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Article

Assessing the Potential Stem Growth and Quality of Yellow Birch Prior to Restoration: A Case Study in Eastern Canada

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Abstract: Past silvicultural treatments have resulted in the high-grading mixed temperate forests of Québec, Canada. Despite recognition of this issue, the low occurrence of yellow birch (*Betula alleghaniensis* Britton) within current stands raises questions about the potential of the species to grow and eventually constitute a high-quality forest resource. The objective of this study was to assess this potential using tree characteristics, forest structure and additional site and climatic conditions as predictors. A total of 145 trees were sampled in two areas located in the same bioclimatic zone. Lower-Saguenay-Charlevoix was chosen as an area where a restoration plan could be implemented, whereas Portneuf was selected as a reference. We used nonlinear mixed models to investigate which environmental factors are likely to influence the radial growth and stem quality of yellow birch sample trees. Our results suggest that topographic and climatic conditions, as well as the competitive environment of the trees, are important factors to consider in the evaluation of yellow birch production. Despite the limited occurrence of yellow birch, the potential for growth and quality was high in the Lower-Saguenay-Charlevoix area. For equivalent topographic, climatic, and competitive environment conditions, there was no significant difference in either radial growth or stem quality with Portneuf. We suggest that the economic interest of producing high quality timber should be used to justify the implementation of a restoration strategy in the Lower-Saguenay-Charlevoix area.

Keywords: yellow birch; forest restoration; stem quality; site and climatic conditions

1. Introduction

The natural disturbance regime of the temperate forests of northeastern North America is dominated by frequent partial disturbances that create localized gaps in the forest canopy, while severe disturbances are more unusual [1–3]. In contrast, past silvicultural practices mainly consisted of large clearcuts or diameter-limit cuts that create conditions more similar to those associated with severe natural disturbances [4–6]. Comparisons between pre-industrial forests and current forests have highlighted the effect of such harvesting practices on forest composition and stand structure [7–13]. In addition to the inversion of the distribution of stand ages in favor of younger stands, shade-intolerant species were favored over shade-tolerant species. For example, it was found that mixed temperate forests normally dominated by balsam fir (*Abies balsamea* (L.) Mill.) in eastern Canada have now evolved to a more deciduous canopy, composed mainly of low-value species such as red maple (*Acer rubrum* L.), striped maple (*Acer pennsylvanicum* L.), and white birch (*Betula papyrifera* Marsh) [9,11,14].

In addition to balsam fir, the late-successional mixewood stands that mark the transition between the boreal and temperate forest biomes can contain a proportion of yellow birch (*Betula alleghaniensis* Britton) [15]. This valuable deciduous species, which has intermediate tolerance to shade, has also suffered from past forest management practices [5,14,16]. A recent study of early land survey records reported an important decrease in the dominance of the species since the pre-settlement period [17]. Despite the fact that an estimated 50% of the current standing resource in this species is located within the province of Quebec [18], yellow birch has become merely a minor species with isolated occurrence in some parts of the balsam fir-yellow birch bioclimatic zone. The annual allowable cut has recently decreased by approximately 20%, and the proportion of quality sawlogs in current supplies is also declining [19,20]. This has serious implications for the financial viability of the forestry woodchain. For example, on the public land of the province in 2009–2010, stumpage prices for trees of "sawing" grades ranged from CAD 1.40 to 11.89 per cubic meter, whereas the "pulp" grade averaged only CAD 0.27 [21]. Provided that they are of sufficient quality, yellow birch stems are appreciated for value-added end-uses such as flooring or furniture.

The factors affecting the natural regeneration of the species after harvesting are well documented. Yellow birch is sensitive to the availability of an adequate seed bed (deadwood, exposed mineral soil or disturbed humus) and to the amount of light available [22–24]. Seedlings also reach their maximum growth rate at approximately 55% of incident light [22,25,26], which suggests that partial cuts with some scarification of the litter layer on the ground would represent a suitable regeneration method [27]. However, in addition to ecological incentives, financial benefits may also be required for restoration measures to be implemented. Since producing "pulp" grade yellow birch would not add any financial value to the current forest resource, the potential quality of the resource needs to be considered to justify the decision to invest in a forest restoration plan on public land. In areas where the current occurrence of the species is marginal, this potential is largely unknown.

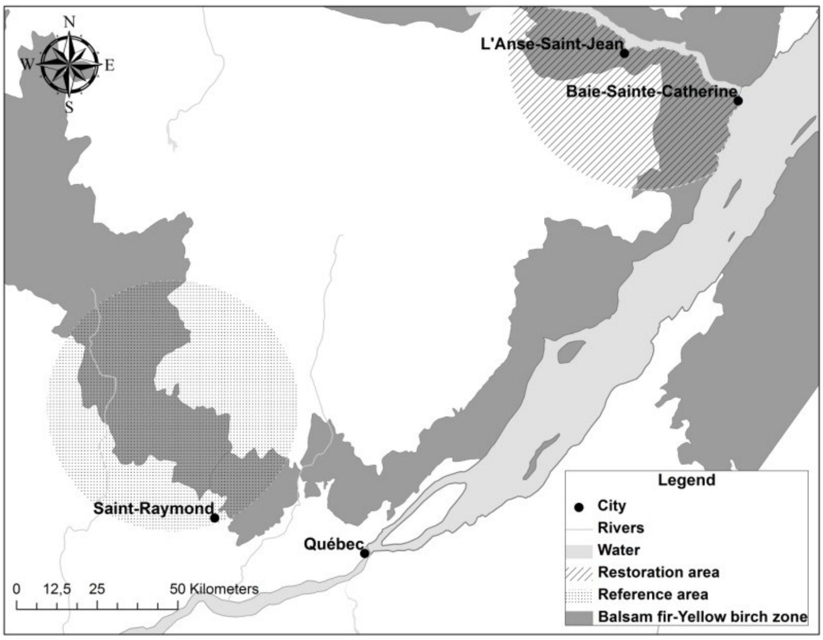
This study aimed to evaluate the possibility to produce high-quality yellow birch sawlogs in a forest area where a restoration plan is envisaged by local authorities [28]. For comparison, we used a second forest area located within the same bioclimatic domain, but where the species represents an important proportion of the forest cover. Using a modeling approach, we investigated which environmental factors influence radial growth and stem quality. Our main hypothesis was that, given an adequate competitive environment, yellow birch trees have the potential to grow into a high-quality resource in the area where forest restoration is envisaged.

2. Experimental Section

2.1. Field Sampling

Two study areas were selected at the northern edge of the yellow birch—balsam fir bioclimatic domain [18]. The bioclimatic domain refers to the expected composition of late-successional forest stands on well-drained (mesic) soils [29]. The first area, hereafter referred to as the "reference" area, was located in Portneuf, approximately 90 km west of Quebec City (Canada) (Figure 1). The forests of this area contain an important standing stock of high quality stems, which is a significant source of supply for local sawmills. The second area, hereafter referred to as the "restoration" area, was located in the Charlevoix-Lower-Saguenay region, approximately 215 km northeast of Quebec City, near the confluence of the St. Lawrence and Saguenay rivers. Although the restoration area is located in the same bioclimatic domain, yellow birch currently constitutes a negligible part of the forest cover. In the absence of hardwood sawmills in this region, the small volumes of yellow birch timber extracted from logging operations are sent directly to pulp mills.

Figure 1. Geographical localization of the reference and restoration areas presented in this study. Both areas are located within the balsam fir–yellow birch bioclimatic domain.



Quebec's network of temporary sample plots (TSPs) was first used in order to locate plots with occurrences of yellow birch. An examination of the TSP database revealed that yellow birch represented 9.1% (17,013/187,271) of observations (*i.e.*, the sum of all trees measured in the TSPs) in the reference area compared with only 3.3% (4,065/93,025) in the restoration area. In contrast, trembling aspen (*Populus tremuloides* Michx.) proportions were 1.8% (3396/187,271) in the reference area compared with 9.1% (8460/93,025) in the restoration area. Here, it is worth mentioning that we use the term "restoration" in its general sense, *i.e.*, not in terms of conversion to other land use, but in terms of actions to counteract the negative effects of disturbance and stress on forest composition (rehabilitation) [30]. Our assumption was that the low occurrence of yellow birch in the restoration area is at least partly attributable to severe anthropic disturbances such as logging operations or settlement fires [17,31].

A stratification strategy was applied to ensure that the overall range of growing conditions found in each area would be covered. Altitude (0–200, 201–500 and 501–700 m), latitude and longitude (3 equal classes of each) were used as the first stratification level. Stand structure (even or uneven aged), mean age (1–20, 21–40, 41–60, 61–80, 81–100 and >100 years) and stand density (fully stocked *vs*. non fully stocked) were retained as a second level. A list of available TSPs was made and the final selection was made randomly within each category. In cases where plots were inaccessible, the next TSP on the list was chosen. In total, 41 TSPs were visited during the summer of 2010.

Up to four yellow birch trees (if available) were randomly selected and measured in each plot. In the many cases where fewer than five yellow birch trees were present in the plot, all available trees were sampled. Data from various observation scales were collected: (1) tree-level characteristics; (2) competitive environment around the sample tree; (3) permanent plot conditions; and (4) local climate. At the tree level, diameter at breast height (1.3 m, DBH), tree height and crown size were first measured. A stem quality assessment was then made, using the protocol described below. To measure cambial age and radial growth, two sample cores were also taken perpendicularly to each other at 1.3 m above the ground. A total of 67 trees were sampled in the restoration area and 78 in the reference area. Their main characteristics are summarized in Table 1.

Table 1. Characteristics of the temporary sample plots used in this study in the reference and restoration areas. Ranges give the minimum and maximum values. Standard deviations are given in brackets next to the mean value. Abbreviations: TSP = Temporary Sample Plot, DBH: Diameter at breast height, H: Total tree height, d^2h: DBH^2 × *H*, *BAI5Y*: ring are increment over the last 5 years; *SLC4F*: sum of longest clearbole sections on each of the four faces.

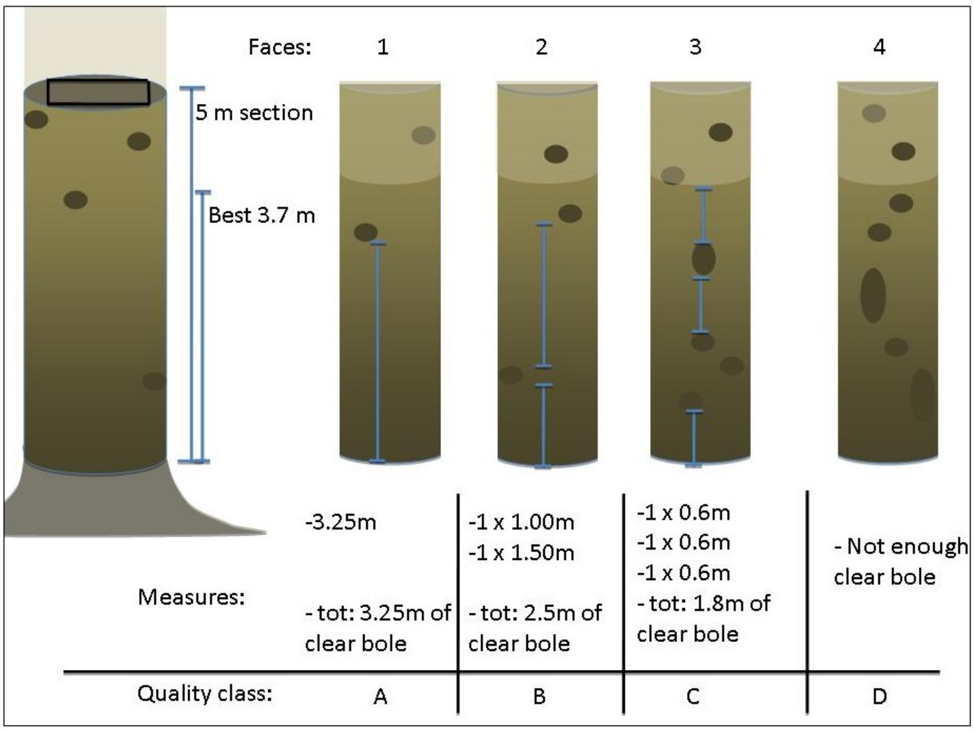
Area	Number of TSPs	Number of trees (cm)	DBH (cm)	*H* (m)	d^2h (m^3)	Age (years)	*BAI5Y* (cm^2/ 5 years)	*SLC4F* (m)
Reference	22	76	3.7–67.5	6.1–24.6	0.01–8.06	14–231	43.7 (32.2)	9.7 (4)
Restoration	19	66	2.5–53.2	2.73–20	0–4.78	16–229	34.7 (26.8)	8.3 (3.6)

2.2. Stem Growth and Quality Assessments

Radial growth and stem quality were assessed separately. The former was defined as the increment in basal area over the period of five years prior to sampling (*BAI5Y*, $cm^2/5$ years). The radial increments used to measure *BAI5Y* corresponded to the average of those measured on the two sample cores from each tree. A five-year growth period was chosen because it was assumed to be linked to the current competitive status of the tree [32]. Basal area was chosen as it was less dependent on cambial age than the radial growth [33,34].

The stem quality assessment was derived from the broadleaf stem classification system developed and used by Quebec Ministry of Natural Resources. This classification, known as the "ABCD" system [35], was derived from a log grade classification system developed in the United States by Hanks [36] and later adapted to Canada by Petro and Calvert [37]. It uses four stem quality classes to express the processing potential of a tree: A (veneer), B (large sawlog), C (small sawlog) and D (pulp). Different factors are considered to assign a class, such as DBH (with thresholds for A > 39 cm, B > 33 cm, C and D > 23 cm) and the presence of defects on the stem. For the latter, the best 3.7 m log located in the lower 5 m of the stem is assessed. It is then split into four virtual faces, deemed to represent the faces obtained in grade-sawing [38]. The presence and length of clearbole sections are assessed on the third-best face and reduction rules are applied to defects such as external signs of rot (Figure 2). This classification system was shown to be related to the proportion of different log grades (and hence value) found in a tree of a given DBH [39].

Figure 2. Example of standing hardwood tree classification as described by Monger [35]. The blue bars on each face represent the clear bole sections, which were used in our stem quality assessment.



For the purpose of this study, adjustments had to be made to this system because we were interested in quantifying stem quality for trees of any size, including some smaller than 23 cm in DBH. Stem quality was therefore treated as a continuous variable defined as the sum of the clear bole sections (*i.e.*, without any visual defect) on each of the four faces (*SLC4F*, m). This choice was inspired by the link that exists between the evaluation of faces proposed by the ABCD classification and the grade-sawing applied to high quality hardwood logs. Similarly to the ABCD system, the analysis was focused on the lower five meters of the stem.

2.3. Independent Variables

Variables related to the climatic and topographic conditions, stand competition and productivity were also collected for each TSP (Table 2). Climate variables correspond to annual averages of degree-days, length of the frost-free period, daily minimum, mean and maximum temperatures, and precipitations. These data were obtained using the Bio-SIM software, which provides climate information for a specific geographical location through an interpolation from different weather stations located nearby [40].

Table 2. Mean characteristics of the variables used as covariates in the study. Standard deviations are given in brackets. ANOVA tests were performed on each variable to assess the equality of population means across both areas. Abbreviations: Temp.: Temperature; CI1: distance-independent competition index [Equation (1)]; CI2: Distance dependent competition index (2); CYB: Conifers and Yellow birches; M: Sugar and red Maples; O: Other species.

Area	Degree Days (°C/year)	Growing Season (days)	Temp. Daily Min (°C)	Temp. Daily Mean (°C)	Temp. Daily Max (°C)	Precipitations (mm)	Altitude (m)	CI1	CI2	Site Index	Main Competitor species
Reference	2154 (145)	134 ** (9)	−4.8 ** (0.8)	1.3 ** (0.7)	7.4 ** (0.6)	1317 ** (62)	492 ** (118)	9.6 ^{ns} (10.5)	3.5 ^{ns} (5.6)	11.6 * (0.8)	CYB: 33 M: 6 O: 37
Restoration	2262 (69)	151 ** (8)	−3.5 ** (0.8)	1.8 ** (0.5)	7.1 ** (0.3)	1034 ** (26)	288 ** (86)	9.9 ^{ns} (13)	4 ^{ns} (6)	11.4 * (0.7)	CYB: 32 M: 9 O: 25

* $p < 0.05$; ** $p < 0.01$; ^{ns} $p > 0.05$.

Topographic variables were used to express permanent site conditions. They correspond to the latitude, longitude, altitude and topographical exposure. TOPEX was used as an indicator of general site exposure [41], computed using ArcView 3.2 (ESRI, Redlands, CA, USA). It represents the sum of the slope angles for eight cardinal directions around a target point, taking negative values for an exposed site, close to 0 for a flat site and positive for a sheltered site [42].

The current competitive environments of the sample trees were measured using a distance-independent and a distance-dependent competition index [32,43]. The distance-independent index was a sum of the ratios of diameters of a subject tree to those of its competitors:

$$[CI1 = \sum_{j=1}^{n} d_j/d_i] \quad (1)$$

where d_j is the diameter of the competitor tree j; d_i is diameter of subject tree i; n is the total number of competitors within a 5 m radius around the subject tree. The distance-dependent index was similar to the distance-independent one, but the ratios were weighted by the distance between the competitor and the subject tree:

$$[CI2 = \sum_{j=1}^{n} \frac{d_j/d_i}{Dist_{ij}}] \quad (2)$$

where $Dist_{ij}$ is the distance between trees i and j. Both indices are widely used and proved to perform as well as more complex indices for predicting individual tree growth [44].

To account for stand composition around the sample tree, we introduced a variable representing the types of dominant competitor species. Three groups of species were defined on the basis of types of forests that they represent: "Sugar and red maples" represented species most commonly associated with temperate hardwoods, "conifers and yellow birch" the temperate mixed-woods, and "other species" were mostly associated with pioneer stands dominated by trembling aspen and white birch [29]. Forest plots were each attributed to a particular group based on the characteristic of their species composition, assessed from the competitive environment within a 5 m radius of the sample trees. Results were attributed based on which group of species was the most frequent among the measured competitors in each plot.

2.4. Model Development

Statistical analyses were performed in R [45] using the *nlme* package [46], which was specifically used to fit nonlinear mixed models to the data. Nonlinear equations were used to describe the relationship between the independent variable and the size of the sample tree. The individual tree size was represented by the multiplication of DBH^2 (m) and tree height (m) (d^2h). This was chosen over DBH and h separately because it provided a reduced variability in both the *BAI5Y* and *SLC4F* to size relationships. The variable d^2h can be seen as a surrogate for the volume of the tree [47]. For both *BAI5Y* and *SLC4F* the relationships were found to saturate above a given value of d^2h. A nonlinear approach was hence used to reflect the intrinsic nature of the relationships and avoid the potential drawbacks associated with log-transformed variables [48]. To account for heteroscedasticity in the data, the within-group variance ε_{ij} was weighted by a power function of the absolute value of d^2h [49]:

$$[Var(\varepsilon_{ij}) = \sigma^2(d^2h)^k] \quad (3)$$

Mixed effect models were fitted to account for the hierarchical structure of the data (*i.e.*, trees within plots) [50]. Plot-related variability was detected (not shown), so this variable was included as a random component of the models. The following combined exponential and power function was chosen for the analysis of *BAI5Y*:

$$[BAI5Y_{ij} = (a + \alpha_j) \times d^2h^{(b+\beta_j)} \times (c + \gamma_j)^{d^2h} + \varepsilon_{ij}] \quad (4)$$

where $BAI5Y_{ij}$ (cm^2/5 years) is the basal area increment over a 5-year period for tree i in plot j; a, b, c are the parameters associated with the fixed part of the model; α_j, β_j, γ_j are the random parameters associated with the between-plot variations; ε_{ij} is the residual error term assumed to be normally distributed and independent from the random effects.

For *SLC4F*, an exponential function of d^2h was found to adequately represent the observed pattern of variation:

$$[SLC4F_{ij} = (a + \alpha_j) + (b + \beta_j) \times exp^{(c+\gamma_j)/d^2h} + \varepsilon_{ij}] \quad (5)$$

where $SLC4F_{ij}$ (m) is the sum of the longest clearbole sections observed on the four faces of tree i in plot j.

The model building strategy used in this analysis consisted of four steps. Model fitting was first initiated by fitting the fixed effects components of Equations (4) and (5) (*i.e.*, functions of d^2h—Step 1). Next, the random effects were added (Step 2). Then, we investigated the effect of additional covariates on the response (Step 3). To achieve this, we used plots of the estimated random effects against the candidate covariates (and their mathematical transformations including the inverse, the square root and the squared) to identify any remaining patterns. Covariate-coefficient pairs for which patterns were observed were tested for inclusion in the model. The procedure was sequentially repeated until no further patterns were found. This resulted in the expression of the fixed effects parameters in Equations (4) and (5) as functions of the covariates:

$$[a = a_0 + a_1 \times cov_1 + \cdots + a_n \times cov_n] \quad (6)$$

where $(a_0, a_1, \ldots, a_n)$ are the fixed-effects parameters associated with each covariate. Finally, we tested if plot-level random effects were still needed after including covariates (Step 4). As recommended by Pinheiro [51], the ratio between a random effect's standard deviation and the absolute value of the corresponding fixed effect was computed to assess the inter-group variability for the coefficient. Model selection among successive fits was based on an analysis of the residuals, information criterion statistic (AIC) and the likelihood ratio tests (LR) for nested models [49].The evaluation of model performance was based on visual observations of diagnostic plots including residuals *vs*. fitted values, Q-Q plot of residuals and observed *vs*. fitted values, as well as on selected goodness-of-fit statistics. The root mean square error (RMSE) was used to represent the standard error of the estimate, and mean absolute error (MAE) was used to assess the average error associated with a single prediction [52]. Model efficiency (EF) [52] was used as a dimensionless statistic analogous to R^2, which provides information on both the degree of correlation between variables and the magnitude of the model errors. Similarly to R^2, a perfect model is characterized by EF = 1, but it can also take negative values for poor models.

Because the parameters of the nonlinear models were rather complex to interpret, we used a simulation analysis based on the fitted equations to further investigate (i) the influence of different covariates on the radial growth and stem quality and (ii) if regional differences in the values of these covariates lead to significant differences in the radial growth and stem quality potentials between both areas. Simulated data were analyzed by analysis of covariance (ANCOVA).

3. Results

3.1. Basal Area Increments

Table 3 shows the characteristics of the statistical model for $BAI5Y$ at different stages of fit. Including random effects to account for the random variability between plots significantly improved the model ($LR_{1–2} = 36.9$, $p < 0.0001$). The addition of altitude and the main competitor species was also found to be significant ($LR_{2–3} = 14.2$, $p < 0.001$). However, the difference between the groups of competitors "conifers and yellow birch" and "other species" was not significant. Both groups were thus merged, resulting in significantly different parameters for "sugar and red maple" and "other species" as dominant competitors. The presence of the covariates in the model led to a marked reduction of the standard deviations of the random effects for b and c (Table 3). This indicated that most of the plot-to-plot variation in the values of these parameters can be explained by differences in altitude as well as in the competitive environment of the trees. The ratio (R) of the standard deviations of the random effect to the absolute value of the corresponding fixed effect suggested that random effects on b ($R_b = 0.005$) and c ($R_c = 0.001$) should be tested for exclusion. This was confirmed by the lower AIC obtained when random effects were only included for a, and by the absence of a difference in fit ($LR_{3–4} = 0.02$, $p = 0.99$). A subsequent comparison with a model including no random effects revealed that a plot random effect was still needed for a ($LR = 27.6$, $p < 0.0001$). The final $BAI5Y$ model was:

$$BAI5Y_{ij} = (a_0 + \alpha_j) \times d^2h^{(b_0 + b_1 \times Alt)} \times (c_0 \times MC_{SRM} + c_1 \times MC_{OS})^{d^2h} + \varepsilon_{ij} \quad (7)$$

where Alt is the altitude of the plot (m); MC is a dummy variable taking value 0 or 1 standing for the main competitor species. Diagnostics plots of the final model given by Equation (7) were used to confirm the quality and the stability of the fit (not shown).

To illustrate how altitude influenced the radial growth of the trees, we simulated $BAI5Y$ values for the range of altitudes within the dataset, with d^2h held to a fixed value. An ANCOVA performed between $BAI5Y$ and altitude with d^2h as covariate highlighted that both the intercept and the slope of the relationship differed across the range of d^2h values. We therefore grouped d^2h into 3 classes (≤ 0.5 m^3, $0.5 < d^2h \leq 2$ m^3, ≥ 2 m^3) to simulate the $BAI5Y$ and altitude relationship. While the radial growth of small trees tended to increase with altitude, the opposite was trend was found for larger trees (Figure 3). Between 300 m and 600 m in altitude, $BAI5Y$ was predicted to increase by 30% for small trees, while it would decrease by almost 20% for larger trees.

Sample trees in plots dominated by maple had a significantly slower growth rate than other plots. For example, trees with $d^2h = 3$ m^3 in a plot dominated by any other species was predicted to grow twice as fast (74.3 cm^2/5 years) than in a plot dominated by maple trees (37.4 cm^2) (Figure 4).

Competition indices were not included in the final model because Pearson's correlation coefficients showed a very high degree of correlation between log(d^2h) and log($CI1$) ($r = −0.79$, $p < 0.0001$). An ANCOVA was performed between $BAI5Y$ and $CI1$ for our d^2h classes (≤ 0.5 m^3, $0.5 < d^2h \leq 2$ m^3, ≥ 2 m^3) showed that the slope of the relationship only was significant for the smallest trees ($t_1(100) = −2.75$, $p = 0.01$; $t_2(100) = −0.09$, $p = 0.93$; $t_3(100) = −0.17$, $p = 0.87$). Competition indices also varied over wider ranges of values for smaller stems ($\overline{CI1_1} = 16\ (\pm 13)$, $\overline{CI1_2} = 4\ (\pm 4)$, $\overline{CI1_3} = 2\ (\pm 3)$).

Table 3. Statistics of nonlinear mixed-effects models for *BAI5Y*. Standard deviations are given in parentheses. Symbols and abbreviations: (a_0, b_0, b_1, c_0, c_1) correspond to the fixed parameters associated with variables and covariates given in Equation (4) and (6), respectively; in this case, covariates are associated with b_1 and c_1 and corresponds to the altitude and the main competitor species, respectively; α_{0j}, β_{0j}, γ_{0j} corresponds to the random plot-level parameters associated with variables given in Equation 4; ε_{ij} is the residual error term; AIC: Aikake information criterion; RMSE: Root Mean Square Error; MAE: Mean Absolute Error; $MAE/\overline{BAI5Y}$: Mean Absolute Error relative to the observed mean. Step 1: fixed-effects model; Step 2: random effects model; Step3: random-effects model with selected covariates; Step 4: random effects model with covariates and selected random effects.

Step	a_0	b_0	b_1	c_0	c_1	σ_{plot} (α_{0j})	σ_{plot} (β_{0j})	σ_{plot} (γ_{0j})	ε_{ij}	AIC	$RMSE$ cm²/ 5 years	MAE cm²/ 5 years	$MAE\%$ %	EF
1	64.6 ** (6.8)	0.5 ** (0.1)		0.8 ** (0.05)					21.4	1307.6	23.7	17.7	44.8	0.38
2	54.0 ** (5.8)	0.4 ** (0.1)		0.9 ** (0.05)		16	5.0×10^{-5}	2.9×10^{-5}	21.3	1284.6	18.4	14.0	35.3	0.63
3	55.2 ** (5.7)	0.7 ** (0.1)	0.7 ** (2.2^{-4})	0.7 ** (0.08)	0.9 ** (0.08)	16.9	4.0×10^{-5}	3.0×10^{-6}	19.9	1274.4	16.8	13.1	33.1	0.69
4	55.1 ** (5.7)	0.7 ** (0.7)	0.7 ** (2.2^{-4})	0.7 ** (0.08)	0.9 ** (0.09)	16.9			19.9	1264.4	16.8	13.1	33.2	0.69

** $p < 0.01$.

Figure 3. Effect of altitude and tree size on basal area increment over a 5-year period (*BAI5Y*). Simulated values for *BAI5Y* for each size class were obtained by fixing d^2h to its mean value within each class.

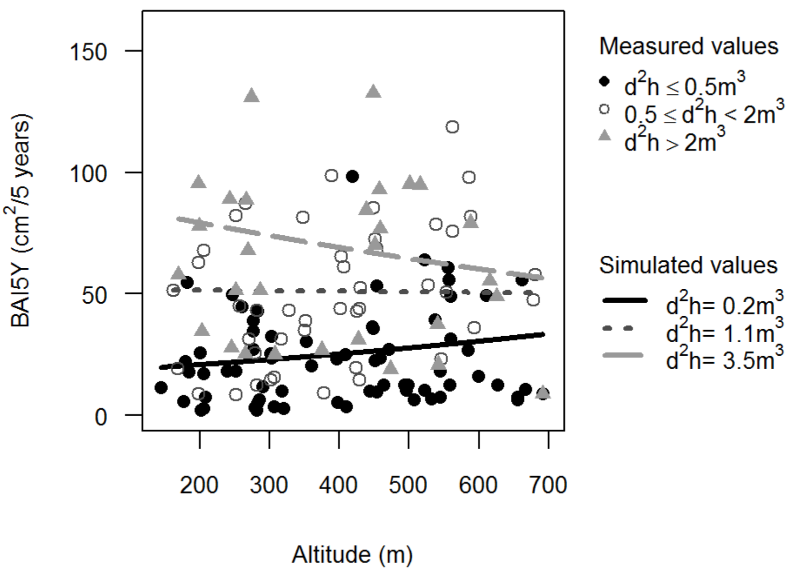
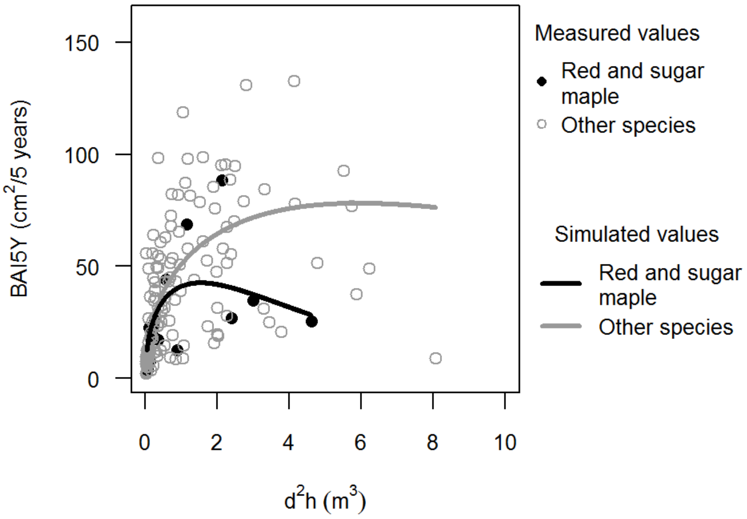


Figure 4. Effect of the main competitor species (MCS) of the subject tree on its basal area increment over a 5 years period (*BAI5Y*). Values for *BAI5Y* were simulated across the range of d^2h represented in the dataset for each class of MCS in order to remain within the domain of validity of the model. Altitude was fixed to its mean value within the dataset (397 m).



Including the geographic area in the model did not result in any significant improvement. This indicates that potential differences in radial growth between both areas would be explained by differences in the values of the covariates. There was an altitudinal gradient among the plots measured in both areas, but the overall values were significantly higher in the reference area (see Table 2, $F(140, 1) = 135.5$, $p < 0.0001$). To determine if altitude induced a difference in the growth potential between areas we performed, for each d^2h classes, an ANCOVA on the relationship between *BAI5Y* and altitude with geographical area as a factor. The results confirmed that at a given altitude there was no overall difference in the growth potential between both areas ($t_1(30) = -0.59$, $p = 0.56$, $t_2(12) = 1.07$, $p = 0.31$, $t_3(4) = -0.83$, $p = 0.45$). The competition levels around sample trees ($F_{CI1}(140, 1) = 0.029$, $p = 0.87$; $F_{CI2}(140, 1) = 0.323$, $p = 0.57$) did not differ between areas (Table 2).

3.2. Stem Quality

Table 4 shows the characteristics of the statistical model for *SLC4F* at different stages of fit. The sum of annual precipitations was found to improve the model significantly ($LR_{2\text{–}3} = 9.9$, $p = 0.002$). Again, adding a covariate strongly reduced the standard deviation of the plot-level random effects for a and c (Table 4). The ratios of the standard deviations of the random effect to the absolute value of the corresponding fixed effect suggested that random effects on a ($R_a = 0.0016$) and c ($R_c = 0.00054$) should be tested for exclusion. Comparing the simplified model with the previous fit resulted in no significant difference ($LR_{3\text{–}4} = 4.3 \times 10^{-4}$, $p = 0.99$), so these random effects were dropped. However, a comparison with a model without any random effects indicated a plot-level random effect was still needed for b ($LR = 23.7$, $p < 0.0001$). The final *SLC4F* model was:

$$SLC4F_{ij} = (a_0 + a_1 \times P) + (b_0 + \beta_j) \times exp^{c_0/d^2h} + \varepsilon_{ij} \quad (8)$$

where P is the sum of annual precipitations (mm). Again, diagnostics plots of the final model were used to confirm the quality of the fit (not shown). Figure 5 shows the important effect of tree size on *SLC4F*. The maximum *SLC4F* value of 20 was approached for only one tree in the dataset.

Table 4. Statistics of nonlinear mixed-effects models for *SLC4F*. Standard deviations are given in parentheses. Symbols and abbreviations: (a_0, a_1, b_0, c_0) correspond to the fixed parameters associated with variables and covariates given in Equations (5) and (6), respectively; the covariate is associated with a_1 and corresponds to the sum of annual precipitations; α_{0j}, β_{0j}, γ_{0j} corresponds to the random plot-level parameters associated with variables given in Equation (5); ε_{ij} is the residual error term; AIC: Aikake information criterion; RMSE: Root Mean Square Error; MAE: Mean Absolute Error; $\mathrm{MAE}/\overline{\mathrm{SLC4F}}$: Mean Absolute Error relative to the observed mean. Step 1: fixed-effects model; Step2: random effects model; Step3: random-effects model with selected covariates; Step 4: random effects model with covariates and selected random effects.

Step	a_0	a_1	b_0	c_0	$\sigma_{plot}(\alpha_{0_i})$	$\sigma_{plot}(\beta_{0_i})$	$\sigma_{plot}(\gamma_{0_i})$	ε_{ij}	AIC	$RMSE$ m	MAE m	$MAE\%$ %	EF
1	5.5 ** (0.4)		9.3 ** (0.7)	−0.6 ** (0.1)				2.4	657.1	2.4	1.9	21.0	62.0
2	5.3 ** (0.2)		8.9 ** (0.7)	−0.5 ** (0.07)	3.3×10^{-4}	1.7	1.0×10^{-6}	2.4	642.7	2.1	1.7	18.4	70.9
3	9.6 ** (1.4)	−5120.9 ** (1579.0)	8.9 ** (0.7)	−0.4 ** (0.07)	1.6×10^{-4}	1.5	2.0×10^{-6}	2.3	634.9	2.1	1.6	18.0	71.3
4	9.6 ** (1.4)	−5118.6 ** (1579.1)	8.9 ** (0.7)	−0.4 ** (0.07)		1.5		2.3	630.9	2.1	1.6	18.0	71.3

** $p < 0.01$.

An ANCOVA performed with our classes of d^2h revealed that differences in intercept values were only significant between the following two classes of d^2h: ≤2 m^3 and ≥2 m^3. As illustrated on Figure 6 trees in plots with more precipitations tended to have longer clearbole sections. For a 10% increase in rainfall, *SLC4F* was higher by 5.5%.

An ANCOVA performed between *SLC4F* and *CI1* with d^2h as categorical covariate showed that although intercepts were significantly different ($t(100) = 20.4$, $p < 0.0001$), the relationship between *SLC4F* and *CI1* was equivalent across d^2h classes ($t(100) = 1.5$, $p = 0.14$). A subsequent test performed with 3 classes of d^2h (≤0.5 m^3, $0.5 < d^2h \leq 2$ m^3, ≥2 m^3) highlighted that the slope of the relationship was not significant for any of the size classes ($t_1(100) = -1.6$, $p = 0.10$; $t_2(100) = 0.36$, $p = 0.71$; $t_3(100) = 0.75$, $p = 0.45$). This result indicates that contrarily to radial growth, stem quality was not found to be sensitive to the competitive environment, for a given tree size.

As for *BAI5Y*, including the geographical area in the *SLC4F* model did not result in any further improvement, which suggests that variations in stem quality can be statistically explained by local differences in precipitations. Precipitations were higher in the reference area than in the restoration area (see Table 2, $F(140, 1) = 1182$, $p < 0.0001$). An ANCOVA performed between *SLC4F* and precipitations with area as a factor for the two d^2h classes previously mentioned did not reveal any significant interactions ($t_1(39) = 1.72$, $p = 0.09$; $t_2(99) = 0.31$, $p = 0.76$). This confirms that for a given amount of precipitations both areas would have the same potential to produce high quality logs of yellow birch.

Figure 5. Measured against predicted values from Equation (8) highlighting the important effect of the volume of the tree (d^2h) on the longest clearbole section on each of the four faces (*SLC4F*) of the stem.

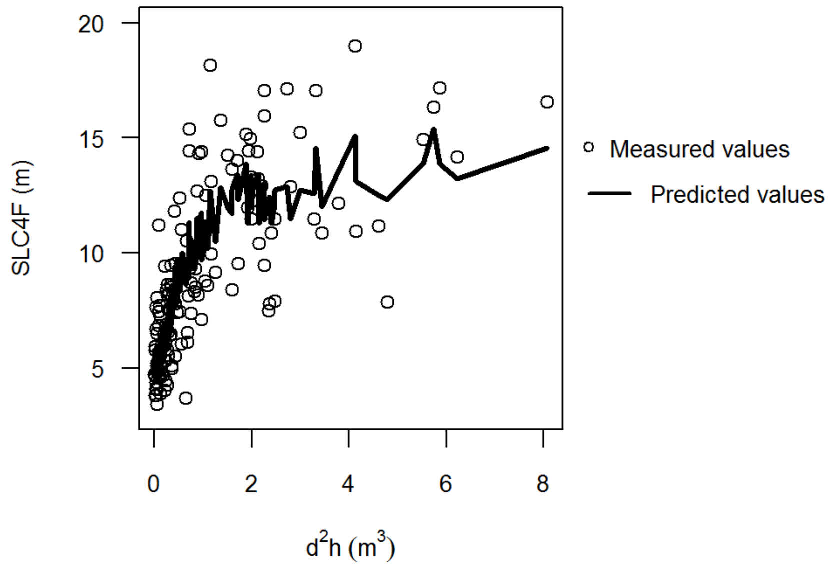
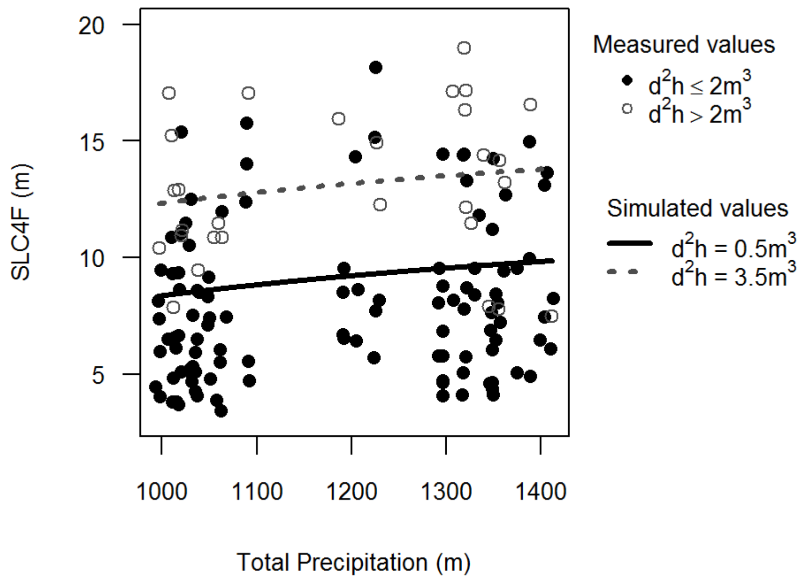


Figure 6. Effect of the annual amount of precipitations (mm) on the sum of the longest clearbole sections on each of the four faces (*SLC4F*) of the stem.



4. Discussion

Overall, our results confirm the potential of yellow birch to grow and eventually constitute a significant source of quality sawlogs in the Charlevoix-Lower-Saguenay region. For given site conditions and competitive environments, the restoration and reference areas showed identical potentials for growth and stem quality. Although this confirms our initial hypothesis, it also raises questions about the observed difference in forest composition. The silvicultural history of the stands sampled in this study was unknown, so it was not possible to determine to which extent forest practices could have differed between the two areas. However, the prevalence of trembling aspen in the Charlevoix-Lower-Saguenay region may be the result of escaped settlement fires, which were commonly used for the development of agriculture in the region less than 100 years ago [31]. Similar impacts of settlement fires have been reported in other regions of Quebec [17,53].

In any case, the warmer climate observed in Charlevoix-Lower-Saguenay confirms that conditions are not those of boreal forests, which are beyond the northerly limit of yellow birch [18]. Like in Portneuf, the hardwood component of late-successional mixedwoods stands should therefore be typically composed of yellow birch instead of trembling aspen or white birch [54,55]. Despite the fact that ecological site classifications already identify the balsam fir–yellow birch association as the typical late-successional forest composition on mesic sites [15,29], forests of the region are usually managed to maintain a mixture of balsam fir and trembling aspen. We suggest that our results are used as a basis for an evaluation of the long-term financial implications of restoration measures for yellow birch. Stumpage prices and end-products value have historically been much higher for yellow birch than for trembling aspen sawlogs [56]. There may thus be synergies between the ecological and economical dimensions of this issue.

Our results can help identify suitable sites for the restoration of yellow birch. For instance, stem quality tended to be higher in sites with higher annual precipitation. Although a direct causal link between stem quality and precipitations is unlikely, this finding is consistent with the fact that yellow birch grows well in cool climates with abundant precipitation [18]. However, precipitations were generally lower in Charlevoix-Lower-Saguenay than in Portneuf. Restoration measures in the former area should therefore be initiated in sites receiving the largest amounts of precipitations, which are often located at higher altitude.

Altitude was found to have an effect on radial growth, but the relationship was more difficult to interpret due to an interaction with stem size. For large trees, the slower radial growth at higher altitude may be a consequence of the harsher climatic conditions. However, the faster radial growth of small stems at higher altitude was unexpected. We can hypothesize that this was due to an interaction with competition. Indeed, small trees were more affected by competition than bigger trees in this study, which was expected due to their respective positions in the canopy of uneven-aged stands. In such situations, the less vigorous growth of large competitors at a high altitude might have benefited the smaller stems in lower canopy positions.

In terms of forest composition, the presence of sugar and/or red maple also appeared to affect the growth of yellow birch. Sugar maple can be an efficient competitor in such forests. Its high tolerance to shade makes it prone to the establishment of dense advance growth, which can develop vigorously when a gap is created in the canopy [57,58]. Its presence in the forest cover has increased markedly following anthropic disturbances such as fires for colonization and forest cuts [11,17]. It is also the dominant species of the bioclimatic domain immediately to the south of our study areas. Red maple's presence in North American deciduous forests was found to increase as a result of selective harvesting of yellow birch and sugar maple [18]. It also has the capacity to sprout vigorously after a cut. Therefore, initial restoration efforts in the Charlevoix-Lower-Saguenay region should avoid sites already dominated by maple trees, which are likely to occur where the best growing conditions prevail.

As indicated by its more northerly natural distribution limit [18], yellow birch should tolerate the harsher site conditions that typically prevail in the upland sites of the region.

Although the recommendations made here apply to a regional case study, our methodology may have broader applicability. Uncertainties about the growth and stem quality potential can represent important limiting factors for restoration efforts of any hardwoods. In such species, poor stem morphology and/or the prevalence of defects can lead to the absence of any valuable sawing material in a given tree [59]. The capacity to produce sawlogs will be largely unknown if the targeted species only has a marginal occurrence in a given forest area. In such cases, a tree-level modeling approach such as that used in this study can prove useful. One advantage of studying the growth of individual stems scattered in the landscape is that it can help provide a more rapid assessment than empirical studies based on the establishment of new trees. Unlike historical studies [7,9,11,12], it also provides an assessment of the current capacity to grow in a given area. With the rapid pace of environmental change and the complexity of anthropic disturbances, Hobbs *et al.* [60] argued that restoration should consider the 'novel' characteristics of ecosystems. In our restoration area, both the current presence (although limited) and current growing capacity of yellow birch were confirmed by this study.

In terms of stem quality, our assessment using a continuous value between 0 and 20 m of clear bole differs from other hardwoods stem quality classifications used in practice by being independent of the tree DBH [35–37]. This has for advantage to allow a stem quality assessment for a wide range of tree sizes. Our model shows that the sum of clear bole lengths on four faces of the stem tends towards an asymptote at $d^2h \approx 5$. The increase up to this point reflects the self-pruning that occurs as the tree develops and is subjected to competition for light. Beyond this point, stem quality may stop improving due to the appearance of defects on the bole, such as cankers, or stem cracks [35]. Such defects are also likely to affect internal wood properties, which were not directly considered in this study. For end-uses such as flooring and furniture, the value of lumber pieces might be affected by the presence of red heartwood within the stems [61]. This discoloration of the xylem is known to have a traumatic origin, and unpruned dead branch stubs constitute the main entry points along the stem [62,63]. Future work could therefore aim to link the external stem growth and quality models from this study with the internal model of red heartwood development proposed by Havreljuk *et al.* [61].

5. Conclusions

Our results support our initial hypothesis that there is a potential to grow high quality yellow birch stems in our restoration area. For a similar altitude, precipitation level and competitive environment, there were no differences in stem growth or quality between the restoration and the reference areas. Despite the fact that different climatic conditions prevail in each area, the production of quality yellow birch appears as a realistic goal in the Charlevoix-Lower-Saguenay region, at least for sites located at higher altitude. In addition to ecological considerations, the implementation of restoration measures should be motivated by the fact that alternative species such as trembling aspen, are of lower commercial interest than yellow birch. Sites dominated by sugar and/or red maple should not be favoured for investments in restoration treatments, because competition from these species was found to restrict the radial growth of yellow birch. Mesic sites, where the forest succession should naturally evolve to a balsam fir–yellow birch composition, should be prioritized. The competitive environment was confirmed as an important driver for radial growth and stem quality development. Silviculturists may use the models developed in this study to feed further empirical trials that aim to find an optimal balance between radial growth and the development of a defect-free bole.

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Conflicts of Interest

The authors declare no conflict of interest.

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