Forest Ecology and Management 555 (2024) 121703

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Retaining the largest aspen stems during motor-manual release allows to control aspen suckering in young mixedwood stands

Léa Darquié [a,*], Patricia Raymond [b], Annie DesRochers [a]

[a] Institut de Recherche sur les Forêts - Université du Québec en Abitibi-Témiscamingue, 341 Principale Nord, Amos, QC J9T 2L8, Canada

[b] Direction de la Recherche Forestière - Ministère des Ressources naturelles et des Forêts du Québec, 2700, rue Einstein, Québec, Québec G1P 3W8, Canada

A R T I C L E I N F O

Keywords:
Silviculture
Motor-manual release
Aspen suckering
Thinning from below
Black spruce growth
Mixedwood

A B S T R A C T

Mixedwood stands containing aspens (*Populus tremuloides* or *P. grandidentata*) often convert to hardwood-dominated stands after harvesting due to the rapid regeneration of aspen from root suckers, even when sites are promptly replanted with conifer seedlings. Without the use of herbicides, this problem is usually dealt with several passes of motor-manual ("manual") release of overtopped seedlings. The aim of this study was to test a variation of thinning from below treatment (thinning; only 20% of the largest aspens are retained), and to compare it against two traditional release treatments: broadcast brushing (brushing; 100% removal of aspen) or crop tree release (CTR; removal of competing vegetation 60 to 90 cm around planted spruce) and an un-treated control. The thinning treatment left the 20% larger aspen stems in place, in order that they continue exerting apical dominance on smaller suckers and limit re-suckering of the treated plots. Aspen suckering and growth of planted black spruce seedlings (*Picea mariana* (Mill.) B.S.P) were measured two- and four-growing seasons following treatments. Results four years after release application showed that the thinning and CTR treatments reduced aspen density by 61% compared to the brushing treatment. In addition, aspen individual stem volume in the thinning treatment was almost 10 times larger than the brushing and twice that of the CTR treatments. Spruce height and ground collar diameter (GCD; 5 cm aboveground line) were both measured, and while height increment was similar in all treatments, diameter increment was greater in the thinning treatment (+42%) compared to the control, brushing and CTR treatments (+17%). Thinning yielded better short-term results than the brushing release in terms of aspen re-suckering and aspen sawlog potential, highlighting the need for adapted silvicultural treatments based on the species' ecology.

1. Introduction

Mixewood stands containing aspens (*Populus tremuloides* or *P. grandidentata*) often convert to hardwood-dominated stands after harvesting due to the aggressive natural regeneration by root suckering of aspens, even if the sites are quickly replanted with black spruce (*Picea mariana* (Mill.) BSP) seedlings. The abundance and fast early growth rates of aspen suckers lead to a decrease of height and diameter growth of spruce seedlings (black spruce for Wang et al., 2000; white spruce (*Picea glauca* (Moench) Voss for Kabzems et al., 2015) and if competition is too intense, a lower survival rate (Jobidon, 1995). It brings the need for release (also called thinning) early in stand development to limit aspen competition and provide improved light conditions to the planted spruce trees (Filipescu and Comeau, 2007; Thiffault and Hébert, 2013). As Quebec has prohibited the use of chemical release since 2001 (Thiffault and Roy, 2011), the main method of release is motor-manual ("manual"), and usually consists in cutting all competing vegetation. However, new aspen suckers are quickly produced after manual release and re-invade the sites, rapidly overtopping spruce plants again, thus increasing costs and reducing effectiveness of this silvicultural treatment (Thiffault et al., 2003). The aim of our study was to find an alternative manual release treatment in order to avoid abundant re-suckering of aspen in aspen-dominated mixed stands.

Aspen suckering is contingent on the auxin/cytokinin ratios, phytohormones produced respectively in the aboveground tissues and the roots (Eliasson, 1971; Thimann, 1977). When auxins are present in higher quantities than cytokinins in the roots, sucker bud initiation is inhibited, and apical dominance remains active. After the stems are harvested, apical dominance is removed which triggers suckering (Farmer, 1962; Perala et al., 1990; Peterson and Peterson, 1992;

* Corresponding author.
E-mail address: lea.darquie@uqat.ca (L. Darquié).

https://doi.org/10.1016/j.foreco.2024.121703
Received 26 October 2023; Received in revised form 5 January 2024; Accepted 8 January 2024

Jobidon, 1995; Frey et al., 2003). Since root systems of aspen trees are highly interconnected (DesRochers and Lieffers, 2001a; Jelínková et al., 2009), auxins from remnant trees can continue travelling into the "communal" root system after harvest, maintaining a certain level of apical dominance in the stand (Frey et al., 2003) and limiting the number of root suckers produced.

To control aspen suckering, Mulack et al. (2006) studied the effects of leaving residual aspen at diverse densities (0, 500 and 1500 stems per ha) while performing a cleaning in a 10-year-old stand. While short-term results showed a 23–39% aspen suckering decrease relative to complete removal, the regeneration was still too abundant to effectively manage aspen density. A uniform spacing of residual stems (an average of 1233 stems ha^{-1}) in the thinning treatment was also found to decrease aspen regeneration by suckering compared to complete removal 3 years post-treatment, but this effect was no longer apparent after 13 years (Kabzems et al., 2022). Keeping the largest stems during a thinning treatment is a well-known silvicultural method in Canada (thinning from below, Stiell, 1980; Helms, 1998), but is usually applied later in the stand developmental stages in Quebec (Laflèche et al., 2013; Prévost and Gauthier, 2012).

Considering that larger stems probably exert stronger apical dominance hindering aspen suckering, we tested the hypothesis that leaving the largest aspen suckers during the release treatment, instead of using a desired residual density or uniform spacing, would more effectively reduce the amount of re-suckering, as well as increase the sawlog potential of the remaining aspens. We chose to leave the largest stems, since the amount of suckering is directly correlated to the amount of root biomass left behind after harvesting (DesRochers and Lieffers, 2001b). These stems should reinstate the balance between aboveground (leaf area) and belowground biomass more quickly, and thus rapidly restore apical dominance in treated stands and reduce the amount of re-suckering after manual release.

We compared this thinning treatment against two traditional manual release treatments, broadcast brushing (brushing; removal of all aspen stems) and crop tree release (CTR, removal of all aspen stems 60–90 cm around planted spruces) (Wiensczyk et al., 2011; Pitt et al., 2015; Comeau, 2022; Kabzems et al., 2022) and an untreated control. The thinning treatment left in place the 20% largest diameter aspen suckers that invaded the stands post-harvest, in order that they continue exerting apical dominance on smaller suckers and limit re-suckering of the treated plots. Its advantage over a more traditional CTR release method is that it is easier to leave the biggest aspen stems than to locate each spruce tree underneath the competitive vegetation and then release them.

Our predictions were that the number of suckers produced after manual release would be greatest in the brushing treatment (all apical dominance removed) and smallest in the thinning and CTR treatments (maintenance of apical dominance), with little or no re-suckering in the untreated control. In contrast, we expected that volume per ha would be the highest in the control but that volume per aspen stem would be greatest in the thinning and smallest in the brushing treatments.

2. Materials and methods

2.1. Study site and experimental design

The study site was located in Abitibi-Temiscamingue region, Western Quebec, Canada, near the town of Saint-Édouard-de-Fabre (47°12'0''N, 79°22'0''W) and belonged to the balsam fir – yellow birch bioclimatic domain (Gosselin et al., 1998). Before harvest, the site was a mixedwood stand dominated by aspens (trembling aspen and largetooth aspen) and balsam fir (*Abies balsamea* (L) Mill.), with an understory of balsam fir and red maple (*Acer rubrum* L.) advance regeneration. Annual total precipitation from the nearest weather station (Ville-Marie, 47°20'0''N, 79°26'0''W) averaged 836 mm (656 of rain and 181 mm of snow) with a daily average temperature of 3.1 °C (Climate normals 1981–2010, Environment and Natural Resources Canada, 2013). The soil had an average thickness of 0 to 50 cm and rare to frequent rocky outcrops. It originated from glacial deposits with an undifferentiated till (Ministère des Forêts, de la Faune et des Parcs, 2021).

This site was harvested in 2013 using careful logging around advanced growth (CLAAG; Larouche et al., 2013) to preserve advanced regeneration and reduce machinery traffic on cutovers (Beaupré et al., 2016). As the site was rapidly overtaken by aspen suckers (trembling aspen and largetooth aspen), mechanical site preparation was applied in 2016 to facilitate planting of spruce seedlings. The excavator scraped 2 × 2 m plots to remove the organic layer (395 ± 43 microsites ha^{-1} or an average of 16% of the stand area) at a 10–15 cm depth to plant four black spruce seedlings in 2017 in each microsite (1580 ± 172 stems ha^{-1}).

In May 2019, we divided the study site into three 4-ha replicate blocks, each sub-divided into four 1-ha experimental units (EU). Each EU was randomly assigned one of the 3 manual release treatments and an un-treated control. The release treatments were completed in June 2019, when the aspens were 5 years old using portable brush saws and consisted in 1) broadcast brushing release (brushing): all vegetation except any encountered softwood species is cleared, 2) crop tree release (CTR): all competing vegetation was removed 60–90 cm around any softwood species, 3) thinning-from-below (thinning): all aspen suckers were removed except for 20% of the largest diameter stems and 4) untreated. The thinning treatment required an initial inventory to identify the diameter at breast height (DBH) size threshold (1.97 cm on average) at which aspen stems were retained.

2.2. Growth measurements

In late August to early September 2020 and 2022 (2 and 4 full growing seasons since manual release), 3 plots of 4 m radius (50 m^2) were installed in each EU to measure aspen re-suckering, as well as aspen and spruce growth (at stand age 7 and 9). Aspens were identified either as remnant aspens ($aspen_{rem}$) or new suckers ($aspen_{new}$) for the 2020 measurements but were not differentiated in 2022. Aspen density was measured in 2020 and 2022 by counting the number of aspens present in the plots. Ground collar diameter (15 cm aboveground, GCD) and height of all spruce seedlings and all aspen suckers taller than 30 cm height were measured in the same plots. Basal area (BA, cm^2) was calculated using GCD, and stem volume (SV, cm^3) was estimated from height (H, cm) and GCD (cm) by using an adaptation of Honer's equation (Pitt et al., 2004):

$$SV(cm^3) = \frac{GCD^a}{b + \frac{c}{H}} \quad (1)$$

where *a*, *b* and *c* are parameters estimates. Aspen SV parameters estimates were: $a = 1.6488$, $b = -0.00055$ and $c = 2.1227$.

As the purpose of manual release is to provide better access to light for spruce seedlings, photosynthetically active radiation (PAR) was measured in 2020 with a LI-191R Line Quantum Sensor (LI-COR, Lincoln, Nebraska). In each EU, 3 transects composed of ten 1.13 m radius subplots (4 m^2) spaced 5 m apart were randomly set up. For each subplot (4 m^2), two light measurements were taken from just above the closest four spruce seedlings: one in the North-South direction and the other in the West-East direction. Incident light (above the canopy) was measured into nearby openings or outside the stands, 3 times per transect (at the 1st, 5th and 10th microplots). Measurements were taken on sunny days. Percent incident light (transmittance) was calculated for each spruce by using the light above-spruces and the closest in time light above-canopy record (% transmittance = [above-spruce PPFD/incident PPFD] × 100).

2.3. Statistical analyses

Statistical analyses were done using R software 4.0.4 version (Team, R.C, 2021), with a significance level of $p < 0.05$. Naturally established spruce seedlings (representing 6.5% of the total spruce seedlings), much larger than the planted spruce, were not included in the analyses. As the brushing treatment removed all aspen suckers, we only analyzed $aspen_{rem}$ density for the thinning and CTR treatments, as well as for the untreated control.

Variables measured in 2020 (density and volume of $aspen_{rem}$ and $aspen_{new}$ (per ha and per stem), GCD and height of black spruce seedlings) and 2022 (spruce and aspen ($aspen_{total}$) volume (per ha and per stem) and density), as well as 2-year height, GCD, volume and density increments (2021–2022) were each tested using a generalized linear mixed model (GLMM), with the four treatments as fixed effects and block as a random effect. A fourth root transformation was used on the variables when the assumptions of the models could not be validated (normality of the residuals and homoscedasticity). We also examined the effect of the release treatments on light availability. When the ANOVA showed at least one difference between two treatments, a Wald chi-squared test (Liu, 2015) was performed on the models followed by multiple comparisons of means using pairwise Tukey post-hoc tests. Finally, we investigated the effect of light availability on aspen BA, volume per ha and density by performing a regression analysis.

3. Results

3.1. Aspen regeneration

Mean $aspen_{total}$ density between 2020 and 2022 significantly decreased in the control (-1225 ± 1361 stems ha^{-1}) compared to the thinning and brushing treatments (-200 ± 1361 and $+1362.5 \pm 1539$ stems ha^{-1}, $P < 0.05$, Fig. 1A, Table S1). CTR treatment had an intermediate density variation (-1022 ± 920 stems ha^{-1}, Fig. 1A, Table 1). In 2022, the brushing treatment had a higher $aspen_{total}$ density than the thinning treatment (6875 ± 1489 and 3355 ± 832 stems ha^{-1} respectively, $P < 0.01$, Table S1). $Aspen_{total}$ density in the control (3975 ± 832 stems ha^{-1}) decreased to similar levels found in the thinning treatment in 2022, while the CTR treatment had the lowest density for both years (Table S1).

The brushing treatment produced the highest levels of re-suckering (mean number of $aspen_{new}$ 5512 ± 1317 stems ha^{-1}), compared to the other treatments (1977 ± 602 stems ha^{-1} on average, $P < 0.01$, Fig. 1B, Table 1), while the untreated treatment produced the lowest re-suckering (912 ± 392 stems ha^{-1}, Fig. 1B, Table 1).

Since no aspen suckers were removed in the control treatment, it contained the highest number of $aspen_{rem}$ (4287 ± 1373 stems ha^{-1}), while the CTR and thinning treatments had fewer ($P < 0.01$, Table 1) but similar mean numbers of $aspen_{rem}$ (755.5 ± 276 stems ha^{-1}, Fig. 1C).

3.2. Aspen growth

Between 2020 and 2022 (i.e., two and four growing seasons after release), $aspen_{total}$ in all treatments grew at the same rate, with BA increments between 50.5 ± 48.1 and 94.7 ± 97.6 m^2 ha^{-1} ($p > 0.05$, Table 2). $Aspen_{total}$ BA in the thinning treatment and control were the greatest in both years (1.97 ± 0.6 m^2 ha^{-1} in 2020 and 3.04 ± 1.1 m^2 ha^{-1} in 2022 on average) compared to the CTR and brushing treatments (0.66 ± 0.2 m^2 ha^{-1} in 2020 and 1.89 ± 0.4 m^2 ha^{-1} in 2022 on average, $P < 0.05$, Table S1). On a per stem basis, $aspen_{total}$ in the thinning treatment had the highest mean BA, both in 2020 (5.58 ± 0.8 cm^2 $stem^{-1}$) and 2022 (9.42 ± 1.2 cm^2 $stem^{-1}$), while the brushing treatment produced $aspen_{total}$ stems with the smallest BA (1.10 ± 0.1 cm^2 $stem^{-1}$ in 2020 and 1.93 ± 0.4 cm^2 $stem^{-1}$ in 2022, $P < 0.05$, Table S1). BA of aspen stems in the control and CTR

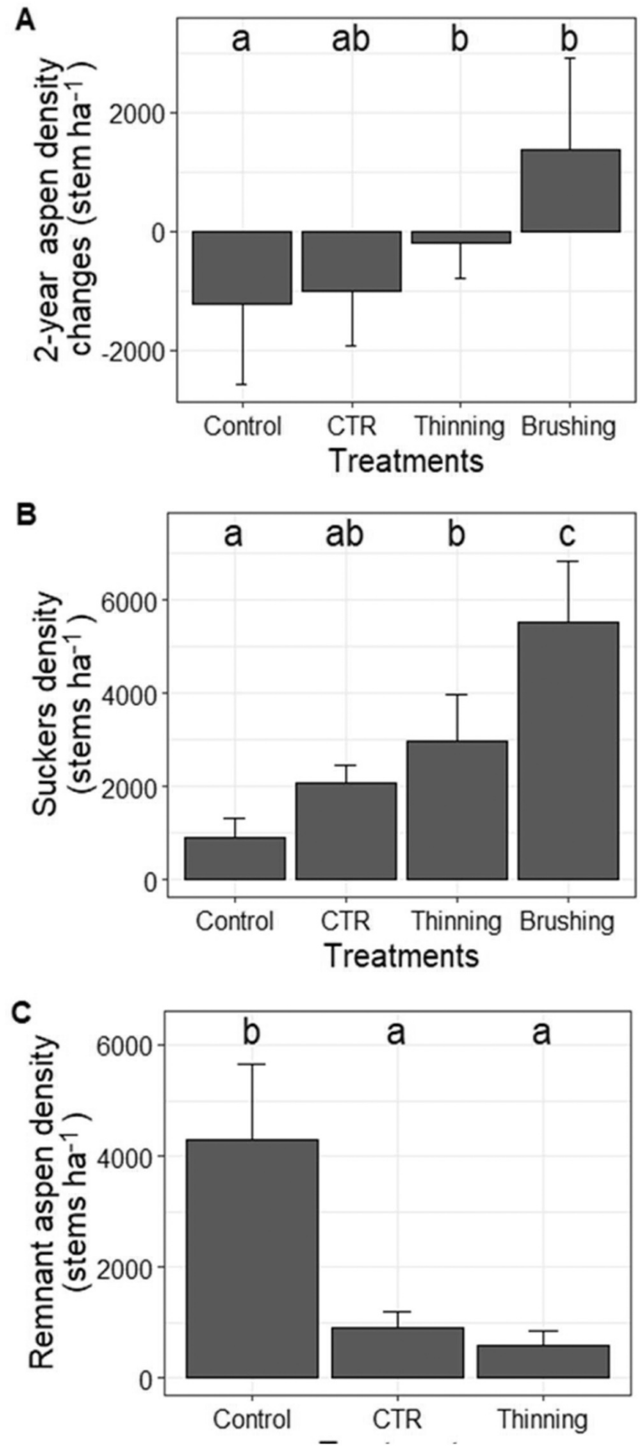

Fig. 1. (A) 2-year aspen density changes (2021–2022), (B) $aspen_{new}$ and (C) $aspen_{rem}$ density (2020) for each release treatment: control, crop tree (CTR), thinning and broadcast brushing (brushing). Means ± SEM. Different letters above bars for each graph indicate a significant difference ($P < 0.05$).

treatments was intermediate, both in 2020 (3.26 ± 0.4 cm^2 $stem^{-1}$ on average) and 2022 (6.67 ± 0.7 cm^2 $stem^{-1}$ on average, Table S1).

Mean BA of $aspen_{new}$ per stem or per ha were smaller in the control (0.5 ± 0.05 cm^2 $stem^{-1}$ and 0.047 ± 0.02 m^2 ha^{-1}, respectively) compared to those in the thinning and brushing treatments (1.36 ± 0.1 cm^2 $stem^{-1}$ and 0.5 ± 0.2 m^2 ha^{-1} on average respectively, $P < 0.05$, Figs. 2A, 2B, Table 2). $Aspen_{rem}$ had the highest mean BA per ha in the control (1.93 ± 0.5 m^2 ha^{-1}) and the smallest in the CTR

Table 1
Analyses of deviance (Type II Wald chi-square tests) and associated probabilities (P > Chisq) for aspen regeneration between the release treatments. The models were all built as follow: Parameter ~ Treatment + (1 | Block).

	Parameter	Chisq	Df	Pr (>Chisq)
Aspen regeneration	2-year total density change	6.974	3	0.073 *
	Sucker density in 2020	29.611	3	**< 0.01**
	Remnant aspen density in 2020	48.814	2	**< 0.01**

Note: Significant differences between at least two treatments (Pr(>Chisq) < 0.05) are indicated in bold. To simplify the presentation, the source of variation "Treatment" (fixed) and the random effect "block" are not presented. Remnant aspens represent the suckers left on site during the release treatments ($aspen_{rem}$) and suckers represent the new suckers ($aspen_{new}$). Df = degrees of freedom. The Pr(>Chisq) with an * was investigated for multiple comparisons of means despite being > 0.05.

Table 2
Analyses of deviance (Type II Wald chisquare tests) and associated probabilities (P > Chisq) for aspen growth between the release treatments. The models were all built as follow: Parameter ~ Treatment + (1 | Block).

	Parameter	Chisq	Df	Pr (>Chisq)
Aspen growth	2-year BA increment	0.627	3	0.890
	Sucker BA per ha in 2020	12.889	3	**< 0.01**
	Remnant aspen BA per ha in 2020	7.596	2	**0.022**
	Sucker BA per stem in 2020	7.463	3	0.059 *
	Remnant aspen BA per stem in 2020	938.86	2	**< 0.01**
	2-year stem volume per ha increment	7.656	3	0.054 *
	Sucker volume per ha in 2020	23.231	3	**< 0.01**
	Remnant aspen volume per ha in 2020	5.545	2	0.063 *
	Sucker volume per stem in 2020	7.923	3	**0.048**
	Remnant aspen volume per stem in 2020	183.71	2	**< 0.01**

Note: Significant differences between at least two treatments (Pr(>Chisq) < 0.05) are indicated in bold. To simplify the presentation, the source of variation "Treatment" (fixed) and the random effect "block" are not presented. Remnant aspens represent the suckers left on site during the release treatments ($aspen_{rem}$) and suckers represent the new suckers ($aspen_{new}$). Df = degrees of freedom. The Pr(>Chisq) with an * were investigated for multiple comparisons of means despite being > 0.05.

treatment (0.60 ± 0.2 m^2 ha^{-1}, $P < 0.05$, Fig. 2C), with the thinning being intermediate (1.51 ± 0.6 m^2 ha^{-1}). When investigating $aspen_{rem}$'s BA per stem, the thinning treatment had the largest aspens (25.14 ± 1.8 cm^2 stem^{-1}), almost four times the BA in the CTR treatment (6.6 ± 1.2 cm^2 stem^{-1}) and 5 times that in the control (4.43 ± 0.3 cm2 stem^{-1}, $P < 0.01$, Fig. 2D, Table 2).

Two years after release, height of $aspen_{new}$ was similar among all treatments and the control (97.2 ± 4.5 cm on average). $Aspen_{rem}$ were the tallest in the thinning treatment (469.9 ± 14.3 cm, $P < 0.05$), almost twice the height of $aspen_{rem}$ in the control and in the CTR treatments (264.4 ± 31.2 cm on average, $P < 0.01$). In 2020, the shortest $aspen_{total}$ were in the brushing treatment (96.5 ± 2.6 cm), followed by the ones in the CTR and thinning treatments (152.3 ± 11.2 cm on average, $P < 0.01$). $Aspen_{total}$ in the control were the tallest (208 ± 7.2 cm, $P < 0.01$, Table S1). In 2022 (i.e., 4 years after release), the brushing treatment still had the shortest $aspen_{total}$ (137.8 ± 4.5 cm), compared to the ones in the control, CTR and thinning treatment, that had similar heights (302.1 ± 16.4 cm on average, $P < 0.01$, Table S1).

The 2-year $aspen_{total}$ volume increment was respectively 8 and 5 times greater in the thinning treatment (7.76 ± 3.9 m^3 ha^{-1}) and the control (5.18 ± 1.4 m^3 ha^{-1}) than in the brushing treatment (0.93 ± 0.3 m^3 ha^{-1}, $P \leq 0.05$, Fig. 3, Table 2). $Aspen_{total}$ volume increment in the CTR treatment was similar to the other treatments (2.49 ± 1.21 m^3 ha^{-1}, Fig. 3). In 2020, the highest volume of $aspen_{total}$ per ha was in the control and the thinning treatment (2.86 ± 0.9 m^3 ha^{-1} on average), which was approximately 8 times greater than the volume found in the brushing treatment (0.36 ± 0.08 m^3 ha^{-1}, $p < 0.01$, Table S1). The CTR treatment had intermediate $aspen_{total}$ volumes (1.1 ± 0.45 m^3 ha^{-1}), significantly greater than in the brushing treatment ($P < 0.01$, Table S1). When considering individual stem volume, the thinning treatment produced the largest $aspen_{total}$ stems in 2020 (813.8 ± 139.8 cm^3 stem^{-1}), 12 times the size of the aspens found in the brushing treatment (66.3 ± 4.9 cm^3 stem^{-1}) and twice the volume of aspens in the CTR treatment (398.3 ± 93.5 cm^3 stem^{-1}, $P < 0.01$, Table S1). This pattern was the same for the stem volume in 2022 ($P < 0.01$, Table S1).

In 2020, the volume of $aspen_{new}$ stems was similar between CTR, thinning and brushing treatments (71.8 ± 8.1 cm^3 stem^{-1} on average), while they were smaller in the control (38.2 ± 4.9 cm^3 stem^{-1}, $P < 0.05$, Fig. 4B, Table 2). Volume of $aspen_{rem}$ was the greatest in the thinning treatment (4447.9 ± 309.1 cm^3 stem^{-1}) compared to CTR treatment and control (1136 ± 273.6 and 605.7 ± 56.8 cm^3 stem^{-1} respectively, $P < 0.01$, Fig. 4D, Table 2). On a per ha basis, the brushing treatment had an approximatively ten-fold greater $aspen_{new}$ volume per ha (0.33 ± 0.08 m^3 ha^{-1}) compared to the control and two-fold compared to CTR treatment (0.037 ± 0.015 and 0.15 ± 0.03 m^3 ha^{-1} respectively, $P < 0.01$, Fig. 4A, Table 2) in 2020. The thinning treatment produced intermediate mean $aspen_{new}$ volume per ha (0.22 ± 0.08 m^3 ha^{-1}, Fig. 4A). Mean volume per ha of $aspen_{rem}$ in the control and thinning treatment were similar and highest (2.73 ± 0.9 m^3 ha^{-1}) while it was lowest in the CTR treatment (1.04 ± 0.43 m^3 ha^{-1}, $P < 0.01$, Fig. 4C, Table 2).

3.3. *Spruce growth and light availability*

The 2-year density increment as well as mean density of spruce seedlings in 2020 and 2022 were similar between all treatments ($P > 0.05$, Table 3, Table S1). Two-year spruce height increment was similar between all treatments, ranging between 15.62 ± 3 – 18.5 ± 1.27 cm ($P > 0.05$, Table 3). Only spruces in the control and thinning treatments were significantly taller in 2022 (47 ± 7.1 cm and 40.6 ± 8.8 cm respectively) compared to 2020 (25.1 ± 5.6 cm and 24.6 ± 6.2 cm respectively, $P < 0.05$). Height of spruce seedlings was similar between treatments, 2 years (29.2 ± 4.8 cm on average, $P > 0.05$, Table S1) and 4 years post-release (43.6 ± 7.9 cm on average, $P > 0.05$, Table S1). Between 2020 and 2022, spruce seedlings GCD increment in the thinning treatment was greater (2.06 ± 0.9 mm) than for seedlings in the control and the CTR treatment (0.95 ± 0.4 mm on average, $P < 0.01$, Fig. 5, Table 3), with the brushing treatment being intermediate ($1.66 \pm .05$ mm). Nevertheless, GCD was statistically similar between all treatments in 2020 (3.9 ± 2.8 mm on average, $P > 0.05$, Table S1) and 2022 (4.8 ± 1 mm on average, $P > 0.05$, Table S1), and similar between both years for each treatment ($P > 0.05$).

Spruce seedlings in the brushing treatment had better access to light in 2020 (53 ± 2%), compared to the control and thinning treatments (41 ± 2% on average, $P < 0.05$, Table 3). Incident light in the CTR treatment was intermediate (48 ± 2%). No relationship was found between incident light and $aspen_{total}$ BA, volume per ha, density or height in 2020 ($P > 0.05$, Fig. S1).

4. Discussion

The aim of our study was to find an alternative manual release treatment in order to avoid abundant re-suckering of aspen in aspen-dominated mixed stands. Considering the natural suckering self-regulation by hormonal balance and the interconnected root network,

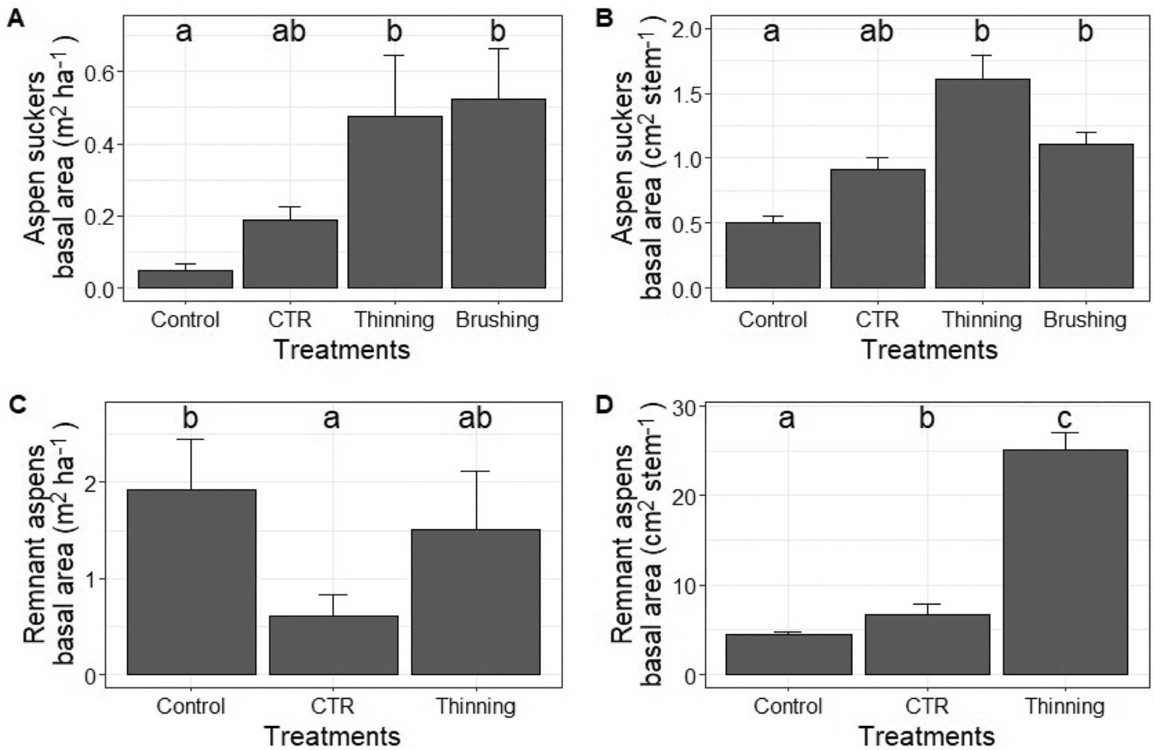

Fig. 2. Basal area of aspen$_{new}$ (A) per ha and (B) per stem, as well as aspen$_{rem}$ (C) per ha and (D) per stem in 2020, for each release treatment: control, crop tree (CTR), thinning and broadcast brushing (brushing). Means ± SEM. Different letters above bars for each graph indicate a significant difference (P < 0.05). Note that the y-axes are different between the 4 panels.

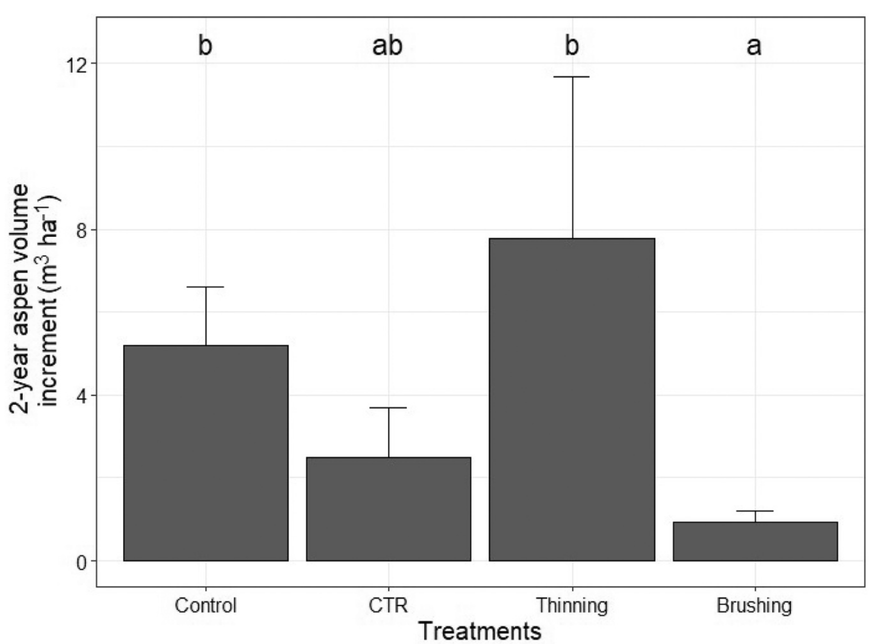

Fig. 3. Two-year aspen$_{total}$ volume increment (2020–2022) for each release treatment: control, crop tree (CTR), thinning and broadcast brushing (brushing). Means ± SEM. Different letters above bars for each graph indicate a significant difference (P < 0.05).

the general hypothesis was that keeping a small percentage of the biggest aspen stems on site and alive would naturally reduce re-suckering.

4.1. Aspen regeneration and growth

Our short-term results show that the thinning treatment is an effective alternative to the CTR treatment, as the post-release suckering was similar between both treatments and the application in the field easier. Since remnant aspens continue producing auxins that travel down into

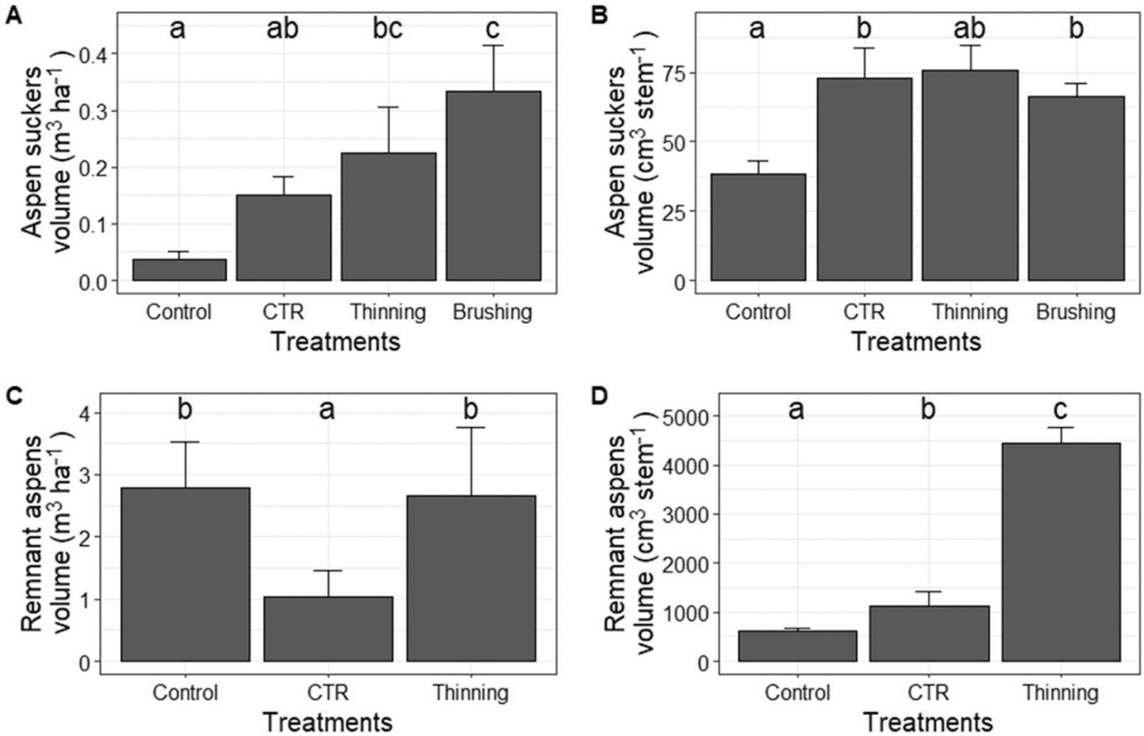

Fig. 4. Mean aspen volume of $aspen_{new}$, expressed in (A) m^3 per ha and (B) cm^3 per stem, and $aspen_{rem}$ in (C) m^3 per ha and (D) cm^3 per stem for each release treatment: control, crop tree (CTR) thinning and broadcast brushing (brushing). Means ± SEM. Different letters above bars for each graph indicate a significant difference ($P < 0.05$). Note that the y-axes are different between the 4 panels.

Table 3
Analyses of deviance (Type II Wald chisquare tests) and associated probabilities (P > Chisq) for light availability and spruce growth between the release treatments. The models were all built as follow: Parameter ~ Treatment + (1 | Block).

	Parameter	Chisq	Df	Pr (>Chisq)
Light availability	Incident light in 2020	10.563	3	**0.0143**
Spruce growth	2-year density increment	4.177	3	0.243
	2-year height increment	0.934	3	0.817
	2-year CGD increment	20.314	3	**< 0.01**

Note: Significant differences between at least two treatments (Pr(>Chisq) < 0.05) are indicated in bold. To simplify the presentation, the source of variation "Treatment" (fixed) and the random effect "block" are not presented. Df = degrees of freedom.

the communal root system (DesRochers and Lieffers, 2001b), we expect that re-suckering will remain low in the long term.

As expected, the number of $aspen_{new}$ after brushing release reached pre-treatment levels two years later, with similar densities and height than in the control treatment where nothing was done. Moreover, density of aspens in the brushing treatment was the only one where density increased between 2020 and 2022. This means that 4 years after the release treatment, the number of aspen stems in the brushing treatment was greater than in the control, up to nearly 7000 stems ha^{-1} versus 4000 stems ha^{-1}. This result is consistent with previous studies (Bell et al., 1999; Harper et al., 1999; Pitt et al., 2000; Mulak et al., 2006; Hamberg et al., 2011) and confirms the short-term inefficiency of brushing treatment to control aspen suckering in regenerating mixed-wood stands. The densities measured here appear significantly lower than in other studies: 91,000 stems ha^{-1} for Mulak et al. (2006), 50,000 stems ha^{-1} for Harper at al. (1999) and 24,000 stems ha^{-1} for Pitt et al. (2000). This could be due to different site conditions as observed by Pitt et al. (1999) and Comeau (2022), and the fact that the site preparation by scraping may have removed/killed parts of the aspen root system.

$Aspen_{new}$ in all treatments were the same height in 2020, but their individual BA differed, which means that the release treatments only impacted their diameter growth, at least for the first two years after release. Overall, BA of $aspen_{new}$ in the thinning treatment was 30% greater and density decreased by 86% compared to brushing treatment. $Aspen_{new}$ in the thinning treatment were also 70% bigger and less numerous (68% less) compared to the $aspen_{new}$ in the control, while they were of similar size and density to the CTR treatment. These results show that keeping the largest BA aspens on site is a better approach to limit aspen re-suckering after release and improves aspen sawlog potential. When considering all aspen stems ($aspen_{total}$), the thinning and CTR treatments had 35–51% and 45–71% fewer aspens respectively, than the brushing treatment 2 and 4-year post-release. The 2-year post-release aspen density decrease observed in our thinning treatment compared to brushing is similar to results found in 38% decrease (Mulak et al., 2006). While the CTR treatment was already known to be more efficient to control aspen's aggressive re-suckering than the brushing release method (Jobidon and Charette, 1992; Cyr and Thiffault, 2009; Comeau, 2022; Kabzems et al., 2022; Comeau et al., 2023), its application in situ can be difficult when the planted spruce seedlings are small and have to be located underneath the competition for the workers to cut around.

Since the largest stems were kept in the thinning treatment, mean aspen size variables (volume, BA, height) naturally shifted upward compared to the CTR treatment or the brushing treatment, explained as the "chainsaw" effect by Bjelanovic et al. (2021) and also observed by others (Penner et al., 2001; Bokalo et al., 2007). The higher mean volume increment per ha in the thinning treatment is likely a byproduct of this chainsaw effect. Remnant aspens in the thinning treatment were twice as high as those in the control or the CTR treatments. This increased height and BA could increase merchantable stem length and volume (i.e., an increase potential sawlog, Perala, 1977; Stiell, 1980; Kabzems et al., 2015).

We did not find any relationship between incident light and aspen

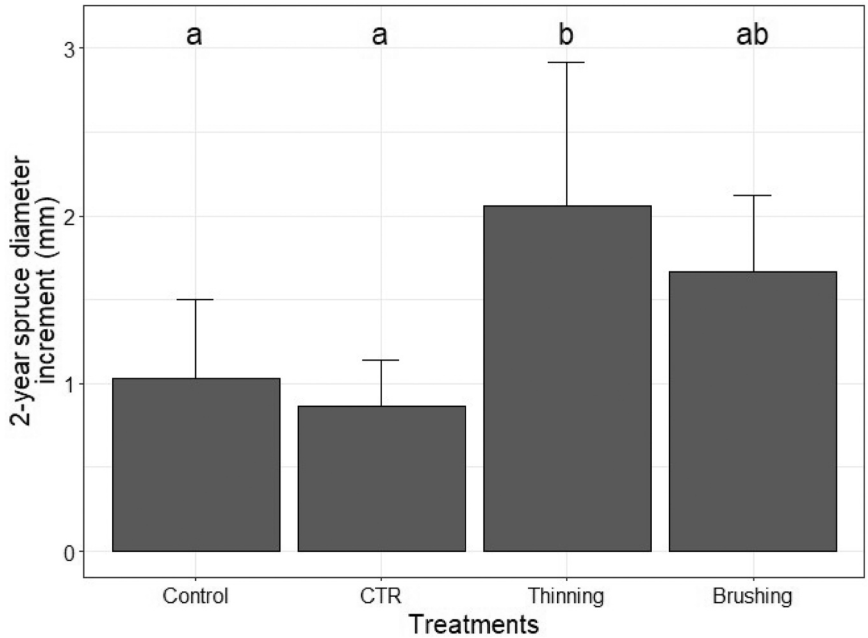

Fig. 5. 2-year GCD increment (2021–2022) for each release treatment: control, crop tree (CTR), thinning and broadcast brushing (brushing). Means ± SEM. Different letters above bars for each graph indicate a significant difference ($P < 0.05$).

size variables such as density and BA. Comeau et al. (2006) found that aspen BA did not influence light availability when below 5 m^2 ha^{-1}. Knowing that the highest aspen BA found in our study was calculated from GCD (instead of DBH) and only reached 3.16 m^2 ha^{-1}, our results were expected. Comeau (2002) also reported that density was a poor predictor of light availability.

4.2. Spruce growth

The main goal of manual release is to increase spruce survival and growth where heavy competition reduces access to light (Thiffault and Hébert, 2013). Black spruce's light threshold for vegetation management was set at 60% incident light (Jobidon, 1994; Thiffault et al., 2003). The highest percentage of incident light measured in this study was 53%, in the brushing treatment, while the lowest light levels were found in the control and thinning treatments (mean of 41%), two years after the release treatments were applied. Since we found no relationship between light and aspen density or growth, the light levels may have been the results of differing site conditions or the effect of understory competition such as ferns, red raspberry (*Rubus idaeus* L.) or other hardwood species (mainly red maple [*Acer rubrum*] and alders [*Alnus spp*]). Spruce seedlings nevertheless showed a positive response to release in the thinning and brushing treatments, as mean GCD increment was the highest in these treatments. Bokalo et al. (2007) as well as Prévost and Charette (2017) found a delay in black and white spruce response to release (4 years and 10 years, respectively). It is thus likely that spruce diameter growth response to release will be stronger later on. Comeau (2022) yet reported that CTR treatment increased white spruce diameter compared to the control, as early as two years after release whereas the GCD increment for the CTR treatment in our study was the lowest, and similar to the control. As the spot cutting radius for our treatment was 60 to 90 cm, and Comeau's was 1.5 to 2 m, it may be that our radius was not large enough to have a significant effect on spruce diameter growth despite reducing aspen re-suckering. The increase in spruce height was similar in all treatments; it is well known that diameter growth is a lot more impacted by competition than height (Jobidon, 2000; Wagner, 2000).

Early thinning of aspens was proven to increase individual volume of the remaining stems, which in turn reduces the rotation time to reach commercial size (Rice et al., 2001; Pitt et al., 2015; Prévost and Gauthier, 2012) and promotes survival and growth of conifers (Rice et al., 2001; Prévost and Charette, 2017). As our short-term results agreed with the increased individual aspen volume and spruce diameter increment was the highest in the thinning treatment, we can assume that hypothetical long-term results would follow Rice et al. (2001) as well as Comeau (2021) and offer a better environment for spruce survival and growth than the other treatments. Comeau (2021) also reported a reduced aspen yield but higher spruce yield at age 26 when aspens were thinned under 4000 trees ha^{-1} at age 5. Considering that our thinning treatment led to an aspen density of 3355 trees h-1 compared to the 6875 trees ha^{-1} found in the brushing treatment at age 4, we can expect larger spruces in the thinning treatment in the long term.

According to our results showing similar spruce growth between thinning and brushing treatments, one can assume that the short-term effect of less but larger aspens on spruce growth is the same as a large density of small aspens. However, early competition affects stand structure, favoring small spruce stems and a greater diversity in sizes (Thiffault et al., 2003). This – coupled with the knowledge that release and thinning treatments promote spruce survival and growth– seems to indicate that the earlier the application of the release, the greater the effect on spruce seedlings growth on the long term. However, timing (i.e., when the manual release is applied) may also influence aspen suckering and spruce responsiveness, as showed by Bell et al. (1999). According to their study, thinning is more effective on reducing aspen regeneration when done in June or July. Applying a well-adapted and effective release method as early as the seedling stage in a regenerating aspen-dominated stand is essential to promote black spruce growth and could potentially reduce rotation time for spruce – and aspen – harvest (Bjelanovic et al., 2021; Cyr and Thiffault, 2009).

Considering that aspen will inevitably return by root suckering into mechanically treated stands, it seems more advantageous to select release treatments that decrease its density and at the same time increase the quality of stems such as the thinning treatment tested here. Even if spruce growth did not significantly increase in the thinning compared to the brushing treatment in the short term, having a small proportion of large aspens in mixed stands was shown to enhance spruce growth (Man and Lieffers, 1999; Légaré et al., 2004; Légaré et al., 2005) and stand productivity (MacPherson et al., 2001) in the long term. We thus expect that spruce growth will continue to increase in the thinning treatment while it could start decreasing in the brushing treatment because of the high aspen densities that it generated. Although we only conducted our study in black spruce-aspen mixture, the thinning treatment should also be effective in other mixtures where aspen suckers aggressively take over a stand to the detriment of other naturally regenerated or planted species. Indeed, we speculate that the effects of the thinning treatment should be similar in most stands as it only considers aspen auto-ecology and not of the other species. Species such as white spruce (Kabzems et al., 2015), red pine (*Pinus resinosa* Ait.; Puettmann and Reich, 1995), balsam fir (Prévost and Gauthier, 2012) or ponderosa pine (*Pinus ponderosa*; Dey et al., 2019) for example could also benefit from a more effective thinning treatment during the early development stage of mixed stands with aspen.

5. Conclusion

Because of its regeneration strategy by root suckering, aspen should be treated differently than other seed-origin species when developing silvicultural approaches to control its density in young mixedwood stands. The brushing treatment, although easier to plan and apply, produced the highest amount of re-suckering and the smallest aspen stems, while the thinning from below treatment significantly reduced aspen density and increased individual stem volume. The root connections between aspen stems allow hormones to continue circulating and exert a certain level of apical dominance, reducing the amount of re-suckering after treatment. Keeping the largest aspen stems during the release treatment produced mixedwood stands with less aspen suckers of better quality (larger) and no negative impact on spruce survival and growth after four years.

CRediT authorship contribution statement

Darquié Léa: Data curation, Formal analysis, Investigation, Writing – original draft. **Raymond Patricia:** Writing – review & editing. **DesRochers Annie:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Acknowledgements

The research was funded by the Ministère des Forêts, de la Faune et des Parcs du Québec (now the Ministère des Ressources naturelles et des Forêts du Québec, project #142332153-2017-D), Norbord Inc. and the Natural Sciences and Engineering Research Council through a CRD grant (#RDCPJ522016-17) to A. DesRochers. We are grateful to the many summer interns for their help gathering field data.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2024.121703.

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