Assessing the effects of sugar maple tapping on lumber production

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ABSTRACT
Production goals for certain stands previously used mainly to produce sugar maple (*Acer saccharum* Marsh.) lumber are being revised due to the growing demand for products made from maple sap. This paper therefore estimates the impacts that maple sap production may have for maple lumber production. We began by developing a model able to predict sugar maple lumber losses due to tapping for sap collection. We then used the model to simulate two management scenarios: one for timber production alone, and one for production of both lumber and maple sap in the same stand. The results suggest that the net harvested volume of lumber declines by approximately 40% in the co-production scenario, compared to the timber production scenario.

Key words: maple syrup, hardwood lumber, selection cutting, tapping

RÉSUMÉ
La demande croissante des produits confectionnés à partir de la sève d'érable amène à revoir les objectifs de production pour certains peuplements qui étaient jusqu'à présents destinés à une production prioritaire de bois d'œuvre d'érable à sucre (*Acer saccharum* Marshall). Il est donc pertinent d'estimer les impacts que la production acéricole pourrait avoir sur la production de bois d'œuvre d'érable à sucre. Nous avons d'abord mis au point un modèle permettant de prévoir la perte de bois d'œuvre dans un érable à sucre causée par l'entaillage pour la collecte de la sève. Nous avons ensuite utilisé ce modèle pour simuler deux scénarios d'aménagement : un pour la production de bois d'œuvre seule et un pour la co-production de bois et de sève dans un même peuplement. Les résultats obtenus suggèrent que le volume net de bois d'œuvre récolté d'érable à sucre est diminué d'environ 40 % dans le scénario de co-production comparativement au scénario de production de bois.

Mots-clés : acérico-forestier, acériculture, bois d'œuvre feuillu, coupe de jardinage, entaillage


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Introduction

Canada's forests cover an area of 3.6 million km^2, and approximately 2.6% (95 500 km^2) of these forests are maple-dominated stands (IFNC 2021), i.e., stands dominated by sugar maple (*Acer saccharum* Marsh.) and red maple (*Acer rubrum* L.). In the United States, forests and woodlands account for roughly one-third of the country, covering an estimated 3.3 million km^2. More than 13% (approximately 440 000 km^2), mostly in the north-eastern portion of the country, is occupied by maple-dominated stands (Oswalt *et al.* 2019).

Maple sap is harvested (maple production) from maple-dominated stands in these two countries, mainly in the eastern provinces of Canada (Ontario, Québec, New Brunswick) and the north-eastern American states (Maine, Wisconsin, Michigan, New Hampshire, New York, Pennsylvania, Ver-

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mont). The main maple product is maple syrup, but other products such as pure maple water and a large number of derivatives including maple sugar and maple candies are also sold. In 2018, the global market value of maple syrup was US $1.24 billion, a figure that is expected to rise to US $1.7 billion in 2023 (Atlantic Corporation 2019). Québec, which produces 92% of Canada's maple syrup, is the largest producer in the world, accounting for 71% of global production in 2016-2020 (MAPAQ 2021). The growing food demand for maple products supports an increase in production (MAPAQ 2021).

The forestry industry also occupies an important place in the North American economy and as a result, maple forests are also sought-after as a source of hardwood lumber. In 2020, Québec produced 922 000 m^3 of hardwood lumber, or 93% of Canada's total production (Delisle 2021), while the United States produced 18 million m^3 in 2019 (HMR 2020). Despite the demand for maple saw logs, maple syrup production would still be more profitable than wood production for forest owners (Ouimet *et al.* 2018).

A private landowner or a State owner of public land can choose the type of production on which to focus: hardwood lumber, maple products or other resources. In the case of maple products, the trees must be tapped every year by drilling holes in the trunks to harvest the sap. This creates wounds that impact butt log lumber potential. Tap holes are considered defects, and they diminish the manufacturing value of boards (NHLA 2007). In addition, tapping causes the wood to become stained around the tap hole because the tree reacts to the wound by producing chemical substances to protect against infiltration of air and micro-organisms (Houston *et al.* 1990). Staining occurs over an area of approximately 1.25 cm on either side of the tap hole and up to 46 cm or more above and below the tap hole (Houston *et al.* 1990). It therefore reduces the value of sugar maple boards; in Québec, for example, prices can double, depending on whether the board is stained (dark brown wood) or pale (sapwood) (source: Bureau de mise en marché des bois, Ministère des Ressources naturelles et des Forêts). There is also a process known as compartmentalization, or the erecting of anatomical barriers (Shigo and Marx 1977). While these barriers are designed to limit the spread of the micro-organisms responsible for staining and rot, laterally, radially, and vertically, they also prevent sap from circulating, meaning that the compartmentalized area cannot be used to harvest sap.

Little research has been done into lumber volume lost to tapping (Farrell 2012). Sendak *et al.* (1982) carried out a study in Vermont in 1975 in four stands with apparently variable tapping histories: one stand had only been tapped for three years, and the tapping history of the other three had not been published. By cutting the butt logs, they estimated an average loss of approximately 5% of the board value. They also noted that their estimate did not include situations in which the butt logs were rejected from log batches to reduce the risk of equipment damage from overgrown metal objects left in the trees after maple production activities.

In the current context, where maple forests used exclusively for lumber production could now be used for sap production as well, it would be useful to estimate the impacts that sap production may have on sugar maple lumber production. The question arises mainly in connection with public forests and with forestry companies that own large tracts of forests. While these areas are often assigned to wood processing mills that have specific supply expectations, they are also sought-after for sap harvesting. The question also arises in connection with uneven-aged mature stands that are managed by selection cutting which consists in thinning the stand by harvesting some trees in order to stimulate growth of the remaining while fostering the establishment and development of regeneration (Chapeskie *et al.* 2006; Guillemette *et al.* 2013). The objectives of this study are: 1) to estimate the impacts of tapping on sugar maple lumber production; and 2) to assess management scenarios in which lumber and sap could both be produced simultaneously in a single uneven-aged mature stand.

Materials and methods

We began by developing a model to estimate lumber loss due to abandonment of tapped sugar maple butt logs, and we then simulated two management scenarios over a 30-year period: selection cutting with and without taps and, in both cases, production of sugar maple lumber. In the no-tap scenario, the volume of lumber in the trees was at the maximum level, while in the tap scenario, it was reduced by the volume of abandoned butt logs where those logs were lumber grade.

Lumber content modelling

The sugar maple lumber prediction model developed by Havreljuk *et al.* (2015) was used for the trees that were not tapped. For the tapped trees, we developed a method to remove a portion of lumber from the trees that were used to calibrate Havreljuk *et al.* (2015)'s model, and then added the tap effect to the model (taps present = 1, taps absent = 0).

Data

The database used in the model was composed of 2080 sugar maple trees sampled between 2002 and 2014 by the Ministère des Ressources naturelles et des Forêts du Québec at 17 sites located in Québec's public forests (Havreljuk *et al.* 2015). These trees, all of which had a diameter at breast height (dbh 1.3 metres from the ground) of at least 23.1 cm, were selected prior to harvesting. In addition to measuring dbh, the MSCR (Boulet and Landry 2015) class was also noted. The MSCR system is used to classify trees by probability of mortality in the next cutting cycle based on the presence of defects. It was used in the growth simulation along with the SaMARE model (Fortin *et al.* 2009) and was also used to model the wood products. In this system, trees are classified as moribund (M), surviving (S), growth for conservation (C) or reserved (R), in decreasing order of probable mortality. M trees often exhibit fungal infections, extensive rot, or crown dieback; S trees often have cracked trunks or small amounts of rot; C and R trees are considered to be healthy and vigorous. C trees usually have small defects that do not affect survival, such as crooks or curved trunks.

Once cut, the trees were bucked into logs and classified according to quality using the Canadian method developed by Petro and Calvert (1976), which is similar to Rast *et al.* (1973)'s American rules. At this stage, logs were identified as suitable for conventional sawing, and those of lesser quality were sent for pulp production. Some non-conventional saw logs (bolts) were identified during the classification process, but they were marginal in terms of volume (see Havreljuk *et* *al.* 2015). We therefore had a database containing the dendrometric characteristics and quality classifications of every log for every sampled tree. For additional details of the methodology used in forest product data collection see Havreljuk *et al.* (2015).

Portion affected by tapping

To assess the portion of the trunk affected by tapping, we used tap height and snow cover data gathered at two research sites (Lejeune [LJ] and Mont-Laurier [ML], Fig. 1). Snow cover data was compared with large-scale meteorological data models (Brown and Brasnett 2010) compiled at ecological region level (Fig. 1, Saucier *et al.* 2009) and with information from the literature (Fig. 2 and Table 1). Snow cover in maple stands affects the height at which sap collection equipment can be installed, and hence the potential tapping height range (Allard and Belzile 2004). However, other operational factors such as topography, the need to circulate reasonably in the maple stand (above or below the piping system), tapping ergonomics and the ability to drill quality tap holes also affect the tappable area (Table 1). Snow cover at the two sites encompassed the median values (Mont-Laurier) and maximum values (Lejeune) observed in the ecological regions of southern Québec but was approximately 25 cm more than the minimum estimated values in the Lower Ottawa Plain and the Montreal Archipelago (ecological region 1a), and in the Eastern Township Small Hills (ecological region 2c, Table 1, Fig. 1).

Given the mean (163 to 166 cm) and maximum (259 to 305 cm) values observed at the two sites and the compartmentalization lengths shown by Houston *et al.* (1990) above and below the tap hole (46 cm), we assumed that the first section of the trunk, equivalent to a log measuring 250 to 310 cm in length (8 to 10 feet), could not be processed into lumber, to eliminate the area affected by wounds and stains resulting from tapping. The butt log started at 30 cm from the ground (stump height). Therefore, the section eliminated in our hypothesis is situated between 280 and 340 cm from the ground. This is above the average tapping height to which a compartmentalization trim allowance of 46 cm would be added (total of approximately 210 cm), but is close to the maximum heights obtained with the trim allowance (309 and 355 cm).

Lumber loss algorithm

To calculate butt log lumber loss from taps, for each tree in the database, an algorithm was created as follows:

- If the first log was lumber grade and had a nominal length of 2.5 m to 3.1 m, this saw log volume was removed from the tree (case 1: 25% of the trees).

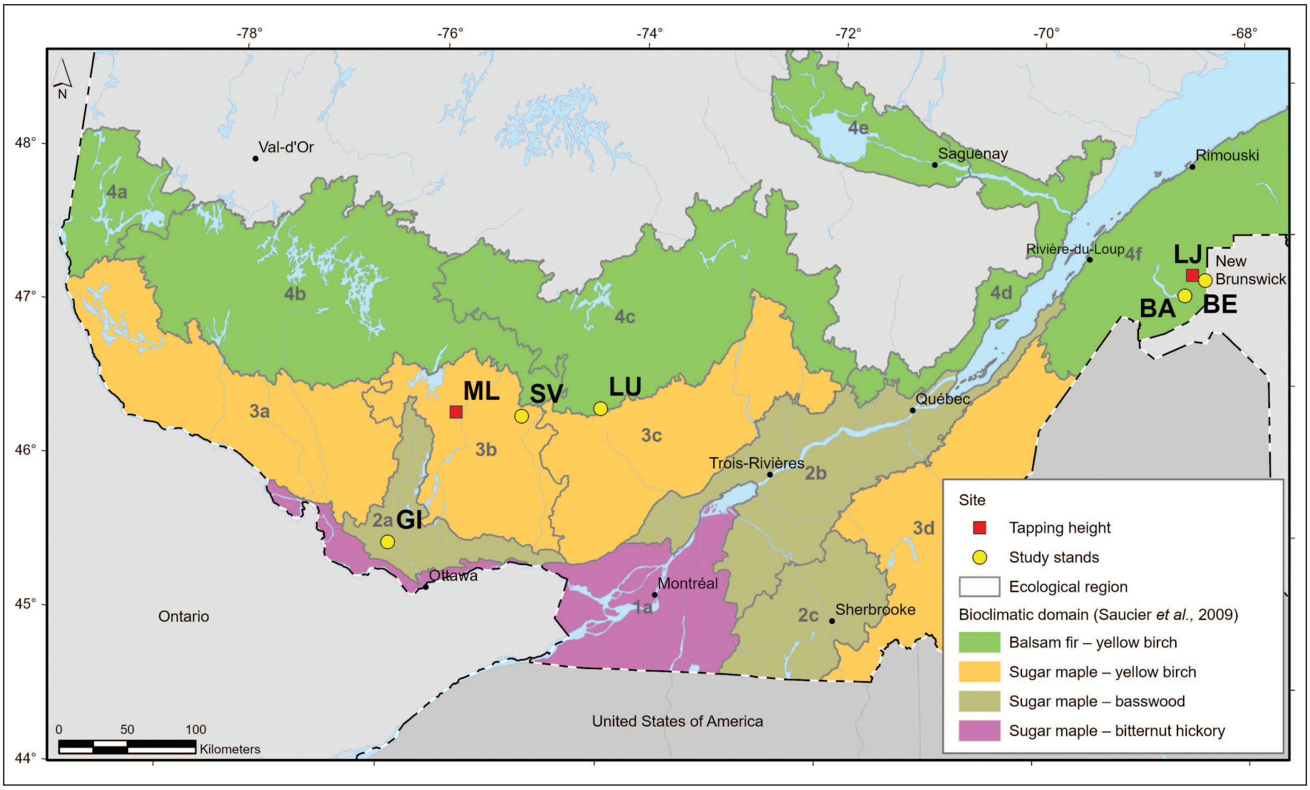

Fig. 1 Map showing the locations of the sectors studied by bioclimatic domain and ecological region. BA = Baseley sector, BE = Bénédicte sector, GI = Gatineau forest, LJ = Lejeune, LU = Lac Lusignan, ML = Mont-Laurier, SV = Sainte-Véronique. The ecological regions (Saucier *et al.* 2009): 1a = Lower Ottawa Plain and the Montreal Archipelago; 2a = Lower Gatineau Hills; 2b = St. Lawrence Plain; 2c = Eastern Township Small Hills; 3a = Outaouais Hills; 3b = Lake Nominingue Hills; 3c = Lower Saint-Maurice High Hills; 3d = Lower Appalachian Small Hills; 4a = Lake Simard Plains and Small Hills; 4b = Cabonga Reservoir Small Hills; 4c = Middle Saint-Maurice Hills; 4d = Charlevoix and Saguenay High Hills; 4e = Lake Saint-Jean and Saguenay Plains; 4f = Middle Appalachian Hills.

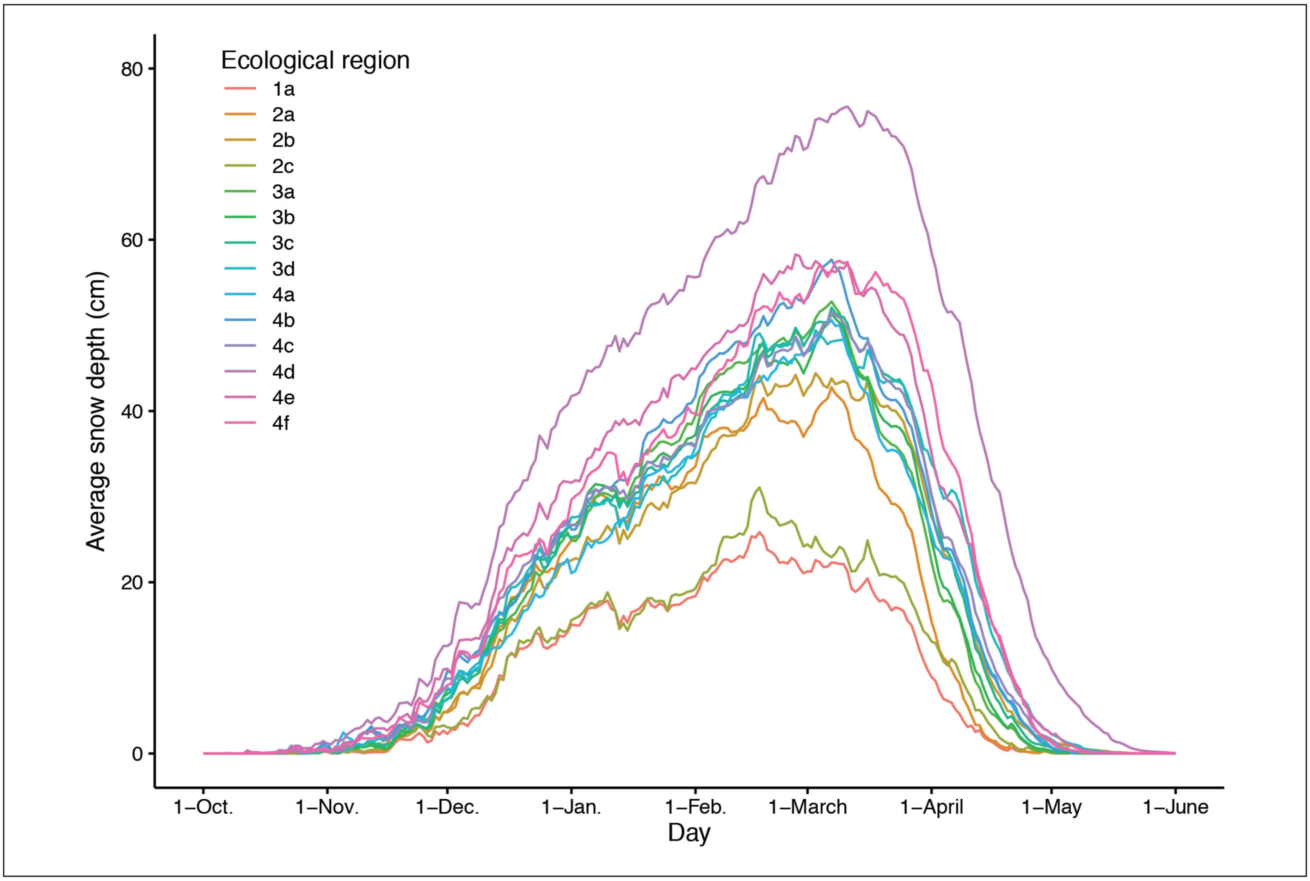

Fig. 2 Average snow depth by date and ecological region. Daily snow depth data from the Canadian Meteorological Centre (Brown and Brasnett 2010) were compiled by ecological region (Fig. 1) for the period 1999–2018 using data collected at every point of a 5′ latitude x 5′ longitude grid.

Table 1. Evaluation parameters for trunk height potentially affected by tapping

	Observed tap height (cm)		Annual snow cover at tapping (cm)		
Site (no. of sightings)	**Mean**	**Maximum**	**Minimum**	**Mean**	**Maximum**
Lejeune (3030/11 yrs)	166	305	61	89	110
Mont-Laurier (3205/10 yrs)	163	259	29	50	81
Ecological region (See Figure 2)			**Maximum annual snow cover (cm)**		
4f (Lejeune)			–	58	–
3b (Mont-Laurier)			–	51	–
2a, 2b, 3a to 4f			43	52*	76
1a and 2c			26	–	31
Other sources					
Sendak *et al.* (1982)	Overgrown metal tapping components suspected up to 300 to 360 cm.				
Houston *et al.* (1990)	Sapwood stain can extend up to 46 cm or more above and below the taphole.				
Allard and Belzile (2004)	Tap height varies from 50 to 200 cm. It is normally adapted to other sap harvesting equipment, so that the sap flow is governed by gravity. Workers placing taps must normally position themselves to be stable during drilling (circular hole) and to be able to obtain the necessary angles (90° from the tangential axis and –5 to –10° from the radial axis) to install the spout properly.				

*Median of regional averages

- If, because of its top diameter and according to Petro and Calvert (1976)'s classification, the first log did not measure 2.5 m (and was therefore not a conventional saw log), the missing portion was sectioned from the second log and the second section removed from the lumber volume (case 2: 15% of the trees).
  - If the remaining portion of the second log after sectioning was long enough to form a single saw log (minimum 2.5 m), we kept the volume of the remaining portion.
  - If that portion was not sufficient on its own but could be combined with the third saw log to form a saw log, it was considered.
  - In cases where these latter two options were not available, the remaining portion of the second saw log was also treated as lumber loss.
- If the first log was lumber grade and measured more than 3.1 m (case 3: 33% of the trees), it was sectioned at 2.5 m and its remaining portion added to the upper saw log to maximize the lumber harvest from the tree, as described for the remaining portion of the second saw log in case 2.
- Lastly, no conventional saw logs could be obtained from 27% of the trees, meaning that no changes were made to them (case 4).

For all the cases, we therefore obtained two lumber volumes for each tree, i.e., the net measured volume and the net volume minus the simulated tapping.

Lumber modelling

Havreljuk *et al.* (2015)'s conditional two-part model was used, with two changes. This type of conditional model was chosen because volume distribution is characterized by an excess of null values. The first part uses a binomial model to predict the presence of saw logs in a tree, while the second part predicts the average volume of the saw logs when there is at least one saw log in a tree.

For the first part, predicting the presence of saw logs, the SAS GLIMMIX procedure (Stroup *et al.* 2018; SAS Institute Inc. 2021) was used, with the random effects for the sample collection sector being specified. One change made to Havreljuk *et al.* (2015)'s model was to add an independent variable to simulate the presence (value = 1) or absence (value = 0) of tapping. The addition produced simple effects in interaction with the model's other variables (tree dbh, quadratic dbh and MSCR class). The unstructured variance-covariance matrix was used to consider the correlation between the measures applied to the same tree over time (with or without tapping).

For the second part of the model, predicting the average volume of saw logs when there is at least one saw log in a tree, the MIXED SAS procedure was used, with the same random effects being specified as for the first part of the model. Net volume data underwent logarithmic transformation to comply with the normality hypothesis and avoid negative volume predictions. To convert the predicted volume to the original scale required a normality-based bias correction (Flewelling and Pienaar 1981). The second change made to Havreljuk *et al.* (2015)'s model was to use the net volume (m^3) of all the saw logs in a tree as a dependent variable in the second part of the model, instead of the net volume of each log grade. As a result, all saw log grades were combined and we did not model pulp logs or bolts. We also added the simulated tapping variable to the independent variables in the second part of the model, with either simple effect or in interaction with the pre-existing variables (tree dbh, MSCR class and the interaction of the two). For both parts of the model, normal distribution of errors and variance homogeneity were verified graphically.

Simulation of management scenarios

Two management scenarios were simulated from year zero in the stands under study: with or without tapping of a maple forest stand also used to produce lumber. The variable of interest for wood production is the net volume of standing and harvested sugar maple timber, simulated over a 30-year period. Maple syrup quantity is a variable of interest for maple production and the number of tap holes is a variable of interest when assessing maple syrup potential.

Study stands

The data from five stands in a selection cut experimental network (Bédard and Majcen 2001, 2003; Majcen *et al.* 2005) were used as the starting point for the two scenario simulations: Gatineau (GI); Baselay (BA); Bénédicte (BE); Lusignan (LU); and Sainte-Véronique (SV) (Fig. 1). These stands are dominated by sugar maples and have a potential of at least 150 taps/ha. The number of taps was obtained by calculating one tap for maple trees with a dbh 23.1 to 39 cm inclusively, and two taps for those with a dbh of at least 39.1 cm based on the tapping standard applicable in Québec (Gouvernement du Québec 2022). The five stands were subjected to a first selection cut between 1988 and 1994, and to a second between 2008 and 2014. In all cases, their ecological type (Saucier *et al.* 2009) was sugar maple-yellow birch (*Betula alleghaniensis* Britt.) on a thin to thick deposit, moderate texture, and mesic drainage (FE32). The one exception was the Sainte-Véronique site, which is located in a sugar maple-basswood forest (*Tilia americana* L.) (FE22).

Dendrometric data

A two-hectare rectangular sample plot (100 m x 200 m), subdivided into eight sub-plots 0.25 hectares each was installed in each stand. All trees with a dbh of 9.1 cm or more, regardless of whether or not they were commercial species, were tallied by species and their diameter was measured in 2-cm classes (e.g., 9.1 cm to 11.0 cm = 10 cm; 11.1 cm to 13.0 cm = 12 cm; etc.) using a caliper. The MSCR class was also noted. These data were then used in the two-part conditional model to calculate net lumber volumes for every sugar maple tree. The net volumes per tree were then added together to obtain the net lumber volume per hectare in each stand in year zero. Here, year zero is the year prior to the selection cut carried out between 2008 and 2014. Table 2 presents the main dendrometric characteristics of the stands studied.

Following the forest inventory, tree marking for selection cutting was carried out in the stands to identify the trees to be harvested in year zero. Tree marking was carried out according to Majcen *et al.* (1990) marking guide which is based on Liocourt (1898) theoretical distributions. With this method, trees are prioritized for harvesting according to a given diameter distribution (*q* factor of 1.09 to 1.14), a maximum diameter of 55 cm and a residual basal area of 16 to 20 $m^2 \cdot ha^-$

Table 2. Stand characteristics before year 0 selection cut (2008 to 2014)

Stands	Gatineau	Baseley	Bénédicte	Lusignan	Sainte-Véronique
Mean DBH (cm)	26	22	26	24	24
Density (n·ha^{-1})	363	572	409	437	416
Merchantable basal area (m^2·ha^{-1})	21.7	25.9	25.1	25.9	23.8
Breakdown of merchantable basal area by species (%)					
Sugar maple	84.6	56.3	86.1	78.2	85.8
American beech	9.6	10.1	0.0	0.0	5.2
Yellow birch	1.1	10.0	12.4	19.6	5.9
Red maple	0.0	20.1	0.6	0.9	0.0
Others	4.8	3.4	0.8	1.3	3.0
Net volume of sugar maple lumber (m^3·ha^{-1})	55.3	37.9	70.4	50.9	51.4
Potential number of taps (n·ha^{-1})	197	220	215	203	217

[1]. Harvesting priority is also given to less desirable or short-lived species such as the American beech (*Fagus grandifolia* Ehrh.) and balsam fir (*Abies balsamea* (L.) Mill.), and to less vigorous hardwood trees (classified as M and S, followed by C and R), while preserving as many sugar maple and yellow birch trees as possible. Although a maximum diameter of 55 cm was used to establish post-cut residual diameter distribution (Liocourt's curve), it was not applied during marking, given the large number of low vigour trees that were prioritized for harvesting. Consequently, the only trees to be harvested above this diameter were low vigour trees. It is important to note that the selection cuts were carried out with a view to improving standing timber quality and not to sap production. However, the selection cut method was similar to that usually recommended for sap production (e.g., MRN-MAPAQ 2000). This type of treatment is designed to improve residual tree vigour while ensuring stand renewal and allowing for an acceptable maple and companion species composition to be maintained. For example, the percentage of maple trees (sugar maple + red maple) increased in every stand after selection cutting, from an average of 83% to an average of 86% of the merchantable basal area.

The marked trees were harvested in the weeks following tree marking. The plots were then re-measured to identify the trees that had actually been cut.

Simulations

We incorporated the dendrometric post-harvest stand data for year zero into the SaMARE 2018 growth model (Havreljuk *et al.* In prep.), which is an update of the SaMARE growth model (Fortin *et al.* 2009), to estimate the changes to the stands over a 30-year period and to simulate another selection cut for which data were extracted. The simulation of the 20-year selection cut was carried out using the same criteria as for year zero.

To estimate production, we estimated the quantity of maple syrup produced by tap (in pounds [lbs] = 0.45 kg) in year zero and year 30 using Tremblay's (2012) equation:

1. $Lbs\_syrup = -4.3278 + 0.3941*dbh - 0.00422*dbh^2$, *coefficient of determination* (R^2) = 0.28

where *Lbs_syrup* is the weight (in pounds) of syrup produced each year by a tap. This equation was calibrated with individual tap sap flow monitoring data collected between 2002 and 2010 inclusively at the Lejeune and Mont-Laurier sites. Sap production was converted to maple syrup using Allard's (1999) approach, which calculates the amount of different products from sap volume and sugar level. Maple trees with a dbh of 20 to 38 cm carried one tap per year, those with a dbh of 40 to 58 cm carried two, and larger trees carried three.

Lastly, when the simulations were completed, we repeated the net hardwood lumber volume calculation for the two scenarios (with and without taps), as well as the number of taps and quantity of maple syrup produced in year 30.

Statistical analyses

Variance analyses (ANOVA) were carried out using real data from five stands in year zero and simulated data for 30 years after selection cutting, with and without tapping, using the SAS version 9.4 MIXED procedure (SAS Institute Inc. 2021) to test the impact of time and tapping. The analyses examined sugar maple lumber volume, the number of taps and annual maple syrup production. The model included only one fixed effect factor for all the analyses, namely the combination of years and tapping for volumes (year 0, year 30, with and without tapping), and only the years (0 and 30) for the other two variables. When the factor was statistically significant ($p < 0.05$), a simulation approach (ADJUST=SIMULATE option for the LSMEANS statement) was used for multiple comparisons to establish where the differences occurred (Edwards and Berry 1987; Westfall *et al.* 1999). The normality and homoscedasticity hypotheses were tested on the residuals using the usual graphs, and the Shapiro-Wilk test (normality) was also performed. When the normality hypothesis was not met and could not be confirmed by any other data process

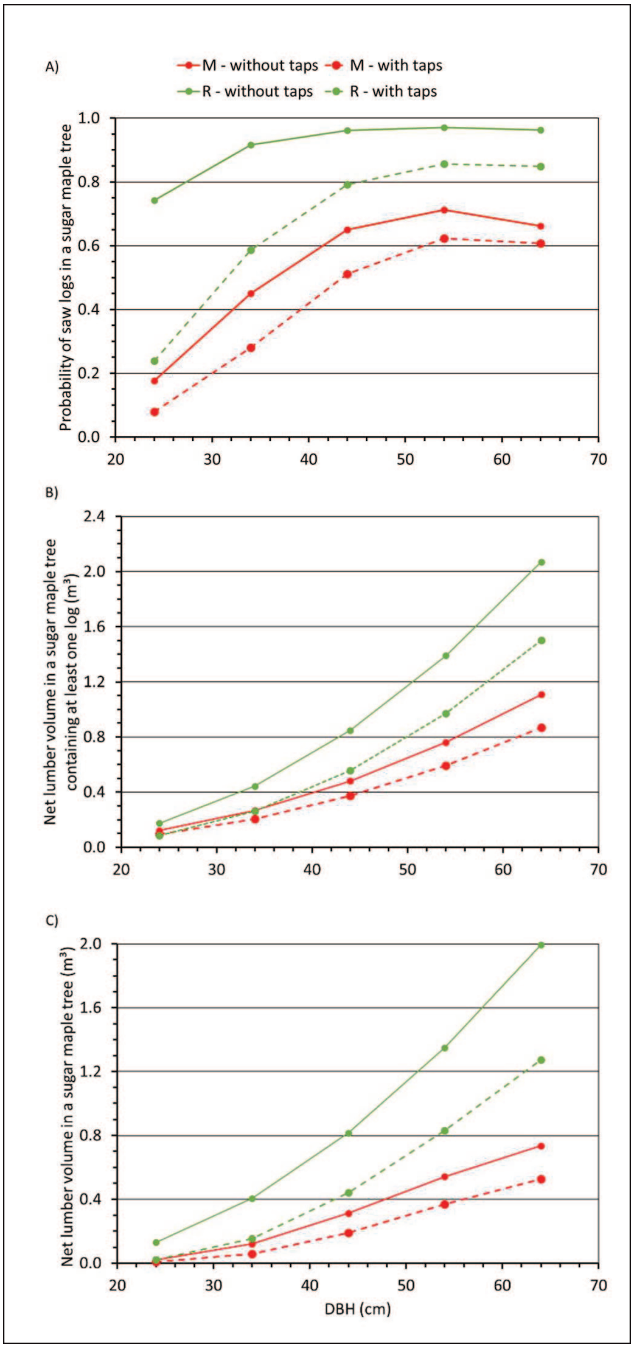

Fig. 3 Probability of saw logs in a sugar maple tree **A)**, first part of the model), net lumber volume in a sugar maple tree containing at least one log **B)**, second part of the model) and net lumber volume in a sugar maple tree **C)**, first part × second part of the model) by dbh for class M and class R trees, for the two simulated scenarios (with and without taps).

(lumber volume), the non-parametric randomization test (Cassell 2002) was used to confirm the results of the parametric test. In this case the results presented are those from the parametric test.

Results

Lumber modelling

The simulated tapping effect for the M and R tree classes are presented in Fig. 3. The values for S and C class trees fall between these two extremes and are not presented. The probability of finding one saw log in a tree increases with dbh regardless of MSCR class ($p < 0.0001$, Fig. 3A). For R class trees, there is a clear difference in saw log probability depending on whether or not tapping takes place ($p < 0.0001$). This difference is less clear for M class trees ($p = 0.0014$). In addition, saw log probability is always higher in tapped R class trees than in untapped M class trees.

The results for the second part of the model, i.e., concerning the net lumber volume in trees with at least one saw log (Fig. 3B), are similar to those for the presence of saw logs; in other words, the net volume increases with dbh regardless of MSCR class ($p < 0.0001$). However, there is a clear difference in volume between tapped and untapped R class trees ($p < 0.0001$). The difference is less clear for M class trees. These trends also hold true for the average net volume predicted by the interaction of the two parts of the model (Fig. 3C).

Management scenarios

Changes to stand basal area are shown in Table 3. The first selection cut produced an average harvest of 6.5 $m^2 \cdot ha^{-1}$, or 27% of the original basal area of 24.5 $m^2 \cdot ha^{-1}$. The basal area was greater at the time of the second simulated harvest (26.8 $m^2 \cdot ha^{-1}$), causing the harvest to increase (8.0 $m^2 \cdot ha^{-1}$ or 30%), while leaving a slightly larger basal area of 18.8 $m^2 \cdot ha^{-1}$ compared to 18.0 $m^2 \cdot ha^{-1}$.

Net sugar maple lumber volume increased from 44 ± 4 $m^3 \cdot ha^{-1}$ (mean ± standard error) after the first selection cut to 63 ± 4 $m^3 \cdot ha^{-1}$ before the second selection cut in year 30 (Table 4). The year 30 volume is significantly higher in the scenario without tapping than with tapping (63 ± 4 $m^3 \cdot ha^{-1}$ versus 30 ± 4 $m^3 \cdot ha^{-1}$ respectively, $p = 0.0002$).

In the scenario without tapping, the net harvested volume of sugar maple lumber was similar in year 0 and year 30, at 9.2 ± 1.7 $m^3 \cdot ha^{-1}$ and 9.1 ± 1.7 $m^3 \cdot ha^{-1}$ respectively ($p = 0.9986$, Fig. 4A). However, the simulated harvest volume 30 years after the first tapping (5.4 ± 1.7 $m^3 \cdot ha^{-1}$) was roughly 40% lower than both these volumes, although there was no statistically significant difference ($p = 0.3012$, Fig. 4B).

An additional analysis for harvesting after 15 years instead of 30 was also carried out to consider the possibility of harvesting at the time the tubing is changed, which normally occurs at about that interval, but the simulation showed that the harvested lumber volume would be only half the volume obtained at 30 years (data not presented).

After the simulated year 30 harvest, the number of taps (174 ± 6 $taps \cdot ha^{-1}$) and annual maple syrup production (720 ± 24 $lbs \cdot ha^{-1}$) were slightly higher than the simulated values after the year 0 selection cut (160 ± 6 $taps \cdot ha^{-1}$ and 645 ± 24 $lbs \cdot ha^{-1}$, respectively), but were not statistically different even though close to the significance threshold ($p = 0.1116$ and 0.0555, respectively, Table 4).

Table 3. Merchantable basal areas (B.a.) of stands before and after each selection cut

	Year 0 (field data)				Year 30 (simulated data)			
Stands	**Initial B.a. (m^2·ha^{-1})**	**Residual B.a. (m^2·ha^{-1})**	**Harvested B.a. (m^2·ha^{-1})**	**Harvested B.a. (%)**	**Initial B.a. (m^2·ha^{-1})**	**Residual B.a. (m^2·ha^{-1})**	**Harvested B.a. (m^2·ha^{-1})**	**Harvested B.a. (%)**
Gatineau	21.7	17.1	4.5	21%	23.2	18.0	5.2	23%
Baseley	25.9	18.9	7.0	27%	29.5	20.0	9.6	32%
Bénédicte	25.1	18.6	6.5	26%	29.0	19.5	9.5	33%
Lusignan	25.9	19.3	6.6	26%	27.6	19.6	8.0	29%
Sainte-Véronique	23.8	15.9	8.0	33%	24.8	17.1	7.7	31%
Mean	**24.5**	**18.0**	**6.5**	**27%**	**26.8**	**18.8**	**8.0**	**30%**

Table 4. Net volumes of sugar maple lumber, number of taps and syrup product weight at year 0 and year 30, by management scenario and timing and by stand

	Year 0, post-cut			Year 30			
				Initial volume (m^3·ha^{-1})		Residual status	
Stands	**Volume (m^3·ha^{-1})**	**Taps (n·ha^{-1})**	**Syrup (lbs·ha^{-1})**	**Without taps**	**With taps**	**Taps (n·ha^{-1})**	**Syrup (lbs·ha^{-1})**
Gatineau	49	167	691	55	28	157	665
Baseley	34	160	619	58	25	188	747
Bénédicte	55	168	694	82	40	193	812
Lusignan	42	152	604	59	28	166	676
Sainte-Véronique	40	153	617	59	29	166	698
Mean	**44**	**160**	**645**	**63**	**30**	**174**	**720**

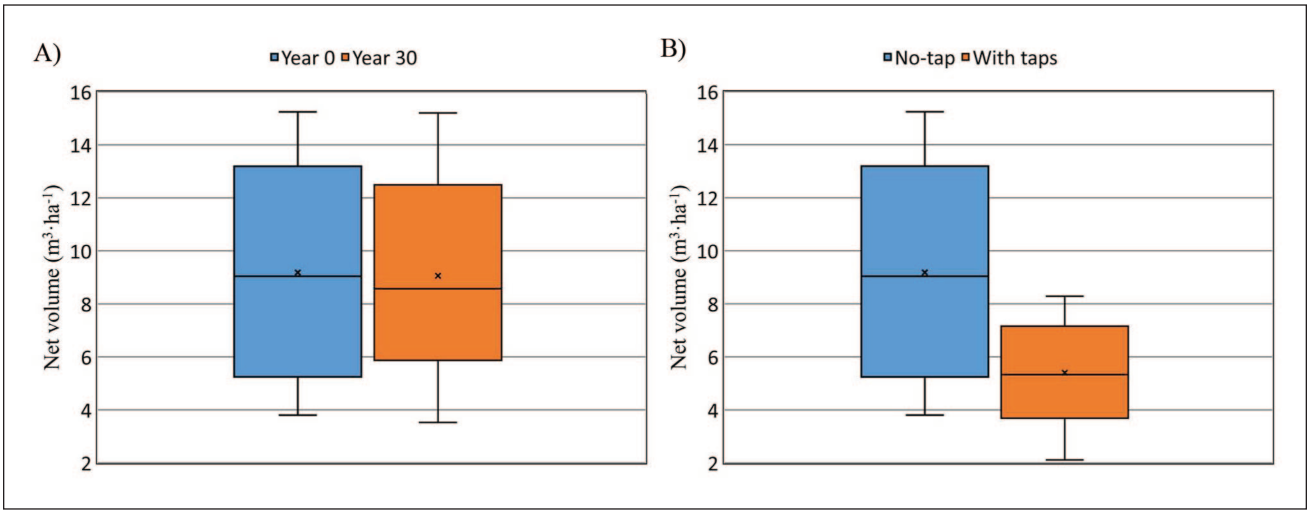

Fig. 4 Net sugar maple lumber volumes harvested in the no-tap scenario at years 0 and 30 **A)** and in both scenarios at year 30 **B)**. The × in the box-and-whisker plot show the median values and the horizontal line shows the mean. The box edges show the first and third quartiles and the whiskers show the minimum and maximum values.

Discussion

We began by developing a model of lumber loss due to tapping of sugar maple trees. The model assumes that the butt log would be rejected rather than processed by a sawmill. Craftspeople sometimes use these butt logs to produce boards with specific features resulting from tap holes or stain. On the other hand, boards containing holes are not standardized products from conventional hardwood sawmill production (NHLA 2007). To obtain a potentially more accurate model, data would be needed from maple trees tapped for longer periods and then cut to quantify the net lumber volume. However, tapping practices have evolved in the last 30 years, meaning that it would be difficult to obtain representative samples of current practices. In addition, it would also be relevant to sample maple trees to identify potential regional differences in tree height and tap height. This latter element may be correlated with average snow cover at the time of tapping, but is also constrained by practical aspects, thereby significantly limiting inter-regional differences, as we noted for the sites studied. The modelling that has been done should be regarded as an average estimate of lumber loss from tapping. However, our model is not intended for large-scale use, and we have not quantified the scope of its potential biases. It is therefore possible that it overestimates lumber losses in locations where snow cover does not justify tapping at the heights observed at the Lejeune and Mont-Laurier sites. Similarly, it may underestimate relative lumber losses at locations where sugar maple trees are lower, such as ecological region 4f (approximately 20 m according to Guillemette *et al.* 2021) and may overestimate relative losses at sites where trees are higher, such as in ecological regions 2a and 3b (approximately 22 m according to Guillemette *et al.* 2021).

We used the model to simulate a joint syrup/lumber production scenario in the sugar maple forest stands and to compare it with lumber production only. In the five stands studied, harvesting accounted for 27% of stand basal area, or 6.5 $m^2 \cdot ha^{-1}$ (Table 3), but only 17% of the net sugar maple lumber volume (9.2 out of 43.9 $m^3 \cdot ha^{-1}$). A 30-year growth simulation showed that the stands would achieve the characteristics required for a second harvest somewhat larger than the first in terms of basal area (8.0 $m^2 \cdot ha^{-1}$, 30%, Table 3). However, the application of identical harvest priorities did not change the net harvested volume of sugar maple (9.1 $m^3 \cdot ha^{-1}$) even though the standing volume increased during the cutting cycle to 62.6 $m^3 \cdot ha^{-1}$. The simulations, therefore, provide a significant improvement in the net standing timber volume for sugar maple trees in stands between selection cuts in a no-tap scenario.

This improvement in the stands (more sugar maple trees with larger dbh that would produce more lumber) would also explain the non-significant upward trends in the number of taps and in maple syrup production (Table 4). In the scenario with tapping, maple syrup production potential would therefore remain relatively stable or at least it would not decrease, oscilliating somewhere between 160 and 210 taps per hectare depending on the number of years after selection cutting (Tables 2 and 4). However, the standing timber volume in the scenario with tapping drops by approximately 50% 30 years after tapping starts and the volume harvested in the second selection cut decreases by approximately 40%, although this reduction is not statistically significant in the stands studied. We used only five stands and there was substantial variability between them. However, Fig. 4B clearly shows that none of the stands would contain a large harvestable volume of sugar maple lumber in the scenario with tapping.

In April 2000, a committee examining the contribution of Québec's public land to syrup production development estimated that post-tap quality losses would result in lumber losses of approximately 50% (MRN-MAPAQ 2000). Our results shown in Fig. 4 (63 ± 4 $m^3 \cdot ha^{-1}$ versus 30 ± 4 $m^3 \cdot ha^{-1}$), also show a volume loss of approximately 50% of available sugar maple lumber before the year 30 cut, compared to the scenario without tapping. Although this relative loss may vary regionally because of several factors, the extent of the loss is likely to be similar (perhaps between 40% and 60%). The committee also estimated an immediate loss of approximately 20% of maple syrup production potential due to the reduction in the number of taps after a selection cut harvest of 20% of the merchantable basal area. This tends to support our results, which showed a loss of 24% of taps after harvesting of 27% of the merchantable basal area.

We did not compare financial profitability for landowners or social economic spinoffs across the two scenarios. To do this, it would have been necessary to include a maple production only scenario. Farrell (2012) published a theoretical financial simulation exercise for landowners choosing between leasing sugar maple trees for maple production or cutting them to sell the timber. His sensitivity analyses led him to the conclusion that landowners would benefit more by harvesting the high value maple trees in the short term, but that it may be better to generate income from tapping the less valuable trees (small dbh, poor quality). However, he did not assess the co-production scenario. Our model could be used to carry out this type of analysis.

Implications for management

The choice of converting a maple forest to maple production is a long-term management undertaking (Farrell 2012). Sendak *et al.* (1982) noted that wood production becomes a secondary goal when sap production is developed. Our study confirms that tapping reduces the net standing volume of sugar maple timber by approximately 40% and reduces the harvestable volume after the first 30-year cycle by approximately 40%. In a co-production scenario, these findings have variable implications depending on the forestry context.

For a hardwood lumber processing company obtaining its supplies from public or private forests, lumber losses caused by the introduction of a third-party sap harvester reduce the lumber harvest potential, especially if harvesting profitability is already marginal. For example, simulated lumber harvest volumes are fairly modest, at 5.4 and 9.1 $m^3 \cdot ha^{-1}$ respectively, for the scenarios with and without tapping. As a comparison, in the late 1990s forestry companies in Québec operationally harvested 9.9 to 24.2 $m^3 \cdot ha^{-1}$ of lumber, depending on the region, in selection cuts (Guillemette *et al.* In press). In addition, harvesting, which is usually delegated to forestry contractors in such lumber co-production, is likely to cost somewhat more than in sole production of lumber because the maple production infrastructures, including the main hanging or underground tubing systems, pumping stations and electricity systems, must be protected, and harvesting must be synchronized with the change of tubing by the maple producer. Despite the higher harvesting costs, a forestry company that owns such a maple forest might still increase its per-hectare profits by adding the income from maple syrup production (Ouimet *et al.* 2018), even if this means sacrificing some of its revenue from logging.

We believe it would be appropriate to assess the financial parameters from the standpoint of a maple syrup producer leasing a public or private sugar bush who would also be responsible for harvesting sugar maple lumber.

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