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**Trees**

Structure and Function

ISSN 0931-1890

Volume 35

Number 1

Trees (2021) 35:1-13

DOI 10.1007/s00468-020-02001-x

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# Effect of tapping for syrup production on sugar maple tree growth in the Quebec Appalachians

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## Abstract

Some studies suggest that tapping sugar maple (*Acer saccharum* Marshall) trees can cause their growth to decline, particularly on poor and acidic soils. We tested this hypothesis in seven sugar bushes located in the Quebec Appalachians by comparing the growth of tapped trees with nearby untapped trees. The sites represented a range of soil fertility, from very good for sugar maple to strongly deficient in calcium. Trees were cored, and individual dendrochronology series were used to analyze trends in basal area growth, from a period of 10 years before, to 8–10 years after tapping began. Basal area growth of sugar maples did not appear to be influenced by tapping ( $p \geq 0.134$ ), except at one site ( $p < 0.001$ ), where the growth of tapped trees decreased by 33% over 10 years. This decline could not be explained only by the poor soil fertility observed at the site. Although a tree biomass distribution budget indicated that maple syrup production represented only 4–6% of the carbon allocated annually to net primary production, the long-term relationship between maple syrup production and tree growth requires further study.

**Keywords** *Acer saccharum* · Tapping · Non-structural carbohydrates · Basal area increment

## Introduction

Maple syrup is produced exclusively in North America, and about 70% of the production comes from Quebec, Canada. According to the province's association of maple producers (PPAQ 2019), the number of taps has increased steadily over the last 30 years in this province, from 17.5 million taps in 1988 to 46.8 million taps in 2018 (+3.2% year<sup>-1</sup>, compounded). A similar trend in the number of taps (+5.2% year<sup>-1</sup>, compounded) has been observed in the northeastern United States (US) between 2007 and 2012 (Perkins et al. 2015a). Sugar maple (*Acer saccharum* Marshall) produces a large concentration of sugars in its xylem.

The sap is a dilute solution of water and sugars, which are 99.9% sucrose, with traces of other non-sugar solids including organic acids, nitrogenous waste, and inorganic salts (Lagacé et al. 2019). Its sugar content can range from 1 to 10%, most often 2–6% being common. Sugars in sap are concentrated by reverse osmosis and evaporation to produce maple syrup (65% sugars; Lagacé et al. 2019).

Between 2001 and 2015, the average annual syrup yield per tap increased by 5.0% year<sup>-1</sup> in Quebec (from 1.72 lb per tap [0.78 kg tap<sup>-1</sup>] to 2.53 lb per tap [1.15 kg tap<sup>-1</sup>]; calculated from the slopes of the linear trends; FPAQ 2006; PPAQ 2019), and by 4.2% year<sup>-1</sup> in the US (Perkins et al. 2015b). The modernization of sap collection methods and processing, with the use of plastic tubing, vacuum pumping, and new tap models can partly explain this increase in yield (Blum and Koelling 1968; Isselhardt et al. 2016; Kelley and Staats 1989). However, some questions remain about possible effects of this increase in sap harvesting on the health of trees. Very crude estimates of the amount of maple's reserves removed from sugaring range from less than 1% to more than 10% (Wilmot et al. 2007). Sap or resin harvesting from other tree species usually affects their growth and health. For instance, tapping of rubber trees (*Hevea brasiliensis* (Willd. Ex A.Juss.) Müll. Arg.) for latex production

Communicated by G. Piovesan.

**Electronic supplementary material** The online version of this article (<https://doi.org/10.1007/s00468-020-02001-x>) contains supplementary material, which is available to authorized users.✉ Rock Ouimet  
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(Silpi et al. 2007, 2006), extraction of resin from the maritime pine (*Pinus pinaster* Ait.) (Genova et al. 2014), slash pine (*Pinus elliotii* Engelman) (Liu and Chen 2004), Scots pine (*Pinus sylvestris* L.) (Paramonov 1969), and Benguet pine (*Pinus kesiya* var. *langbianensis* (A.Chev.) Gausson ex Bui) (Wu et al. 2015) all cause sharp decreases in radial tree growth. Although tapping birch (*Betula* sp.) for a certain number of years does not appear to affect its growth (Maher 2013), it may compromise tree health through the development of wood stain and decay (Nevalainen 2006; Trumer 2009).

The extraction of non-structural carbohydrates (NSC) from trees may decrease NSC reserves. In turn, the replenishment of this NSC pool can compete with other carbon sinks, such as tree growth, following an active, semi-active or even passive process, depending on species metabolism and stress exposure (Chapin et al. 1990; Delaporte et al. 2016; Dietze et al. 2014). For instance, the fact that reduced tree growth under stress was not related to a decline in NSC reserve indicates that trees can reallocate or prioritize carbon storage at the expense of growth (Silpi et al. 2007; Wiley et al. 2013). In the case of sugar maple, some studies showed that tapping can reduce tree growth (Copenheaver et al. 2014; Isselhardt et al. 2016), while another reported no long-term effect of tapping on tree growth or health (Pothier 1996). These conflicting observations may be related to site fertility, since sugar maple is a relatively demanding tree species in terms of mineral nutrition. Its growth and health are highly dependent on soil available nutrients, particularly calcium (Ca) (Bal et al. 2015; Ouimet et al. 2017; Schaberg et al. 2006; Wilmot et al. 1996). Deficiency in mineral nutrients, particularly Ca, is a cause of crown dieback, tree growth reduction, and decline in base-poor northern hardwood stands (Moore et al. 2015). In turn, extractable sap volume is negatively related to crown dieback (Wilmot et al. 1995).

We investigated sugar maple growth at seven sites where it was possible to compare neighboring untapped maple trees with others that had been tapped for a number of years. The sites represented a wide range of soil fertility, allowing us to test the following hypotheses:

- Tapping sugar maple trees reduces their growth compared to untapped sugar maple trees on all sites;
- Tapping sugar maple trees reduces their growth compared to untapped sugar maple trees only on soils having nutrient deficiencies.

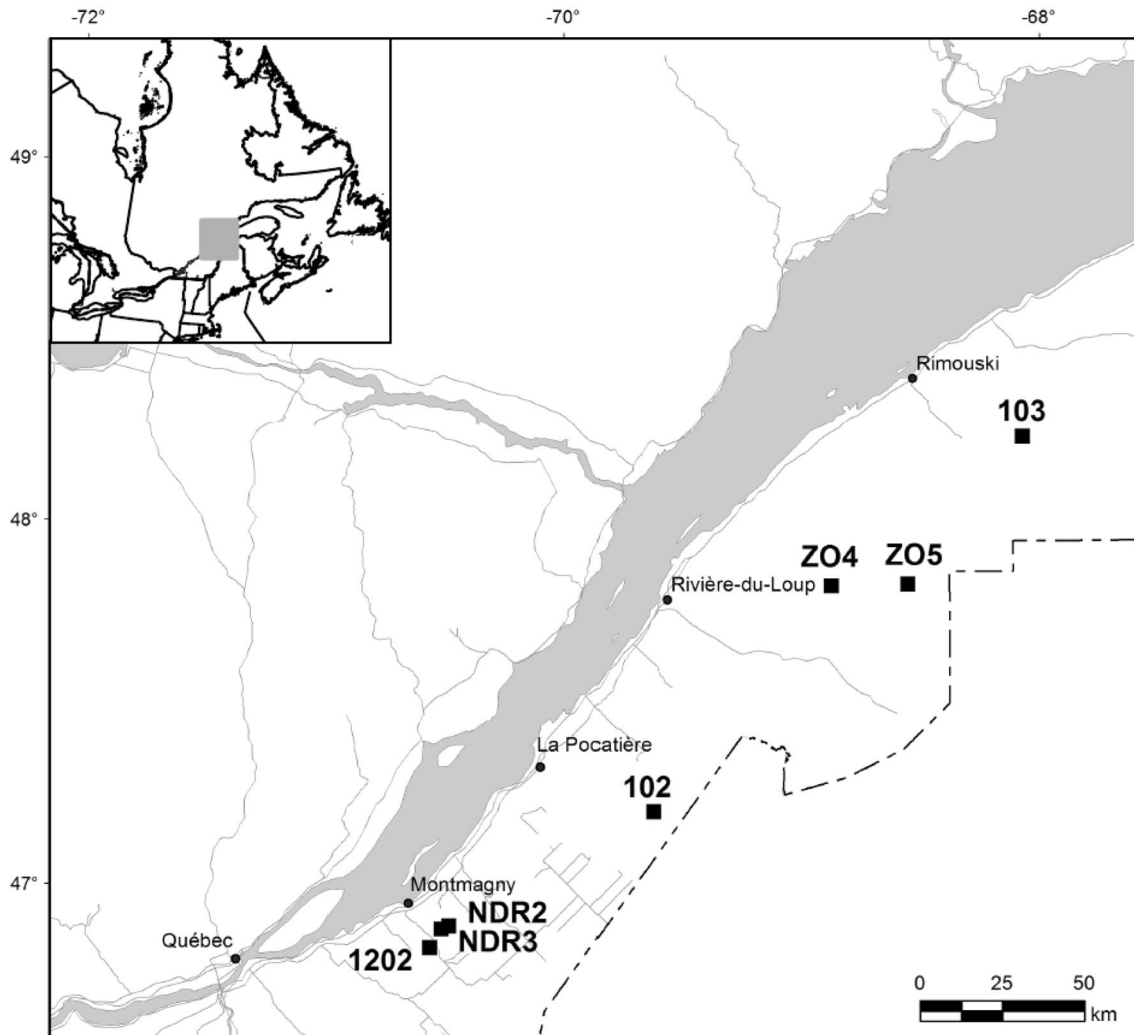
The first hypothesis assumed that replenishing NSC reserves taken up by tapping every spring was an active process competing with growth for carbon allocation, while the second hypothesis assumed that this was the case only under poor soil fertility conditions.

## Materials and methods

### Study sites

The selected sites are all located on Crown land in the Quebec Appalachians, and classified as uneven-aged sugar maple stands of natural origin (Fig. 1). The region is under a snow forest climate (1970–2000 mean annual temperature: 2.4 °C; mean annual precipitation: 1000 mm, of which 38% falls as snow). The soils are sandy loam, moderately well-drained Podzols developed on glacial till derived from the local Appalachians bedrock materials, mainly shale and sandstone. Three sites (102, 103, and 1202) are part of Quebec's Forest Study and Monitoring Network (*Réseau d'étude et de surveillance des écosystèmes forestiers du Québec*, RESEF), established to monitor forest dynamics in response to environmental stresses (Gagnon et al. 1994). These 0.5-ha monitoring plots surrounded by a 100 m-wide buffer protection band have been protected from any human interventions for several decades. The majority of merchantable stems (diameter at breast height [DBH] >9 cm) are sugar maples with a stem diameter ranging from 19 to 35 cm. At the time of sampling in 2015, site basal area of merchantable stems varied from 28 to 31 m<sup>2</sup> ha<sup>-1</sup> (Table 1). The four other sites (NDR2, NDR3, ZO4, and ZO5) are part of a permanent sample plot network established to monitor the effects of forest management through selection cutting (hereafter Selection Cutting Experiment), as practiced in 1999 (NDR) or in 1996 (ZO) in stands unmanaged for several decades (Guillemette et al. 2017). A diameter cutting deemed at high-grading yellow birch could have been done 20–40 years before (exact history unknown). Selection cutting harvested 25–35% of the initial basal area of the stands following tree marking in each diameter class to increase the proportion of quality trees in the residual stand. Post-harvest basal area in the areas preserved from tapping ranged from 19 to 29 m<sup>2</sup> ha<sup>-1</sup>. At the time of sampling in 2018, basal area varied from 25 to 34 m<sup>2</sup> ha<sup>-1</sup> in these sites (Table 1). The majority of merchantable stems were sugar maples with a stem DBH ranging from 17 to 39 cm.

Forest stands surrounding the plots protected from tapping were similar to them in all aspects except that they were used for maple syrup production. Tapped trees were equipped with tubing and vacuum. Tap holes were 51–63 mm deep (2.0–2.5 in.) and spout diameter was 7.9 or 11 mm (5/16 or 7/16 in.). As these stands were leased on Crown land, sugaring activities were under strict rules. According to Quebec government norms (Gouvernement du Québec 2018), the minimum size for tapping maple trees was DBH class of 20 cm (DBH >19 cm) and only 1 tap per tree was allowed for trees in the 20–40 cm DBH range.



**Fig. 1** Location of the study sites

### Sample tree selection

A total of 20 relatively young sugar maple trees in the 20- to 30-cm DBH class were selected at each site: Ten untapped trees located at the border of the protected or control area of the sites, and ten tapped trees located at the border of the tapped area, within 20 m of the trees selected in the untapped areas. Also, a number of scars from past tapping on these trees indicated that they had been tapped for several years. Only codominant trees with no apparent defects, disease or decline were selected. At a given site, all selected trees were of similar size and grew in the same topographic and climatic conditions.

### Sampling and measures

The following parameters were measured on selected trees: DBH (to the nearest millimeter, with a diameter tape),

tree trunk, and total height (to the nearest decimeter, with a hypsometer), and the ground-projected north–south and east–west crown diameters (to the nearest decimeter). We also collected two cores on each tree in the east–west direction at a height of 80 cm to avoid trunk tapping areas that could have disturbed tree ring growth. The RESEF sites were sampled in August 2015, and those of the Selection Cutting Experiment, in the end of May 2018.

The tree cores were glued on core holders, let to dry, and then sanded. Ring widths were measured at the nearest micrometer using WinDENDRO™ software (version 6.1D, Regent Instruments Inc.) and validated using signature rings to assist in crossdating (Yamaguchi 1991). Visual crossdating was accomplished through recognition of patterns of wide and narrow rings common to all sites (Fritts 2001). This procedure also accounted for locally absent and false rings. Each set of raw tree ring measurements was evaluated using the COFECHA computer program (Grissino

**Table 1** Selected characteristics of the whole stand and of sugar maple trees at the seven study sites

Site	Density (stems ha <sup>-1</sup> ) by DBH class				Basal area <sup>a</sup> (m <sup>2</sup> ha <sup>-1</sup> )	DBH <sup>a</sup> (mean ± SD, cm)	Year tapping started
	from 1.1 to 9 cm	>9 cm	≥20 cm	≥30 cm			
Whole stand							
ZO4	1250	575	275	150	33.4	25.0 ± 10.9	
103	474	594	358	170	36.7	25.0 ± 12.6	
102	1648	374	230	140	30.7	28.0 ± 16.2	
ZO5	1250	400	300	150	28.0	27.8 ± 11.3	
NDR2	2500	500	425	225	33.5	27.8 ± 9.2	
1202	1836	512	260	132	28.6	23.4 ± 12.8	
NDR3	1500	475	225	150	24.5	23.3 ± 11.0	
Sugar maple							
ZO4	1250	575	275	150	33.4	25.0 ± 10.9	2008
103	266	570	338	186	34.3	24.7 ± 12.5	1979–2009 <sup>b</sup>
102	1404	366	228	138	30.2	28.1 ± 16.2	1970–2006 <sup>b</sup>
ZO5	1000	325	250	100	22.0	27.5 ± 10.8	2009
NDR2	0	475	400	200	31.2	27.5 ± 9.3	2010
1202	254	352	182	82	19.2	23.3 ± 12.4	1970–2006 <sup>b</sup>
NDR3	750	350	125	75	14.3	21.1 ± 9.0	2010

<sup>a</sup>Merchantable stems only (DBH >9 cm)<sup>b</sup>Year range when sampled trees reached minimum tapping DBH (20 cm DBH class)

Mayer 2001) to ensure proper crossdating. Ring width values of individual cores were averaged yearly for each tree, and these mean yearly values were converted to basal area increment (BAI, cm<sup>2</sup> year<sup>-1</sup>) using the dplR package (Bunn 2008), version 1.6.8 in the R software environment version 3.5.1 (R Core Team 2018). We selected BAI because it reflects tree volume increases better than diameter increments (Duchesne et al. 2003).

Soils (humus H and the first 15 cm of mineral B horizon) had been sampled previously at each site. The RESEF sites had been sampled intensively every 10 years ( $n \geq 60$ ), while those of the selection cutting network had been sampled only once. Soil samples there were taken at ten points located along a 50-m transect and composited by horizon, air-dried, and passed through a 2-mm sieve. Exchangeable cations (K, Ca, Mg, and Al) were extracted with an unbuffered NH<sub>4</sub>Cl (1N, 12 h) solution and measured by inductively coupled plasma atomic emission spectrometry (Thermo Jarrell-Ash Model 61E). The standard reference materials used were always within 5% of the reference values. Exchangeable acidity (H + Al) was determined by summing the net H<sup>+</sup> (extract H<sup>+</sup> measured by pH probe) and Al concentrations of the extract. The effective cation exchange capacity (CEC) was computed as the sum of exchangeable base cations and exchangeable acidity. Base saturation (BS) was calculated as the proportion of CEC as base cations. Diagnosis of sugar maple nutrient deficiency was based on the soil norms published by Ouimet et al. (2013). Ca deficiency is diagnosed when the following conditions are combined: Ca saturation

of the mineral B horizon  $\leq 28.4\%$ , humus Ca/Mg ratio  $\leq 5.322$  and Ca saturation  $\leq 59.7\%$ . The overall accuracy of these thresholds for diagnosing foliar Ca deficiency is 80.5% (Ouimet et al. 2013).

### Determining the year tapping started

The stands surrounding the four sites of the Selection Cutting Experiment have been leased for maple syrup production by the Quebec government since between 2008 and 2010, according to the sugar makers' official lease contracts. Therefore, the exact years sugaring activities started at these sites are known (Table 1). The three other stands surrounding the RESEF sites have been leased for several decades, and former lease contracts no longer existed to allow us to determine the exact year when tapping started. Therefore, at those sites we assumed that the selected trees were first tapped when they reached the minimum size for tapping (DBH class of 20 cm, i.e., DBH >19 cm) as they were relatively small (20–30 cm DBH class). This approach corresponds to the Intention to Treat Analysis, a strategy that consists of analyzing “the subjects to whom a treatment was assigned, regardless of whether they actually satisfied the entry criteria, the treatment actually received, and subsequent withdrawal or deviation from the protocol” (Hollis and Campbell 1999). In our case, we used dendrochronology to determine the year tapping may have started for the 3 RESEF sites by counting the number of rings (minus one) to decrease tree DBH down to 19 cm. Therefore, one has to

bear in mind that the years tapping started for trees in the RESEF sites are approximations. We further examined the BAI growth of these trees individually to assess the impact of this uncertainty associated with the determination of the start of tapping at the RESEF sites on the results.

### Proportion of net primary production as sugar harvested

In order to discuss the relative importance of syrup production with other tree carbon sinks, we compiled the biomass production required for a given sugar maple according to growth rate scenarios for (1) a slow-growing tree requiring 50 years to grow from 20 to 30 cm in DBH (annual tree ring increment: 1 mm wide), and (2) a fast-growing tree requiring only 25 years to grow from 20 to 30 cm in DBH (annual tree ring increment: 2 mm wide). We estimated biomass accumulation and production from published allometric relationships based on tree DBH. We also evaluated the sustainability of tapping such trees in these scenarios using the Tapping Zone Model of van den Berg and Perkins (2014), but with a slight modification. The growth rate parameter was modified with respect to the growth scenarios defined above. The threshold sustainability value for tapping in conductive wood was set to a minimum of 90% (van den Berg and Perkins 2014). Other model input values were set as the following: current tree DBH: 20 cm (8 in.); dropline length: 61 cm (24 in.); spout size: 0.8 cm (5/16 in.); tapping depth: 51 mm (2.0 in.); number of taps: 1; number of years the tree has been tapped before: 0.

### Statistical analysis

Time series of individual tree BAI values were realigned to set the year tapping started at a value of 1. BAIs were analyzed using a linear mixed model with the tapping treatment (nominal, “tapped”, “untapped”), time (years), the years before and after tapping started (or before trees reached the minimum DBH for tapping; nominal, 0, 1), and their interactions as fixed effects, and trees within treatments as a random effect. The triple interaction among the fixed effects tested whether a change in BAI trend occurred between tapped and untapped trees once tapping started. Each site was analyzed separately, using 10 years of tree BAIs before and 8–10 years of tree BAIs after tapping started, depending on data availability at each site. For these analyses, generalized least squares allowed for the correlated errors between years. An autoregressive first-order covariance structure provided the best fit for the data, based on comparisons of the Akaike Information Criterion (AIC) scores and residual plots. Assumptions of variance homoscedasticity and normality of sample distributions were verified by residual plot analysis. The standardized residuals of these models were

then plotted against all independent variables to detect possible heterogeneity among variances. If present, the heterogeneity was corrected using different variances per strata. The models for which variance function structures had the lowest AIC score were always selected. Adjusted (predicted) and raw means were computed for reporting. Analyses were performed with the nlme package (Pinheiro et al. 2018), version 3.1–137, in the R software environment version 3.5.1 (R Core Team 2018). Differences in tree characteristics between tapped and untapped trees within a site were tested using the two-sided Student's *t* test (*t.test* base R function) assuming unequal variance (i.e., with Welch modification to the degrees of freedom).

We further investigated the assumption we made for estimating the start of tapping at the RESEF sites by performing generalized additive modeling (GAMs) of the BAI time series over time for every tree individually. GAMs allow very flexible smoothing functions (splines) of independent variables that are not constrained and that can deal with non-linearity. The *bam* function of the *mgcv* R package (version 1.8–31; Wood 2017) was used to perform the GAMs with the cubic regression (cr) penalised spline function and the starting basis dimension (knots) equaled the number of observations minus one to maximize the wiggleness in the splines. Then the model penalised back to an “optimal” value for the smoothness. A first-order (AR1) autoregressive error model was employed to reduce autocorrelation in the residuals. We recorded the regions in which the splines were significantly different from zero ( $\alpha = 0.05$ ) by computing the first derivative of fitted splines at 200 equally spaced points using the method of finite differences (*fderiv* function of the *gratia* R package; Simpson 2020); the derivatives, and their standard errors were then used as input in the *find\_difference* function of the *itsadug* R package (van Rij et al. 2017).

## Results

### Site and tree characteristics

The soil analyses indicated that sites ZO4 and 103 showed absolutely no mineral deficiency for healthy growing sugar maples, while sites 102 and ZO5 displayed a weak calcium (Ca) deficiency, and sites NDR2, 1202, and NDR3 displayed strong Ca deficiencies, with soil values below the thresholds established for sugar maple (Quimet et al. 2013; Table 2). Sites were ordered by decreasing soil fertility in the tables and figures.

As expected, no notable differences existed between tapped and untapped trees within a site regarding tree DBH, trunk height, total height, crown surface, age, or the last 10-year growth expressed as ring width or BAI ( $p \geq 0.057$ ; Table 3). Tree DBH averaged (mean  $\pm$  SE)

**Table 2** Soil properties and diagnosed nutrient deficiency for sugar maple according to Ouimet et al. (2013) at the seven sites

Soil layer	Site	Base saturation (%)	Ca saturation	Mg saturation	Ca/Mg (eq/eq)	K/Mg (eq/eq)	Diagnosed deficiency
Humus H	ZO4	100.0	77.7	16.9	4.59	0.31	
	103	99.9	81.3	13.1	3.21	0.42	
	102	99.7	79.2	13.2	3.26	0.54	
	NDR2	69.9	52.4	10.0	5.24	0.74	
	ZO5	71.2	48.1	15.2	3.15	0.48	
	1202	99.9	69.7	17.1	2.18	0.78	
	NDR3	33.9	19.5	7.3	2.66	0.90	
Mineral B (first 15 cm)	ZO4	67.5	55.4	9.5	5.80	0.22	–
	103	38.2	29.6	6.5	2.40	0.34	–
	102	29.6	24.1	3.7	3.35	0.46	Weak Ca
	ZO5	30.0	21.0	6.2	3.42	0.42	Weak Ca
	NDR2	13.6	8.0	2.4	3.37	1.17	Strong Ca
	1202	7.4	4.6	1.3	1.85	0.95	Strong Ca
	NDR3	6.5	3.9	1.0	3.86	1.21	Strong Ca

The sites are ordered by descending Ca saturation value in the mineral B soil horizon

**Table 3** Characteristics of selected trees at the seven sites

Site	Treatment	Characteristics of selected trees (range)					Past 10-year growth (mean $\pm$ SD)	
		DBH (cm)	Trunk height (m)	Total height (m)	Crown surface (m <sup>2</sup> )	Age <sup>a</sup> (years)	Tree ring width (mm year <sup>-1</sup> )	Tree basal area increment (BAI) (cm <sup>2</sup> year <sup>-1</sup> )
ZO4	Untapped	21.9–31.4	8.1–13.7	19.3–25.7	11.8–57.7	59–115	1.26 $\pm$ 0.31	10.3 $\pm$ 5.0
	Tapped	19.8–31.2	7.9–11.9	18.3–22.7	13.9–43.4	57–108	0.99 $\pm$ 0.33	7.7 $\pm$ 4.5
103	Untapped	22.6–30.2	10.3–13.2	21.3–24.8	14.7–46.7	53–94	1.10 $\pm$ 0.32	8.8 $\pm$ 3.3
	Tapped	20.3–31.9	8.3–13.7	19.7–23.8	14.0–62.0	59–79	1.40 $\pm$ 0.50	11.2 $\pm$ 4.3
102	Untapped	21.7–33.8	5.6–10.5	19.2–25.8	28.0–44.0	53–128	1.55 $\pm$ 0.70	11.7 $\pm$ 6.3
	Tapped	23.1–34.9	8.0–12.2	19.3–23.0	28.5–84.9	67–102	1.40 $\pm$ 0.37	12.2 $\pm$ 4.1
ZO5	Untapped	21.5–30.5	8.8–11.3	18.2–21.7	14.2–41.2	55–99	1.07 $\pm$ 0.27	8.3 $\pm$ 3.9
	Tapped	22.4–31.7	7.0–11.5	16.5–22.3	23.6–56.5	42–93	1.53 $\pm$ 0.47**	11.2 $\pm$ 4.1
NDR2	Untapped	19.2–29.1	9.7–14.4	20.9–24.8	12.9–43.6	63–102	1.03 $\pm$ 0.28	9.1 $\pm$ 4.9
	Tapped	20.2–29.4	7.9–13.7	20.0–24.4	20.7–52.2	50–91	1.21 $\pm$ 0.41	7.3 $\pm$ 3.3
1202	Untapped	20.4–29.4	5.9–10.7	16.9–22.2	6.8–64.6	56–94	1.58 $\pm$ 0.61*	11.0 $\pm$ 3.8
	Tapped	20.7–31.1	6.5–10.0	16.6–22.6	26.3–64.3	58–102	1.08 $\pm$ 0.37	8.7 $\pm$ 3.0
NDR3	Untapped	19.0–31.8	7.6–10.9	16.8–22.8	20.4–60.1	55–108	1.32 $\pm$ 0.40	9.5 $\pm$ 4.0
	Tapped	22.9–29.5	6.0–8.4	17.2–20.3	31.6–53.5	41–104	1.62 $\pm$ 0.45	11.6 $\pm$ 4.6

Difference between mean values for treatments at a given site is significant at  $\alpha \leq 0.05$  (\*) or  $\alpha \leq 0.01$  (\*\*)

<sup>a</sup>Age of trees measured at ~80 cm above the ground

26  $\pm$  3 cm, tree trunk and total height averaged 9.7  $\pm$  0.2 and 20.8  $\pm$  0.2 m, respectively, horizontal crown surface averaged 36.4  $\pm$  1.2 m<sup>2</sup>, and tree age averaged 76  $\pm$  2 yrs. Growth, in terms of the last 10-year tree ring width or BAI, was more or less similar within a site ( $p \geq 0.059$ ). The only differences in growth were at site ZO5, where the last

10-year mean tree ring width was 43% greater for tapped than for untapped trees ( $p \leq 0.001$ ), and at site 1202, where the last 10-year mean tree ring width was 46% lower for tapped trees than for untapped trees ( $p = 0.050$ ). However, these differences were no longer significant ( $p \geq 0.140$ ) when growth was expressed in terms of BAI.



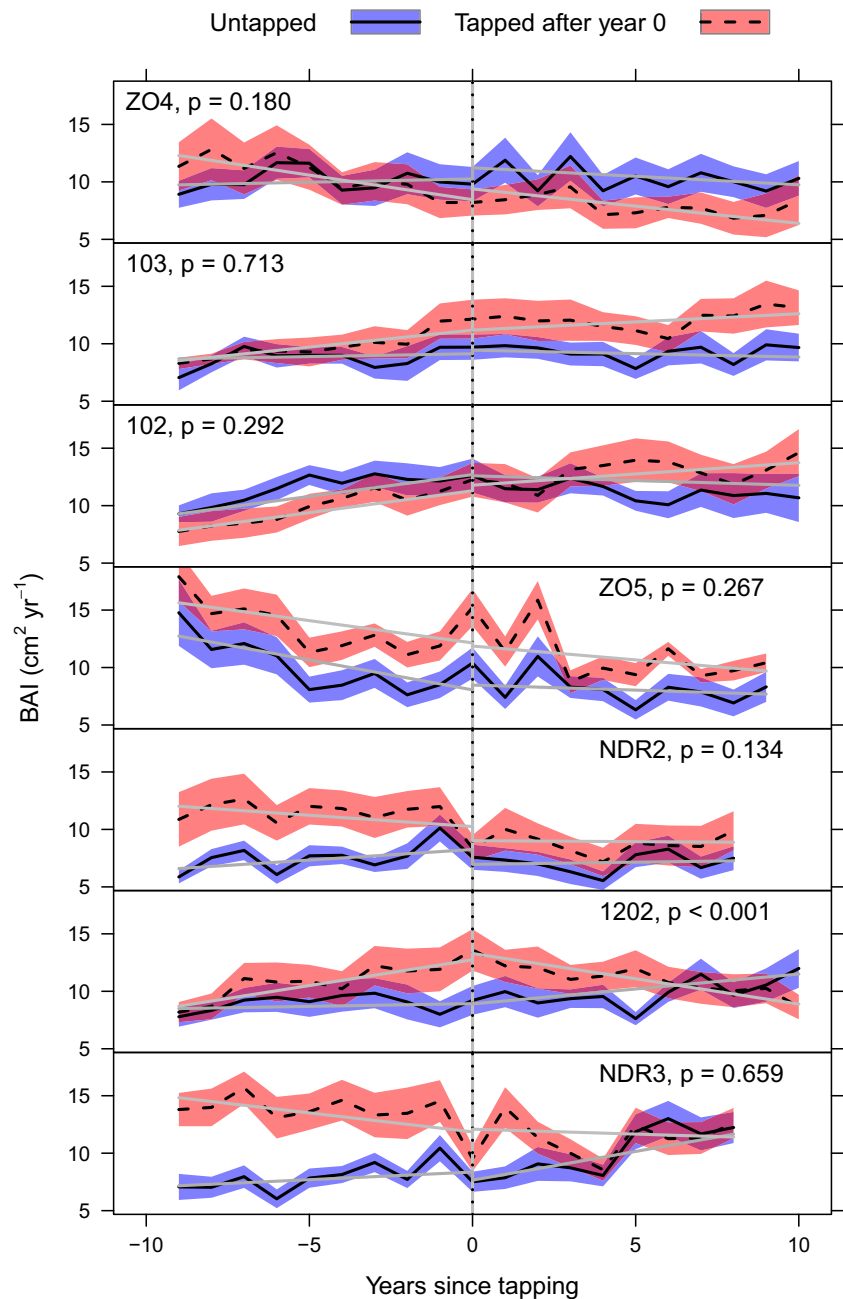
### Effect of tapping

The estimated year tapping started for trees varied considerably within the three RESEF sites (Table 1), given that the stands surrounding the monitoring plots had been used for sugar production for several decades and the fact we chose trees with a sensible range in DBH (Table 3). No effect of tapping on tree BAI growth trend (i.e., no significant triple interaction among the fixed effects) was found in six of the seven studied sites ( $p \geq 0.134$ ; Fig. 2). The raw means in Fig. 2 suggest that BAI growth decreased at sites NDR2 and NDR3 only the year before tapping started and that growth

resumed at the previous level the following year. However, the story at site 1202 was different: The decline in BAI growth of the tapped trees was linear and synchronous with the start of tapping the trees (from  $13.3 \pm 1.3 \text{ cm}^2 \text{ year}^{-1}$  to  $8.9 \pm 1.3 \text{ cm}^2 \text{ year}^{-1}$  over 10 years, resulting in a 33% decrease;  $p < 0.001$ ), while the untapped trees at this site grew steadily ( $p = 0.277$ ; Table 4).

Some other changes in BAI growth related to the start of tapping were detected at some sites. At site 103, the BAI growth trend of the tapped trees decreased once tapping started. The difference of  $-0.153 \pm 0.085 \text{ cm}^2 \text{ year}^{-2}$  is marginally significant ( $p = 0.074$ ; Table 4), although

**Fig. 2** Aggregated time series (raw means) of basal area increment (BAI) of tapped and untapped sugar maple trees (means with colored intervals representing  $\pm 1$  standard error), 10 years before and up to 10 years after tapping began. The dotted vertical line at year 0 represents the year before the trees reached the minimum DBH for tapping. The  $p$  values of the triple interaction among the fixed effects (tapped vs. untapped, time, and time after tapping began) are presented. The gray lines represent adjusted mean BAI values according to the analysis of variance models presented in Table 1S in the Supplementary Material



**Table 4** Effect of tapping on the trend in basal area increment (BAI) of sugar maple trees 10 years before and up to 10 years after the year tapping started

Site	Treatment	BAI trend (mean $\pm$ SE) Before tapping	(cm <sup>2</sup> year <sup>-2</sup> ) After tapping	Difference between the two periods (mean $\pm$ SE) (cm <sup>2</sup> year <sup>-2</sup> )	$P_{diff=0}$	Difference in BAI trend between tapped and untapped trees over time (mean $\pm$ SE) (cm <sup>2</sup> year <sup>-2</sup> )	$P_{diff=0}$
ZO4	Untapped	0.057 (0.138)	-0.148 (0.138)	-0.205 (0.172)	0.235		
	Tapped	-0.427 (0.135)	-0.300 (0.146)	0.127 (0.177)	0.473	-0.484 (0.193)	0.013
103	Untapped	0.049 (0.065)	-0.060 (0.083)	-0.109 (0.082)	0.187		
	Tapped	0.295 (0.065)	0.142 (0.086)	-0.153 (0.085)	0.074	0.246 (0.079)	0.002
102	Untapped	0.379 (0.070)	-0.083 (0.149)	-0.462 (0.188)	0.014		
	Tapped	0.381 (0.070)	0.195 (0.142)	-0.186 (0.182)	0.307	0.002 (0.099)	0.980
ZO5	Untapped	-0.520 (0.139)	-0.088 (0.133)	0.432 (0.164)	0.009		
	Tapped	-0.387 (0.160)	-0.241 (0.155)	0.147 (0.198)	0.461	0.133 (0.202)	0.512
NDR2	Untapped	0.184 (0.133)	0.038 (0.152)	-0.146 (0.140)	0.298		
	Tapped	-0.196 (0.146)	-0.016 (0.166)	0.180 (0.165)	0.278	-0.380 (0.189)	0.044
1202	Untapped	0.047 (0.141)	0.260 (0.140)	0.212 (0.195)	0.277		
	Tapped	0.449 (0.180)	-0.441 (0.160)	-0.890 (0.237)	<0.001	0.402 (0.229)	0.080
NDR3	Untapped	0.133 (0.122)	0.500 (0.176)	0.367 (0.201)	0.069		
	Tapped	-0.331 (0.126)	-0.086 (0.162)	0.245 (0.190)	0.199	-0.463 (0.175)	0.009

Data presented are coefficients calculated from the ANOVA analyses

in general, the growth trend of the untapped trees remained higher over the whole study period (difference of  $+0.246 \pm 0.079$  cm<sup>2</sup> year<sup>-2</sup>,  $p_{\text{treatment} \times \text{time}} = 0.002$ , see also Table 1S in the Supplementary Material). At site 102, the BAI growth of untapped trees increased until it reached a plateau when trees reached the minimum DBH for tapping ( $p = 0.014$ ), at which point both tapped and untapped trees experienced a decrease of  $-0.462 \pm 0.188$  cm<sup>2</sup> year<sup>-2</sup> in BAI growth ( $p_{\text{tapping period} \times \text{time}} = 0.014$ ). At site ZO5, BAI growth of untapped trees decreased until the year tapping started, then remained stable ( $p = 0.009$ ). Finally, at site NDR3, BAI growth of untapped trees increased marginally once tapping started (by  $0.367 \pm 0.201$  cm<sup>2</sup> year<sup>-2</sup>,  $p = 0.069$ ). A similar but statistically nonsignificant trend was observed for tapped trees at this site ( $0.245 \pm 0.190$  cm<sup>2</sup> year<sup>-2</sup>,  $p = 0.199$ ). Overall, no consistent differences between tapped and untapped trees were found regarding BAI trends over time, with differences ranging from  $-0.484$  to  $+0.402$  cm<sup>2</sup> year<sup>-2</sup>, depending on the site (Table 4).

## Discussion

### Tree response to tapping

To assess the impact of annual sap harvesting on sugar maple growth, we analyzed BAI trends of tapped and untapped trees 10 years before, and 8–10 years after the start of tapping at sites representing a range of soil fertility. We observed no consistent change in growth patterns in relation to tapping during this period. Among the seven sites investigated, only at site 1202 did we observe the synchrony at the start of growth decrease and tapping. This site was strongly

Ca-deficient. However, so such growth decrease with tapping was not observed in the two other sites in the same soil fertility category. Conversely, at site 103, which was rated “good” in terms of soil fertility, we observed a reduction in the maple growth trend after tapping. At sites NDR2 and NDR3, the growth decrease was observed only the year before tapping started, which suggests that trees in these stands could have been affected by operations in preparation for tapping. If some thinning did occur, it might have confounded to some degree the tree growth response to tapping.

Our results did not validate entirely our hypotheses regarding the effect of tapping on maple growth and the impact of mineral nutrient deficiency on this relationship. In a Vermont sugar bush, no growth decrease was detected after 1 year of tapping (Isselhardt et al. 2016). Likewise, in a thinning experiment conducted in Quebec, no impact was reported on annual tapping for 15 years on maple DBH growth (Pothier 1996). The North American Maple Project showed that tree crown health indicators were similar in stands managed for syrup production and those unmanaged (Allen et al. 1992). By contrast, a 50% decrease in growth of tapped trees was observed after 20 to 29 years in two of three sugar bushes located in Pennsylvania and Ontario (Copenheaver et al. 2014). In a study of 18 sugar bush stands in Vermont, the growth rates of many healthy trees were found to be sufficient for long-term tapping (van den Berg et al. 2016), despite the fact 27–42% of sampled trees in these sugar bushes had individual growth rates below the minimum rate considered as sustainable. In all these studies, however, soil fertility status was not reported. Active C allocation to NSC reserves could compete with stem growth, but other mechanisms could also play a role in diverting C from the growth sink. One possibility is that NSCs are used

during the compartmentalization reaction to yearly tapping wounds in the xylem of trees (Walters and Shigo 1978).

### On the uncertainty regarding start of tapping at the RESEF sites

In a sugar bush, sap collection operations are carried on every year during late winter and early spring, prior to bud break. Sugar makers aim at having the maximum number of tapped trees to increase their revenues in this short operational period. However, strict rules govern sap collection operations on Crown land in Quebec. We actually knew with great confidence the year trees started to be tapped in the Selection Cutting Experiment, but not in the RESEF sites. We made the assumption for the latter that the trees started to be tapped at the moment they reached the allowable DBH for tapping. The GAM analysis of growth trend of individual trees over years indicated that the majority of them never experienced a significant reduction in BAI throughout their life span, with the exception of one untapped tree at site 103 (untapped tree #1; see Fig. 1S and 2S in the Supplementary Material). At sites 102 and 103, only two trees per site over the ten located in the tapped zone experienced a statistically significant decrease in BAI during some period of time after they reached the allowable DBH for tapping. So whatever the year tapping started for these trees, the absence of BAI reduction in the time series support the conclusion that there was no evidence of BAI change resulting from tapping the majority of the trees at these sites.

The situation is different for the RESEF site 1202. The GAM analysis indicated that seven of the ten tapped trees experienced a significant BAI reduction during some periods of time, particularly at the moment or a few years after they reached the allowable DBH for tapping between 1970 and 2006 (Fig. 3). The onset of these BAI decreases occurred at different years in the life of trees, but were synchronized with the moment or a few years after trees reached the 20-cm DBH class. It is, therefore, very likely that this BAI reduction was related to the start of tapping. We could not think of any other explanation for these decreases in BAI only when this group of trees reached the allowable DBH for tapping. Such BAI change was not present for the neighbouring untapped trees at this site when the trees reached the 20-cm DBH class. Tapping activities were the only factor that we know may have occurred during these years. Therefore, we are confident that the BAI reduction detected for the tapped trees at site 1202 was actually caused by tapping.

### C allocation by sugar maple

The sugars mobilized in sugar maple sap during the spring for new foliage and stem growth at bud break are mostly produced during the 3–5 previous growing seasons (Muhr et al.

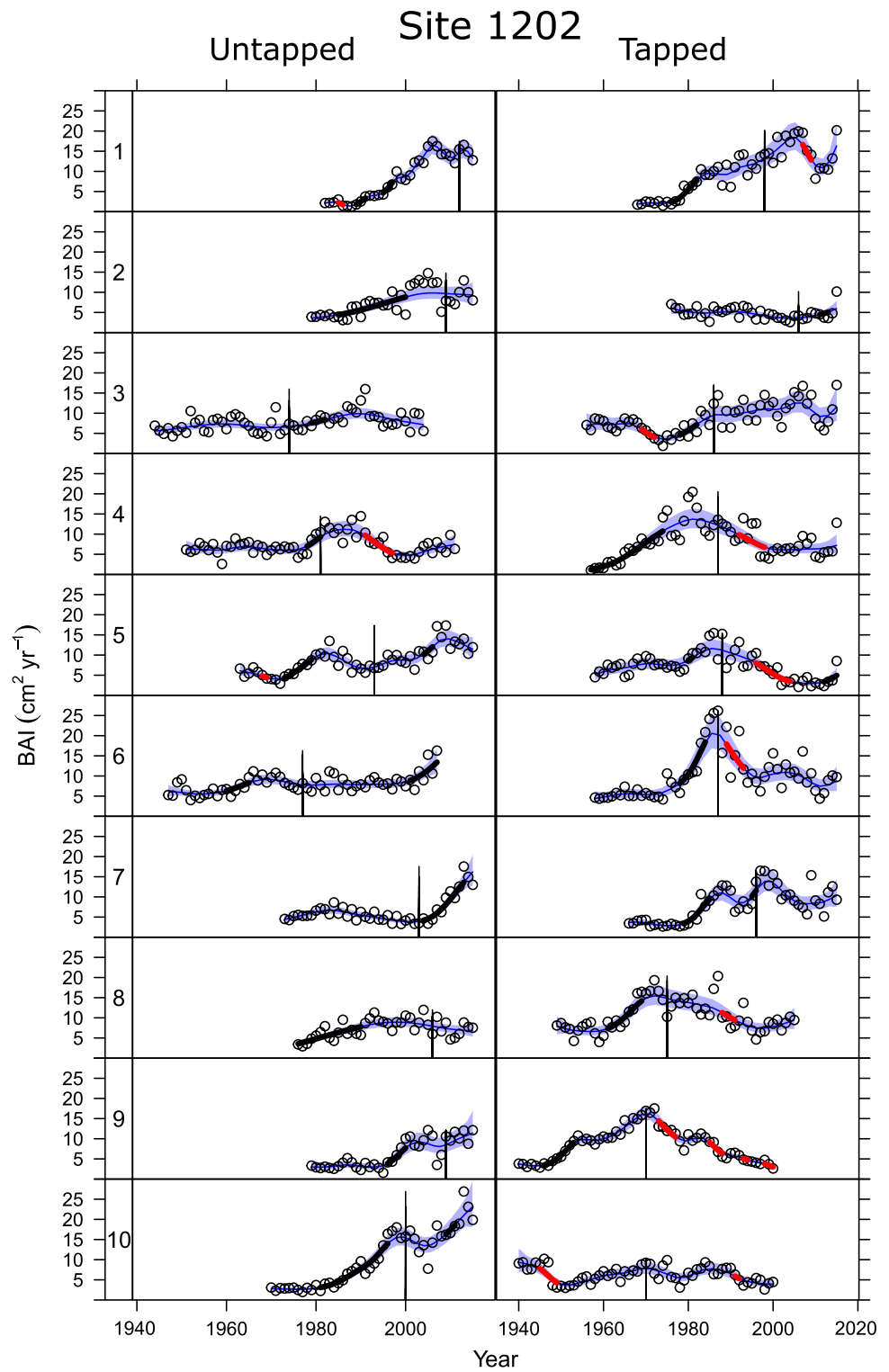
2016). Such observation indicates that a tree's metabolism in the dormant season is fueled by a mixture of C derived from a combination of fast and slow (or more distant) NSC pools (Hartmann and Trumbore 2016). Therefore, sugar maple appears well buffered against single or even several years of negative plant C balance (Muhr et al. 2016).

The compiled budget (Table 5) shows that syrup production amounts to only 4–6% of the annual net biomass production of sugar maple trees growing from 20 to 30 cm in DBH. Assuming biomass is approximately 50% C, this amounts to 4–6% of the C production. The greatest proportion of biomass under these scenarios is allocated to foliage production (34–46% of the total NPP). Stem wood production comes second, followed by fine root and branch production. Apparently, the proportion of C going into syrup production remains low (Isselhardt 2012), whether tree growth is slow or fast. The replenishment of the NSC pool appeared to compete with tree growth in only one case among the seven studied sites. The relatively small NSC allocation to syrup production might explain why we did not find a consistent tree growth response to tapping.

Although some other sinks could play an important role in NSC allocation within trees, they were ignored in this budget because they were too difficult to estimate. For instance, we ignored the annual production of litter matter other than foliage, such as the production of bud scales, dead branch, and root debris. We also ignored seed production as C sink, even though a decline in maple syrup production has been reported following masting (Rapp and Crone 2015). Annual root exudation in the rhizosphere that feeds arbuscular mycorrhizal fungi also appears to be a substantial C sink (Phillips and Fahey 2005) that should be further documented. However, taking these sinks into account would not increase the proportion of C allocated to syrup production. We also assumed that repeating tapping year after year for 25–50 years influenced neither tree growth nor the relationship used between stem DBH and syrup yield. The latter may be unlikely in the slow-growing tree scenario; the number of generated nonconductive columns of wood extending above and below tap holes would let a minimum of 83% of the tapping zone as conductive wood for sap, a value considered “potentially unsustainable” according to the model of van den Berg and Perkins (2014). In the fast-growing scenario, the lowest proportion of conductive wood in the tapping zone reached 91%, a value considered as “likely sustainable” with respect to the tapping practice.

With the advent of plastic tubing collection and vacuum systems, maple syrup producers have increased sap yield from each tapped tree (Blum and Koelling 1968; Isselhardt et al. 2016). Nowadays, even higher vacuum levels (up to 28 inches of mercury [InHg], or 95 kPa) are more often used than the former standard vacuum level of 20 InHg (68 kPa) in order to further increase sap yield. Sap yield will increase

**Fig. 3** Time series of basal area increment (BAI) of individual untapped and tapped sugar maple trees over years at the RESEF site 1202 ( $n = 10$  per treatment). The dots are the measured BAI values. The blue lines represent the smoothed fit  $\pm 1$  standard error from the generalized additive models (GAMs). Bold segments show significant ( $\alpha = 0.05$ ) positive (black) and negative (red) trends (slopes) along the time series. The vertical bars in each panel mark the year trees reached the allowable DBH for tapping (20 cm DBH class)



by 5–7% for each 1 InHg of applied vacuum according to Wilmot et al. (2007). In a 2-year monitoring study, sap yield increased by 38% under the higher vacuum level compared to the standard level, yet no major difference was found between the standard and higher vacuum level regarding sap properties and syrup organoleptic properties (Lagacé

et al. 2019). These researchers also observed that the concentrations of phytohormones (abscisic acid and auxin) in syrup did not vary according to vacuum levels, which suggests that greater vacuum levels did not increase tree stress. However, some concerns still remain about the sustainability of the continuous and annual application of such high-yield

**Table 5** Estimation of biomass distribution for a slow-growing (ring width increment = 1 mm year<sup>-1</sup>) and a fast-growing (ring width increment = 2 mm year<sup>-1</sup>) sugar maple tree growing from a DBH of 20 to 30 cm

Compartment	Biomass at		Mean annual net biomass productivity from 20 to 30 cm DBH				Details/source
	DBH = 20 cm	DBH = 30 cm	Slow-growing tree		Fast-growing tree		
	(kg tree <sup>-1</sup> )	(kg tree <sup>-1</sup> )	(kg tree <sup>-1</sup> year <sup>-1</sup> )	%	(kg tree <sup>-1</sup> year <sup>-1</sup> )	%	
<b>Accumulation<sup>a</sup></b>							
Branches	40.5	106.0	1.3	7	2.6	10	Allometric equation from Lambert et al. (2005)
Stem wood	134.3	343.1	4.2	21	8.4	31	Allometric equation from Lambert et al. (2005)
Stem bark	20.1	43.9	0.5	2	1.0	3	Allometric equation from Lambert et al. (2005)
Stump + coarse roots (≥5 mm diam.)	35.7	93.1	1.1	6	2.3	8	Allometric equation from Ouimet et al. (2008)
<b>Annual production<sup>b</sup></b>							
Foliage	6.3	12.4	9.3	46	9.3	34	Allometric equation from Lambert et al. (2005)
Fine root (<5 mm diam.)	2.1	4.2	2.5	13	2.6	9	Allometric equations of fine root biomass and turnover for broadleaved species from Chen et al. (2004), assuming a stand age of 100 yrs. Diameter at the ground surface vs. DBH relationship was taken from Wharton (1984)
Syrup yield (as sugars)	0.8	1.4	1.1	6	1.1	4	Allometric tree DBH – maple syrup yield relationship from Grenier (2007) who used one tap per tree and 20 InHg (68 kPa) vacuum, and converting syrup to sugars assuming 65% sugars in maple syrup (Lagacé et al., 2019)
<b>Total</b>	<b>239.3</b>	<b>604.0</b>	<b>20.0</b>	<b>100</b>	<b>27.2</b>	<b>100</b>	

At these rates, such growth would take 50 years for the slow-growing tree and 25 years for the fast-growing tree

<sup>a</sup>Annual mean net biomass productivity from component accumulation is calculated as the difference between biomass at a DBH of 30 cm and biomass at a DBH of 20 cm divided by time

<sup>b</sup>For each component production, annual mean net biomass productivity is calculated as the average yearly biomass production for a tree growing from 20 to 30 cm DBH

operations. The concerns remain until long-term controlled studies on this subject are completed.

## Conclusion

Sugar maple BAI growth was measured at seven sites representing a wide range of soil fertility to determine tree response to yearly tapping for sugaring, using trees that had been tapped for 8 to 10 years and neighboring untapped trees. The hypotheses that (1) tapped trees would show a growth decline synchronous to the start of tapping, and (2)

tapped trees would display a growth decline only at sites where soil fertility conditions are deficient, were not validated for all sites. Only one site, which displayed a strong Ca deficiency, showed a consistent reduced tree growth related to tapping.

The budget constructed to assess the importance of syrup production in tree NSC allocation indicated that syrup production represented only about 4–6% of the annual tree net C production. Nonetheless, the growth decline associated with tapping at one site and those reported elsewhere raise some concern about the sustainability of the continuous and annual application of tapping operations in sugar bushes,

particularly if soil fertility conditions are deficient and greater vacuum levels are used.

**Acknowledgements** This research was supported by the Ministère des Forêts, de la Faune et des Parcs du Québec (projets Nos. 142332065 and 142332053). We wish to thank Mr. Simon Désalliers, Benoît Toussaint and Jocelyn Hamel for their technical help, the staff of our inorganic and organic chemistry Lab for the soil analyses, Ms. Denise Tousignant for English editing, and Dr. Timothy D. Perkins and an anonymous reviewer for their constructive comments on a previous version of the manuscript.

**Author contribution statement** All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Rock Ouimet and François Guillemette. The first draft of the manuscript was written by Rock Ouimet and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

## Compliance with ethical standards

**Conflict of interest** The authors declare no conflict of interest.

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