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silviculture

Potential for Sugar Maple to Provide High-Quality Sawlog Trees at the Northern Edge of Its Range

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The management of sugar maple (*Acer saccharum*) at the northern edge of its range is mainly oriented toward timber production, from trees of higher grades. However, both the quality of mature trees in natural stands and how the quality may vary depending on the silvicultural treatment are unknown, especially under northern conditions. The objective of this study was to describe the variation in stem quality of mature maple trees (diameter >33 cm) according to climatic, geographic or soil variables, and to evaluate the effects of a first selection cutting cycle on this quality. Annual temperature (1.7–4.1° C) was the most important variable explaining differences in the proportion of higher-grade trees, with a 16 percent gain associated with every additional increase in degrees Celsius. The practice of a first selection cutting was associated with an 11 percent gain in this proportion. Although the actual proportion of high-quality trees was below 35 percent on the coolest sites, a proper tree selection through silviculture could likely improve this proportion in future decades, whereas the potential effects of climate change are unclear.

Keywords: selection system, tree grade, climate change, stand improvement, stand quality

Sugar maple (*Acer saccharum* Marshall) is one of the most abundant hardwood species in eastern North America (Godman et al. 1990). Its primary range extends between 35° and 48° latitude north, from the state of Tennessee (United States) to the province of Québec (Canada). Several studies have suggested that the climate of the region has become warmer and wetter over the past 100 years. Climate models predict that the region will become even warmer and wetter in the future, but may also be more prone to drought (Rustad et al. 2012). Following the anticipated changes in climate, the climatic range of sugar maple is expected to move northward (Périé et al. 2014). Consequently, growing conditions for sugar maple stands now located at the northern edge of the species' range could improve if both temperature and summer precipitation increase; this would make management more attractive in the future.

However, the incentive to manage sugar maple depends on the potential financial return. In some forests near cities and towns in the northeastern part of the species range, sugar maple stands are used for syrup production. Otherwise, maple stands are mainly managed for timber production. For the harvest of sugar maple to be profitable under conditions found in the most remote forests, it is necessary to also be able to harvest a minimum volume of high-value logs from trees of higher grades, stem forms, or vigor classes (Hanks 1976, Fortin et al. 2009a, Cecil-Cockwell and Caspersen 2015, Castle et al. 2017). The minimum required varies according to distance to markets and market prices.

The potential of sugar maple to produce high-quality trees at the northern edge of its range is not well documented, and its growth potential under anticipated climate warming is unknown. Sugar maple on northerly sites is known to be affected by frost cracks and to have a high proportion of red heartwood, or dark heart, both of which reduce its value for lumber (Burton et al. 2008, Havreljuk et al. 2013, 2014). Trees from one northern site have shown a lower proportion of high-grade lumber than expected from studies in the northeastern American states (Bédard et al. 2019). The quality of standing hardwood trees, as

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commonly described by Hanks (1976), has been studied mainly on more southerly sites (e.g., Strong et al. 1995, Sendak et al. 2000, Gronewold et al. 2012, Brown et al. 2017).

Previous studies have not clearly demonstrated that long-term selection cutting management in mature or old-growth stands (hereafter referred to as mature stands) can significantly affect the quality of standing sugar maple trees (e.g., Eyre and Zillgitt 1953). Indeed, most studies related to hardwood tree grades have been conducted in second-growth stands (e.g., Erickson et al. 1990, Swift et al. 2013, Schuler et al. 2016) where a natural increase in mean diameter may lead to an increase in quality simply because of the fact that larger trees can reach better grades. For instance, in Hanks (1976), the best grade (grade 1) is only assigned to trees with a dbh (measured 1.3 m above the ground) of at least 40 cm (16 in.). Moreover, several published tree grade studies lack a reference to the natural forest, either to be indicative of stand initial quality before treatment, or to provide replicated observations in unmanaged control stands (e.g., Gronewold et al. 2012). Some other studies used a regional forest inventory to estimate the potential tree grade distribution (Yaussy 1993, Power and Havreljuk 2016), but they could not capture the effects of different silvicultural practices in their region. Nevertheless, it is known that high grading practices, such as most diameter-limit harvests, can reduce the quality of hardwood stands (Nyland 1992, Strong et al. 1995). Consequently, for a given species and tree diameter class, it is uncertain whether good silvicultural practices can improve the proportion of high-quality trees observed in unmanaged mature stands.

As a result, there is a need to know what level of quality is expected to be achieved in natural stands of northern hardwood tree species at maturity, and how this level of quality may vary according to climate, site conditions, or silvicultural treatment. The objectives of this study are therefore to describe the variation in the quality of mature sugar maple trees in relation to climatic, geographic, or soil variables, and to evaluate the effects of a first selection cutting on tree quality. Emphasis is placed on the most northerly conditions, with some sites further north than the bioclimatic domain of sugar maple. The main hypotheses are that: (1) the proportion of high-quality mature trees is mainly related to temperature rather than other climatic, geographic, or soil variables, and (2) the proportion of high-quality trees is higher in treated stands than in the unmanaged reference stands.

Material and Methods

Study Area

Thirteen experimental blocks, each composed of a selection cut plot and an untreated control plot, were selected from a network of experimental blocks established from 1984 to 2005 in uneven-aged, mature, northern hardwood stands within the temperate forest zone of Québec, Canada (Tables 1 and 2, Figure 1). Sugar maple was abundant in the selected blocks (33–99 percent of the basal area); associate species varied in abundance, the most abundant being yellow birch (*Betula alleghaniensis* Britton) and American beech (*Fagus grandifolia* Ehrhart). Moreover, these blocks were selected because they were thought to have a similar history at the time of plot establishment: (1) they had not been cut for at least two to three decades; (2) the last cuts would have been of low intensity and would have targeted mainly secondary species, although sugar maple may not have been spared; and (3) they were mature stands at the beginning of the study according to the classification of Lorimer and Halpin (2014), i.e., the basal area of trees with a dbh of 26 cm or larger was at least 20 $m^2 ha^{-1}$. Mean preharvest stand basal area was 27.2 ± 0.3 $m^2 ha^{-1}$ (mean ± standard error, Table 2), of which 23.3 ± 0.5 and 5.2 ± 1.8 $m^2 ha^{-1}$ comprised trees in the 26-cm and 46-cm dbh or larger classes, respectively. The blocks cover a latitudinal gradient of mean annual temperature (1.7–4.1° C) and a longitudinal gradient (west–east) of mean annual precipitation (968–1,388 mm).

Experimental Design and Treatments

Each experimental block consisted of a plot treated with selection cutting and an untreated control plot; both treatments were randomly assigned to the plots having similar initial basal area, composition, and density (Table 2). In the treated plots, 25–35 percent of the initial basal area was harvested following tree marking in each 10-cm dbh class. In addition, tree marking prioritized the harvesting of the most defective trees, those that were susceptible to die within the first cutting cycle (20 ± 5 years, Majcen et al. 1990). Tree marking was done independently of tree grade; using a risk-product classification approximating a gradient from acceptable to unacceptable growing stock (see Guillemette et al. 2008 for more detail). This risk-product classification was developed to help tree marking and focuses on the presence of major defects increasing the risk of mortality. This system is used to rapidly assess a tree's quality on the basis of its potential to produce lumber; it is not intended to grade the specific quality of trees in the manner described in the next paragraph. Mean postharvest stand basal area was 19.1 ± 0.3 $m^2 ha^{-1}$ in the treated plots.

The plots were either 0.5 hectare or 1 hectare in area, and contained standard forestry metrics for permanent sample plots, such as tree number, status, species, and dbh. Measurements were taken prior to cutting, immediately after cutting, and every 5 years afterwards. Starting in 2005, which is between the 10th and the 25th year following a first selection cutting in the treated plots, hardwood trees were also graded for factory lumber. The tree grades used in this study (MRNQ 1995, Table 3) are similar to those commonly used in the United States after Hanks (1976). Depending on a tree's dbh, length, and number of defect-free sections on the surface of the second-worst face of the best 3.7 m log located on its butt log (first 5 m), and percentage volume deduction for crook, sweep, and rot within the log, the stems are classified into four grades (A, B, C, and D, corresponding to 1, 2, 3, and below grade after Hanks

Management and Policy Implications

This research quantified the decline in the quality of standing sugar maple trees on the coolest sites, those located at the northern limit of its range. However, it remains uncertain whether or not the quality of maple trees will increase following the anticipated climate change, because all the processes involved are not clearly understood. Indeed, an increase in temperature might not improve tree growth conditions. However, proper tree selection through a first selection cutting produced a gain in standing tree quality that was still noticeable after 10–25 years, which is currently the best way to improve the quality of these stands. Our recommendation to field foresters in preparation of silvicultural treatments for timber production under the most northerly conditions is to protect and release the smallest sawlog-sized maple trees, which have both the potential to produce higher grade sawlogs and characteristic indicators of good diameter growth, such as smooth bark.

Table 1. Main abiotic characteristics of the studied blocks.

Block	Year of cutting	Mean annual temperature (°C)	Minimum annual temperature (°C)	Mean annual precipitation (mm)	Elevation (m)	B horizon, base saturation (%)	H horizon, K/Mg ratio
Gatineau Forest	1984	4.1	–36.0	995	354	23.8	2.5
Duchesnay	1988	2.9	–36.2	1,383	320	10.1	3.0
Lac-Mégantic	1988	3.8	–34.0	1,332	515	24.9	1.9
Restigouche	1990	2.3	–35.2	1,082	273	25.0	2.0
Telfer	1990	3.5	–38.2	968	348	29.2	1.9
Bois Franc	1991	3.2	–38.4	1,013	366	21.5	2.5
Harrington	1992	4.1	–37.0	1,160	325	15.8	1.5
Lusignan	1992	1.7	–41.8	1,022	537	18.6	2.3
Sainte-Véronique	1993	3.1	–39.8	1,051	393	22.6	2.2
Sainte-Véronique	1994	2.9	–39.8	1,055	436	20.5	2.6
Mitchinamecus 1	2005	1.9	–42.4	1,030	455	17.5	2.5
Mitchinamecus 2	2005	1.8	–42.5	1,030	467	22.3	2.1
Mitchinamecus 3	2005	1.7	–42.6	1,030	482	16.7	2.6
Mean		2.8	–38.8	1,089	405	20.6	2.3

Table 2. Main biotic characteristics of the studied plots (block and treatment).

		Basal area (m^2 ha^{-1})					Initial stem	
Block	Treatment	Initial	Residual	%SM	%YB	%Beech	density (ha^{-1})	%AB
Gatineau Forest	C	25.3		93	0	1	425	32
	SC	26.1	18.7	95	0	3	398	40
Duchesnay	C	26.2		58	23	15	414	45
	SC	25.1	17.1	62	15	22	394	39
Lac-Mégantic	C	28.4		85	6	8	325	65
	SC	28.9	18.6	71	11	16	381	65
Restigouche	C	25.6		68	19	0	461	31
	SC	28.5	19.4	60	29	0	484	61
Telfer	C	26.1		71	1	26	379	73
	SC	26.5	18.0	58	2	36	432	76
Bois Franc	C	25.8		83	7	0	407	54
	SC	25.2	17.6	87	9	0	395	69
Harrington	C	29.2		61	2	21	340	64
	SC	27.6	19.1	66	2	28	328	87
Lusignan	C	27.3		56	33	0	470	28
	SC	29.3	20.2	80	18	0	476	33
Sainte-Véronique 93	C	28.3		61	14	23	487	36
	SC	27.7	19.8	73	4	22	428	50
Sainte-Véronique 94	C	29.5		99	1	0	470	41
	SC	30.5	21.6	87	6	3	474	30
Mitchinamecus 1	C	25.1		33	49	0	325	19
	SC	26.3	19.1	40	53	0	375	29
Mitchinamecus 2	C	27.0		78	21	0	413	15
	SC	28.0	20.1	86	14	0	445	32
Mitchinamecus 3	C	27.9		67	29	0	410	18
	SC	26.3	18.8	68	29	0	455	33
Mean		27.2	19.1	71	15	9	415	45

Note: C, control; SC, selection cutting; %SM, proportion of initial basal area in sugar maple; %YB, proportion of initial basal area in yellow birch; %Beech, proportion of initial basal area in American beech; %AB, proportion of sugar maple studied stems graded A or B.

[1976], respectively). The main differences between the tree grades used in Québec and those used in the United States stem from the conversion of the imperial units into metric units and the absence of a minimum diameter inside bark at the top of the grading section. Grades A and B have minimal dbh thresholds of 39.1 and 33.1 cm, respectively. Finally, a stem or crown defect, considered as the most important defect on the tree according to Boulet (2007), was also recorded on each tree. Thus, the presence of each of the defects of a tree was not completely listed, but the way to identify defects was the same for every plot.

Climatic, Geographic, and Soil Variables

Several climatic variables (30-year running average for 1981–2010) were estimated for each plot using BioSIM software (Régnière and Saint Amant 2008), which estimates local climatic conditions based upon data from the closest weather stations (mean distance: 26 km; range: 3–48 km) that are adjusted to the geographic coordinates of the plot, including elevation. The selected climatic variables were: minimum annual temperature (from –42.5 to –34.0° C), mean annual precipitation, and mean annual temperature. The geographic variables included the plot's coordinates for elevation (from 270 to 539 m), latitude (from 45.5 to 47.9°N), and longitude (from 67.2 to 78.6°W, Figure 1). From 2010 to 2013, the plots were revisited for soil sampling. A composite soil sample was also collected from two pits within each plot, for the H horizon of the forest floor and the uppermost 10 cm of the B horizon. The soil-collection procedures and physical and chemical analyses were the same as those described by Gauthier et al. (2015). The selection of soil chemical variables for testing was based on results from Ouimet et al. (2013) and Sullivan et al. (2013) on sugar maple health. From the upper 10 cm of B horizon mineral soil, the variables were Ca

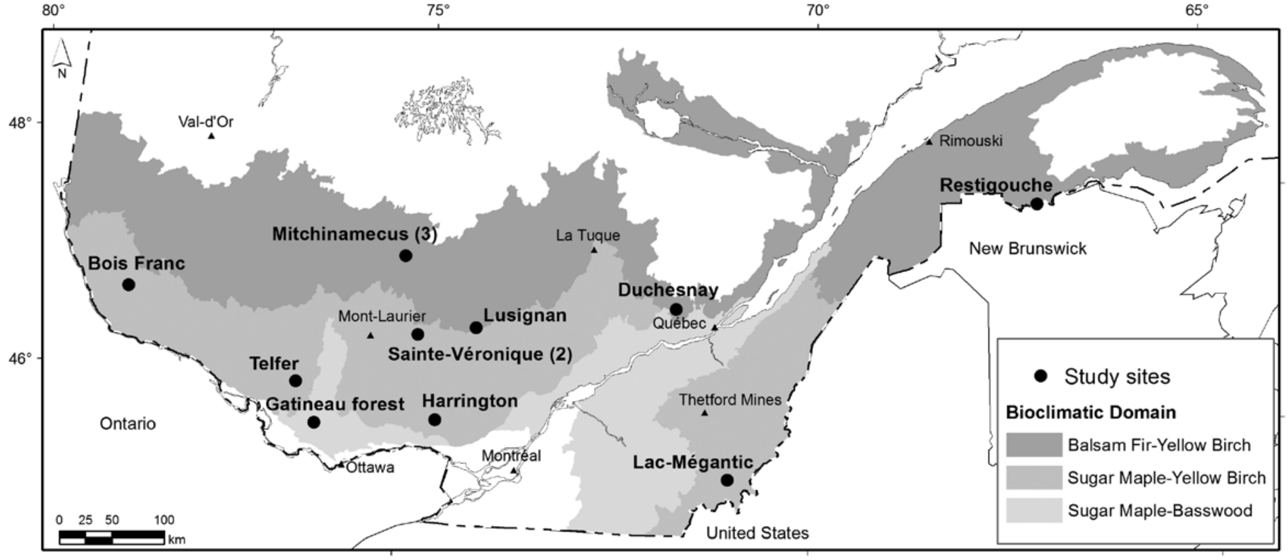

Figure 1. Location of the study blocks. The presence of more than one block is shown by the number of blocks in parentheses. Colored areas indicate the bioclimatic domains of Saucier et al. (2009): sugar maple—basswood (*Tilia americana* L.); sugar maple—yellow birch; balsam fir (*Abies balsamea* [L.] Mill.)—yellow birch.

Table 3. Main characteristics of hardwood tree grades (adapted from MRNQ 1995).

Variable	Grade A		Grade B	Grade C	Grade D
Minimum dbh (cm)	39.1	45.1	33.1	23.1	23.1
Minimum cumulated length of defect-free sections (m)	3.1		2.5	1.8	0
Maximum number of defect-free sections	1	2 of at least 1.5 m each	2 of at least 1 m each to cumulate 2.5 m	3 of at least 0.6 m each	No maximum
Maximum percentage volume deduction for crook, sweep, and rot	10		10[a]	50[b]	100

Note: [a] Could also include grade A trees with 15 percent of volume deduction for crook and sweep and a maximum volume deduction of 40 percent.

[b] Could also include grade A or B trees with a maximum volume deduction of 60 percent.

(from 5.5 percent to 26.8 percent), Mg (from 1.4 percent to 5.6 percent) and total base cation saturation (from 9.5 percent to 36.6 percent), the Ca/Mg ratio (from 4.9 to 16.5), the K/Mg ratio (from 0.9 to 4.6), and pH (in H_2O, from 4.9 to 5.3). From the forest floor H horizon, the variables were Ca saturation (from 29.9 percent to 78.1 percent), Ca/Mg ratio (from 6.7 to 13.9), K/Mg ratio (from 1.4 to 3.2), and pH (in H_2O, from 4.1 to 5.2).

Statistical Analyses and Model Selection

The proportion of sugar maple trees graded as either A or B (hereafter referred as AB) for trees having a dbh of at least 33.1 cm was modeled to identify which tree- or stand-level, geographic (including soils) or climatic variables best explained its variation. The interest in trees graded AB comes from studies indicating that these trees yield the best lumber products and have the highest lumber value (Havreljuk et al. 2014, Bédard et al. 2019). These grades are not possible for trees smaller than 33.1 cm in dbh (MRNQ 1995). There were no grade A sugar maples in three of the 26 plots, and fewer than seven in most plots. Twenty-two to 78 trees were studied in each plot, for a total of 1,163 trees.

A linear mixed model with the MIXED procedure (SAS Institute Inc. 2008) was applied to the data to model the proportion of AB trees with the experimental blocks specified as random effects. Tree grade is an ordinal measure, so it is appropriate to conduct statistical analyses on the proportion rather than on the average tree when the grades are represented by a number ($A = 1$, $B = 2\ldots$) (Brown et al. 2017). Although the dependent variable was a proportion, data ranged from 15 percent to 87 percent, with an average of 45 percent, which allowed the use of a procedure assuming normal distribution of errors and homogeneity of variances, both of which were checked visually with normalized plots of residuals.

Similar to the method presented in Guillemette et al. (2017), the difference in the corrected Akaike information criterion ($\mathrm{difAICC}_{x\text{–}y}$) between two particular models (x and y) having one differing variable was assumed to represent the contribution of the variable that differed between the models. Although the multimodel inference method of Burnham and Anderson (2002) was not used, because it required a much more balanced set of candidate models than those formulated for the purpose of this study, the method of interpretation was based on similar concepts, namely that an absolute $\mathrm{difAICC}_{x\text{–}y} < 2$ indicates that the two models are similar, whereas an absolute $\mathrm{difAICC}_{x\text{–}y} > 10$ indicates very strong evidence that the models are different. We used the particular case of one candidate model being nested in the other candidate model. In addition, the correction of the Akaike information criteria was preferred because of the small number of observations ($n = 26$).

The selection of candidate models was performed to test the effects of treatment, minimum annual temperature, and mean annual temperature, and to evaluate the possible effects of other potential explanatory variables. Stem selection through tree marking before selection cutting was assumed to have a potential effect on the proportion of AB trees 10–25 years later. The potential effect of time since cutting (10–25 years) was initially checked in the treated plots, but it was not significantly correlated to the proportion of AB trees (Pearson correlation coefficient = .53, P = .0598). In addition, because this variable involved the exclusion of the data in the control plots and the test for a treatment effect, it was rejected from the candidate variables. Hence, treatment was only considered as a categorical variable. Minimum annual temperature was previously identified as an explanatory variable in describing the amount of discolored wood in sugar maple (Havreljuk et al. 2013), which is thought to be linked to stem quality (Germain et al. 2015). Mean annual temperature is often found as a significant variable in growth models developed in the study area (e.g., Fortin et al. 2009b). The dbh increment could also influence stem quality because of the minimum diameters associated with each tree grade.

Because of the high number of other possible explanatory continuous variables and expected correlations between some variables, a cluster analysis was performed with the VARCLUS procedure (SAS Institute Inc. 2008). Within each cluster, a variable having both a low inter- and high intracluster correlation was selected for inclusion in the candidate models. As shown in Table 4, the base saturation of the B horizon, latitude, mean annual precipitation, elevation, and K/Mg ratio of the H horizon were selected to represent the clusters 1–5, respectively. In addition, multicollinearity of the candidate continuous variables in the models was checked using the variance inflation factors (VIF) and the COLLIN options presented in the REG procedure (SAS Institute Inc. 2008). Moreover, Pearson correlation coefficients (r) and tests of the correlation being significantly different from 0 (P value) were calculated using the CORR procedure for the independent continuous variables listed above (SAS Institute Inc. 2008). Candidate models were not allowed to include variables that were significantly correlated ($P < .05$).

The full model (1) included the five variables representative of clusters 1–5 and the treatment effect. Candidate models 2–8 were developed to evaluate the difference in AICC from this full model after either a model simplification or the replacement of a variable. Models 2–7 accounted for the effect of removing one of the clusters or the treatment variable. Model 8 accounted for the replacement of latitude by mean annual temperature in cluster 2, which is a variable of interest in this study. It was not possible to develop a candidate model based on model 1, but in which the variable representative of cluster 3 would have been minimum annual temperature instead of mean annual precipitation, because of significant correlations with both latitude (r = .44, P = .0241) and elevation (r = .55, P = .0038). Models 9–13 represent simpler models with combinations of minimum annual temperature, mean annual temperature, and treatment. Note that no model includes both minimum annual temperature and mean annual temperature, because these two variables were too closely correlated (r = .73, P < .0001), although they were not in the same cluster. Model 14 is an empty model, i.e., with only an intercept and without an explanatory variable. The AICC of each candidate model was calculated using the maximum likelihood method in the MIXED procedure, whereas the parameters of the best model (lowest AICC) were estimated using the residual (restricted) maximum likelihood (REML) method (SAS Institute Inc. 2002).

Finally, to better support the discussion of the results, correlations (r) with the continuous variables listed above were calculated for two other variables: mean dbh increment of the 10 years preceding tree grading (0.9–3.8 mm yr^{-1}) and the proportion of trees in which a crack was noted (14–43 percent).

Results

Model 11 (treatment and mean annual temperature) was the best model with an AICC of –27.6, whereas the next closest model (model 9) had an AICC of –23.2 and a difAICC$_{9\text{–}11}$ of 4.4 (Tables 5 and 6). This second best model included minimum annual temperature instead of mean annual temperature, which are two significantly correlated variables (see Methods). The proportion of AB trees was 11 percent higher in the selection cutting treatment, and increased with mean annual temperature (Table 6 and Figure 2). On the coldest sites, the proportion of AB trees ranged from 15

Table 4. Results of the cluster analysis, with the coefficient of determination (R^2) of each variable within the cluster and of each variable with the next closest cluster.

		R^2	
Cluster	Variable	Within the cluster	With the next closest cluster
1	**B horizon, base cation saturation**	.9789	.3041
	B horizon, Ca saturation	.9160	.3037
	B horizon, Mg saturation	.7972	.3276
2	Mean annual temperature	.7363	.1230
	Latitude	.8426	.0573
	B horizon, pH	.3417	.1065
	H horizon, Ca/Mg ratio	.3423	.0719
3	**Mean annual precipitation**	.7282	.0894
	Minimum annual temperature	.6817	.2786
	Longitude	.6689	.0881
4	**Elevation**	.6492	.1044
	B horizon, Ca/Mg ratio	.4728	.1497
	B horizon, K/Mg ratio	.6608	.1874
5	H horizon, pH	.6689	.3396
	H horizon, Ca saturation	.5408	.2204
	H horizon, K/Mg ratio	.8183	.1524

Note: Within each of the five clusters, the variable in bold was selected first for modeling.

percent to 33 percent, whereas it ranged from 64 percent to 87 percent on the warmest sites. However, both plots in the Gatineau Forest showed a considerable gap with the general model. Although a part of the variation in the proportion of AB trees was explained by mean annual temperature, this variable was not significantly correlated to the previous 10-year mean dbh increment of the trees (r = .003, P = .9881, 2.2 ± 0.1 mm yr^{-1}) or to the proportion of trees in which a crack was noted (r = .13, P = .5271, 26.7 percent ± 1.7 percent).

The worst models are those with a higher AICC value than that of the empty model, model 14, which only has an intercept (AICC = −14.4, rank = 9). Models 1 (difAICC$_{1-14}$ = 0.7), 9 (difAICC$_{9-14}$ = 0.9), 5 (difAICC$_{5-14}$ = 3.2), 7 (difAICC$_{7-14}$ = 3.6) and 3 (difAICC$_{3-14}$ = 3.8) all include mean annual precipitation and the variables of clusters 1 and 5, which only represent the soil chemical properties.

Discussion

Results corroborated our two hypotheses. Compared to untreated plots, the proportion of trees graded as A or B for factory lumber was higher 10–25 years after selection cutting (hypothesis 2) and increased with mean annual temperature in the study area (1.7–4.1° C, hypothesis 1). The treatment effect was expected because of the effect of tree marking to improve the quality of the residual growing stand. The models that included minimum annual temperature (from −42.5 to −34.0° C) closely followed those containing mean annual temperature, but had higher AICC values. The two climatic variables were closely correlated.

This temperature effect was not correlated to previous 10-year dbh increment of the trees or to the proportion of cracks noted on the trees. Consequently, the fact that sugar maple trees are of a higher quality on sites with higher temperatures is not the result of a higher dbh increment in the recent past. The trees were not cored to determine their age, but younger sugar maple trees are expected to produce higher-quality logs and products (Dey et al. 2017), whereas trees exposed to long periods of suppression are expected to grow slower and to contain more defects (Baral et al. 2016).

Moreover, under lower-temperature regimes, it is expected that the freezing temperatures will extend later into spring, a factor associated with a higher decay extent (Frank et al. 2018). As previously discussed by Burton et al. (2008), a high proportion of trees with frost cracks is typical of regions characterized by prolonged periods of low temperatures in winter, sudden large changes in temperature, and the presence of injuries (natural or logging). Injuries reduce the surface area of intact wood that has to resist the tangential tensions because of humidity and temperature gradients in the wood. This in turn increases the risk of crack formation under low temperatures (Kubler 1983). The variation in mean annual temperature among the studied sites may not have been large enough for us to observe a significant variation in the occurrence of cracks. In addition, the study variables described annual averages, but did not capture specific episodes of climate extremes that could affect crack

Table 5. Variables in each of the 14 candidate models, their AICC values, and the rank of the models.

		Cluster and selected variable								
		1	2	2	3	3	4	5		
Model	Treatment	B hor., base saturation	Latitude	Mean annual temperature	Mean annual precipitation	Minimum annual temperature	Elevation	H hor., K/Mg ratio	AICC	Rank
1	1	1	1		1		1	1	−13.7	10
2	1		1		1		1	1	−18.0	6
3	1	1			1		1	1	−10.6	14
4	1	1	1				1	1	−17.6	8
5	1	1	1		1			1	−11.2	12
6	1	1	1		1		1		−17.7	7
7		1	1		1		1	1	−10.8	13
8	1	1		1	1		1	1	−13.5	11
9	1					1			−23.2	2
10						1			−18.4	5
11	1			1					−27.6	1
12				1					−21.6	3
13	1								−19.1	4
14									−14.4	9

Note: The presence of a variable in a model is denoted with a 1.

Table 6. Parameter estimates and statistics of model 11.

Model Effect		Estimate	Standard error	t value	Probability > |t|
Intercept		−0.0586	0.1158	−0.51	.6204
Treatment	Selection cutting	0.1054	0.0291	3.62	.0030
	Control	0.0000			
Mean annual temperature		0.1601	0.0383	4.18	.0010
Covariance Effect		Estimate		Z value	Probability > Z
Block		0.0132	0.0070	1.89	.0292
Residual		0.0059	0.0024	2.45	.0072

formation. We would have needed meteorological stations installed at each site over a very long period to study this phenomenon in greater depth. In addition, the methods did not include a complete census of every crack on each tree. Instead, only the worst defect for each tree was recorded according to the classification of Boulet (2007). A crack was only noted if a fungus, a canker, or a major scar was not observed on the bole of the tree. The absence of any correlation between temperature and the occurrence of cracks remains to be further investigated in the study area.

The most evident outlier plots were in the Gatineau Forest (Figure 2). The effect of past high-grading in the Gatineau Forest may have been underestimated and could have resulted in a lower-than-expected quality of the sugar maple trees. In fact, the previous 10-year dbh increment of the trees for this site (1.7 mm yr^{-1}) was much lower than generally expected (3 mm yr^{-1}) at the beginning of the study; thus the largest studied trees could be remnants of a previous high grading (see Methods). Another possible explanation is that the mean annual temperature in the Gatineau Forest (Table 1) is among the highest in the study area, and the growing season is characterized by frequent droughts, which is not the case for other sites. Drought can induce stress in trees, reducing their growth and vigor, and increasing the risk of insect damage, such as those related to the sugar maple borer (*Glycobius speciosus* [Say]). This type of damage was observed on 15 percent of the maple trees on the Gatineau site, compared to an average of 7 percent on all the studied sites combined. The sugar maple borer wounds the tree, and the exposed wood is susceptible to stain and rot that potentially reduces the tree's quality for lumber. Moreover, this site was also affected by the 1998 ice storm, which caused tree crown breakage.

Comparison of these results with other experiments is limited because of differences in methods, stand composition, climate, and stand structure. The most comparable results are from the Upper Peninsula of Michigan (mean annual temperature: 5° C) in a long-term experiment of selection cutting within a sugar-maple-dominated forest (Gronewald et al. 2012). More than 50 years after the beginning of the study, 44 percent to 58 percent of the trees with a dbh >36.9 cm were grade 1 or 2 (or approximately the grade AB in this study). In second-growth pole size northern hardwood stands located in northeastern Wisconsin (5° C), Strong et al. (1995) observed that 57–66 percent of the trees (dbh > 24.3 cm) reached grades 1 or 2 (grade AB) after a fifth 10-year cutting cycle of selection cutting. Some studies on more southerly sites evaluated only the proportion of grade 1 trees (grade A in this study). In the Allegheny Mountains of West Virginia, this proportion was between 20 percent and 50 percent over a 25-year period of selection cutting management in six forest compartments (Brown et al. 2017). These results are in contrast to the data in the present study, in which the presence of grade A trees was sometimes nil, if not very low. Merging grades A and B presents the advantage of simplifying tree grading in the forest.

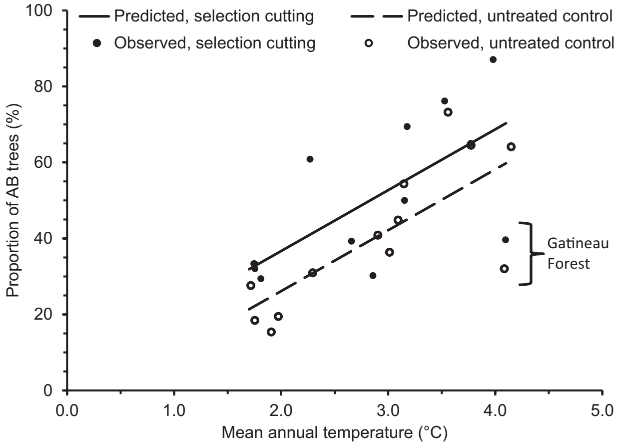

Figure 2. Observed and predicted proportions of sugar maples graded AB according to the mean annual temperature of the site and the plot treatment.

These results also support the possibility that sugar maple stands now located at the northern edge of its range could gain in stem quality in some regions under anticipated climate warming. However, this remains uncertain because all of the processes involved in these changes are not clearly understood, such as the absence of a strong correlation of temperature with either dbh growth or the presence of cracks on the boles. For instance, in a study of growth chronologies of sugar maple trees in the Adirondack Mountains of New York, Bishop et al. (2015) reported that only a small minority of trees increased their growth rates during a period in which the climate should have been more favorable to maple (warmer and wetter growing seasons). Moreover, results obtained in the Gatineau Forest could also indicate the possible negative impacts of a warmer climate on tree quality. Indeed, the climate in this region is already among the warmest in the study area. The growing season is also longer and is characterized by frequent droughts, a condition similar to the conditions predicted by climate models for the future (Rustad et al. 2012). In addition, insects and diseases could increase their damage to stressed trees. If climate change results in improved growing conditions at the northern edge of sugar maple range and improved tree quality development, it could take several decades for the benefits to be observed in the harvests because of the long period of tree development necessary for the production of high-quality logs.

Implications for Management

These results highlight the challenge of managing sugar maple stands for lumber production at the northern edge of its range, as the proportion of high-quality trees (grades A or B) can be low (15–33 percent). In addition, these trees are more prone to having a large dark heart that reduces log grade, as indicated by two of the variables reported by Germain et al. (2015): lower tree grade (this study), and frequent trees with a rough or flaky bark type associated with slower growth (Gauthier and Guillemette 2018). Nonetheless, these results indicate that the selection system and the tree marking rules used in this study to remove low-vigor and poor-quality trees could improve stand quality. However, this silvicultural system is often difficult to apply because of the poor market for low-quality trees. Still, there may be potential for quality improvement over the long term with a warmer climate and proper tree selection, such as what was done through tree marking for selection cutting. Removing poor quality and nonvigorous trees and maintaining structural diversity with the selection system should also help to favor forest resilience. Indeed, silvicultural scenarios could be developed to protect and release trees with a dbh smaller than 34 cm having a smooth bark type, a high growth potential, and a butt log having the potential for grade B or better. The scenarios could be modeled to identify one or more quality thresholds below which the development of these maple stands for timber production would not be profitable. In the mean time, management options for these stands should focus on developing markets for lower-value products, such as firewood, pulpwood, or biomass. Regions and sites that are already susceptible to drought and prone to become drier under future climate conditions should also be considered as less suitable for the production of high-quality sugar maple lumber.

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