TREE-RING RESEARCH, *Vol. 73(1), 2017, pp. 35–41*
DOI: http://dx.doi.org/10.3959/1536-1098-73.1.35

RESEARCH REPORT

DENDROCLIMATIC RESPONSES OF SUGAR MAPLE TAPPED FOR MAPLE SYRUP: A CASE STUDY FROM PENNSYLVANIA

CAROLYN A. COPENHEAVER[1]*, **DYLAN E. DAWSON**[1], **MARIO N. GARZA**[2], and **DEBORAH G. NEMENS**[1]

[1]Department of Forest Resources and Environmental Conservation, Virginia Tech, Blacksburg, VA 24061, USA

[2]Department of Geography, Virginia Tech, Blacksburg, VA 24061, USA

ABSTRACT

Maple syrup is a regional, non-timber forest product in the United States that depends upon healthy, mature sugar maple (*Acer saccharum* Marshall). We examined whether tapping for maple syrup altered the dendroclimatic response of sugar maple. Ring width indices from two sites (tapped and reference) in central Pennsylvania were correlated with regional temperature, precipitation, and Palmer Drought Severity Index (PDSI). Both sites had significant correlations between summer and fall PDSI and radial growth. Spring PDSI was significantly correlated with growth at the reference site, but not at the tapped site. Both tapped and reference trees experienced below-average growth during years with dry spring conditions (PSDI < 0), but tapped trees had a higher percentage of years (27%) with below-average growth during years with moist spring conditions (PDSI > 0) compared to reference trees (15%). These results indicate that tapping for maple syrup may have altered the dendroclimatic response of sugar maple to moisture availability during the spring months.

Keywords: dendroclimatology, maple syrup, *Acer saccharum*, dendroecology, sugar maple.

INTRODUCTION

Maple syrup is a product unique to North America and a valuable, regional, non-timber forest product. In 2014, U.S. maple syrup producers sold 14.5 million liters of syrup, at a value of $117 million (USDA 2015). Converting the sap of sugar maple (*Acer saccharum*) into maple syrup occurs in the early spring when leaf-out increases the physiological activity of the tree and the combination of cold nights and warm days causes the tree's sap to move up and down the tree's bole (Whitney and Upmeyer 2004). Collection of maple sap involves drilling a hole into the bole of a tree and placing a metal or plastic spile into the hole to collect the sap in metal buckets or through a plastic vacuum tubing system (Kelley and Staats 1989). After collection, sap is boiled down in an evaporator to concentrate the sugar and produce maple syrup (Graham *et al.* 2006). Most maple syrup producers follow best practices guidelines, which suggest a minimum tapping diameter of 25 cm at breast height (1.4 m) and as tree size increases the number of taps can increase to a maximum of three taps per tree in trees larger than 64 cm in diameter at breast height (Davenport and Staats 1998). Maple syrup production typically involves small, single family operations and the income provides an important supplement to landowners who are primarily engaged in farming or forestry (Hinrichs 1998). The seasonal production of maple syrup is identified as an important cultural activity that helps connect rural landowners to their agricultural heritage and fosters appreciation for the sustainability of forest lands (O'Brien 2006).

The maple syrup industry depends upon healthy and vigorous sugar maple in the regions where trees are tapped in the early spring for syrup production. Radial growth rate is a good measure of the vigor of a tree because healthy trees will be capable of higher rates of growth than trees with compromised health. However, variation in the radial growth of sugar maple does not simply reflect

---

*Corresponding author: ccopenhe@vt.edu; Fax 540-231-3330; Telephone 540-231-4031 tree vigor, but it also records historical fluctuations in temperature and precipitation (Lane *et al.* 1993; Tardif *et al.* 2001), extreme climatic events (Pisaric *et al.* 2008), and competition from other vegetation (Cho and Boerner 1995). Previous research has shown that sugar maple's growth is significantly correlated to climate. The climatic factors most influential to growth vary across the species' range. In the central portion of sugar maple's range, growing-season temperature was the climatic variable most influential to radial growth (Lane *et al.* 1993; Tardif *et al.* 2001; Goldblum and Rigg 2005; He *et al.* 2005; Bishop *et al.* 2015). At more southern and eastern sites, spring and summer precipitation increased in influence on radial growth (He *et al.* 2005; Bishop *et al.* 2015). At many sites, a lag exists between climatic conditions of the previous year and radial growth in the current year. This lag results from favorable conditions at the end of the growing season, allowing trees to store more carbohydrates and have higher growth rates in the following year (Lane *et al.* 1993).

Tapping for maple syrup production reduces radial growth of sugar maple trees. Copenheaver *et al.* (2014) compared growth rates in individual sugar maple trees prior to the trees being tapped for maple syrup with the growth rates after the trees were tapped for maple syrup production and found sugar maple radial growth was significantly slower after tapping began. They also compared growth rates between tapped and reference populations of sugar maple trees and found slower growth rates in the tapped trees. We hypothesize that tapping for maple syrup may also change the dendroclimatic response of sugar maple. We used one of the datasets collected for the growth response study (Copenheaver *et al.* 2014) to examine paired tapped and reference sugar maple tree-ring data to identify whether tapping for maple syrup production reduced, increased, or did not change dendroclimatic responsiveness.

METHODS

Study Area

The study area is located in south-central Pennsylvania (40.4°N, 78.1°W) near the shoreline of Raystown Lake. Tree-ring samples were collected from sugar maples growing on property owned by Juniata College's Raystown Field Station. The two sites (tapped and reference) were located in adjacent cove forests separated by a common spur ridge (Figure 1). The tapped site has been in annual maple syrup production since the 1950s and the reference site has never been used for maple syrup production (Charles Yohn, Executive Director of the Raystown Field Station, personal communication). At the tapped site, sugar maple sap is extracted every spring by drilling a hole in the side of the tree, placing a metal spile in the drilled hole, and collecting the sap in a metal bucket that hangs from the spile (Figure 1A). Sap is emptied from the buckets once or twice a day for a one- to two-week period in March, when the weather maintains a mixture of warm days and below-freezing nights. The paired tapped and reference study sites were dominated by mesic species such as sugar maple, red maple (*Acer rubrum* L.), and tulip poplar (*Liriodendron tulipifera* L.) (Braun 1950). There was no forest management aimed at timber production at either site, but the tapped site does have a system of tractor trails used for collecting the sap and transport to the evaporator. The dominant soil type in both study sites was Berks-Weikert (Merkel 1978). The elevation of the two sites was 240 m a.s.l. Winter temperature (based on 122 years) averaged −2.2°C and summer averaged 20.8°C (NOAA 2015). The total annual precipitation averaged 990 mm.

Field and Laboratory Methods

At both the tapped and reference sites, 25 dominant and co-dominant sugar maple trees were cored. Two cores were taken from each tree at 0.5 m above the root collar at a position that was perpendicular to the slope to avoid reaction wood. A few trees had substantial basal rot, so we extracted cores 1 m above the root collar for these individuals. All increment cores were air dried and glued to wooden core holders. Mounted samples were sanded with increasingly finer grit sandpaper until divisions between annual rings were clearly apparent under a microscope. Samples were visually crossdated using narrow rings as signature years (Yamaguchi 1991). Many of the samples had synchronized white rings caused by defoliation from regional gypsy moth outbreaks (Jeffrey Kraus, U.S. Army Corps of

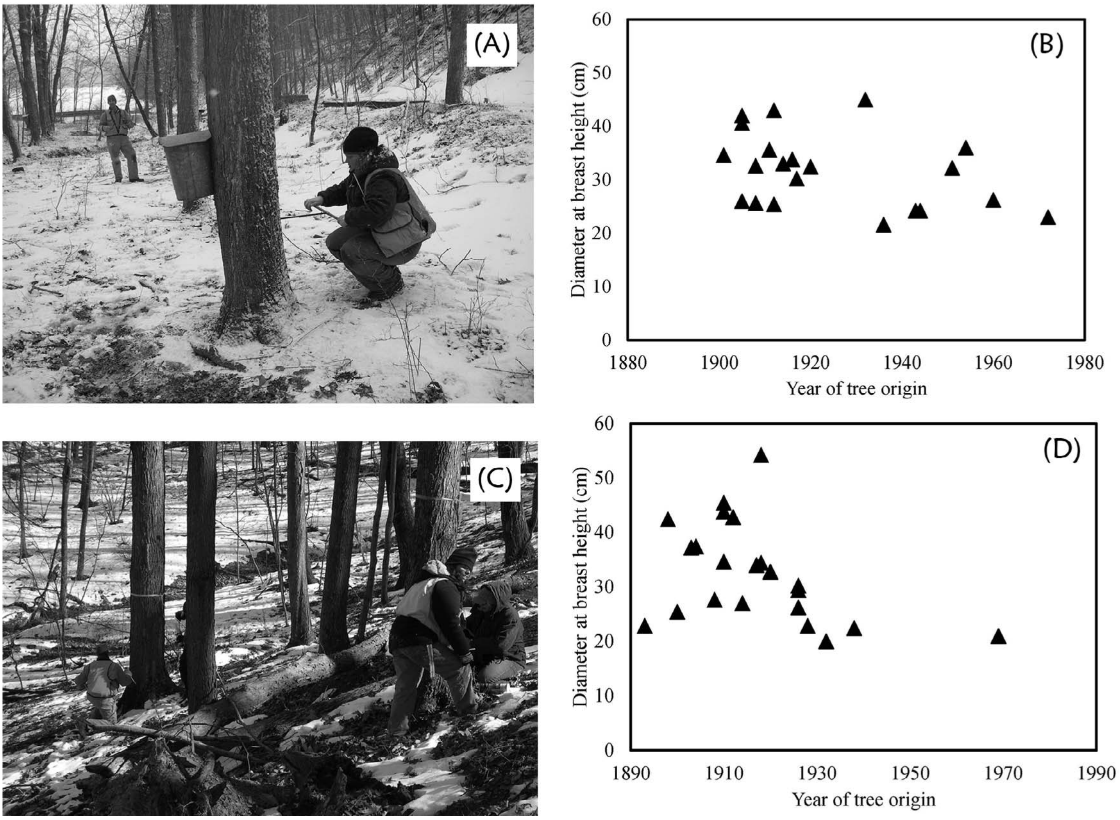

Figure 1. (A) The tapped sugar maple site with metal buckets used to collect sugar maple sap for maple syrup production on some of the trees. (B) Diameter and age distribution of the sugar maple trees cored from the tapped site. (C) The reference site of sugar maple trees that had never been tapped for maple syrup production. (D) Diameter and age distribution of sugar maple trees cored from the reference site. Please note that the diameter and age graphs do not represent stand structure because they only include trees sampled for this dendroclimatology study.

Engineers, personal communication). The synchrony of these features proved useful for crossdating cores where the outside rings were damaged during coring. After visual crossdating, tree-ring widths were measured using a Velmex TA Tree-Ring Measurement System (Velmex Inc., Bloomfield, NY). Visual dating of tree-ring measurements was verified with the dating verification program COFECHA (Grissino-Mayer 2001). Dating errors identified by this program were re-examined. If it was deemed possible to correct the error, the annual rings on the core were re-measured and the sample was re-evaluated with COFECHA. There were a number of cores that did not crossdate well with other trees from the sites and these cores were eliminated from further analysis. After crossdating, the sugar maple annual ring width measurements from the tapped site had an interseries correlation of 0.61 based on 40 increment cores from 21 trees. The reference site had an interseries correlation of 0.58 based on 38 increment cores from 22 trees. An interseries correlation reflects the strength of the common signal within tree-ring samples from a given area (Fritts 1976).

Data Analysis

The tapped and reference sites yielded crossdated samples that provided reasonably comparable trees of similar sizes and ages (Figure 1), where the only difference was whether the trees had been tapped annually for maple syrup production.

Table 1. Correlation coefficients between sugar maple tree-ring width index and various seasonal climatic variables. The value in parenthesis is the p-value and significant correlations are identified with bold text and an asterisk. Sugar maple trees that had been tapped annually for maple syrup production are identified as 'Tapped', and 'Reference' trees had never been tapped for maple syrup.

	Winter	Spring	Summer	Fall
Minimum temperature				
Tapped	−0.02 (0.89)	−0.02 (0.86)	−0.07 (0.61)	0.04 (0.76)
Reference	−0.03 (0.87)	0.08 (0.61)	−0.08 (0.63)	0.07 (0.69)
Maximum temperature				
Tapped	−0.02 (0.87)	−0.14 (0.30)	−0.22 (0.10)	0.07 (0.60)
Reference	−0.15 (0.37)	−0.15 (0.36)	−0.29 (0.08)	−0.05 (0.76)
Average temperature				
Tapped	−0.02 (0.88)	−0.07 (0.59)	−0.10 (0.48)	0.08 (0.54)
Reference	−0.09 (0.57)	0.07 (0.66)	−0.15 (0.35)	0.06 (0.70)
Total precipitation				
Tapped	0.15 (0.28)	−0.02 (0.91)	**0.40 (0.00)***	0.09 (0.53)
Reference	0.21 (0.20)	0.05 (0.76)	0.30 (0.06)	0.27 (0.10)
Palmer Drought Severity Index				
Tapped	**0.34 (0.01)***	0.21 (0.13)	**0.35 (0.01)***	**0.30 (0.02)***
Reference	0.23 (0.16)	**0.39 (0.02)***	**0.46 (0.00)***	**0.52 (0.00)***

There was no obvious pattern in ring width related to tree age; therefore, we detrended the raw tree-ring widths with a negative line to remove differences in growth that may have been related to site quality. Two master chronologies (tapped, n = 40 and reference, n = 38) were developed using ARSTAN to average the detrended tree-ring series. Tree-ring data are often significantly autocorrelated because growth in a given year influences growth in the following year. This characteristic violates Pearson's correlation's assumption of independence. We used the Durbin-Watson Test of Independence to examine the autocorrelation of the two standard master chronologies and found both the tapped (autocorrelation = 0.483, Durbin-Watson Statistic = 0.973, $p < 0.0001$) and the reference (autocorrelation = 0.591, Durbin-Watson Statistic = 0.715, $p < 0.0001$) sites had significant autocorrelation. Therefore, we used the residual chronology developed by the ARSTAN program because it removes the autocorrelation but retains information about forest growth (tapped site autocorrelation = −0.017, Durbin-Watson Statistic = 1.006, p = 0.494; reference site autocorrelation = 0.078, Durbin-Watson Statistic = 1.751, p = 0.216). The ring width index (RWI) values from the residual master chronology at the tapped and reference site were then compared with seasonal temperature (average, minimum, and maximum), total precipitation, and Palmer Drought Severity Index from Pennsylvania's Climate Division 08: South-central Mountains (NOAA 2015) using Pearson's correlation coefficient. Using regionally averaged climate division data is more suitable when working in mountainous regions than using single station data because the divisional data do not include the microclimatic signal from individual weather stations, which would not match the microclimatic conditions of the study sites (Blasing *et al.* 1981). We defined the seasons as winter (December of the prior year, January, February), spring (March, April, May), summer (June, July, August), and fall (September, October, November). The climate data were lagged one year from the tree-ring data to test for a delayed climatic influence on tree-ring growth and correlation coefficients were calculated for these lagged data. A significance level of α = 0.05 was used to identify significant correlations.

RESULTS

Temperature (minimum, maximum, or average) had no significant correlation with RWI during any season at either the tapped or reference sites (Table 1). Summer precipitation was positively, significantly correlated (r = 0.401, p = 0.002) with RWI at the tapped site, but was not significantly correlated with RWI at the reference site (Table 1). Palmer Drought Severity Index was positively, significantly correlated with RWI at the tapped site during winter (r = 0.345, p = 0.009), summer (r = 0.351, p = 0.008), and fall (r = 0.304, p = 0.023).

Table 2. Site-level matrices of percent and number of years (in parentheses) when spring PDSI was recorded as drought conditions (PDSI < 0) or non-drought conditions (PDSI > 0) when RWI was above average (RWI > 1) or below average (RWI < 1). At the tapped site, sugar maple trees were tapped annually for maple syrup production, and at the reference site trees had never been tapped.

	Percentage and Number of Years with Given Condition	
	Above Average RWI (>1)	Below Average RWI (<1)
Tapped		
Droughty spring	16% (9)	32% (18)
Non-droughty spring	25% (14)	27% (15)
Reference		
Droughty spring	15% (6)	35% (14)
Non-droughty spring	33% (13)	15% (6)

At the reference site PDSI was positively, significantly correlated with RWI during the spring ($r = 0.386$, $p = 0.015$), summer ($r = 0.462$, $p = 0.003$), and fall ($r = 0.521$, $p = 0.001$). During the summer growing season, when PDSI was significantly correlated with RWI at both the tapped and reference sites, there was a slightly stronger correlation at the reference site ($r = 0.462$) compared to the tapped site ($r = 0.351$). There were no significant relationships between the lagged temperature (minimum, maximum, or average) and RWI at either the tapped or reference sites. There were no significant correlations between lagged precipitation and RWI at the tapped or reference sites and there was no significant correlation between lagged PDSI and RWI at either site.

To further explore the relationships between spring drought and tree growth, we noted that both tapped and reference sugar maple experienced below-average growth during years when the spring growing conditions had lower moisture availability (PDSI < 0) (Table 2). In years when moisture was more readily available during the spring (PDSI > 0), sugar maple tapped for maple syrup production had a higher percentage of years (27%) when there was below-average RWI compared to sugar maples from the reference site (15%). This indicates that the significant correlation between RWI and spring PDSI at the tapped site (Table 1) may result from growth responses that occur during years with more available moisture in the spring.

DISCUSSION

Climate has been identified as an important factor determining radial growth rate in sugar maple (Lane *et al.* 1993; Tardif *et al.* 2001; He *et al.* 2005). In the northern and central portion of sugar maple's range, temperature limits radial growth (Lane *et al.* 1993; Tardif *et al.* 2001; Goldblum and Rigg 2005; He *et al.* 2005; Bishop *et al.* 2015). In more southern and eastern locations, drought and precipitation become more limiting to growth (Bishop *et al.* 2015). The results from this study add new information about sugar maple's dendroclimatic response from a site that represents the southernmost study site of sugar maple. In Pennsylvania, drought and precipitation were the most important climatic factors influencing radial growth in sugar maple (Table 1). The more moisture available to sugar maple, the higher growth rates the trees experience. The summer and fall correlations between radial growth and moisture availability are likely because sugar maple produce xylem cells from mid-June to mid-September (Wong *et al.* 2009) and moisture availability during this period results in more xylem cells being formed. The spring and winter correlations between radial growth and moisture availability are more likely indirect relationships. From mid-February to April, sugar maple are transitioning from a period of winter dormancy and becoming more physiologically active. Mid-April to June is the period of primary growth, and sugar maple grow their annual foliage (Wong *et al.* 2003). For a mesic species such as sugar maple, having moisture readily available during the spring likely results in higher photosynthetic rates and thus more xylem growth in the summer and fall.

Tapped sugar maple did not have a significant correlation between RWI and spring PDSI; but, the reference sugar maple had a significant correlation between RWI and spring PDSI (Table 1). Spring months are the periods of leaf expansion (Wong *et al.* 2003) and also the period when sap is extracted for maple syrup production. During years with low spring moisture availability (PDSI < 0), both tapped and reference trees experienced below-average growth, but during years with more moisture available in the spring, the reference trees had a higher percentage of years with above-average growth than the tapped trees (Table 2). These results indicate that during spring months with readily available moisture, the loss of carbohydrates from sap extraction may prevent tapped sugar maple from taking advantage of the good growing conditions and results in a non-significant correlation between spring PDSI and RWI. Thus, tapping for maple syrup may cause a difference in the dendroclimatic response of sugar maple during the spring tapping period.

Sugar maple's modelled growth under potential climate change scenarios predicts the tree will experience a reduction of area at the southern limit of the species (Brown *et al.* 2015). The addition of climate change as a stressor on sugar maple, a species that has already struggled with a decades-long dieback caused by air pollution (Bal *et al.* 2015), means solidly understanding the impact of annual tapping for maple syrup, is an important first step in planning for the sustainable future of maple syrup production. Sugar maple producers must make a concerted effort to regularly monitor the health of the trees tapped for maple syrup and reduce tapping intensity for trees that appear to be experiencing a reduction in vigor.

In conclusion, tapping for maple syrup production appears to weaken the strength of the climatic signal in the tree-ring record during the spring, but climate remains an important determinant of growth during the rest of the year. The two sugar maple populations studied (tapped and reference trees) came from the same location, yet because of differences in maple syrup production the two chronologies have slightly different climatic information archived in their tree-ring widths.

ACKNOWLEDGMENTS

This study was partially funded by a USDA NIFA Grant #2016-67003-24944 with additional funding from the USDA McIntire Stennis Program. The authors acknowledge field and laboratory assistance from K. Kovac and B. Bradburn.

REFERENCES CITED

Bal, T. L., A. J. Storer, M. F. Jurgensen, P. V. Doskey, and M. C. Amacher, 2015. Nutrient stress predisposes and contributes to sugar maple dieback across its northern range: A review. *Forestry* 88(1):64–83.

Bishop, D. A., C. M. Beier, N. Pederson, G. B. Lawrence, J. C. Stella, and T. J. Sullivan, 2015. Regional growth decline of sugar maple (*Acer saccharum*) and its potential causes. *Ecosphere* 6(10):1–14.

Blasing, T. J., D. N. Duvick, and D. C. West, 1981. Dendroclimatic calibration and verification using regionally averaged and single station precipitation data. *Tree-Ring Bulletin* 41:37–43.

Braun, E. L., 1950. *Deciduous forests of eastern North America*. The Blakiston Company, Philadelphia; 596 pp.

Brown, L. J., D. Lamhonwah, and B. L. Murphy, 2015. Projecting a spatial shift in Ontario's sugar maple habitat in response to climate change: A GIS approach. *The Canadian Geographer* 59(3):369–381.

Cho, D. S., and R. E. J. Boerner, 1995. Dendrochronological analysis of the canopy history of two Ohio old-growth forests. *Vegetatio* 120(2):173–183.

Copenheaver, C. A., R. C. McCune, E. A. Sorensen, M. F. J. Pisaric, and B. J. Beale, 2014. Decreased radial growth in sugar maple trees tapped for maple syrup. *The Forestry Chronicle* 90(6):771–777.

Davenport, A. L., and L. J. Staats, 1998. *Maple Syrup Production for the Beginner*. Cornell University Cooperative Extension. Available at http://maple.dnr.cornell.edu/pubs/maple_syrup_production.pdf.

Fritts, H. C., 1976. *Tree Rings and Climate*. Academic Press, New York; 567 pp.

Goldblum, D., and L. S. Rigg, 2005. Tree growth responses to climate change at the deciduous-boreal ecotone, Ontario, Canada. *Canadian Journal of Forest Research* 35(11):2709–2718.

Graham, G. W., P. C. Goebel, R. B. Heiligmann, and M. S. Bumgardner, 2006. Maple syrup production in Ohio and the impact of Ohio State University (OSU) extension programming. *Journal of Forestry* 104(2):94–101.

Grissino-Mayer, H. D., 2001. Evaluating crossdating accuracy: A manual and tutorial for the computer program COFECHA. *Tree-Ring Research* 57(2):205–221.

He, J. S., Q. B. Zhang, and F. A. Bazzaz, 2005. Differential drought responses between saplings and adult trees in four co-occurring species of New England. *Trees: Structure and Function* 19(4):442–450.

Hinrichs, S. C., 1998. Sideline and lifeline: The cultural economy of maple syrup production. *Rural Sociology* 63(4):507–532.

Kelley, J. W., and L. J. Staats, 1989. High-vacuum pumping effects on maple sap sugar yield. *Northern Journal of Applied Forestry* 6126–128.

Lane, C. J., D. D. Reed, G. D. Mroz, and H. O. Liechty, 1993. Width of sugar maple (*Acer saccharum*) tree rings as affected by climate. *Canadian Journal of Forest Research* 23(11):2370–2375.

Merkel, E. J., 1978. *Soil survey of Huntindon County, Pennsylvania*. Soil Conservation Service.

NOAA, 2015. US Division Data, Pennsylvania Division 8 Data archived in the National Climatic Data Center.

http://www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp#. Accessed 15 September 2015.

O'Brien, E. A., 2006. A question of value: What do trees and forests mean to people in Vermont? *Landscape Research* 31(3):257–275.

Pisaric, M. F. J., D. J. King, A. J. M. MacIntosh, and R. Bemrose, 2008. Impact of the 1998 ice storm on the health and growth of sugar maple (*Acer saccharum* Marsh.) dominated forests in Gatineau Park, Quebec. *Journal of the Torrey Botanical Society* 135(4):530–539.

Tardif, J., J. Brisson, and Y. Bergeron, 2001. Dendroclimatic anlaysis of *Acer saccharum, Fagus grandifolia*, and *Tsuga canadensis* from an old-growth forest, southwestern Quebec. *Canadian Journal of Forest Research* 31(9): 1491–1501.

USDA, 2015. *Northeast maple syrup production*. National Agricultural Statistics Service. Northeastern Regional Field Office.

Whitney, G. G., and M. M. Upmeyer, 2004. Sweet trees, sour circumstances: The long search for sustainability in the North American maple products industry. *Forest Ecology and Management* 200(1-3):313–333.

Wong, B. L., K. L. Baggett, and A. H. Rye, 2003. Seasonal patterns of reserve and soluble carbohydrates in mature sugar maple (*Acer saccharum*). *Canadian Journal of Botany* 81(8):780–788.

Wong, B. L., K. L. Baggett, and A. H. Rye, 2009. Cold-season patterns of reserve and soluble carbohydrates in sugar maple and ice-damaged trees of two age classes following drought. *Botany* 87(3):293–305.

Yamaguchi, D. K., 1991. A simple method for cross-dating increment cores from living trees. *Canadian Journal of Forest Research* 21(3):414–416.

Received 10 February 2016; accepted 1 November 2016.