# Shelterwood cutting in a boreal mixedwood stand: 5-year effects of the final cut on development of aspen suckers and released conifers

by Marcel Prévost[1*] and Lise Charette[1]

**ABSTRACT**

We used the two-step shelterwood cutting to release conifer advance growth and limit the development of trembling aspen (*Populus tremuloïdes*) suckers in a stratified mixed aspen – conifer stand. This study presents the effects of the final cut, applied 12 years after the establishment cut, on the 5-year response of advance regeneration and aspen sucker development. Suckering was inversely proportional to the intensity of the establishment cut, with 19000, 14900 and 6800 stems/ha two years after the final cut, respectively, in the initial removal of 35%, 50% and 65% basal area. By year 5 however, the treatment effect on stem density was no longer significant due to high aspen mortality in the 35% and 50% cuts. At this time, the density of conifer stems taller than 100 cm was comparable to that of aspen stems in the 35% and 50% cuts, while conifers dominated the 65% cut. Standing mortality was higher for hardwood (22–28%) than for conifer (4–9%) advance growth, except in the uncut control (14% and 9%, respectively), while windthrow averaged 4% and 8%, respectively, in the three partial cuts without being related to treatment. Small merchantable conifer stems (diameter at breast height – DBH 9.1–15.0 cm) that were retained were most affected by windthrow, but overall losses were found acceptable considering DBH and height growth of the surviving stems. This study confirms that the two-step shelterwood cutting that secures conifer advance regeneration should be considered to limit hardwood conversion in the boreal mixedwood forest.

**Key words:** ecosystem-based forest management; hardwood expansion; stratified species mixture; conifer advance growth; small merchantable stems

**RÉSUMÉ**

Nous avons utilisé la coupe progressive en deux phases afin de dégager la régénération résineuse préétablie et de limiter le drageonnement du peuplier faux-tremble (*Populus tremuloïdes*) dans un peuplement mixte stratifié de trembles et de conifères. Dans le présent article, nous présentons les effets de la coupe finale, appliquée 12 ans après la coupe d'établissement, sur le développement de la régénération préétablie et des drageons de tremble après 5 ans. Le drageonnement s'est révélé inversement proportionnel à l'intensité de la coupe d'établissement, avec 19000, 14900 et 6800 tiges/ha 2 ans après la coupe finale, respectivement, dans les prélèvements initiaux de 35, 50 et 65 % de la surface terrière. Cependant, dès l'année 5, l'effet du traitement sur la densité des tiges n'était plus significatif, en raison du taux élevé de mortalité du tremble dans les coupes à 35 et à 50 %. La densité des tiges de conifères dépassant les 100 cm était alors comparable à celle des tiges de tremble dans les coupes à 35 et à 50 %, mais les conifères dominaient la coupe à 65 %. Le taux de mortalité sur pied était plus élevé pour les feuillus (22–28 %) que pour les conifères (4–9 %) préétablis, à l'exception du témoin non coupé (14 et 9 %, respectivement). Cependant, le chablis était respectivement de 4 et 8 %, en moyenne, dans les trois coupes partielles, et ce, sans lien au traitement. Les petites tiges marchandes de conifères (diamètre à hauteur de poitrine – DHP de 9,1–15,0 cm) qui avaient été retenues ont été les plus touchées par le chablis. Toutefois, les pertes globales ont été jugées acceptables, compte tenu de la croissance en DHP et en hauteur des tiges ayant survécu. Cette étude confirme que la coupe progressive en deux phases basée sur la régénération préétablie devrait être envisagée pour limiter l'enfeuillement en forêt mixte boréale.

**Mots-clés :** aménagement écosystémique; enfeuillement; mélange stratifié d'essences; régénération préétablie de conifères; petites tiges marchandes.

Marcel Prévost

Lise Charette

[1]Ministère des Forêts, de la Faune et des Parcs du Québec, Direction de la recherche forestière, 2700 rue Einstein, Québec, QC, Canada G1P 3W8 ; *Corresponding author: marcel.prevost@mffp.gouv.qc.ca

## Introduction

The problem of hardwood expansion, (or invasion), which is the replacement of conifer species by broadleaved species across the landscape, is well recognized in the Canadian boreal mixedwood forest (Greene *et al.* 2002; Grondin *et al.* 2003; Laquerre *et al.* 2009). Shade-intolerant hardwoods, such as trembling aspen (*Populus tremuloides* Michx.) and paper birch (*Betula papyrifera* Marsh.), can occupy cutover sites to the detriment of conifers such as balsam fir (*Abies balsamea* (L.) Mill.), white spruce (*Picea glauca* (Moench) Voss) and black spruce (*Picea mariana* (Mill.) B.S.P.). For instance, in stands that contain aspen even in small proportions, management difficulties result from its root suckering ability and rapid early growth that is supported by the parent-tree root system, which gives it a strong advantage over conifers (Greene *et al.* 1999). Maintaining a conifer component to preserve natural species diversity is suitable at the stand level. Moreover, mixedwood stands may have greater productivity (Man and Lieffers 1999; Edgar and Burk 2001; MacPherson *et al.* 2001; Kabzems *et al.* 2007), increased resilience against insects and diseases (Su *et al.* 1996; Jactel *et al.* 2005) and a greater diversity of forest products (MacDonald 1995). Therefore, a sound silvicultural approach for mature aspen – conifer mixtures should aim to modulate the establishment of the new cohort by limiting aspen development and promoting conifer species. Some silvicultural experiments have already shown that partial canopy removal can limit aspen development and accelerate the establishment and growth of shade-tolerant species in aspen – conifer mixtures (e.g., Prévost and Pothier 2003; Man *et al.* 2008; Groot *et al.* 2009).

The two-step shelterwood system can be used to create conditions that favour the establishment of a new cohort under a partial overstory (Matthews 1989; Nyland 2002). In this system, the establishment cut aims most often to promote natural seeding or can alternatively aim to release an advance regeneration stratum (Smith *et al.* 1997). The final cut (or removal cut) is usually applied 5–15 years later to remove the overstory and completely release the advance regeneration. The merit of the establishment cut mainly relies on establishing a new stand of desired species before the final cut, but growth and mortality of the residual cover must also be considered (e.g., Prévost *et al.* 2010; Urgenson *et al.* 2013). Furthermore, the advance regeneration response to the final cut must be evaluated for an overall assessment of the shelterwood system. While the establishment cut provides ideal shelter for the acclimation of advance regeneration and the establishment of new seedlings, the removal cut is often necessary to optimize growth (Smith *et al.* 1997).

We experimented with this system to accelerate natural succession in a stratified trembling aspen – conifer stand containing a dense advance conifer regeneration in Quebec, Canada. The establishment cut was carried out in 2001 and was successful in securing conifer regeneration and limiting aspen sucker development (Prévost and DeBlois 2014). As expected, light interception by the residual cover and the preserved advance growth was harmful to shade-intolerant aspen during the establishment phase. In addition to the silvicultural function of casting shade on emerging aspen suckers, the growth response of residual stems was another positive outcome (Prévost and Dumais 2014). The establishment cut permitted the harvesting of imminent aspen mortality and favoured conifer survival and recruitment to merchantable size (diameter at breast height – DBH ≥9.1 cm). In addition, the retention of small merchantable conifer stems (9.1–15.0 cm DBH) contributed substantially to basal area (BA) gains during the establishment phase.

The final cut was applied in the fall of 2013, 12 years after the establishment cut. At this time, the conifer advance regeneration was around 8-m in height, with some individuals reaching 10-m (Prévost and DeBlois 2014), and a complete release appeared to be timely. It was anticipated that these conifer saplings would respond to overstory removal and limit aspen development in the new stand. This paper presents the effects during the first five years after the final cut on the development of the second cohort of aspen suckers in relation to the response of conifer advance growth. We hypothesized that: (*i*) aspen suckering will be inversely proportional to the intensity of the first cut; (*ii*) the shade cast by the retained advance growth will limit aspen sucker development; and (*iii*) balsam fir will show a better growth response than spruce (*P. glauca* or *P. mariana*) to the final cut (e.g., Prévost *et al.* 2016).

## Material and methods

### Study site and experimental design

The stand under study was located in the balsam fir – yellow birch bioclimatic domain (region 4d) in the High Hills of Charlevoix and Saguenay (Saucier *et al.* 2009), approximately 160 km northeast of Québec City, Quebec, Canada (47° 55' N, 70° 03' W). The initial merchantable BA of 26 $m^2$/ha was composed of 53% trembling aspen, 28% paper birch, 11% balsam fir, 3% white spruce, 2% black spruce and 2% red maple (*Acer rubrum* L.). Mature aspen of 80–90 years-of-age dominated the main canopy whereas conifers of 40–50 years old generally occupied the intermediate layer. The density of advance conifer regeneration ≥1.3 m in height and <9.1 cm DBH was 1400 stems/ha and consisted primarily of balsam fir.

The experiment consisted of four complete randomized blocks, each one containing five treatments on 50 m × 50 m experimental units: an uncut control (0%), three partial cutting intensities (uniform removal of 35%, 50% and 65% of BA), and a careful logging around advance growth removing 100% of merchantable hardwoods and conifers with DBH ≥15.1 cm. For the conifer fraction (16% of BA), this 100% cut roughly corresponds to a CPPTM (Coupe avec Protection des Petites Tiges Marchandes) in Quebec (Ruel *et al.* 2013) and to a HARP (Harvesting with Regeneration Protection) in Ontario (Groot *et al.* 2005). All small merchantable conifers (9.1–15.0 cm in DBH) were also retained in the three partial cuts, while the stems to be removed were selected in the following order: 1) aspen (which was almost mature); 2) birch or maple (the less vigorous of the two); 3) mature fir to avoid losses by windthrow; and 4) spruce (mature or declining only). This establishment cut was done in late summer 2001 using a chainsaw for felling. Trees were debranched and slashed on site, to be transported to the landings with a F4 Dion track forwarder from 50-m equidistant trails. The final (or removal) cut was carried out in the three partial cuts in the fall of 2013, 12 years after the first cut, protecting small merchantable conifers and using the same logging procedure. The stand and the experimental design are described in detail in Prévost and DeBlois (2014).

### Vegetation monitoring

Each experimental unit contained a 20 m × 20 m central plot (400 m$^2$) and sixteen 2 m × 2 m quadrats (4 m$^2$) for vegetation monitoring. After the first cut in 2001, all residual stems of commercial species ≥1.3 m in height were numbered in the 400-m$^2$ plot. Species, DBH, total height, crown height and four crown radii (N, E, S, and W) were then recorded. These stems were surveyed at years 1, 2, 3, 5, 7 and 10 post-harvest during the establishment phase (Prévost and DeBlois 2014); those that survived to the final cut in 2013 were measured in 2014, 2015, 2016 and 2018 (years 1, 2, 3 and 5 post-removal). Species, DBH, total height and crown height were recorded. Meanwhile, the sixteen 4-m$^2$ quadrats were used to do post-removal regeneration surveys. Commercial species (balsam fir, black spruce, white spruce, trembling aspen, paper birch, red maple) and the principal non-commercial species, beaked hazel (*Corylus cornuta* Marsh.), mountain maple (*Acer spicatum* Lam.), striped maple (*Acer pensylvanicum* L.), mountain ash (*Sorbus americana* Marsh.) and willow (*Salix* spp.) were tallied by height class (1–5, 6–30, 31–60, 61–100, 101–200, 201–300, >300 cm up to 9.0 cm DBH).

### Statistical analyses

Regeneration density measured in 2011, two years before the final cut (2013), and at years 1, 2, 3 and 5 post-cut (2014–2016 and 2018) was analyzed separately by species for balsam fir, spruce (pooled white and black spruces), trembling aspen, paper birch, red maple, mountain maple, striped maple and beaked hazel. Linear mixed models with repeated measurements were used with a variance-covariance matrix to take into account the correlation between measurements that were performed on the same experimental units. The choice of this matrix was made using goodness-of-fit and parsimony criteria and took into account the unequal time intervals. Intensity of the establishment cut, measurement year and their interaction were introduced into the model as fixed-effect factors, whereas block was considered as a random effect. For significant interactions between main factors, levels of one factor were compared at a fixed level of the other factor. All regeneration data were transformed ($\sqrt{x}$) to improve homogeneity of variance. For commercial species, the density of saplings ≥1.3 m in height immediately after the establishment cut was tested as a covariate but was rejected in all cases.

The effects of cutting intensity and species (trembling aspen and conifers) on regeneration density among height classes (A: 6–100 cm, B: 101–200 cm, C: 201–300 cm and D: >300 cm) were evaluated 1, 2, 3 and 5 years after the final cut using a classic four-way analysis of variance with establishment cut intensity, species and height class as fixed effects and block as a random effect. For this analysis, we conducted tests of simple effects (Winer 1971) using the triple interaction to make comparisons of interest within a third factor. We opted for this approach whether the triple interaction was significant (years 1, 2 and 3) or not (year 5), considering all main effects were significant (Iacobucci 2001). The cubic root transformation was used and values are presented in their original scale.

Height and DBH of pre-established conifers were analyzed with the same classic four-way analysis, 0 and five years after the final cut, except that height class was replaced by initial DBH class (saplings: DBH <9.1 cm, merchantable: DBH ≥9.1 cm), based on the last measurement conducted in 2011, two years before the cut. We considered that stems with a DBH ≥8.0 cm in 2011 would have recruited to merchantable size (DBH ≥9.1 cm) in two years (2013). For both height and DBH, stem height measured immediately after the establishment cut was used as a covariate to account for possible differences prior to the treatment. This covariate was adjusted beforehand to take into account the different ranges of values in the two DBH classes (Milliken and Johnson 2002).

Data for mortality of pre-established stems were analyzed separately for standing mortality and windthrow, and for years 0 and 5 after the final cut, comparing two species groups (hardwoods = paper birch, red and sugar maples; conifers = balsam fir, black and white spruces). We used a three-way analysis of variance with establishment cut intensity and species group as fixed effects and block as a random effect. This analysis included all stems that were established prior to the first cut and still alive in 2011, two years before the final cut. The rate of mortality was expressed in % (100 × number of dead stems at year 0 or 5 / number of live stems at year –2).

All analyses were performed on experimental unit values with the MIXED procedure of SAS (v. 9.4, SAS Institute Inc., Cary, North Carolina) for regeneration density, height and DBH of conifer advance regeneration, and with the GLIMMIX procedure for mortality data, the latter using the logit-link function and a binomial distribution. The Kenward-Roger method was used for approximating the denominator degrees of freedom. The statistical significance was based on $p < 0.05$ for all analyses and tests. In all cases where a factor or an interaction was significant, the Westfall method was used to assess differences (Westfall 1997). The 0.05 error rate was applied within each fixed level of the main factors, as a separate-family approach (Westfall et al. 2011). Homogeneity of variances and normality were assessed on residuals using standard graphical methods, along with the Brown and Forsythe test (homogeneity) and the Shapiro-Wilk test (normality).

## Results

### Regeneration dynamics

Establishment cut intensity and time relative to the final cut interacted for the density of trembling aspen, paper birch and beaked hazel >5 cm in height (CI × T, $p \le 0.005$, Table 1). Aspen density was not different among cutting intensities two years before the final cut (310–4650 stems/ha, Fig. 1). However, an increase in density was observed one year after the final cut in the 35%, 50% and 65% cuts (all $p < 0.001$, results of multiple comparison tests not presented in the table). As a result, at years 1, 2 and 3 post-cut, aspen density was higher in the 35% (respectively 18700, 19000 and 15200 stems/ha) and 50% cuts (12400, 14900 and 12600) than in both the 100% cut (2900, 2400 and 2100) and control (3900, 800 and 1200, $p \le 0.037$). In addition, the density was higher in the 35% compared to the 65% cut at years 2 and 3 (respectively 6800 and 4800 stems/ha, $p \le 0.052$). At year 5, the treatment effect was no longer significant, since aspen density strongly decreased between years 3 and 5 in the 35% and 50% cuts ($p \le 0.042$). For paper birch, the CI × T interaction was related to density changes in the 35% cut, with an increase at year 1 post-cut (from 200 to 9900 stems/ha, not shown) and a decrease between years 3 and 5 (from 1700 to 300, $p \le 0.044$). For

**Table 1. Analysis of variance and associated probabilities (*P* > F) for regeneration density (stems/ha, >5 cm in height) related to establishment cut intensity (0%, 35%, 50%, 65% and 100% basal area removal) and time relative to the final cut (two years before and 1, 2, 3 and 5 years after)**

| Source of variation | *df* | Balsam fir | Spruce | Trembling aspen | Paper birch | Red maple | Mountain maple | Striped maple | Beaked hazel |
|---|---|---|---|---|---|---|---|---|---|
| Cutting intensity (CI) | 4 | 0.241 | 0.490 | **<0.001** | 0.119 | 0.230 | 0.531 | 0.286 | **0.012** |
| Time (T) | 4 | **<0.001** | **0.005** | **<0.001** | **0.002** | **<0.001** | **<0.001** | **0.002** | **0.001** |
| CI × T | 16 | 0.422 | 0.800 | **<0.001** | **0.005** | 0.265 | 0.197 | 0.342 | **0.001** |

**Note**: *df* = degrees of freedom of the numerator. Denominator degrees of freedom according to Kenward-Roger: CI = 11.5 to 18.7, T = 12.0 to 59.7, CI × T = 17.9 to 59.4. Variance-covariance matrix: spatial power (balsam fir, spruce, trembling aspen, red maple, mountain maple), variance components (beaked hazel) and unstructured (paper birch, striped maple). Data were transformed for all species (√x). Significant *p*-values are presented in **boldface type**.

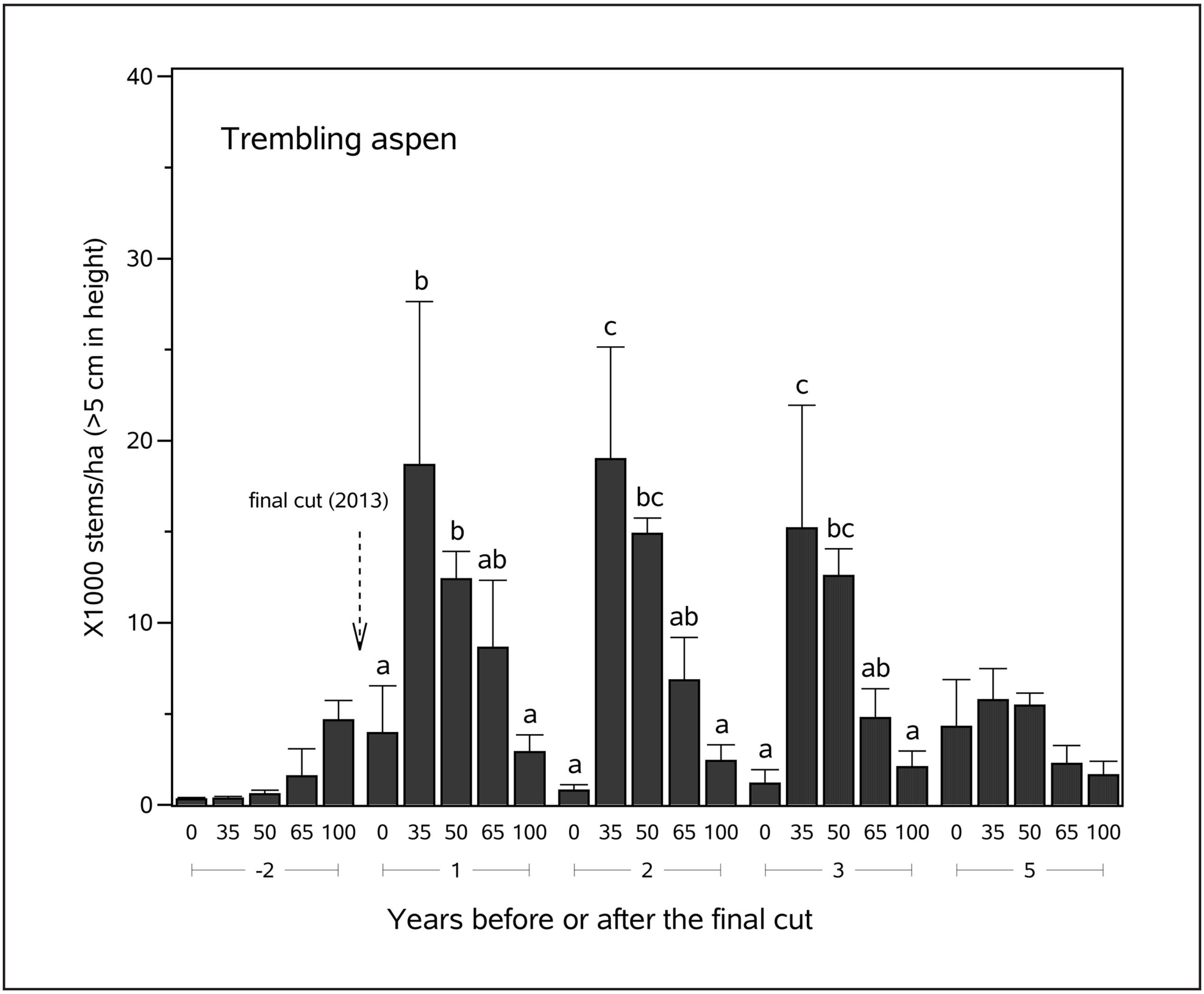


**Fig. 1.** Density of aspen suckers (stems/ha, >5 cm in height) related to establishment cut intensity (0%, 35%, 50%, 65% and 100% basal area removal), two years before and 1, 2, 3 and 5 years after the final cut of 2013. For each year, means associated with a different letter are statistically different (*p* < 0.05, simulation-based adjusted *p*-values). Error bars represent the standard error of treatment means (n = 4).

beaked hazel, the density was higher in the 100% cut (17700 stems/ha, not shown) than in the 65% cut (6000) before the final cut ($p = 0.019$) and at year 1 post-cut (15800 vs. 5800, $p = 0.052$). In addition, beaked hazel density was higher in the 35% cut (15600 stems/ha) than in both the 65% cut and the control at year 5 (respectively 5100 and 6000, $p \leq 0.027$).

A time effect was found for density of balsam fir, spruce, red maple, mountain maple and striped maple taller than 5 cm ($p \leq 0.005$, Table 1, Fig. 2). The overall balsam fir density tended to increase between years 2 and 3 post-cut (from 20300 to 25000 stems/ha, $p = 0.055$) and significantly decreased between years 3 and 5 (to 17300, $p < 0.001$). At a smaller scale, spruce density decreased from 600 to 400 stems/ha between years 3 and 5 ($p = 0.047$). For both mountain maple and striped maple, the density gradually decreased between years 1 (respectively 12000 and 3100 stems/ha), 2 (9400 and 1700) and 3 (5400 and 700, $p \leq 0.018$) post-cut. A decrease from 14700 to 7900 stems/ha was also observed in years 2–3 for red maple ($p < 0.001$). An increase was finally detected in years 3–5 for red ($p = 0.065$) and striped maples ($p = 0.002$).

### Height classes of aspen vs. conifers

Establishment cut intensity, species and height class all interacted for stem density (CI × Sp × HC, $p \leq 0.003$, Table 2) for the first three years after the final cut. Conifer density was generally higher than trembling aspen density (Table 3), in the control (years 1–3: all classes; year 5: A, D; $p \leq 0.061$), in the 65% (year 1: all classes; years 2 and 3: A, D; year 5: A, C, D; $p \leq 0.049$) and 100% cuts (all years: A, B, C; $p \leq 0.054$) (200–23 000 vs. 0–7600 stems/ha). During the study, conifer density was also higher in some classes of the 35% (year 1: C,

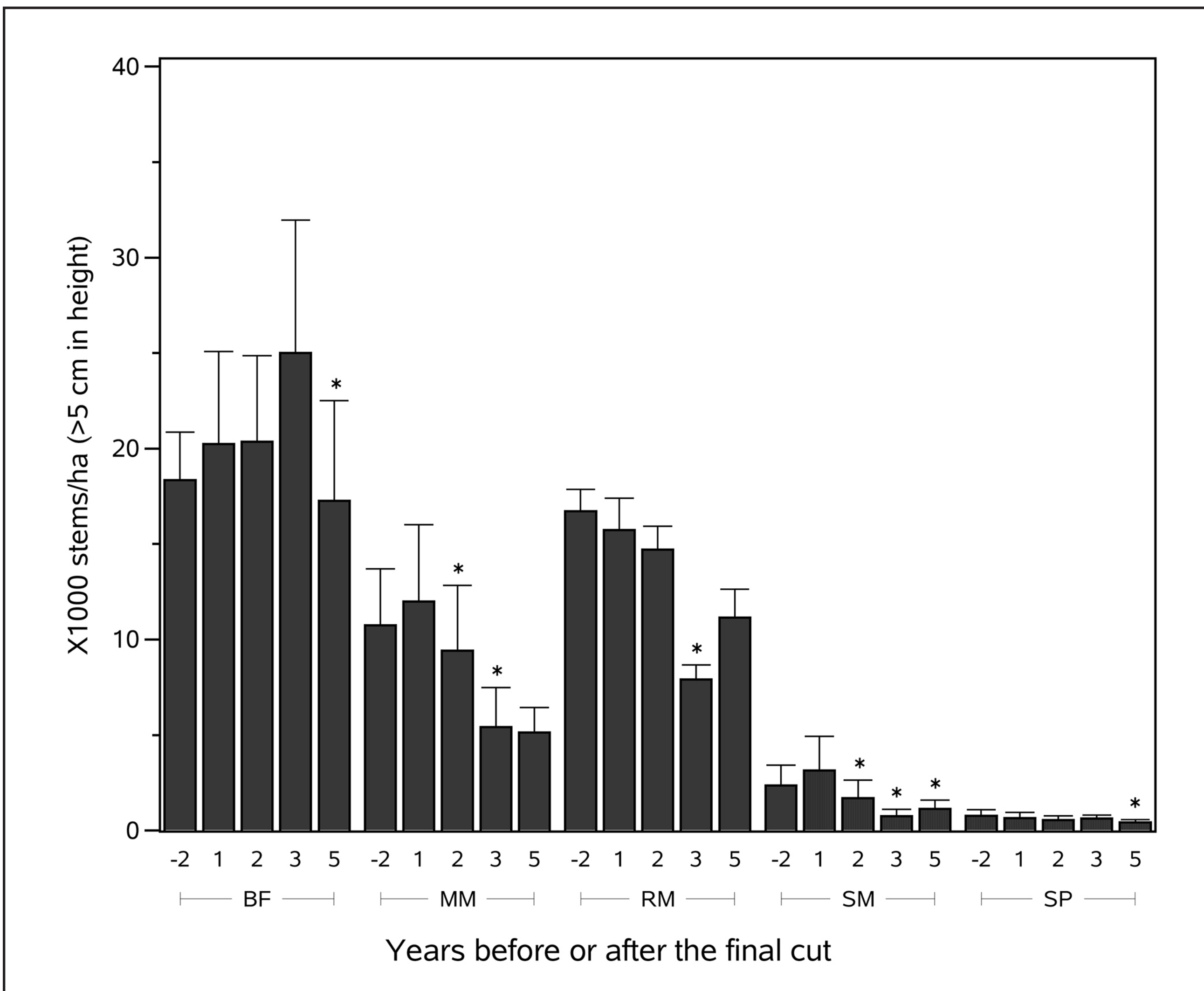


**Fig. 2.** Overall density of balsam fir (BF), mountain maple (MM), red maple (RM), striped maple (SM) and spruce (SP) regeneration (stems/ha, >5 cm in height) two years before and 1, 2, 3 and 5 years after the final cut of 2013. For each species, a mean associated with an * indicates a significant time effect with the preceding measurement year ($p < 0.05$, simulation-based adjusted $p$-values). Error bars represent the standard error of treatment means (n = 4).

D; year 2: A, D; years 3 and 5: A; $p \leq 0.065$) and 50% cuts (year 1: C, D; year 2: D; years 3 and 5: A; $p \leq 0.017$) (500–36 500 vs. 0–7600 stems/ha). At years 2 and 3, however, aspen density was higher than conifer density in class B of both the 35% and 50% cuts (5700–9000 vs. 1100–1600 stems/ha, $p \leq 0.015$). A similar tendency was found in class C of the 35% cut at year 3 (2500 vs. 600 stems/ha, $p = 0.066$). At year 5, classes B, C and D of the 35% and 50% cuts contained a comparable density of aspen (600–2100 stems/ha) and conifers (500–1500).

**Table 2. Analysis of variance and associated probabilities (*P* > F) for regeneration density (stems/ha) related to establishment cut intensity (0%, 35%, 50%, 65% and 100% basal area removal), species (trembling aspen, conifers) and height class (A = 6–100 cm, B = 101–200 cm, C = 201–300 cm, D = >300 cm) 1, 2, 3 and 5 years after the final cut**

| Source of variation | *df* | Year 1 | Year 2 | Year 3 | Year 5 |
|---|---|---|---|---|---|
| Cutting intensity (CI) | 4 | 0.063 | **<0.001** | **<0.001** | **0.002** |
| Species (Sp) | 1 | **<0.001** | **<0.001** | **<0.001** | **<0.001** |
| CI × Sp | 4 | **0.006** | **<0.001** | **<0.001** | **<0.001** |
| Height class (HC) | 3 | **<0.001** | **<0.001** | **<0.001** | **<0.001** |
| CI × HC | 12 | **<0.001** | **<0.001** | **<0.001** | **<0.001** |
| Sp × HC | 3 | 0.362 | **<0.001** | **<0.001** | **<0.001** |
| CI × Sp × HC | 12 | **<0.001** | **0.002** | **0.003** | 0.067 |

**Note:** *df* = degrees of freedom of the numerator. Denominator degrees of freedom according to Kenward-Roger: CI = 12 to 120, all other factors and interactions = 105 to 120. Analyses were done on the cubic root of regeneration density. Significant *p*-values are presented in **boldface type**.

### Advance growth mortality

Immediately after the final cut (year 0), the rate of standing mortality was globally higher for hardwood (11%) than conifer (2%) advance growth (Sp, $p < 0.001$, Table 4). At year 5 post-cut, this was the case for all treatments (22–28% vs. 4–9%) except for the control (14% vs. 9%) (CI × Sp, $p = 0.006$). The rate of windthrow was not related to treatment, species group or year, with an average of 4% and 8%, respectively for hardwoods and conifers, in the three partial cuts at year 5.

### Height and DBH of conifers related to DBH class

At both measurement years, the cutting intensity and DBH class interacted for DBH and total height of pre-established conifer stems, balsam fir and spruce combined (CI × DBHC, all $p < 0.001$, Table 5, Fig. 3). In the sapling class, mean DBH was similar among treatments at years 0 (5.3–6.3 cm) and 5 (5.8–7.6 cm). In the merchantable class, the DBH was highest in the control, intermediate in the 100% cut and lowest in the partial cuts (respectively 14.2, 12.4 and 11.0–11.6 cm, $p \leq 0.049$) at year 0, and higher in the control than in the three partial cuts (15.3 vs. 13.3–14.0 cm, $p \leq 0.016$) at year 5. The height of conifer saplings was not related to treatment (446–534 cm) at year 0 but was higher in the 100% cut (683 cm) compared to the 0%, 35% and 65% cuts (495–542 cm, $p \leq 0.027$) at year 5. The height of merchantable conifers was higher in the control than in all other treatments for both years

**Table 3. Density (stems/ha) of trembling aspen and conifer (97% balsam fir) regeneration by height class (A = 6–100 cm, B = 101–200 cm, C = 201–300 cm, D = >300 cm) related to establishment cut intensity (% basal area removal) at years 1, 2, 3 and 5 after the final cut**

| | 0% | | 35% | | 50% | | 65% | | 100% | |
|---|---|---|---|---|---|---|---|---|---|---|
| Height Class | Aspen | Conifers | Aspen | Conifers | Aspen | Conifers | Aspen | Conifers | Aspen | Conifers |
| *Year 1* | | | | | | | | | | |
| A | **3945** | **17 031** | 17 187 | 27 539 | 11 992 | 10 078 | **7578** | **16 094** | **0** | **12 070** |
| B | **0** | **586** | 1445 | 1328 | 352 | 1172 | **156** | **2305** | **78** | **4531** |
| C | 0 | 195* | 0 | 469* | **0** | **508** | **117** | **937** | **195** | **1641** |
| D | **0** | **781** | **39** | **1172** | **39** | **742** | **781** | **1875** | 2617 | 3359 |
| *Year 2* | | | | | | | | | | |
| A | **781** | **12 969** | **7578** | **31 055** | 8008 | 13 555 | **3750** | **14 570** | **39** | **11 016** |
| B | **0** | **508** | **8984** | **1562** | **5898** | **1211** | 2305 | 2383 | **78** | **4766** |
| C | 0 | 234* | 2148 | 469 | 937 | 469 | 117 | 898 | 195 | 1172* |
| D | **0** | **703** | 273 | 1289* | **39** | **742** | **664** | **1758** | 2109 | 3125 |
| *Year 3* | | | | | | | | | | |
| A | **1172** | **18 906** | **5117** | **36 523** | **5625** | **16 953** | **1719** | **23 008** | **0** | **11 406** |
| B | **0** | **547** | **6875** | **1094** | **5742** | **1289** | 2070 | 2500 | **0** | **4687** |
| C | 0 | 195* | 2500 | 586* | 937 | 469 | 273 | 1016 | **39** | **1523** |
| D | **0** | **703** | 703 | 1250 | 273 | 625 | **703** | **1797** | 2031 | 3047 |
| *Year 5* | | | | | | | | | | |
| A | **4023** | **13 242** | **1563** | **26 276** | **1883** | **9385** | **940** | **11 930** | **78** | **7187** |
| B | 273 | 664 | 1980 | 1238 | 2138 | 1506 | 643 | 2081 | **0** | **3984** |
| C | 0 | 156 | 644 | 508 | 606 | 460 | **195** | **1021** | **0** | **1172** |
| D | **0** | **703** | 1558 | 1269 | 829 | 782 | **469** | **1961** | 1562 | 2891 |

**Note**: Means presented in **boldface type** are significantly different ($p < 0.05$) between aspen and conifers for a given height class within a cutting intensity.
*Indicates that a clear tendency for a difference was observed ($p \leq 0.066$)

**Table 4. (A) Analysis of variance (ANOVA) related to establishment cut intensity (0%, 35%, 50%, 65% and 100% basal area removal) and species group (hardwoods [H] or conifers [C]) immediately after (year 0) and 5 years after the final cut, and (B) Rate of standing mortality and windthrow**

| (A) ANOVA *p* values | | Standing mortality | | Windthrow | |
|---|---|---|---|---|---|
| **Source of variation** | ***df*** | **Year 0** | **Year 5** | **Year 0** | **Year 5** |
| Cutting intensity (CI) | 4 | 0.318 | 0.941 | 0.394 | 0.387 |
| Species group (Sp) | 1 | **<0.001** | **<0.001** | 0.824 | 0.837 |
| CI × Sp | 4 | 0.251 | **0.006** | 0.629 | 0.850 |

| (B) Rate of mortality | Standing mortality (%) | | | | Windthrow (%) | | | |
|---|---|---|---|---|---|---|---|---|
| **Cutting intensity** | **Year 0** | | **Year 5** | | **Year 0** | | **Year 5** | |
| | **H** | **C** | **H** | **C** | **H** | **C** | **H** | **C** |
| 0% | 5 | 2 | 14 | 9 | 1 | 1 | 1 | 1 |
| 35% | 9 | 5 | 22 | 8 | 4 | 4 | 4 | 5 |
| 50% | 18 | 3 | 28 | 9 | 7 | 12 | 7 | 12 |
| 65% | 15 | 1 | 26 | 4 | 1 | 5 | 1 | 7 |
| 100% | 8 | 1 | 25 | 9 | 1 | 0 | 1 | 0 |

**Note:** *df* = degrees of freedom of the numerator. Denominator degrees of freedom according to Kenward-Roger: CI = 11.8 to 14.9, Sp and CI × Sp = 30.0. Significant *p*-values are presented in **boldface type**. Species groups: hardwoods = paper birch, red and sugar maples; conifers = balsam fir, black and white spruces

**Table 5. Analysis of variance and associated probabilities (*P* > F) for diameter at breast height (DBH) and total height of preestablished conifers related to establishment cut intensity (0%, 35%, 50%, 65%, and 100% basal area removal), species (balsam fir or spruce) and DBH class (saplings [DBH <9.1 cm] or small merchantable stems [DBH = 9.1 to 15.0 cm]) immediately following the final cut (year 0) and 5 years after treatment**

| | | DBH | | Total height | |
|---|---|---|---|---|---|
| **Source of variation** | ***df*** | **Year 0** | **Year 5** | **Year 0** | **Year 5** |
| Cutting intensity (CI) | 4 | **<0.001** | 0.310 | **<0.001** | **<0.001** |
| Species (Sp) | 1 | **0.005** | **0.014** | 0.166 | 0.292 |
| CI × Sp | 4 | 0.467 | 0.632 | 0.167 | 0.276 |
| DBH class (DBHC) | 1 | **<0.001** | **<0.001** | **<0.001** | **<0.001** |
| CI × DBHC | 4 | **<0.001** | **<0.001** | **<0.001** | **<0.001** |
| Sp × DBHC | 1 | 0.809 | 0.890 | 0.076 | 0.617 |
| CI × Sp × DBHC | 4 | 0.791 | 0.727 | 0.854 | 0.790 |
| Covariate | 1 | **<0.001** | **<0.001** | **<0.001** | **<0.001** |

**Note**: *df* = degrees of freedom of the numerator. Denominator degrees of freedom according to Kenward-Roger: CI = 10.7 to 11.7, Sp, CI × Sp, DBHC, CI × DBHC, Sp × DBHC and CI × Sp × DBHC = 40.3 to 41.9, and covariate = 53.0 to 55.7. Significant *p*-values are presented in **boldface type**. Spruce includes black and white spruces.

0 (1094 vs. 812–886 cm) and 5 (1213 vs. 929–1050 cm, all $p < 0.001$), and was higher in the 100% cut (1050 cm) than in the 35% and 65% cuts (respectively 962 and 929 cm, $p \leq 0.037$) at year 5. Finally, for all treatments and DBH classes combined, spruce DBH was slightly higher than balsam fir DBH at years 0 (Lsmean = 9.0 vs. 8.6 cm) and 5 (10.7 vs. 10.2 cm) (Sp, $p \leq 0.014$, Table 5, Fig. 3).

## Discussion

The density of aspen regeneration was relatively low 10 years after the establishment cut (year –2) and, as expected, the final cut triggered aspen suckering (Fig. 1). This effect was proportional to the number of aspen stems that were initially left standing and harvested 12 years later, i.e., inversely proportional to the intensity of the establishment cut, which confirms our first hypothesis. As a whole, the first-year density of suckers was lower than the density of 15000–29000 stems/ha observed after the first cut (Prévost and DeBlois 2014). Our initial BA removal of 35% resulted in comparable suckering following the first (15400 stems/ha) and final cuts (18700). However, the priority harvesting of aspen accelerated suckering in higher BA removals, with two and three times more suckers after the first cut than after the final cut in the 50% (23400 vs. 12400 stems/ha) and 65% cuts (29200 vs. 8600). Therefore, the first cut removed much of the aspen suckering potential in these two-step scenarios. In this context, the two-step shelterwood cutting approach provides an opportunity to influence the distribution of this vegetative reproduction between the establishment cut and the final cut, contrary to the clearcut which affects all aspen root systems at the same time.

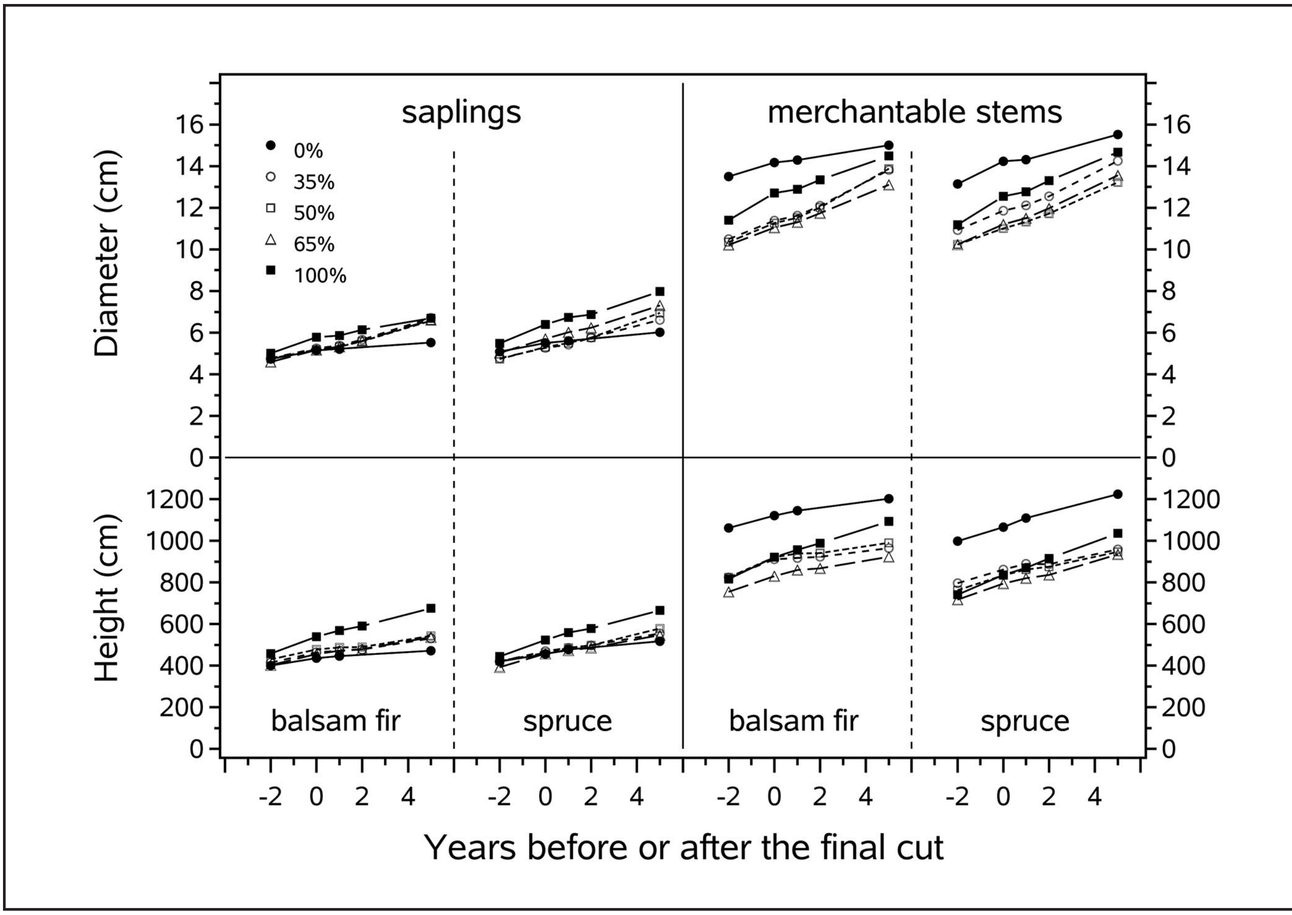


**Fig. 3.** DBH and total height related to species and establishment cut intensity (0%, 35%, 50%, 65% and 100% basal area removal) two years before and 1, 2, 3 and 5 years after the final cut of 2013.

The analysis of stem density by height classes showed that conifers outnumbered aspen in all classes of the control and up to 300 cm in height in the 100% cut (Table 3). In the two-step scenarios, the final cut impacted regeneration dynamics in the 35% and 50% initial BA removals, while the effect was less pronounced in the 65% BA removal. From year 2, aspen outnumbered conifers in the 100–200 cm class of the 35% and 50% cuts, and in the 200–300 cm class of the 35% cut. As with the establishment cut (Prévost and DeBlois 2014), the driving factor was the hormonal imbalance in the root system (Schier 1973). However, this effect was transient, since the densities of aspen and conifers taller than 100 cm were similar by year 5, which indicates limited aspen recruitment in taller classes. At this time, conifers dominated the three taller classes in the 65% cut, unlike in the 35% and 50% cuts. Therefore, the first cut removing 65% of BA provided the best control of aspen five years after final removal. Future recruitment of aspen in taller classes of the two lowest BA removals will indicate the best scenario in relation to species composition of the new cohort. In comparison, aspen made up about one third of the taller stems in the 100% cut applied 17 years earlier (Table 3). The use of the CPPTM approach in the presence of dense conifer regeneration permitted the maintenance of a good proportion of conifers in the new cohort, which should persist in the long term.

Aspen is very intolerant to shade and requires full sunlight to thrive (Perala 1990). Survival of suckers was particularly restricted between years 3 and 5 after the final overstory removal, with mortality rates of 50–60% in two years (Fig. 1). Although self-thinning may have contributed, this high mortality confirms our second hypothesis of a detrimental shading effect from the tall conifer advance growth. Retention of small merchantable conifers certainly contributed to limiting light availability for taller aspen stems, especially because of their sustained height growth following the final cut (Fig. 3), which supports this practice as a basic strategy to limit hardwood expansion.

After five years, all treatments contained comparable densities of aspen, including the control, where significant suckering occurred in years 3–5 (Fig. 1). Such suckering was described by Schier and Smith (1979) as a normal and regular phenomenon in uncut aspen clones. In the present study, most residual aspens were near- to over-mature trees (Pothier *et al.* 2004). Field observations revealed that both standing mortality and windthrow of a few aspen stems caused the suckering observed in the control. This confirms that the first cut was successful in harvesting the dying aspens (Prévost and Dumais 2014), as observed in a comparable stand of the Lower Appalachians (Prévost *et al.* 2010).

The use of partial cutting in this study to secure the conifer advance growth raises the issue of windthrow hazards (e.g., MacDonald and Thompson 2003; Ruel *et al.* 2003). For instance, dispersal of residual trees, shallow-rooting and topographical exposure may lead to significant wind damage (Ruel *et al.* 2000; Lavoie *et al.* 2012; Mitchell 2013). However, in the species mixture under study, almost all mortality during the establishment phase occurred gradually on standing trees, particularly through aspen senescence in the 35% cut and paper birch decadence in the 65% cut (Prévost and Dumais 2014). Standing mortality was also gradual for both species groups after the final cut (Table 4) and evenly distributed across the site. This form of mortality was responsible for 90% of hardwood losses, with red maple being the most affected pre-established species, particularly in years 2–3 (Fig. 2). Sudden exposure to open conditions may have imposed physiological stress and induced mortality (Bladon *et al.* 2006; Busby *et al.* 2006; Lavoie *et al.* 2012). It is worth mentioning that red maple was of low quality and vigour, being at its northern limit close to the $48^{th}$ parallel where the experiment was conducted. As reported following the establishment phase (Prévost and Dumais 2014), borderline ecological conditions may have limited the ability of red maple saplings to respond to the final release. Data also suggest that stressful open conditions may have contributed to the low survival of paper birch that established rapidly after the final cut, while beaked hazel captured a part of the growing space through vegetative reproduction (Tappeiner 1971).

Unlike hardwoods, conifers were equally affected by standing mortality and windthrow in the three partial cutting intensities (Table 4). While standing mortality was gradual, most windthrow occurred early after the final cut between late fall 2013 and June 2014 and in two groups of contiguous experimental units. As these units were located on the upper slope of forwarding trails connected to the two landings, we believe that wind was funneled from adjacent open areas (see Ruel *et al.* 2003). Therefore, the topographical exposure and trail network interacted for wind damage in this experiment which was conducted in the High Hills of Charlevoix. More precisely, the timing of extreme winds relative to the final harvest was probably the driving factor in windthrow (see Mitchell 2013).

Our finding that windthrow may affect a part of the released advance growth after the shelterwood system final cut merits further consideration. As observed in other studies (e.g., Thorpe *et al.* 2008; MacIsaac and Krygier 2009), most windthrow occurred in the first years after the final cut, and after five years the critical period should be over. According to Riopel *et al.* (2010), potential losses are a major constraint to widespread application of harvesting with protection of small merchantable stems in coniferous forests. These authors suggested considering the low merchantable value of the lost stems (DBH ≤ 15.0 cm) and the potential long-term gains of surviving stems to assess acceptability of these losses. Although small merchantable conifers were the most affected in this study, the global rates under 10% appear to be acceptable (Table 4), considering the DBH and height growth gains observed for the live stems (Fig. 3). We conclude that retention of small merchantable conifers will certainly contribute to shorten the rotation period in this stand.

Balsam fir is known to have a greater ability than spruce to respond to release (Davis 1989). However, patterns of height and DBH of conifers after the final cut did not confirm our third hypothesis concerning a stronger growth response in balsam fir compared to spruce (Fig. 3). Conversely, there is a clear indication that spruce was able to compete with balsam fir although the significant DBH advantage of 5% for spruce was marginal in biological terms. This is an interesting result because maintaining the spruce component of the boreal mixedwood stands is an important issue. Furthermore, the analysis of conifer height for two DBH classes confirms the ability of small merchantable stems to capture the growing space and maintain a dominant position following the final cut (Pothier *et al.* 1995).

### Management implications

Within the wider framework of this study, it was previously shown that the establishment cut of a two-step shelterwood system can limit aspen regeneration in an aspen-dominated mixedwood stand presenting a dense conifer regeneration. However, to evaluate the overall merit of the two-step shelterwood system based on advance growth, it was necessary to assess the effects of the final cut. Although a 5-year period may be short to draw solid conclusions, relevant guidelines can be established. The establishment cut was successful in limiting aspen development up to 65% BA removal. Results indicate that, despite some paper birch decadence during the establishment phase, this high intensity cut allowed removal of most of the suckering potential prior to the final cut, while increasing conifer growth, and in turn, led to the best aspen control in the first years after the final cut. Therefore, removing up to two-thirds BA and as much aspen as possible in the establishment cut would be recommended to permit a greater proportion of conifers to be maintained in the new stand. Long-term observations will indicate how the harvesting intensity in each step may affect stand dynamics, composition and structural development. As for the 100% cut, conifers made up two thirds of stem density in the taller class after 17 years, and this proportion should persist in the future. This supports a previous conclusion (Prévost and DeBlois 2014) that small patch-clearcuts would alternatively permit the maintenance of a proportion of conifers in the presence of a dense advance regeneration.

The protection of conifer advance growth during both the establishment and final cuts was very important to confer a competitive advantage over aspen suckers. Retention of small merchantable conifers contributed to aspen decline and rapid site occupancy by conifers. Although some of the larger stems were blown down during an extreme wind event after the final cut, the overall losses remained acceptable. Nevertheless, it might be appropriate to harvest all merchantable stems during the final cut on sites with a high risk of windthrow.

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