



# American beech outgrows sugar maple at the sapling stage regardless of partial harvest intensity in northern hardwood forests

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## ABSTRACT

Sugar maple (*Acer saccharum* Marsh) is a key species in the northern hardwood forests of North America and management has historically focused on promoting its regeneration and yielding high-quality timber. A decrease in the abundance of sugar maple to the advantage of American beech (*Fagus grandifolia* Ehrh.) has been observed over the last decades. Together with the spread of beech bark disease, the understory dominance of American beech has often resulted in depleted, low vigour forest stands (i.e., with a low proportion of healthy trees). To favour regeneration and growth of sugar maple, increasing harvest intensity of partial treatments has been suggested, but the harvest intensity required remains unclear. In this study, we monitored the radial growth of saplings in 12 northern hardwood stands located in the Province of Quebec, Canada. These were commercially harvested with removal intensities ranging from 0% to 80% of the basal area. Using generalized additive mixed models, we investigated the effect of harvest intensity on the growth response of both species. Our results revealed that American beech saplings consistently had a much stronger radial growth response than sugar maple after harvest, regardless of treatment intensity. Consequently, modulating the intensity of partial harvests cannot singlehandedly favour the growth of sugar maple regeneration where American beech saplings dominate the understory. Additional silvicultural interventions are thus needed to control advance understory beech.

## 1. Introduction

Sugar maple (*Acer saccharum* Marsh.) is a key economic, ecological, and cultural species in the northern hardwood forests of North America (Rogers et al., 2022). This shade tolerant species dominates mature forests over a vast bioclimatic zone, which contributes to a variety of ecosystem services including carbon storage (Pan et al., 2011), water quality, and climate regulation (de Groot et al., 2002), while also providing wildlife habitat (Doyon et al., 2005). Sugar maple is highly valued by the well-developed forest industries appearance wood products (such as furniture, flooring, cabinets, etc.) and sugar maple syrup production (CRIQ, 2002). As a result, sugar maple is one of the most valuable species in northern hardwood forests, and management has historically focused on promoting its regeneration and providing a sustainable yield of high-quality sugar maple timber.

Despite this management objective, a decrease in the abundance of sugar maple in favour of American beech (*Fagus grandifolia* Ehrh.;

thereafter beech) has been observed over the last decades in the northern hardwood forests of North America (Brisson et al., 1994; Duchesne et al., 2005; Gravel et al., 2011). Indeed, the spread of beech bark disease (BBD) is a major contributing factor to the formation of dense beech understories (Garnas et al., 2011). Increased mortality as well as decreased growth and recruitment of sugar maple trees were reported at the end of the 20th century and are also thought to have contributed to the development of a beech sapling cohort (Duchesne et al., 2005). Once established in the understory, a combination of factors provide an advantage to beech over sugar maple at the seedling and sapling stages, including its greater shade tolerance (Canham, 1988), its ability to regenerate aggressively by root sprouting (Beaudet and Meslier, 2008; Forcier, 1975) and its lower sensitivity to soil acidity (Duchesne and Ouimet, 2009). Albeit unintentionally, past management practices may also have favoured beech regeneration over that of sugar maple, as logging operations trigger root sprouting by damaging roots of residual beech trees (Beaudet et al., 1999; R. H. Jones and Raynal,

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1988), which were often left behind due to the low demand by the forest industry (Boulet and Huot, 2013; Majcen et al., 2003).

In addition, BBD has spread westwards through Canada since its introduction in Nova Scotia in 1890 and is now present on the entire beech range in the province of Quebec (Ministère des Ressources naturelles et des Forêts, 2019), adding to the issue surrounding beech understory dominance. This disease consists of an insect-fungus complex caused by a beech scale insect (*Cryptococcus fagisuga*) and a canker fungus (*Neonectria* spp.). BBD hastens tree death and increases the abundance of understory beech root suckers (Cale et al., 2017; Garnas et al., 2011; Houston, 1994). Yet, these affected beech saplings are unlikely to mature and become suitable for timber production, nor to bring the ecological benefits associated with the presences of large, old trees. Dense tickets of beech saplings are known to proliferate abundantly in the understory of affected stands, which is detrimental to the regeneration of cooccurring species, including sugar maple (Bohn and Nyland, 2003; Giенcke et al., 2014; Nyland et al., 2019). In many areas, the positive feedback between the proliferation of the disease and the increased beech regeneration has resulted in severely depleted northern hardwood stands dominated by trees of low quality and vigour (Pothier et al., 2013), thereby threatening the ecological services and the economic viability of these managed forests.

In the province of Quebec, northern hardwood forests are mainly harvested by partial cutting interventions that typically remove about 30% of the initial basal area of the stand, thus favouring shade-tolerant species such as sugar maple and beech (Larouche et al., 2013; Neundorff et al., 2007). However, previous studies have shown the inability of sugar maple to outgrow beech in terms of diameter (Nolet et al., 2015; Bannon et al., 2015; Finzi and Canham, 2000; Beaudet et al., 2007) and height (Takahashi and Lechowicz, 2008) under low light conditions. It has thus been suggested that increasing harvest intensity through irregular shelterwood systems that typically apply greater harvesting rates (30–50% of initial stand basal area) may favour the regeneration and growth of sugar maple at the expense of beech (Nolet et al., 2008; Boulet and Huot, 2013; Dracup and MacLean, 2018). Despite being largely implemented in practice across the province of Québec through commercial logging operations, there is a lack of empirical validation that such approach is efficient at favouring the establishment and development of sugar maple regeneration over beech (St-Jean et al., 2021). While recent findings have suggested that the abundance and growth of sugar maple seedlings could be favoured by a greater opening of the canopy when the presence of beech in the overstorey is limited (St-Jean et al., 2021), there is still very little information on the efficiency of increasing harvest intensity to enhance the transition success of sugar maple from saplings to small merchantable trees. Yet, this transition is crucial to promote a viable succession for these stands. While past studies primarily evaluated height development of small trees (e.g. Beaudet and Messier, 1998), or diameter growth of large ones (e.g. Jones et al., 2009), we wanted to assess the change in radial increment of small understory beech trees after release by overstorey cutting. More specifically, we hypothesized that beech saplings should grow faster in diameter than sugar maple following low harvest intensity, but that this advantage would tend to dissipate with increasing treatment intensity and canopy opening.

## 2. Methods

### 2.1. Study area

Sampling was conducted in the Outaouais and Laurentides regions of southern Quebec, Canada, (Fig. 1). The study area is located between longitudes 74° 30' 0" W and 76° 30' 0" W and latitudes 45° 47' 60" N and 46° 36' 0" N. The mean annual temperatures range from 2.5° to 4.0°C with mean annual precipitation of approximately 1000 mm (Saucier et al., 2009). The study area is located within the sugar maple - yellow birch bioclimatic domain (Saucier et al., 2009). The forest is

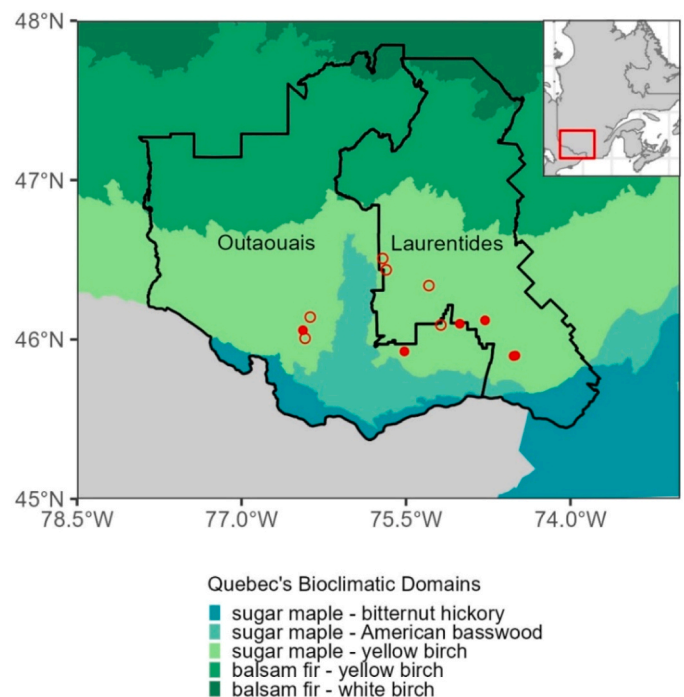


Fig. 1. Study area and location of the 12 harvesting sites. The full dots represent the sites in which we detected the presence of BBD.

dominated by sugar maple, but also includes American beech, yellow birch (*Betula alleghaniensis* Britton), red oak (*Quercus rubra*), balsam fir (*Abies balsamea* [L.] Miller), eastern hemlock (*Tsuga canadensis* [L.] Carrière), American hop-hornbeam (*Ostrya virginiana* [Mill.] K. Koch), and American basswood (*Tilia americana* L.). The study area has been harvested at least twice in the last century by a range of partial cutting methods, including diameter-limit, single-tree selection, and irregular shelterwood cutting. BBD was detected in half of the study sites at the time of sampling (Fig. 1).

### 2.2. Data collection

A database of pre-harvest sample plots was provided by the *Ministère des Ressources naturelles et des Forêts du Québec* (MRNF). Throughout the study area, plots were systematically established every 150–200 m prior to harvest. The inventory consisted of variable-radius plots in which each tree with a diameter at breast height (DBH) > 9 cm was tallied and the occurrence of regeneration (trees smaller than 30 cm in height) was recorded for each species. We first selected 12 felling sites that were harvested between 2013 and 2016 with three different types of partial cuts, i.e., single-tree selection, continuous-cover irregular shelterwood and extended irregular-shelterwood. These three types of cuts are uneven-aged silvicultural treatments, and their objective was to reduce mortality losses among overstorey trees and improve stand quality (Larouche et al., 2013). The single-tree selection cut consists in harvesting about 30% of the initial basal area of the stand at regular intervals. The continuous-cover irregular-shelterwood cut is similar to the single-tree selection cut, but the intensity of removal and the interval between cuts vary over the course of the rotation. The extended irregular-shelterwood cut essentially consists in establishing a regeneration cohort with an initial cut, and then to perform a removal cut following an extended period compared to that of the usual shelterwood method. See Raymond et al. (2009) for detailed explanations of each irregular-shelterwood system. For each of the 12 felling sites, we randomly selected eight ground plots in which > 25% of the basal area (BA) consisted of either sugar maple or beech. This process resulted in a total of 96 sample plots where post-treatment inventories were

conducted.

Our post-treatment inventory was conducted during the summer of 2019, two to five years after harvest. First, we updated the pre-treatment inventories for all trees with a DBH > 9 cm. We identified all living and dead trees, as well as stumps of harvested trees, which were used to validate harvest intensity and residual BA at the plot level. We also noted the presence or absence of BBD in each plot. For the sapling inventory, we established three circular subplots with a 2.82 m radius, systematically located 10 m from the plot center in the north, east and south directions. All saplings were tallied in DBH classes of 2 cm (2, 4, 6, 8), species and social status (dominant, codominant or overtopped). However, as sprouts become functionally independent from the parent tree over time (Jones and Raynal, 1986), sapling origin could not be determined in this study. In each subplot, a disc was sampled at breast height for sugar maple and beech saplings of each DBH class (2,4,6,8) when present. For each sampled disk, the height and social status of the sapling were recorded. The sampling resulted in similar distributions in terms of DBH and social status for both species (Table S1). The disks were air dried, finely sanded, and annual ring widths were measured using a Velmex micrometer ( $\pm 0.002$  mm). A total of 322 disks were measured and analyzed, corresponding to 112 sugar maple and 210 beech saplings.

### 2.3. Statistical analyses

To investigate the difference between the radial growth response of sugar maple and beech saplings to partial harvest, we first converted raw annual ring widths (mm) to annual basal area increment (BAI,  $\text{mm}^2$ ), which provided a more meaningful growth index from a forest yield perspective (Jones et al., 2009). We calculated the mean BAI for each sapling before and after the treatment. Before treatment, five years of growth were available for most saplings; with two young saplings having only three and four years of growth before treatment. After treatment, the number of years of growth varied between two and five years depending on the timing of the harvest at the felling sites.

Because the three types of partial cuts resulted in similar forest structures and showed high intra-treatment variability in terms of BA removal (Table 1), we used the percentage of BA removed in each plot as a continuous variable to represent the treatment intensity (TI).

Two steps were used to investigate the influence of the cut on the BAI of saplings. First, we compared the sapling BAI before and after treatment and between the species to determine the overall effect of harvest on sapling growth. Second, we investigated the effect of the treatment intensity of the sapling BAI after treatment as well as the influence of other biotic and abiotic factors.

In the first step, we built a mixed linear model using the sapling mean BAI as the response variable. Two explanatory variables were considered: timing relative to the treatment (i.e., whether the growth was measured before or after the treatment), and species. An interaction between the two explanatory variables was included in the model as we expected the growth response to differ between the two species. The

**Table 1**

Type of partial cut applied as a harvesting treatment and description of the basal area of the plots before and after the treatment.

Treatment	Number of plots	BA before (m <sup>2</sup> /ha) median (min-max)	BA after (m <sup>2</sup> /ha) median (min-max)	%BA removed median (min-max)
Single-tree selection	28	24 (12–42)	14 (6–22)	30.8 (0–80)
Continuous-cover irregular-shelterwood	26	24 (14–36)	14 (8–26)	38.5 (17–64)
Extended irregular-shelterwood	25	20 (10–36)	12 (4–24)	38.2 (0–73)

model was built using the “nlme” package (Pinheiro et al., 2021) in the R environment (R Core Team, 2018). Model assumptions were carefully checked by visually examining the model residuals and were best met when using a log-transformation on the BAI. Nested random effects were added for each subplot within a plot within a site (Site ID / Plot ID / Subplot ID) to account for the nested structure of the sampling design. Finally, a pairwise comparison test was conducted on the model results using a post-hoc Tukey test, with p-values adjusted for multiple comparisons. The latter was implemented using the “lsmeans” package (Bates et al., 2021).

In the second step, we tested for the influence of factors acting at the plot, subplot, and sapling scales. At the plot level, we investigated the effect of TI, presence of BBD, and plot BA after treatment (PlotBA). At the subplot scale, we tested the effect of subplot BA of saplings (SaplingBA) as a proxy for competition between saplings, and subplot location (within a skid trail or not) as it may influence the local amount of light reaching the understory (St-Jean et al., 2021). Finally, at the sapling level, we investigated the effect of species, age and social status (dominant, codominant, or overtopped among the cohort of saplings). We also tested the effects of the number of years included in the calculation of the mean BAI after treatment ( $N_{\text{years}}$ ) to account for a potential time lag in tree responses to resource changes (Jones and Thomas 2004, Moreau et al., 2019). Lastly, sapling BAI before the treatment ( $\text{BAI}_{\text{before}}$ ) was included in the model, as prior growth rate is also known to affect tree growth responses (Black and Abrams, 2003, 2004). As preliminary analyses suggested that the age of a sapling had a non-linear effect on BAI (Fig. S1), we used generalized additive mixed models implemented with the “gam4” package (Wood, 2011) to test the effect of all variables. Preliminary analyses indicated that all variables were to be included as linear predictors except for age and  $N_{\text{years}}$  which were modelled using smoothing functions. The model was fitted using a gamma family and a log-link, which was appropriate for our dataset according to the diagnostic plots. The interaction terms species and age; species and TI, and species and BBD, were also tested in preliminary analyses. None were found to be significant and were thus not included in the final model. Nested random effects were specified as in the previous step. All the listed variables were combined in a full model except for PlotBA and TI, for which the high degree of correlation ( $r = -0.71$ ; Fig. S2) prevented their inclusion in the same model. Because the PlotBA is a useful variable when planning silvicultural interventions, we built a second full model in which TI was replaced by PlotBA. The fixed effects of the final models were included as follows:

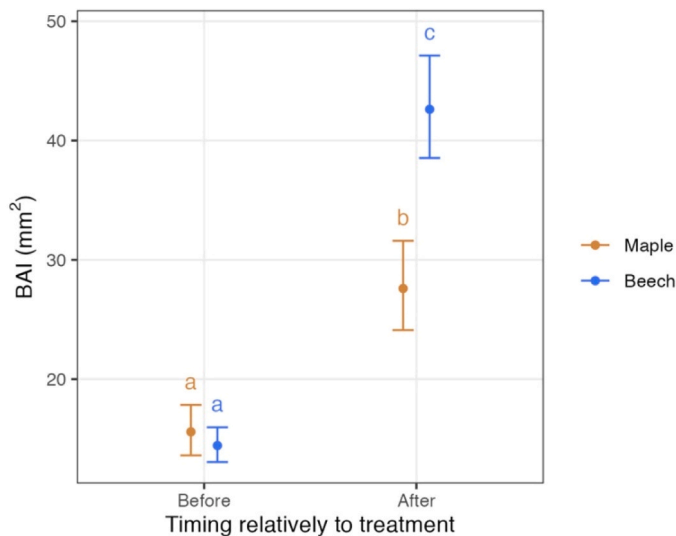
$$\text{BAI}_{\text{after}} \sim \text{Species} + \text{TI/PlotBA} + \text{BBD} + \text{SaplingBA} + \text{Subplot location} + s(\text{Age}) + \text{Social status} + s(N_{\text{years}}) + \text{BAI}_{\text{before}}$$

where  $s()$  refers to a smoothing function. The two models were then compared using the Akaike information criterion (AIC) and R-squared. This allowed us to determine whether TI or the PlotBA was the best variable to include in the final model. Post-hoc Tukey test was used to conduct pairwise comparisons among the different levels of the categorical variable social status, with p-values adjusted for multiple comparisons. This test was performed with the “emmeans” package (Lenth, 2022).

## 3. Results

### 3.1. Sapling BAI before and after the treatment

Both sugar maple and beech radial increment responded positively to the treatment, although the magnitude of the response differed between the species as indicated by the significant interaction between timing and species ( $p = 0.018$ ; Fig. 2). Before harvest, both species displayed similar BAI as revealed by the post-hoc test ( $p = 0.967$ ; Fig. 2). After harvest, the BAI of both sugar maple and beech differed significantly from their respective BAI before harvest, with the model predicting a



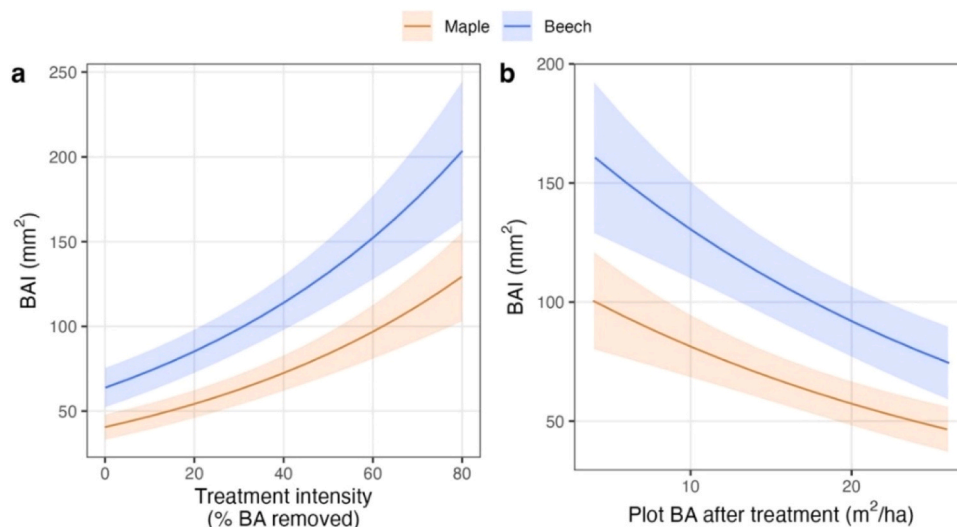
**Fig. 2.** Model predictions for mean BAI  $\pm$  SE ( $\text{mm}^2$ ) before and after the treatment for sugar maple (brown) and American beech (blue). The letters above the upper SE represent the results of the post-hoc Tukey test, with different letters indicating significant differences.

77% increase in BAI ( $p < 0.001$ ) for sugar maple, and a 195% increase for American beech ( $p < 0.001$ ). Accordingly, the growth response to the treatment was greater for beech saplings than for sugar maple ( $p = 0.043$ ; Fig. 2).

### 3.2. Factors influencing BAI after harvest

When investigating the factors influencing sapling BAI after harvest, we found that the TI performed better than PlotBA for predicting sapling growth. Indeed, the AIC of the model including TI (3284.5) was lower than that of the model built with the PlotBA (3291.1). The adjusted R-squared was also slightly higher (0.60 compared to 0.58) for the model using TI. When compared, the effect of both explanatory variables was coherent, as increased TI increased sapling BAI (Fig. 3a) whereas a higher PlotBA reduced sapling BAI (Fig. 3b). In accordance with the better performance of the model using TI, this model was retained to evaluate the effects of the other variables as described below.

In line with the first step of the analysis, the growth of beech saplings



**Fig. 3.** Predicted mean annual BAI ( $\pm$  SE; shaded areas) after harvest as a function of species (brown = sugar maple, blue = American beech) and (a) treatment intensity (% BA removed) or (b) and plot BA after treatment ( $\text{m}^2/\text{ha}$ ).

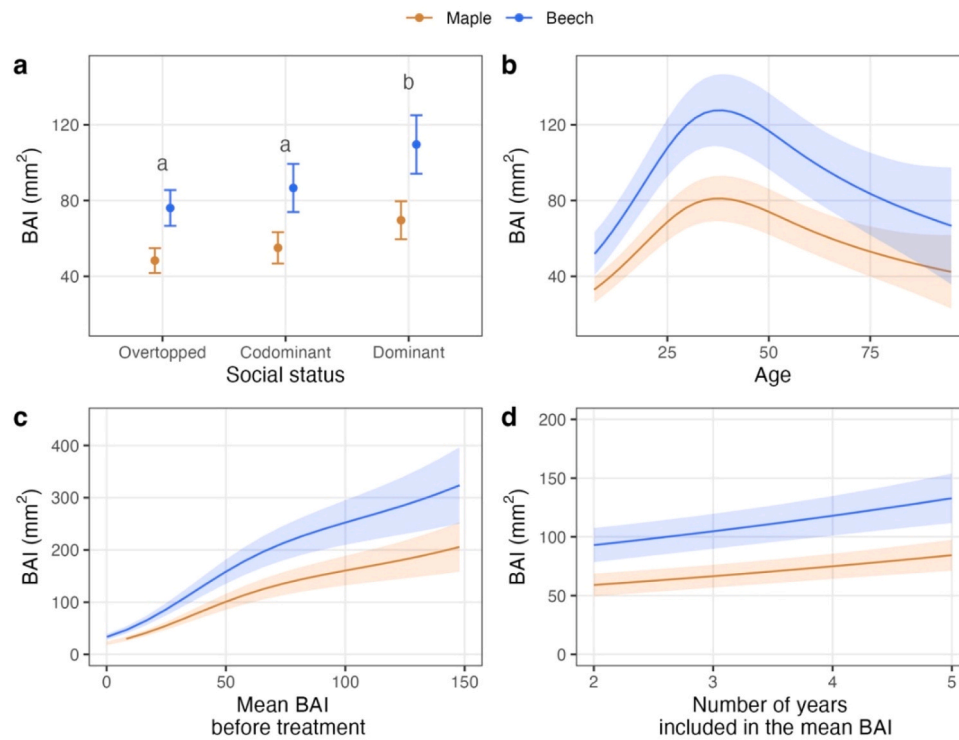
after treatment was greater than that of sugar maple ( $p < 0.001$ ; Fig. 4). We found no effect of variables acting at the plot and subplot levels, such as the occurrence of BBD, the subplot location, or the overall BA of saplings (i.e., sapling competition; Table 2). However, variables acting at the sapling scale significantly influenced BAI. Indeed, sapling social status had a significant effect on BAI, with dominant saplings showing higher BAI than codominant and overtopped saplings ( $p = 0.037$  and  $p = 0.003$ , respectively; Fig. 4a). The number of years included in the mean BAI after treatment was also significant ( $p = 0.013$ ), suggesting that growth increases over time following the treatment (Fig. 4c). Sapling age had a non-linear effect on sapling growth with a significant smoothing function ( $p < 0.001$ ; Fig. 4b) that indicated that BAI after treatment peaked at a sapling age of about 35 years for both species. Sapling BAI before the treatment was also positively related to the BAI after treatment, with a slightly non-linear relationship, as indicated by the significant smoothing function ( $p < 0.001$ ; Fig. 4d).

## 4. Discussion

We compared the radial growth of sugar maple and American beech saplings following a variety of commercial partial cuts to determine whether treatments of higher intensity could stimulate a better response in maple growth compared to beech. As expected, the treatments resulted in growth releases for both maple and beech saplings, which increased with the amount of basal area harvested. However, beech consistently showed a stronger growth response than maple after harvest, regardless of the treatment intensity.

These results are in accordance with other studies that have measured radial growth of saplings and reported a stronger growth for beech relative to maple (Nolet et al., 2015; Bannon et al., 2015; Finzi and Canham, 2000). Our results are also in line with studies focussing on height growth of saplings which showed that beech outperforms maple in small canopy gaps ( $< 80 \text{ m}^2$ ; Takahashi and Lechowicz, 2008). Inversely, the canopy openness generated by silvicultural treatments of greater intensities, such as clear cutting (Nolet et al., 2015; radial growth), or group selection cutting resulting in large gaps  $> 1500 \text{ m}^2$  (McClure et al., 2000; height growth), have shown greater potential to favour maple growth over beech. Overall, these results suggest that the canopy openness associated with commercial partial harvest treatments are insufficient to allow the sapling release of maple to outperform that of beech.

Many factors may contribute to the greater growth increase observed for beech saplings following cutting treatments of different intensities.



**Fig. 4.** Effect of sapling (a) social status, (b) age, (c) BAI<sub>before</sub>, and (d) number of years included in the mean BAI after treatment on sugar maple (brown) and American beech (blue) sapling BAI after the treatment. Predictions ± SE are presented. The letters above the upper SE represent the results of a post-hoc Tukey test, with different letters indicating significant differences.

**Table 2**

Estimated parameters for the factors influencing sapling BAI after harvest. Significance is indicated in the last column, with \* indicating p-values < 0.05; and \*\* indicating p-values < 0.01. The variables Species, BBD, SubplotLocation, and Status are categorical variables with the level indicated in parenthesis being compared to the reference level. The reference level is represented by the Intercept, and corresponds to a maple sapling in a subplot where the BBD is absent, not located in a skid trail. The reference level for the social status is overtopped. The Treatment intensity is defined as the percent of the plot BA removed, the saplingBA as the BA of the saplings in the subplot (as a proxy for competition), and N<sub>years</sub> as the number of years after treatment included in the sapling BAI.

Parametric coefficients	Coefficient	Std. Error	t-value	p-value	
(Intercept)	2.517	0.252	9.997	< 0.001	**
Species (Beech)	0.454	0.106	4.280	< 0.001	**
Treatment intensity	0.014	0.003	4.479	< 0.001	**
BBD	0.085	0.130	0.655	0.513	
SubplotLocation (SkidTrail)	-0.044	0.130	-0.345	0.730	
SaplingBA	-0.018	0.021	-0.845	0.399	
Status (Codominant)	0.130	0.123	1.058	0.290	
Status (Dominant)	0.365	0.115	4.056	0.002	**
N <sub>years</sub>	0.119	0.048	2.494	0.013	*
<b>Smoothing functions</b>		<b>Edf<sup>1</sup></b>	<b>F</b>	<b>p-value</b>	
s(age)		2.796	8.925	< 0.001	**
s(BAI <sub>before</sub> )		4.023	41.396	< 0.001	**

1. Effective degrees of freedom

Acidic soils are detrimental to maple establishment, survival, and growth (Hane et al., 2003), providing beech saplings with an advantage over maple in stands where beech abounds in the canopy. Moreover, beech’s ability to regenerate by root sprouting may contribute to the observed increased growth, as beech of sprout origin usually show higher growth rates than seedlings (Beaudet and Messier, 2008; Dumont et al., 2023). However, sprouts are expected to become functionally

independent from the parent tree over time (Jones and Raynal, 1986), and because sprout-origin saplings could not be distinguished from seed-origin saplings in this study, the influence of root sprouting on our results remains uncertain. Regardless of their origin, a greater growth response of beech saplings over maple is consistent with that observed for mature trees following partial cutting (Jones et al., 2009), which implies that the greater capacity of beech to respond positively to canopy opening is maintained at every development stage.

Shade-tolerant species such as maple and beech have the capacity to endure long periods of growth suppression under low light conditions while maintaining their potential at responding positively to gap creation (Canham, 1985, 1990; Moreau et al., 2019). In line with that, we observed that saplings of both species displayed a long-lasting ability to respond to canopy openings through increased radial growth, which peaked at an age of about 35 years old. To our knowledge, this study is the first to directly quantify the relationship between sapling age and the growth response potential of maple and beech to canopy opening (but see Canham, 1990). Our results highlight the effectiveness of shade-tolerant species to benefit from increased residence time in the understory layer, making them highly adapted to environments characterized by a rare occurrence of disturbances. As expected, we also found that dominant saplings had a greater growth response than co-dominant or overtopped individuals. This relationship between social status on sapling growth potential is well established, as light availability is greater in the upper strata, which allows an enhanced growth of the dominant individuals in the understory layer (Pacala et al., 1994).

#### 4.1. Management implications and concluding remarks

Our study has demonstrated that the strategy implemented across the province of Quebec to apply partial harvests of higher intensity does not meet the objective of facilitating maple regeneration in stands where beech abounds in the understory. This is consistent with previous findings showing that sugar maple regeneration can only be favoured when

the presence of beech is limited (St-Jean et al., 2021; Bohn and Nyland, 2003). In such stands, it is imperative to intervene with additional silvicultural tools to control beech regeneration and promote the establishment of more desired species, otherwise it is unlikely that sufficient proportions of maple saplings will become established and eventually reach the canopy (Mielke et al., 1986; Nyland et al., 2006).

Mechanical control of understory beech has been proven efficient in some cases, especially in the short term (Bédard et al., 2014; Nyland and Kiernan, 2017), whereas longer-term results are variable (Bédard et al., 2022). Yet, the timing of mechanical interventions appears crucial to their efficiency; brushing implemented early in the growing season after the leaves have emerged may be more effective at preventing beech from resprouting due to reduced carbohydrate reserves, as above-ground proportions of saplings accumulate reserves through the summer (Nyland et al., 2006). Furthermore, removing beech saplings before harvesting has been suggested to give maple an advantage by allowing its establishment and release prior to treatment (Nyland et al., 2006). As sugar maple appears to perform better in treatments which intensity is greater than irregular shelterwoods and selection-cuts (McClure et al., 2000; Nolet et al., 2015), another option would be to combine a strip cut or large group selection cut with the removal of beech saplings, which could allow the establishment and release of sugar maple and other less shade tolerant species such as yellow birch (Bédard et al., 2014). However, this approach is unlikely to be effective in stands with high browsing pressure, as beech is particularly avoided by browsers compared to other hardwoods (Bédard et al., 2022). In stands with calcium deficiencies, lime application could be used as a complement, since liming generally has a positive effect on sugar maple's establishment and growth (Juice et al., 2006; Long et al., 2011; Moore et al., 2012), although its effect may be limited (Duchesne et al., 2013; Nolet et al., 2015). Lastly, the use of herbicide has proven to be the most successful in controlling beech regeneration and its efficiency is well-documented (Kochenderfer et al., 2004, 2006; Nyland et al., 2006). However, the use of herbicides has been forbidden in forestry practices in 2001 in Québec (Ministère des Ressources naturelles et des Forêts, 2015). Timely mechanical control together with soil amendments should therefore be applied to complement partial cuts in stands where a shift towards beech regeneration is observed, and monitoring should be pursued to ensure the long-term productivity of northern hardwood forests.

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## CRediT authorship contribution statement

**Leduc Florence:** Investigation, Resources, Writing – original draft, Writing – review & editing. **St-Jean Émilie:** Conceptualization, Investigation, Methodology. **Dumont Sébastien:** Validation, Writing – review & editing. **Moreau Guillaume:** Validation, Writing – original draft, Writing – review & editing. **Chagnon Catherine:** Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Achim Alexis:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Validation.

## 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.

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## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2023.121630.

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