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Radial Growth Response of Black Spruce Stands Ten Years after Experimental Shelterwoods and Seed-Tree Cuttings in Boreal Forest

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Abstract: Partial cutting is thought to be an alternative to achieve sustainable management in boreal forests. However, the effects of intermediate harvest intensity (45%–80%) on growth remain unknown in black spruce (*Picea mariana* (Mill.) B.S.P.) stands, one of the most widely distributed boreal species with great commercial interest. In this study, we analysed the effect of three experimental shelterwood and one seed-tree treatments on tree radial growth in even-aged black spruce stands, 10 years after intervention. Our results show that radial growth response 8–10 years after cutting was 41% to 62% higher than in untreated plots, with stand structure, treatment, tree position relative to skidding trails, growth before cutting and time having significant interactions. The stand structure conditioned tree growth after cutting, being doubled in younger and denser stands. Tree spatial position had a pronounced effect on radial growth; trees at the edge of the skidding trails showed twice the increase in growth compared to interior trees. Dominant trees before cutting located close to the skidding trails manifested the highest growth response after cutting. This research suggests that the studied treatments are effective to enhance radial wood production of black spruce especially in younger stands, and that the edge effect must be considered in silvicultural management planning.

Keywords: dendroecology; ecosystem management; edge effect; even-aged stands; growth yield; partial cutting; sustainable forest management

1. Introduction

The boreal forest produces more than 33% of the world's lumber [1]. Global demand for industrial wood is expected to double in 2030–2050 [2]; consequently, harvesting pressure on the boreal biome will increase significantly. Clearcutting is one of the most widely-used practices in boreal forest silviculture [3], due to economic considerations: cheaper operational cost and greater harvested volume of timber [4]. However, the impacts of clearcutting on the simplification of stand structure [5], biodiversity [6] and sustainability [7] of the boreal forest have been criticized and society has expressed its concern.

In recent years, reducing the impacts on ecosystems and preservation of biodiversity have emerged as major concerns that have led to important changes in forestry practices [8]. These issues have modified traditional forest management [9], mostly centered on wood production. It is from this perspective that the concept of forest ecosystem management has emerged, becoming established as a tool to achieve boreal forest sustainability [10]. Partial cuttings are included in current forest ecosystem management strategies [11]. Their main goal is to combine timber harvesting, preservation of the structure and ecological processes responsible for maintaining forest productivity in the long term to ensure integrity, biodiversity and sustainability [10].

In the last 15–20 years, many partial cutting treatments have been developed in boreal forests [12]. Partial cutting induces an increase in residual tree growth following the decrease in stand density [13] and the higher availability of resources such as solar radiation, water and soil nutrients [14]. The effects of shelterwood and thinning on wood production of residual trees are becoming better understood in the boreal forests of Scandinavia [15–17] and North America [18–20]. However, the effects of partial cutting treatments on growth in black spruce (*Picea mariana* (Mill.) BSP) stands are still poorly quantified. The growth response of black spruce has been studied in immature even-aged stands with commercial thinning treatments [19–21] and in mature uneven-aged stands with Harvest Advance Regeneration Protection treatments (HARP) [19,22]. However, there are currently no studies published on the effects of intermediate harvest intensity (45%–75%) in mature even-aged black spruce stands, such as shelterwood and seed-tree cuttings. Results from commercial thinning or HARP cannot be directly extrapolated to shelterwood or seed-tree treatments because of major differences in harvest intensity and initial stand structure. This study will help to provide knowledge in this field by expanding the range of stands and studied treatments to assess the impact of partial cutting on growth and yield of the boreal forest.

The growth of trees is not homogeneous at stand, spatial and temporal levels, and may be affected by many factors. Stand characteristics influence tree growth. Several studies on black spruce stands have identified that the radial growth usually decreases gradually with stand age [19,22] and high tree density [23,24]. Mechanized partial cutting operations increase the heterogeneity in the opening of the canopy, through the network of regularly spaced extraction trails. The ecological conditions at the edges of trails are substantially different to the interior of the residual strip: more accessibility to nutrients, higher lateral light and wind exposure [25–28]. Phenomena such as inter-tree competition and mortality may therefore be modified [28–30]. Residual trees on the edges of trails will likely thus have a higher growth response after cutting than trees located inside the strip. However, soil compaction caused by machines on extraction trails may have potential negative impacts on soil productivity and root development [31,32]. There has been recent interest in evaluating the influence of tree spatial position on growth [19,33,34], and it has been demonstrated for several species that tree growth decreases with distance from the edge [35–37]. However, the edge effect on growth in black spruce even-aged stands submitted to partial cutting treatments is still unknown. Finally, since growth is dynamic, the effects of silvicultural treatments and stand characteristics change over time. The general temporal growth response after partial cutting treatments occurs in three steps: (1) no response for two to five years; (2) increased growth period for 10 years and (3) growth reduction to before cutting levels [12]. These steps depend on regions, species, age structure, tree status and treatments, so it is necessary to account for these essential factors when evaluating the growth response after partial cutting.

In this study, we investigated the ten-year growth response of even-aged black spruce stands subjected to three experimental variants of mechanized shelterwood and seed-tree silvicultural systems in the boreal forest of eastern Canada. Our main goals were: (i) to evaluate the effect of the study treatments on tree radial growth; (ii) to investigate the effects of stand structure, tree position in the residual strip, growth before cutting and time on tree ring growth response of trees. The hypotheses were:

(i) Shelterwood and seed-tree treatments will show a significant increase in radial growth compared to untreated control plots.
(ii) No significant differences will be found in radial growth among shelterwood treatments; however, seed-trees will produce a greater growth response than shelterwood because of a higher harvest intensity.
(iii) Younger and denser stands will have a faster and greater growth response, due to the growth decrease with age.

(iv) Edge trees will manifest greater differences in terms of radial growth, because they have less competition and more accessibility to nutrients and light compared to interior residual trees.
(v) Suppressed trees before cutting will display stronger growth responses after treatment than dominant trees due to tree selection in the residual strip.

The results should help to better understand the effects of partial cutting in order to improve silvicultural practices within the context of forest ecosystem management.

2. Material & Methods

2.1. Study Area

The study was conducted in even-aged natural boreal forest stands of the Monts-Valin and North Shore region of Quebec, Canada. The studied area extended from 48°45′ to 50°10′ latitude north and from 69°15′ to 70°45′ longitude west in the balsam fir (*Abies balsamea* (L.) Mill.)-white birch (*Betula papyrifera* Marsh.) and the eastern black spruce (*Picea mariana* (Mill.) B.S.P.)—feathermosses bioclimatic zones [38] (Figure 1). The climate is subhumid subpolar, with a short vegetation season of 140 days [39]. Annual mean temperature is −2 to 1.5 °C and average annual precipitation is 950 to 1350 mm [40]. Surface deposits consist primarily of thick glacial till, and rocky outcrops are frequent at the top of steep slopes [41]. The predominant soil is a humo-ferric podzol.

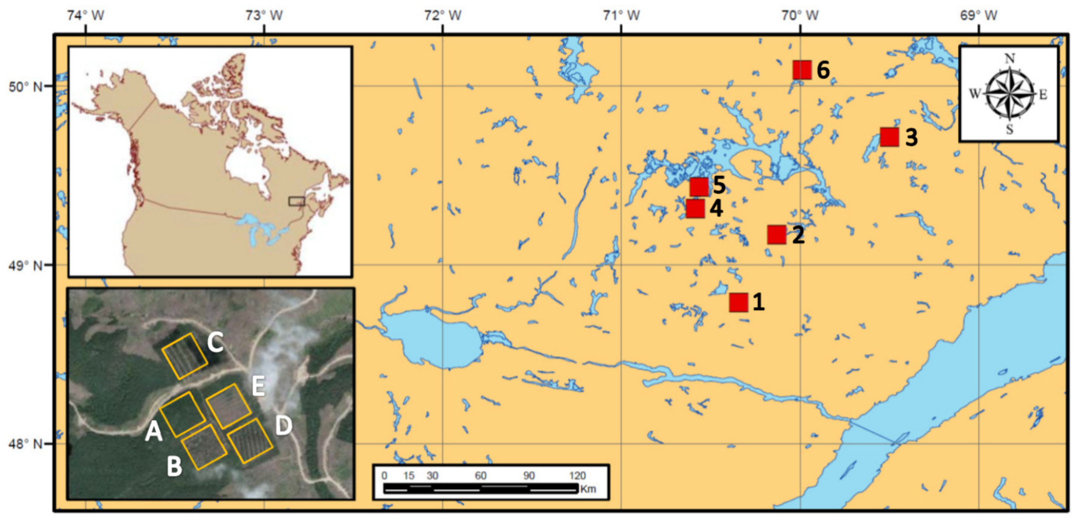

Figure 1. Location of the experimental blocks (1–6). The orthophotograph shows the 3-ha experimental units of block number 2, where: (A) control; (B) mini-strip shelterwood; (C) distant selection; (D) close selection and (E) seed-trees.

2.2. Experimental Design

The experimental design was a factorial in complete randomized blocks. Six blocks were sampled, corresponding to different study sites. Blocks had five experimental units with one replicate of each silvicultural treatment and one untreated control plot (Figure 1, Figure S1 and Table S1). Two stand structures were selected: three blocks were established in low regenerated dense forests (younger stands), while another three were installed in well regenerated open forests (older stands). In all cases, black spruce accounted for at least 75% of the stand basal area. Experimental units consisted of permanent square plots of 3 ha, chosen as being relatively homogeneous and comparable within the same block in terms of species composition and stand density. The experimental factors were the combinations of silvicultural treatment and spatial position of trees relative to the extraction trails (two classes: edge or interior) for a total of 8 levels (4 × 2) plus a control. We considered the edge surface as the area less than 1.25 m on each side of the trails. The silvicultural cuttings were done in 2003.

2.3. Silvicultural Treatments

Four cutting treatments were evaluated: Mini-strip shelterwood (MS), distant selection (DS), close selection (CS) and seed-trees (ST) (Table 1). The first three are partial cutting treatments and are variants of uniform shelterwood. This silvicultural system is applied in premature even-aged stands, with the main goal of promoting advanced regeneration though a uniform opening of the canopy [42,43] followed by an overstory removal to produce a new even-aged stand [44]. The main differences between the studied treatments are in the spatial distribution of skidding trails and characteristics of the residual strip (Table 1 and Figure 2). Harvest intensity of the intervention was 50% of basal area for MS, DS and CS, and 75% in ST. MS consists of a succession of 5 m wide cut strips, with 5 m wide residual strips. ST has wider 15 m cut strips with 5 m wide intact residual strips. In the case of CS and DS, trails are set at 20 m and 30 m intervals, respectively, and trees are partially harvested on each side of the trails, at a maximum distance of 5 m from the trail edge (Table 1 and Figure 2). DS has secondary trails transverse to the main operational trails, each separated by 10 m.

Table 1. Characteristics of experimental treatments.

Treatment	Partial Cutting	Basal Area Harvested (%)	Residual Strip		Skidding Trail		Secondary Trail	Edge Surface [(b)] (%)
			Width (m)	Intact Surface (%)	Width (m)	Surface (%)		
Mini-strip (MS)	Yes	50	5	100	5	50	No	50
Distant selection (DS)	Yes	50	25	20	5 or 10 [(a)]	17	Yes	24.5
Close selection (CS)	Yes	50	15	33	5	25	No	16.3
Seed-trees (ST)	No	75	5	100	15	75	No	50

Note: [(a)] corresponds to the variability in the intervention as a consequence of secondary trails; [(b)] the edge surface was estimated considering 1.25 m next to the edge on both residual strip sides.

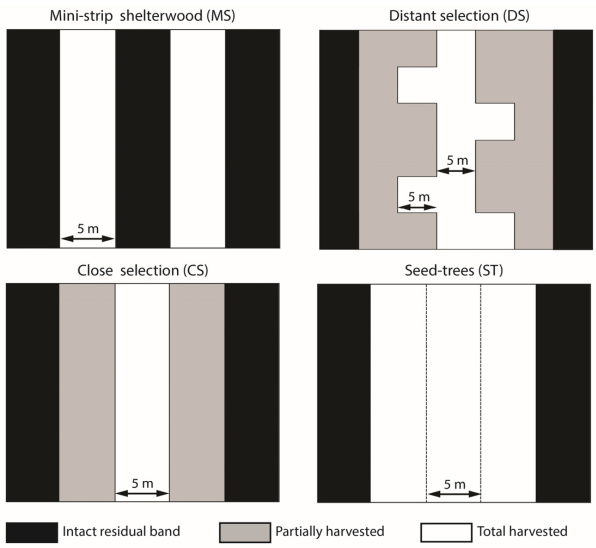

Figure 2. Spatial patterns of study treatments. White areas represent total harvested surface or intervention trails, black areas indicate the intact residual strip and grey areas are the surface of the partially harvested residual strip.

2.4. Plot Measurements and Compilation

In each block, a permanent rectangular (10 × 60 m) sampling plot was established in the center of the experimental unit. The sampling covered the spatial heterogeneity of each silvicultural treatment (trails, edge and residual strip). The measurements were taken in 2002 one year before cutting (b.c.) and ten years after cutting (a.c.). Measurements were taken on trees with diameter at 1.3 m (DBH) greater than 9 cm for all tree species (n = 3739 and n = 2243 b.c. and a.c. respectively): tree species, DBH, wound state and position were noted. A subsample of randomly selected trees was taken (n = 168 b.c. and n = 99 a.c.) with the following additional variables: total tree height, crown length and second DBH measurement. The stand characteristics (density, mortality, basal area and volume) were estimated with the first series of data.

Competition data were by position classes (edge and interior trees), 10 years a.c. for black spruce trees (n = 240). Hegyi's competition index (CI_i) was selected because it is the most strongly correlated with basal area growth in black spruce stands [24]. The distance ($Dist_{ij}$) and DBH of each neighbouring tree ($_j$) within a 4 m radius of the subject tree ($_i$) were measured to calculate the CI_i:

$$CI_i = \sum_{j=1}^{n} \left(\frac{DBH_i}{DBH_J} \times \frac{1}{Dist_{ij}} \right)$$

For the study of age structure, wood disks (n = 349) were collected at the root collar in square plots of 400 m^2 (20 × 20 m) in the cutting area from each block. The age was determined using a binocular microscope to count the tree rings.

2.5. Dendroecological Data

In each plot, 38 cores were taken randomly (one per tree) at 1.3 m height in the summer of 2014. The sample number was chosen following the recommendations by Vincent et al. [20], requiring a minimum of 35 trees per plot to represent individual variation of growth in black spruce stands. The sampling was stratified by the position of trees relative to the residual strips; therefore, half of the cores were taken on edge trees and the other half on interior trees (Figure S1). A total of 1039 black spruce cores were collected.

The samples were prepared, measured and analyzed conforming to standard dendroecological protocol [45]. Cores were air-dried, mounted on wood boards and sanded before tree rings were measured with WinDendro™ system [46] or a manual Henson micrometer with an accuracy of 0.01 mm. The tree-ring series measurements covered the last 30 years, and were cross-dated using TSAP-Win™ (Rinntech, Heidelberg, Germany).

2.6. Data Analysis

2.6.1. Radial Growth Model

A repeated measurement analysis of variance (RM-ANOVA) was conducted to assess annual tree ring width a.c. using the MIXED procedure of SAS 9.2 (SAS Institute, Inc., Cary, NC, USA), assuming a first-order autoregressive covariance structure. The proposed model includes blocks and trees as random effects, and stand structure, treatment, position (edge and interior) and their pairwise interactions as fixed effects. Treatment and position were combined in a single factor to simplify the model structure. Orthogonal contrasts were used to analyse the different combinations of Treatment × Position [47]. Growth before cutting (GBC) corresponds to the average ring width over 20 years b.c. and was considered as a continuous predictor. Logarithmic transformation on annual tree ring width was used to satisfy the assumptions of normality and homogeneity of variance. The SLICE statement was performed to partitioned analysis of the LS-means for the interactions. The coefficient of determination (R^2) was estimated according to Selya, et al. [48].

2.6.2. Factors Influencing Growth Response

A second explanatory analysis was conducted to identify *a posteriori* the most influential factors on tree radial growth responses a.c. applying the percentage growth change filter (PGC) [49].

This technique is an effective analytical tool to determine natural or anthropic disturbances in the tree-ring series, and to estimate the number of released trees after partial cutting [50,51]. PGC series were calculated for each core using the equation: $PGC = [(M_2 - M_1)/M_1] \times 100$, where M_2 and M_1 are the anterior and posterior 4 years radial growth mean. We evaluated radial growth increase (>100% in the PGC series average) for the 20 years b.c. and 10 years a.c. for each tree by stand structure, treatment, position and year.

Step-wise multiple linear regressions were used to identify which factor influenced the differences in radial-growth responses for edge, interior and control trees, and to include predictors that were not initially part of the experimental plan. The mean tree ring width a.c. was used as a dependent variable for testing the sequential hypotheses. A logarithmic transformation was done on radial growth to ensure the homogeneity of variance and normality assumption. The predictor variables were: stand structure, stand age, harvest density, mortality, treatment, dominant height, wound state, DBH b.c. and growth b.c. (GBC). Logarithmic or angular transformations were applied to predictors when necessary. Factors were selected minimizing the Bayesian Information Criterion (BIC). Multi-collinearity was verified on predictor variables using the variance inflation factor (VIF) [52]. Analyses were conducted using JMP Pro 12 software (SAS Institute Inc., Cary, NC, USA).

Analysis of covariance (ANCOVA) was done when comparing stand structure, treatment, position and time effects on annual tree ring width, using GBC as covariate. Variables and covariate were Naperian logarithmic transformed to stabilize the variance. The SLICE statement was performed to partitioned analysis of the LS-means for the GBC × structure × treatment/position × year interaction. To simplify the analyses, time was studied in two periods (0–5, 6–10 years a.c.), and GBC was analysed at three levels (<0.4, 0.4 to 0.8, and >0.8 mm/year).

3. Results

3.1. Stand Attributes

The age analysis determined that all our study sites were even-aged stands, and confirmed that they likely originated from forest fire disturbances. Mean aged ranged between 79 ± 0.39 and 156 ± 4.9 years for the youngest and oldest stands, respectively (Figure 3). Stand age revealed that the low regenerated dense blocks (>2000 trees/ha) correspond to younger stands (<100 years). Younger and older stands were significantly different in terms of density ($p < 0.05$) and age ($p < 0.05$). In the younger stands, 100% of trees were in the same 20-year age-class within each block. Older blocks showed more variability in age structure; only 72% of trees were in the same age-class. Mean density values b.c. were 69% higher in younger than older stands (Table 2); volume and basal area values were also between 15% and 25% higher in younger stands.

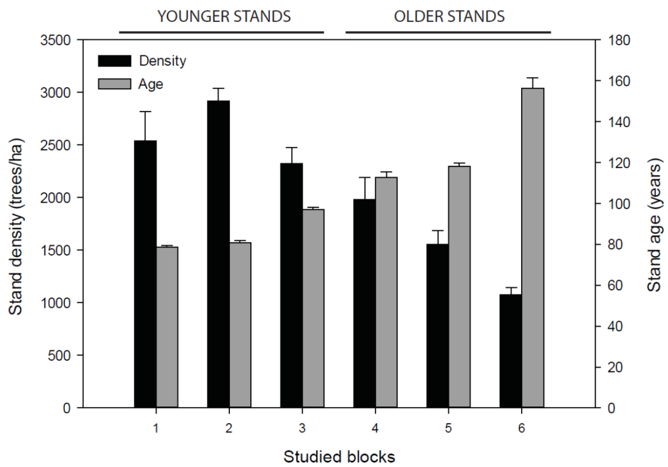

Figure 3. Mean density and age representation by studied blocks. Vertical bars show the standard error.

Table 2. Stand characteristics by silvicultural treatment for each stand structure before and after cutting (mean ± standard error).

Treatment	Density (Tree/ha)					Basal Area (m^2/ha)					Volume (m^3/ha)				
	Initial		Residual		Harvested (%)	Initial		Residual		Harvested (%)	Initial		Residual		Harvested (%)
Control															
-Younger	2316.7	±464.6	2316.7	±464.6	0	38.6	±2.5	38.6	±2.5	0	192.9	±15.8	192.9	±15.8	0
-Older	1272.2	±398.6	1272.2	±398.6	0	25.2	±6.9	25.2	±6.9	0	138.9	±42.2	138.8	±42.2	0
Mini-strip															
-Younger	2355.6	±209.1	1427.8	±138.9	39.4	35.8	±4.2	21.4	±3.2	40.2	169.4	±36.6	100.2	±22.4	40.9
-Older	1888.9	±502.4	888.9	±317.6	53.0	33.8	±8.2	15.5	±5.8	54.1	174.2	±39.4	78.1	±29.3	55.2
Distant selection															
-Younger	2894.4	±373.3	1722.2	±352.5	40.5	41.5	±3.4	23.2	±5.2	44.1	188.2	±10.5	99.9	±23.9	47.0
-Older	1461.1	±231.8	838.9	±198.2	42.6	32.6	±5.8	18.3	±6.1	43.9	187.8	±37.2	104.7	±40.1	44.2
Close selection															
-Younger	2794.4	±382.0	1483.3	±285.9	47.0	49.5	±5.4	26.3	±2.7	46.9	255.9	±28.8	136.0	±10.6	46.9
-Older	1566.7	±337.2	900.0	±279.0	42.6	30.1	±5.8	15.5	±4.9	48.5	162.0	±27.9	78.3	±24.6	51.7
Seed-trees															
-Younger	2683.3	±211.7	850.0	±78.8	68.3	40.5	±3.0	11.7	±1.4	71.1	190.1	±32.6	51.6	±10.0	72.9
-Older	1538.9	±174.9	400.0	±50.9	74.0	32.9	±3.4	8.3	±0.9	74.8	185.3	±17.4	46.2	±4.1	75.0

The inventories one year a.c. revealed the residual stand characteristics (Table 2). The mean residual basal area for shelterwood treatments was 23.6 ± 3.0 and 16.4 ± 4.9 m^2/ha in younger and older stands, respectively, nearly 50% less than control plots. The volume harvest coefficient was close to 50% in shelterwood and 75% for ST in each stand. The mortality b.c. in the study blocks was 6.5% ± 1.0% of trees, but 10 years a.c. it reached 30.6% ± 3.4% in shelterwood treatments and 59.7% ± 9.5% in ST. Older stands showed higher levels of mortality especially in the ST treatment (around 70% of trees). The number of wounded trees was 27% ± 2.3% of residual trees in CS and DS, and less (around 20%) in the case of MS and ST. The CI_i values were 38% higher in younger than older stands (Figure 4). The highest competition values (>5) were detected for interior trees of MS, DS, and control plots of younger stands, and the lowest values (<2) for edge trees of DS and ST in both older and younger stands. CI_i for control trees was significantly higher than edge trees ($p < 0.05$), but was not different from interior trees for older and younger stands. The interior trees showed mean competition values 1.6 to 4 times higher than edge trees in the study treatments. However, in older stands, these differences in CI_i were lower than in younger stands (Figure 4).

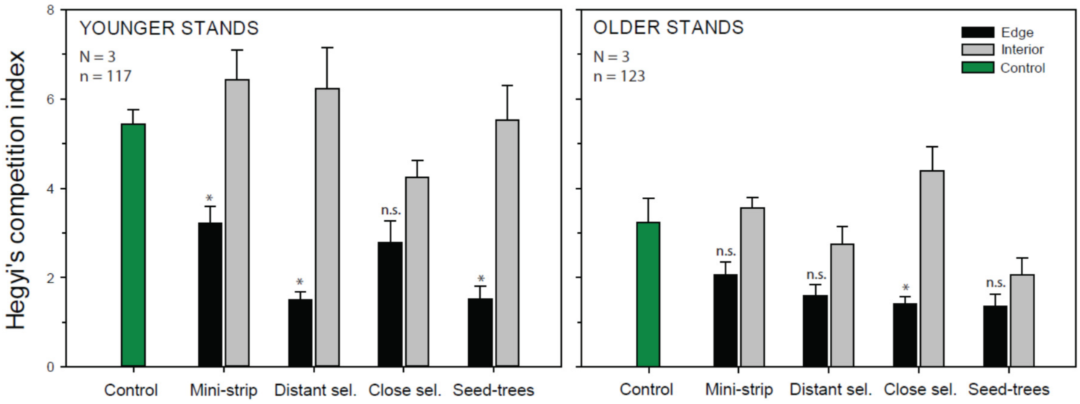

Figure 4. Hegyi's competition values in the study treatments by stand structure and spatial position in the residual strip 10 years after cutting. Vertical bars show the standard error. * shows significant differences between edge and interior trees by treatment ($p < 0.05$). n.s. rrespresents no significant difference.

3.2. Radial Growth Response

Residual trees showed an increase in radial growth after partial cutting. Mean radial growth 8–10 years a.c. in the study treatments was between 41% and 62% higher than in control plots (0.49 mm/year). A mixed model determined that the growth response after partial cutting treatment was different for position classes, stand structure, growth tree ratio b.c., and years after intervention and the combination of these factors (Table 3). The growth response in all cutting treatments was significantly higher compared to the control plots ($p = 0.0228$) and ST showed no significant differences with the partial cuttings treatments ($p = 0.166$); there were also no significant differences between partial cutting treatments. This model explained 42% of total variance.

Percentage of growth change (PGC) gave a clearer view of the variations in growth response over time (Figure 5). PGC results with the minimum threshold 100% highlighted the growth model effects, and showed the number of released trees a.c. The structure influenced the radial growth response of residual trees; overall, the mean PGC values of younger stands were more than double older stands a.c. (Figure 5). When tree position was confounded in a stand level average, DS and MS presented the best growth performance in younger stands, and CS in older stands. However, CS and ST were the treatments with lowest growth responses for younger and older stands, respectively, and showed the lowest number of released trees. The control plots in older stands showed stable values during the study period, contrary to younger control plots that displayed a growth increase (13% of trees).

Table 3. Analysis of variance for repeated measurements (RM-ANOVA) results for after cutting growth response of black spruce residual trees. The analysis assumed a mixed model in which the fixed effects are the two stand structures, four cutting treatments plus a control, position classes, time effect (10 years after cutting) and growth before cutting (GBC) as a covariate.

Effect	*df*	*ddf*	*F*	*Pr > F*
Structure	1	4	10.74	0.0306
Treatment/Position—factor	8	32	2.82	0.0172
Treatment	4	32	2.91	0.0368
-Control vs treated plots	1	32	5.72	0.0228
-Partial cuttings vs seed-tree	1	32	2.01	0.1662
-Close selection vs seed-tree	1	32	4.54	0.0408
-Mini-strip vs distant selection	1	32	1.24	0.2733
Position	1	32	8.52	0.0064
Year	9	36	15.54	<0.0001
Structure × Year	9	36	4.74	0.0003
Treatment/Position × Year	72	288	1.96	<0.0001
Structure × Treatment/Position × Year	72	288	1.40	0.03
GBC	1	9368	906.07	<0.0001
GBC × Structure	1	9368	5.14	0.0234
GBC × Treatment/Position	8	9368	2.62	0.0073
GBC × Year	9	9368	13.16	<0.0001
GBC × Structure × Year	9	9368	3.39	0.0004
GBC × Treatment/Position × Year	80	9368	2.05	<0.0001
GBC × Structure × Treatment/Position × Year	80	9368	1.34	0.0226

Note: Only the significant interactions and orthogonal contrasts are shown.

A general pattern was detected in the growth response over time for younger stands, characterized by three general steps: (1) no response phase during the first 2–3 years a.c. (two years for MS, DS and ST, but three years for CS); (2) growth increase period (3–9 years a.c. in our study); (3) growth decline, after maximum peak growth 9 years a.c. However, older stands showed high variability and slow growth response in time (usually no peak 9 years a.c.). This pattern is not evident on PGC (Figure 5) because of the smoothing effect from the moving average. Furthermore, a time delay was registered between edge and interior trees in younger stands; in the case of MS, the edge trees reacted one year before interior trees; therefore, the growth peak in interior trees was identified one year later (Figure 5). The response time is the time after cutting necessary to find significant differences in growth between control and treatment plots. In our studied treatments, response time was five years for younger stands (except CS that was one year more) and six years for older stands (Figure 5).

The edge trees showed a higher response than interior residual strip trees in terms of radial growth and released trees number; this effect was greater in younger stands, especially in DS and MS (Figure 5). A total of 74% and 60% of DS and MS edge trees had doubled the growth 9 years a.c. in comparison with 26% and 38% for interior trees (nearly 50% more). On the contrary, the difference between position classes was lowest (3%) for CS in younger stands. The highest growth response of interior trees was registered in MS and ST younger stands (38% and 39% of released trees).

Multiple linear stepwise regression results showed the factors that influenced the growth response of trees in each position (Table 4 and Figure 6). The variance explained ranged from 56% for edge trees to 73% for interior trees; residual plot distribution indicated an adequate fitting with a normal distribution of errors. The growth response of control trees had the highest R^2, and was the simplest model influenced by only two factors (age and GBC). Edge trees growth response was conditioned by the effect of treatment, structure, stand age, mortality and GBC. This was thus the most complex model, showing the lowest fitting. Instead, the interior trees response had intermediate fitting (R^2 = 0.61), and decreased with stand age and increased with harvested density, DBH b.c., mortality and GBC. No significant treatment effect was detected for interior trees following the stepwise variable selection.

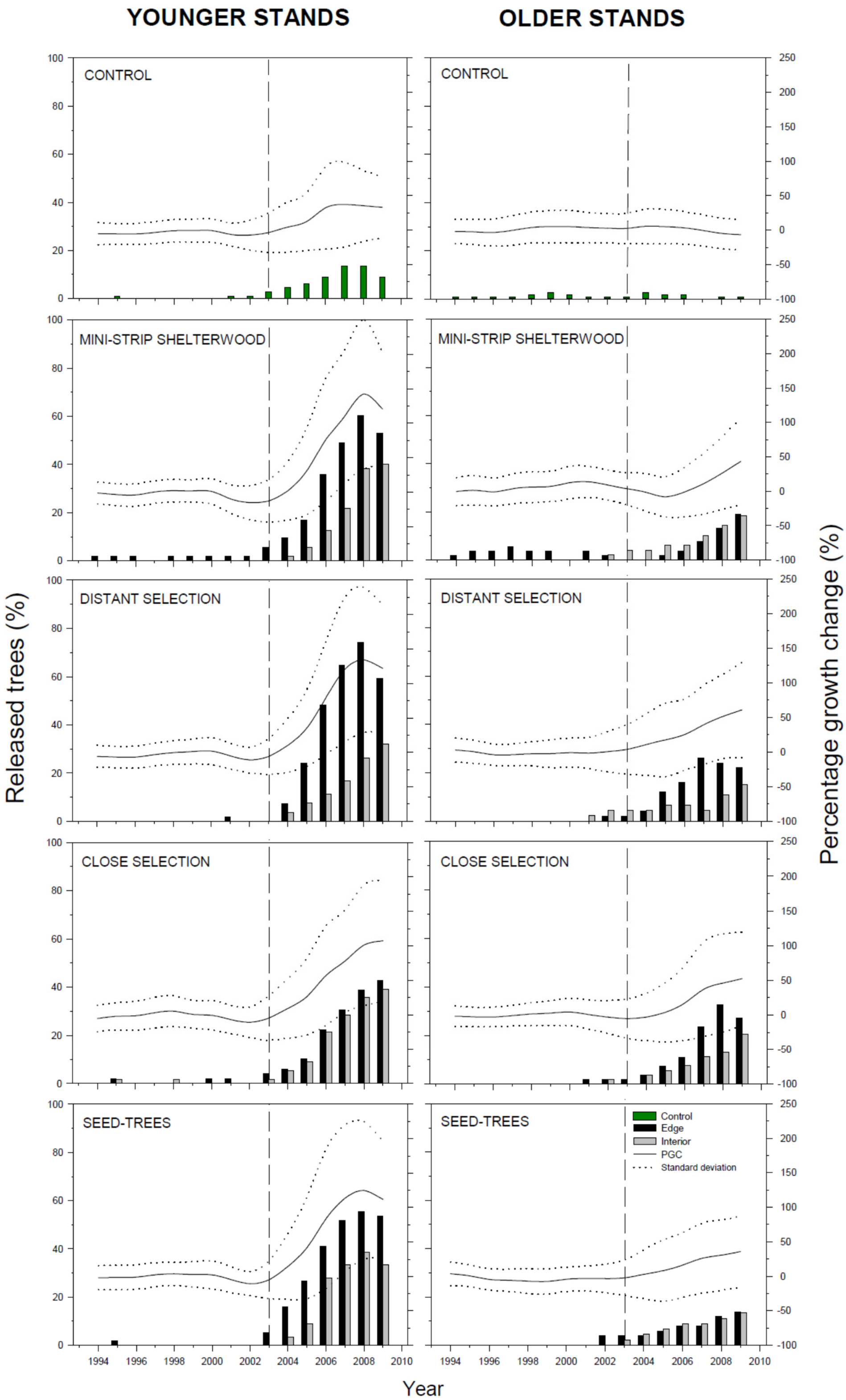

Figure 5. Mean (continuous black lines) and standard deviation (dotted grey lines) of percentage growth change (PGC) for annual tree ring width of studied trees by stand structure and treatment. Bar charts show the percentage of released trees (>100% PGC) by position, treatment and structure. Vertical dashed lines indicate the year of intervention (2003).

Table 4. Best model selected with step-wise multiple linear regressions statistics for the growth responses of black spruce trees for position classes and control trees.

	R^2	*N*	Parameter	Estimate	SE	*t* Ratio	VIF	*p*-Value
Control	0.73	218	stand age	0.20	0.04	4.88	1.07	<0.0001
			GBC	0.93	0.06	15.66	1.61	<0.0001
Edge	0.56	418	treatment	−0.09	0.03	−2.74	1	0.0064
			structure	0.08	0.04	2.34	2.32	0.0190
			stand age	−0.13	0.04	−3.37	2.45	0.0008
			mortality	0.12	0.02	4.11	1.72	<0.0001
			GBC	0.73	0.04	16.42	1.2	<0.0001
Interior	0.61	403	stand age	−0.19	0.05	−3.45	1.48	0.0006
			harvest density	0.73	0.30	2.45	3.15	0.0149
			DBH b.c.	0.02	0.005	3.42	4.54	0.0007
			mortality	0.18	0.06	3.12	5.17	0.0019
			GBC	0.84	0.04	19.90	1.18	<0.0001

Results from stepwise multiple linear regressions using the forward procedure with Bayesian Information Criterion (BIC) as indicator, *N* = total number of trees; VIF = Variance Inflation Factor; GBC = growth before cutting; DBH b.c. = diameter at 1.3 m before cutting.

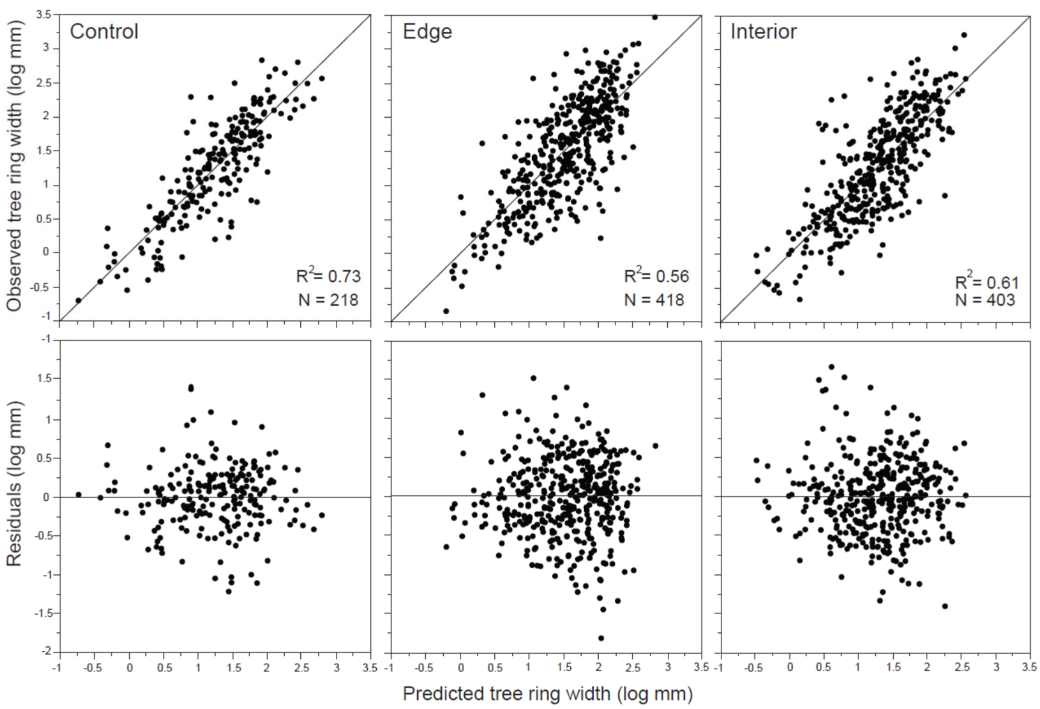

Figure 6. Observed vs. Predicted tree ring width and Residual for the models by position class.

GBC had a strong impact on growth response, and the relationship between growth before and after cutting over 10 years was linear (Figure 7); treatment, position, time and stand structure mostly affected the slope of this relationship. For all trees in older stands and interior trees in younger stands, differences were small when GBC was less than 0.4–0.5 mm/year. The results showed that for edge position in younger stands, suppressed trees strongly increased their radial growth a.c., mostly with DS and MS (Figure 7). In these cases, the edge trees with GBC less than 0.2 mm/year increased their radial growth five-fold between 6 and 10 years a.c. On the contrary, the lowest relative growth response was identified for interior trees in older stands with ST and CS (trees with GBC less than 0.2 mm/year only doubled the radial growth a.c.). However, in absolute values, trees with greater growth prior to cutting showed higher growth response.

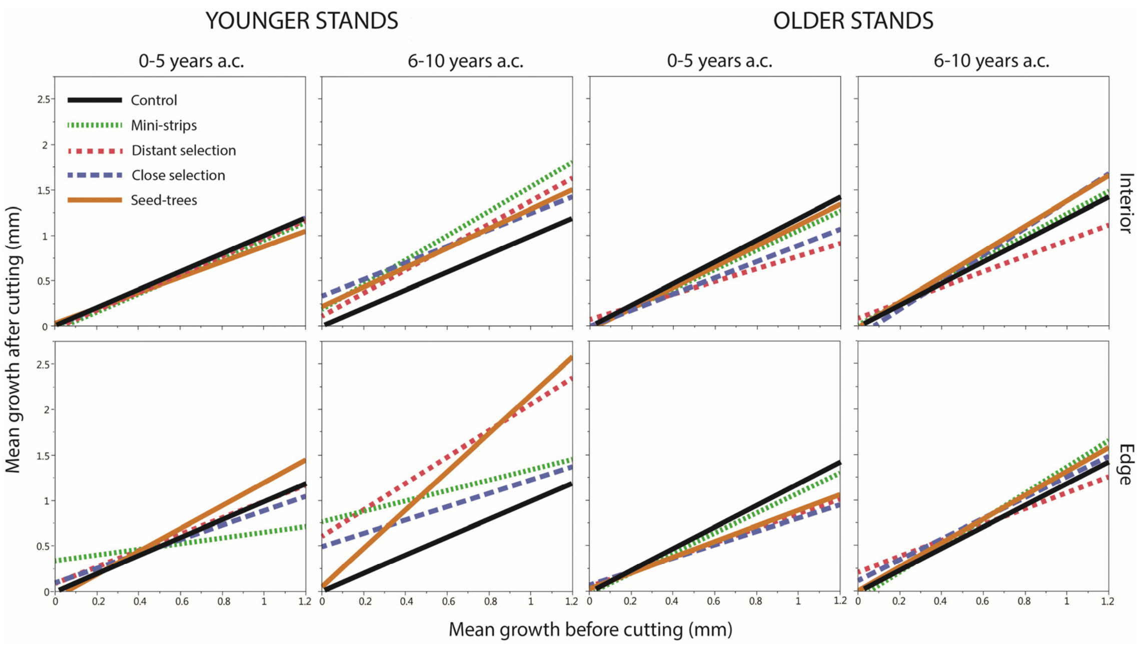

Figure 7. Simple effects of the interaction of treatment/position with growth before cutting, time and stand type on radial growth after cutting.

Differences between treatments for the relationship between GBC and post-treatment growth were significant only for edge trees in younger stands, 6–10 years after treatment (Tables 5 and 6). In this case, for trees with lower growth prior to treatment (<0.2 mm/year), all treatments caused a significant increase in growth in comparison with the control, but none of them significantly outperformed the others. However, MS and DS showed a slightly superior but non-significant response than CS and ST for slow-growing trees. Stronger differences were observed for trees with high GBC (>1 mm/year). CS and MS showed significantly lower responses than other treatments, with values comparable to the control. For trees with high GBC, DS showed the greater growth response, closely followed by ST.

Table 5. Statistics of the analysis of the LS-means (Slicing) for the growth before cutting (GBC) × structure × treatment/position × year interaction.

Structure	Years	GBC (mm/Year)	*df*	*ddf*	*F*	*Pr > F*
Younger	0–5	0.2	8	36	1.24	0.3027
Younger	6–10	0.2	8	36	5.41	0.0002
Older	0–5	0.2	8	36	0.39	0.9170
Older	6–10	0.2	8	36	1.43	0.2189
Younger	0–5	0.6	8	36	0.44	0.8857
Younger	6–10	0.6	8	36	2.73	0.0183
Older	0–5	0.6	8	36	0.98	0.4663
Older	6–10	0.6	8	36	0.49	0.8555
Younger	0–5	1.0	8	36	1.40	0.2282
Younger	6–10	1.0	8	36	2.69	0.0197
Older	0–5	1.0	8	36	1.78	0.1144
Older	6–10	1.0	8	36	0.64	0.7395

Table 6. LS-means comparisons for the relationship between growth before and after cutting by treatment and position in younger stands for 6–10 years post-treatment.

Position Class	Treatment	GBC (mm/Year)		
		0.2	0.6	1.0
Interior	Control		n.s.	
	Mini-strip		n.s.	
	Distant selection		n.s.	
	Close selection		n.s.	
	Seed-trees		n.s.	
Edge	Control	c	c	c
	Mini-strip	a	ab	bc
	Distant selection	a	a	a
	Close selection	ab	bc	c
	Seed-trees	ab	a	ab

Note: GBC represents growth before cutting; n.s. corresponds to no significant differences. Treatments followed by letters are significantly different (p = 0.05), where a > b > c.

4. Discussion

4.1. Radial Growth Response

Quantifying tree growth response following partial cutting treatments is essential for the planning of the long-term timber supply within the context of sustainability of forests to conciliate ecosystem management with wood production. However, improvement of tree growth is not the principal goal in shelterwood systems [44], and the potential of residual trees to increase in wood volume is usually not considered [12,43]. Some authors indicated that these treatments could probably stimulate tree growth during the period of regeneration before final cutting [53,54]. The results of our study confirmed this in black spruce stands.

The residual trees experienced a substantial increase in radial growth. Overall, the mean increase in radial growth was 41% to 62% higher in study treatments with 50%–75% removal than in untreated control plots. This response is similar in amplitude to other boreal forest studies conducted with different species and partial cutting treatments: Thorpe et al. [22] observed double increases in growth rate 8–9 years a.c. with higher harvest intensities in uneven-aged black spruce stands. Fifteen years after different thinning (23% to 44% basal area removed) in young and pure jack pine (*Pinus banksiana* Lamb.) stands, 30% to 70% increases were observed in radial growth [18]. In old-growth white spruce (*Picea glauca* (Moench) Voss) stands, 62% basal area increase was detected in treatment versus control plots 14 years after seed-tree treatment (66% basal area removed) [55]. In planted Norway spruce stands (*Picea abies* (L.) Karst.), growth increased by 41% three years after heavy thinning (40% basal area removed) [15] or 46% to 71% with intermediate thinning 9 years a.c. [17].

Previous research showed that black spruce response depends on the intensity of the partial cutting: The increase in growth is often marginal or not significant for treatments with harvest intensity less than 30%, while it is marked and significant for 50% harvested [20,56,57]. Here, we show that the radial growth response is similar in a harvest intensity range between 45% and 80%. Supported by the findings of previous research, we can confirm that heavy thinning, HARP, shelterwood and seed-tree treatments have similar growth response in black spruce stands.

4.2. Factors Influencing Growth Response

4.2.1. Initial Stand Age and Density

Age and density are essential factors in the forest structure, and influence the growth response; in our experimental treatments, we confirmed the decline in growth with age already observed in other studies [19,22,58]. In younger and denser stands (80–100 years, 2300–2900 trees/ha), radial growth response doubled that in older and open stands (110–160 years, 1300–1900 trees/ha), thus confirming hypothesis 3 (Figure 5). The growth response in older and open stands was lower and shorter, probably due to older trees with lower photosynthetic rates [59] and shorter periods of cambial activity and xylem cell differentiation than younger trees [60]. Older trees were also closer to their maximal height, leaving little room for vertical crown expansion after the release from lateral competition. Growth-age predictions in Thorpe et al. [22] were similar to the results found in our study for older stands. However, our studied variants of shelterwood in younger stands had a higher growth response; the predictions, e.g., indicated an increase of 0.9 mm/year in 100 years old stands 9 years a.c., and we observed 0.7 and 1.6 mm/year for interior and edge trees in DS. This could be explained by the fact that their model did not consider the spatial position and GBC. Nonetheless, the age effect was less significant than treatment, position or GBC.

4.2.2. Silvicultural Treatment

The results demonstrated that all study treatments increased radial growth of residual trees. Contrary to our expectations, no significant differences were found between experimental shelterwoods and seed-trees, with the exception of CS and ST that showed a small significant difference. This difference can be explained by the different stand structure. In older stands, CS is the most effective treatment on radial growth and ST the least. Thus, treatments showed different growth responses for each stand structure (Figure 5). According to the results of released trees, we consider that DS and MS are the best option to promote radial growth in younger stands and CS in older stands. However, in future research, we recommend studying the volume production and mortality at a stand level to assess if the growth responses of the residual trees are able to compensate the reduction in stand density by the partial cutting treatments.

Some minor differences in harvested intensity of our studied treatments were observed between older and younger stands (e.g., MS). This reflects the random variability one can expect from "real-life" mechanized operations with no tree or trail marking prior to the harvest. The causes of such variations are site topography that does not allow regularly spaced trails and different operators who select trees in the application of the silvicultural prescription. These elements are part of the experimental error, and are assumed as such.

4.2.3. Edge Effect

The edge effect created by skidding trails in partial harvests is one of the strongest effects measured in our study, and a subject little studied in boreal forests [61]. To our knowledge, this is the first evaluation of the edge effect on radial growth after partial cutting in black spruce even-aged stands and one of the few studies with dendroecological data.

Our findings confirm that the edge effect of skidding trails on tree radial growth response is a complex phenomenon that interacts with many factors such as stand age and density, trail distribution within the treatments, mortality and tree social status. The stand structures showed different growth response in edge trees that varied depending on stand age and density [22,36]. The results indicated more edge effect influence in younger stands, in accordance with Harper, et al. [61]. In the case of older stands, the growth response of edge trees was similar to the results obtained by Genet and Pothier [29] for black spruce and balsam fir mixed stands in old-growth irregular forest.

Different edge effect growth responses among the studied treatments could be explained by the fact that each treatment has a specific spatial pattern and, consequently, different edge surface and residual strip width (Table 1 and Figure 2). From these results, we can expect that treatments with more edge surface would register higher augmentation in radial growth at the stand level, especially in younger stands where edge effect was greater. For instance, CS was the treatment with the least edge surface; we speculate that this could explain the lowest growth response in younger stands. However, CS had a greater response in older stands due to the low influence of edge effect.

In younger stands, the radial growth of edge trees was twice that of interior trees in DS, MS and ST confirming hypothesis 4. This result is in agreement with the findings in *Pinus radiata* [36] and *Tryplochiton scleroxylon* [35] stands that indicated a decrease of 50% in DBH values for interior trees. In *Pinus contorta,* 31% greater stand basal area was detected in edge trees between 3 and 15 years after road construction [37]. In the case of *Pinus taeda* and *Liriodendron tulipifera*, differences of 5.2 and 8 cm have been identified between interior and edge trees 20 years after edge creation [62]. Thus, it seems that the soil compaction and wounds to the roots and trunk on edge trees caused by machines during the cutting operations did not have a negative impact on growth response in the short term, as shown also in Picchio, et al. [63]. This lack of impact may be related to the high ecological resilience to soil disturbances of this species, which occupies a wide spectrum of environments such as peatlands, permafrost soils, higher northern latitudes or mixed forest [64], and grows at elevations ranging from sea level to 1500 m [65]. Black spruce has the ability to endure stress situations like extreme water deficit [66], and can develop adventive roots exceeding 2 meters (60% of total root length) in one year [67].

Growth differences between edge and interior trees were correlated with the measured CI_i (Figure 4); this relationship has been reported in the literature [26,29,68]. Edge trees in younger stands of DS showed the lowest competition values, and it was the studied shelterwood with the highest growth response. In DS, the numerous small gaps created by the combination of main and secondary trails and the tree selection inside the residual strip explain this situation. In ST, the creation of large gaps contributed to a comparable reduction in CI_i due to the high mortality a.c. of residual trees. Tree selection and mortality in the residual strip promoted the reduction in tree density and produced an increased canopy opening that favored the edge influence on residual trees [25,34]. However, for interior trees in the same stand type, CI_i values for all the treatments were close to trees in control plots. The comparable value of CI_i between MS and CS suggests that tree-selection in CS was not sufficient to significantly reduce competition in comparison with a partial cutting without tree selection. On the contrary, tree selection influenced the smallest differences between edge and interior trees in CS. However, in DS, the growth response of interior trees was lower than CS, probably due to the residual strip being the widest in the studied treatments.

In older stands, the variability of CI_i may be caused either by more heterogeneous initial tree distribution, or by random mortality that occurred after the partial cutting treatment (e.g., ST). Overall, relative differences in CI_i between edge and interior trees and between treatments were less than for younger stands, which is correlated with the smaller growth response of older stands to the treatments. This could be explained by the fact that the same man-made gaps created in each treatment are proportionally less important in older stands than in younger ones, because of differing initial tree spacing and size.

The presence of a growth response even in interior trees that are not subjected to tree selection suggests that the depth of the edge effect probably extends close to 1.25 m from the trails, the distance that we arbitrarily chose for selecting edge trees. We speculate that the depth of the edge effect will be higher in older than younger stands due to less density, and in treatments with tree selection and high mortality a.c. In future investigations, measuring the tree distance from trails, as in Genet and Pothier [29], could be added to our methodology for a more precise evaluation.

4.2.4. Time Response

The growth response was not immediate after treatment, the majority of trees showed a no response step (0–3 years a.c.) in agreement with previous researches [12,21,55]. A possible explanation is resource allocation in the root system due to a stress response to new conditions a.c. (higher wind penetration, light intensity and transpiration) in order to promote stability, and uptake of water and nutrients [20,69–71]. The growth response was delayed around 5–6 years, similar to the results found in other partial cutting studies [55,72]. We speculate that the no response step and the cores extraction at breast height (1.3 m) influenced the delay time.

The temporal response in tree growth a.c. was affected by stand structure and tree positions in the residual strip. Our growth response in younger stands showed a peak 9 years a.c. then started to decrease. We hypothesize that the growth in younger stands continues to decrease gradually to the values shown b.c. [22]. On the contrary, the growth peak in older stands was not obvious due to the high variability of trees; we thus assume that the radial growth would be stable for a few years before decreasing. Long-term monitoring is needed to confirm this. The response time in growth was 5 years in younger stands; this can be explained by windthrow disturbance in a younger control plot (the same year as cutting). We speculate that without this event, the response time would be close to 3 years a.c.

Different growth temporal responses were observed between position classes: Edge trees in MS and ST reacted one year before interior trees in younger stands (Figure 5); the growth peak was the ninth year a.c. in MS and DS edge trees but interior trees continued to grow beyond that year (Figure 5). This delay in temporal response could be explained by the edge trees having more accessibility to nutrients, higher soil temperature, lower competition, higher lateral light intensity than interior trees [25–27,73], and reacted earlier. However, ST interior and edge trees experienced the growth peak in the same year. It is likely that the skidding trails area three times wider (15 m) than MS and DS, and the narrow residual strip (5 m) could affect the edge influence on growth response. In older stands, this delay in temporal response was not observed; we concluded that differences in the temporal response between edge and interior trees are not obvious in older stands.

4.2.5. Growth before Cutting

Our results suggest that the growth response of residual trees depends on GBC. The study demonstrated that suppressed trees show better growth ratio before and post-treatment than dominant trees, in agreement with other studies [15,20,21]. Nonetheless, this phenomenon is influenced by structure, treatment and spatial position effects (Figure 7). The response is amplified in younger and higher initial density stands in MS and DS treatments, notably for edge trees. This could be explained by suppressed trees experiencing more difficult growing conditions b.c. in high density stands, and the edge position decreases the competition for light and nutrients. Other factors that could influence the growth response in suppressed trees is the tree-selection, and mortality in the residual strip, especially in younger stands. Edge and suppressed trees in ST and CS of younger stands had slightly lower growth response than other treatments. This may be caused at least partly by greater drought stress or insolation from the large canopy openings or because ST was the silvicultural treatment with elevated mortality in our study (around 70% of trees), and edge trees with low DBH have high probability of death a.c. [30]. Overall, growth response was stronger for dominant than for suppressed trees in absolute terms, thus not confirming hypothesis 5. This supports the hypothesis of asymmetric competition for light as the main process in the studied stands [74]. For dominant trees on the edge of trails, DS and ST caused the strongest response, probably because of the elimination of a greater number of competitors in the immediate surroundings of the residual trees in comparison with other treatments.

5. Conclusions

First, the experimental shelterwood and seed-tree methods are effective treatments to promote residual tree growth. MS and DS are the most productive treatments in terms of radial growth for younger stands and CS for older stands. Second, the stand structure, edge effect and growth before cutting are key parameters for optimizing the radial growth performance and we recommend the inclusion of these variables in the silvicultural planning and forest management of black spruce stands. Based on our results, age structure and density are two elementary criteria in stand selection before cutting to maximize the growth yield of the treatments; the experimental shelterwood treatments were more efficient in younger and denser stands. An edge effect on growth response has been demonstrated for the first time in black spruce even-aged stands; this suggests caution in the interpretation of traditional growth studies, in which spatial distribution or position classes of the trees were typically not taken into consideration. The growth before cutting was one of the most influential variables in the growth response, and it helped to understand that dominant trees manifest a better growth response in absolute terms. Finally, the studied treatments could be considered as a silvicultural alternative for the implementation of sustainable forest management in the boreal forest.

Supplementary Materials: The following are available online at http://www.mdpi.com/1999-4907/7/10/240/s1.

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