet the assumptions of normality and homoscedasticity [39] and back-transformed to visualize the output. We considered differences as significant when p was <0.05. All statistical analyses were performed using R 3.6.0 [40].

3. Results

3.1. Branch Diameter

Branch diameter varied between 2.0 mm and 39.5 mm for all branches collected and measured from the five silvicultural treatments (Figure 2). CT recorded the largest branches, followed by CLASS (Tables 1 and 2). The other treatments did not differ significantly from the control trees. We observed a curvilinear relationship between maximum branch diameter and distance from the stem apex. The largest branches of the trees were located generally in the lower portion of the live crown, at about

25%–40% of crown height (Figure 2). Maximum branch diameter was situated at a similar height in the crown for all treatments, except for CT, which had a maximum branch diameter located significantly higher in the stem than CLAAG (Table 2).

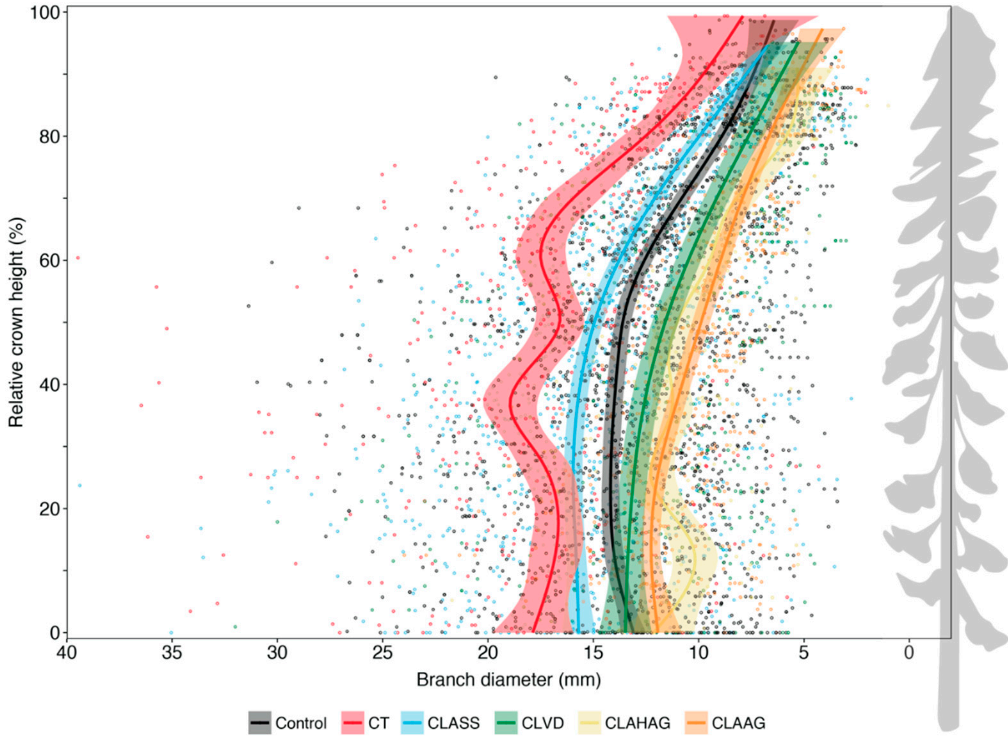

Figure 2. Maximum branch diameter measured within the live crown in residual trees from five silvicultural treatments and control trees. CT: commercial thinning; CLASS: Careful logging around small merchantable stems; CLVD: Careful logging around variable dimensions stems; CLAHAG: Careful logging around high advanced growth; CLAAG: Careful logging around advanced growth.

Table 2. Mean maximum diameter and mean relative height in the crown at maximum diameter of the branches measured in trees from the five silvicultural treatments and control (0% = crown base).

		Partial Cutting			Clearcutting	
	Control	**CT**	**CLASS**	**CLVD**	**CLAHAG**	**CLAAG**
Branch mean maximum diameter (mm)	18.7 ^{c}	26.5 ^{a}	22.4 ^{b}	16.5 ^{c}	15.8 ^{c}	14.9 ^{c}
Mean relative height in the crown at maximum branch diameter (%)	26.2 ^{a,b}	32.4 ^{a}	24.8 ^{a,b}	27.2 ^{a,b}	37.5 ^{a,b}	18.1 ^{b}

For each line of the table, values displaying the same letter do not differ significantly ($p > 0.05$) according to a Tukey's test.

The variables that best explained maximum branch diameter in black spruce did not vary much within the crown; DBH before treatment, whorl area, and treatment explained most of this variation (Table 3). DBH before treatment was the most important variable for explaining branch diameter, especially in the lowest section of the crown where it described approximately 70% of the explained variation. For the upper four sections of the live crown, whorl area was as important as DBH for explaining maximum branch diameter. Time since treatment, tree age, branch age, and whorl relative height had only a relatively small importance in explaining maximum branch diameter.

Table 3. Results of the multiple regression to explain maximum branch diameter within the tree crown. (A) Explanatory variables used in the full model. (B) Explanatory variables included in the best model, and the percentage of the model variance explained by these variables for each section of the live crown. Section 5 is the crown apex.

(A)	**Complete Model**	***Maximum Branch Diameter***	**~**	***Treatment + DBH before Treatment + Time since Treatment + Crown Ratio + Tree Age + Branch Age + Whorl Area + Whorl Relative Height***		
(B)	**Crown Section**	**Model R^2**		**Explanatory Variable**	***p*-Value**	**Relative Importance of the Variable (%)**
	5	0.57		DBH before treatment	<0.001	31.8
				Whorl area	<0.001	29.8
				Treatment	<0.001	17.2
				Branch age	<0.001	13.2
				Crown ratio	<0.001	4.0
				Time since treatment	<0.001	3.3
				Whorl relative height	0.067	0.7
	4	0.64		Whorl area	<0.001	36.1
				DBH before treatment	<0.001	32.7
				Treatment	<0.001	17.3
				Tree age	0.003	5.2
				Crown ratio	<0.001	4.2
				Time since treatment	<0.001	3.0
				Whorl relative height	<0.001	1.5
	3	0.59		Whorl area	<0.001	42.7
				DBH before treatment	<0.001	36.8
				Treatment	<0.001	13.3
				Time since treatment	<0.001	4.7
				Crown ratio	<0.001	2.5
	2	0.48		Whorl area	0.046	37.0
				DBH before treatment	<0.001	35.2
				Treatment	<0.001	13.9
				Tree age	0.068	5.3
				Time since treatment	<0.001	5.3
				Crown ratio	<0.001	3.3
	1	0.41		DBH before treatment	<0.001	69.9
				Treatment	<0.001	14.4
				Time since treatment	<0.001	12.9
				Crown ratio	<0.001	2.8

3.2. *Generalized Additive Model*

When we fixed the most important explanatory variables extracted from the multiple regression model at their median value (DBH before treatment = 9.31 cm, time since treatment = 9 years, crown ratio = 61.7%, tree age = 84 years, branch age = 21 years, and whorl area = 32.08 mm^2), the GAM showed that maximum branch diameter in black spruce trees varied as a function of relative crown height (R^2_{adj} = 0.719, deviance explained = 72.9%) and that the largest branches were located in the lower half of the live crown (Figure 3). The smoothing functions also illustrated that maximum branch diameter was generally higher for treated trees relative to the control trees. In control trees, branch diameter was largest and remained relatively constant from the base to the middle of the crown; branch diameter then decreased gradually toward the top of the tree. CT shared a similar distribution to that of the control trees. For the two clearcutting treatments, branch diameter increased from crown base to a maximum at 30%–40% of the crown length (0% = crown base, 100% = stem apex, Figure 3), before decreasing toward the top of the tree. CLVD showed a resemblance to the clearcutting treatments, but maximum branch diameter was observed higher in the crown (35%–50%

of the crown). The distribution of the maximum diameter of the branches on trees from the CLASS treatment appeared as a cross between all other treatments.

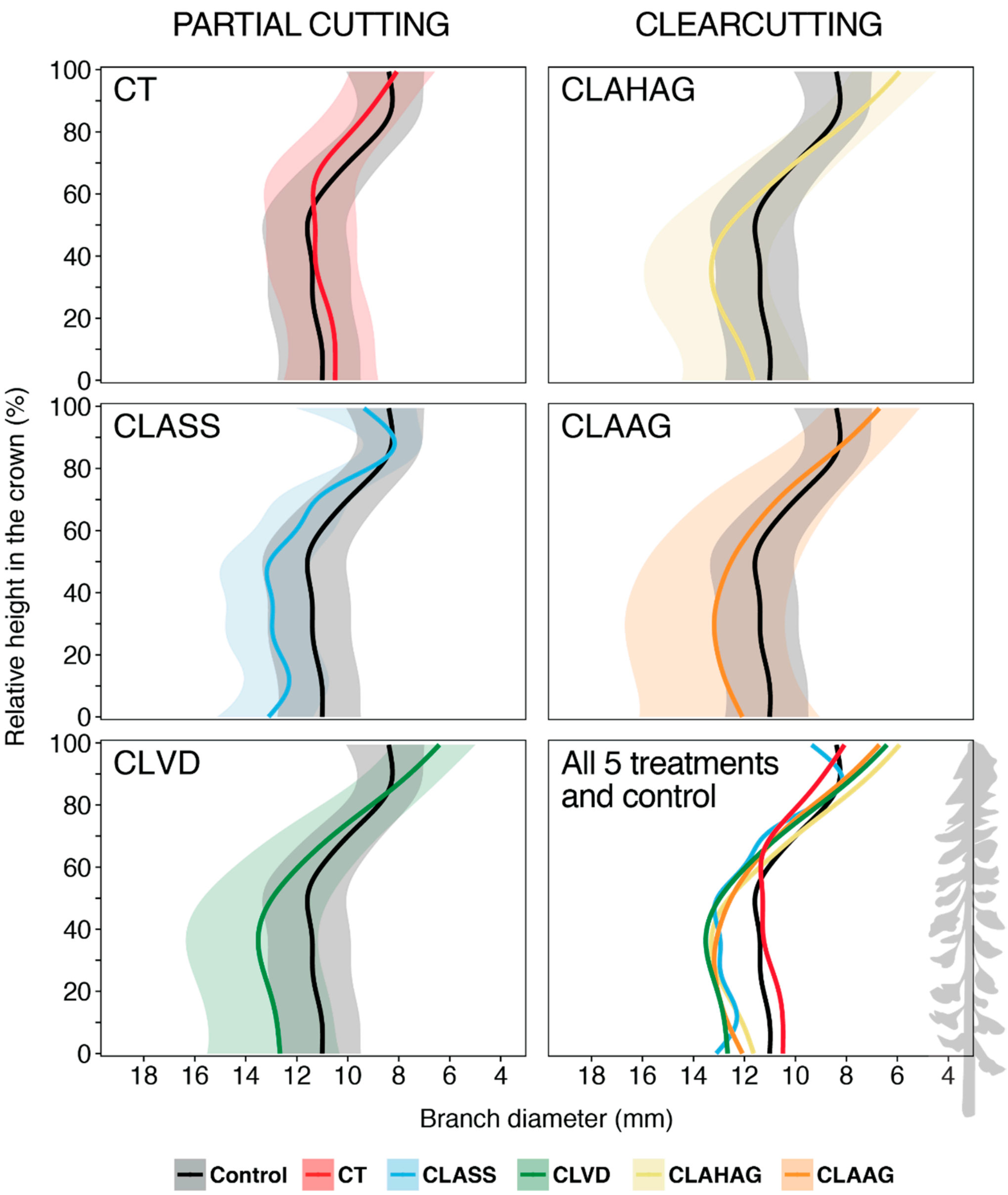

Figure 3. Conditional plot of the maximum branch diameter within the live crown of black spruce as a function of relative crown height, obtained from the generalized additive model (GAM). All other predictor variables were held fixed at their median value. The shaded bands represent the 95% confidence interval.

For CLAAG, CLAHAG, and CLASS, the mean maximum diameter of branches was approximately 1.5 mm greater than that of control trees in the lower half of the crown, and nearly 2 mm greater than that of controls for CLVD. However, the mean maximum diameter obtained from the GAM was similar between CT and the control in the same part of the live crown. The smoothed tendency of the CLASS treatment differed significantly from the control ($p < 0.001$). For the other treatments, the smoothed tendencies were similar between treated and control trees ($p = 0.226$, 0.693, 0.204, and 0.122 for CT, CLVD, CLAHAG, and CLAAG, respectively). We also observed a difference between the different studied treatments as the smoothed tendency of CT differed significantly from that of CLVD, CLAHAG, and CLAAG; otherwise, all the other treatments had smooth tendencies similar to each other.

4. Discussion

4.1. Branch Diameter

In this project, we studied the largest branches from each of five sections within the tree crown of black spruce. From a wood-quality point of view, these larger branches are very important as the quality of sawn timber is partly determined based on the maximum diameter of the branches [3,7]. In all control and treatment trees, the maximum branch diameter reached a peak at 10%–40% of the total length of the live crown (measured from the crown base, Figure 2). Maximum branch diameter then decreased toward the crown apex, a pattern similar to the curvilinear relationship observed in other studies [8,10,14,33]. Mean maximum branch diameter in the lower half of the crown was approximately 15 mm; only a few branches reached >30 mm and were found mainly in the treatment trees. These recorded diameters can be considered as small, and therefore end products from these trees in both the treatment and control stands would be of high quality and value based on knot size. In Canada, in structural joists and planks, the top-grade 'select structural' quality label requires a maximum knot diameter along the center line of the wide face of a 2 × 4 inches (5 × 10.1 cm) lumber piece to be approximately 22 mm. This maximum knot diameter is 57 mm for a 2 × 8 inches (5 × 20.3 cm) lumber piece, and larger knots are tolerated for larger lumber [3]. From all our samples, only 260 of 5900 measured branches had a diameter 22 mm (from 72 trees, of which 25 were control trees); only 29 branches from 18 trees had a diameter 30 mm. Thus, most sampled trees could, in theory, be considered for the highest quality lumber grade.

Our study also showed that the measured maximum branch diameter in black spruce varied depending on the harvesting treatment. The change in spacing after treatment altered the environment of the trees, especially light availability. This change resulted in a range of canopy openings that varied greatly between the five study treatments and the unmanaged controls. Differing environmental conditions around the trees post-treatment likely influenced branch diameter within the crown and the position of maximum branch diameter in the crown. Near the stem apex, all treatments and control shared a similar maximum branch diameter. This portion of the crown already received full sunlight prior to the harvesting treatment; therefore, any canopy opening due to partial cutting or clearcutting did not alter light conditions near the crown apex [7,10].

When comparing partial-cutting treatments, CT had the largest measured branch diameters. In this silvicultural treatment, approximately one-third of stems are removed, and the remaining trees are generally younger and more vigorous than in other silvicultural treatments as thinning is undertaken mainly in productive stands before they reach full maturity [18,29]. We sampled our trees 10 years after thinning; therefore, these trees could still have another 10–15 years of productive growth before the complete harvesting of the stand. On the other hand, CLASS and CLVD, which remove around 70%–90% of the merchantable stems in uneven-aged stands [20,41], are conducted when the trees to be harvested are mature. The remaining saplings and small merchantable stems from these two latter treatments can be older, especially the small merchantable stems, and may respond less to the altered environmental conditions than younger trees. However, these saplings and small stems within CLASS and CLVD stands would typically continue to grow until the next rotation of the stand.

The measured maximum branch diameters in the clearcutting treatments were smaller than those within the studied partial cutting stands. However, the residual trees in these treatments were small—and sometimes young—and our sampling occurred only five years after CLAHAG and, at most, 18 years after CLAAG. Therefore, these trees would normally have until the next stand rotation to continue their growth.

Multiple regression revealed that DBH before treatment was the best predictor of maximum branch diameter in black spruce within all parts of the crown; however, treatment type was also very important in the lower crown. Colin and Houllier [9] also observed that tree size (DBH) was the most effective predictor of maximum branch diameter. Other non-measured predictor variables may have improved our predictive model; branch length, stand density, and trees' social status can also play an additional role in predicting branch diameter [9,42]. Nevertheless, the R^2 of our model reached 0.72 based on our included predictor variables.

4.2. Generalized Additive Model

Although trees sampled from the clearcut CLAAG stands were generally younger and smaller, and the time elapsed since harvesting varied among the treatments, our GAM allowed adjusting to this variability by placing the covariates at the same level for all treatments. The GAM showed that maximum branch diameter remained rather similar following the different silvicultural treatments and in unmanaged control stands. Although the maximum branch diameters appeared slightly higher in some treatments (Figure 3), the associated confidence intervals overlap and the model cannot identify clear differences between the treatments, thus refuting our first hypothesis.

As the diameter of the largest branches and the 95% confidence intervals remain within the limits of the top-grade quality lumber in Canada, all studied treatments should not result in the lumber being downgraded nor wood quality and use being negatively affected. This result contradicts some previous work studying the effect of reduced stand density on branch growth, where branch diameter increased after harvest treatments for Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), loblolly pine (*Pinus taeda* L.), red spruce (*Picea rubens* Sarg.), and balsam fir (*Abies balsamea* (L.) Mill.) [12,13,43]. The silvicultural treatments of these other studies were applied to much younger trees than our sampled trees. Most of the trees in our study were already mature, and many were over 100 years old at the time of treatment. The DBH of the trees in these other studies [12,13,43] was also higher than the DBH measured in our sampled trees, perhaps explaining the different results as we showed that DBH was an important predictor of maximum branch diameter. Moreover, black spruce has a very slow growth rate, especially for older individuals [2]. Thus, even if branches of our sampled trees increased their growth after treatment, as was observed in other studies [15,44], this increase was so small that the effect was minimal at the time of our sampling. The most important effect will likely be branch longevity, as lower branches may remain alive longer [45].

For all treatments except for CLASS ($p < 0.001$), the post-treatment smoothed trends of the diameter of the largest branches did not differ significantly from that of the control trees. As such, the distribution of the maximum branch diameter within the live crown did not differ after a silvicultural treatment. This refutes, in part, our second and third hypotheses. However, despite not being significant, differences between the maximum branch diameters of the treated and control trees occurred mainly in the lower half of the crown. At this lower level, branches may most benefit from changes in stand density after treatment. For example, the lowest portions of Scots pine and Douglas fir crowns react most strongly to canopy openings [7,46].

Overall, the results from the present study suggest that the studied partial cutting and clearcutting treatments can be used in black spruce stands in the boreal forest of Quebec, Canada, without any adverse effects on maximum branch diameter when compared to unmanaged control stands. Thus, regardless of the treatment, there should be no downgrade in wood quality in terms of maximum branch diameter. However, our results indicate that maximum branch diameter was most influenced by DBH prior to treatment, and this variable must be taken into account before any treatment is applied in forest management operations if maximum branch diameter is an important wood quality factor at the time of the final harvest of the stands.

5. Conclusions

For black spruce, maximum branch diameter varied in a curvilinear manner within the live crown, and the largest branches were situated in the lower half of the crown. DBH before treatment, treatment type, and whorl area were the most important variables for predicting maximum branch diameter. Post-treatment, the diameter of the largest branches did not vary significantly between treatment type or the type of cut (partial or clearcutting). The maximum branch diameters within the live crowns remained small; therefore, wood quality and value with respect to the maximum branch diameter should not be negatively affected for black spruce in the trees remaining after the studied silvicultural treatments.

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