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Preliminary Results of Sugar Maple Carbohydrate and Growth Response under Vacuum and Gravity Sap Extraction

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Recent technological advancements have increased the amount of sugar-enriched sap that can be extracted from sugar maple (*Acer saccharum*). This pilot study quantified overall sugar removal and the impacts of vacuum (60 cm Hg) and gravity sap extraction on residual nonstructural carbohydrate (NSC) concentrations and on stem and twig growth. Vacuum sap extraction (VSE) resulted in significantly greater mean sugar removal (1.19 ± 0.46 kg [SE]) than gravity sap extraction (GSE) (0.48 ± 0.14 kg). Residual stem NSC displayed a pattern of increased concentration with increased extraction. Twig residual NSC concentrations were highly variable, perhaps because of the highly dynamic late spring period, and no clear patterns were observed. Mean radial stem growth in the year after sap extraction was greater in untapped trees (2.93 ± 0.58 mm) than with VSE (1.99 ± 0.44 mm) or GSE (1.67 ± 0.12 mm). The results raise the possibility that sap removal shifts sugar maple NSC source-sink relationships toward storage at the expense of growth.

Keywords: maple syrup, nonstructural carbohydrate (NSC), maple sap, growth

Removal of sugar-enriched xylem sap for the production of maple syrup has long been considered a sustainable process (Whitney and Upmeyer 2004). Modern sap production technology uses vacuum pumps to achieve rates of sap collection per tree that are 2–3 times greater than historical methods (Heiligmann et al. 2006). No direct evidence exists to challenge the assumption that high rates of nonstructural carbohydrate (NSC) extraction remain sustainable in terms of tree carbon budget or growth.

Reduced NSC concentrations in sugar maple have been associated with past stress events including drought (Kolb and McCormick 1993, Payette et al. 1996) and defoliation (Gregory and Wargo 1985). Wong et al. (2005) found that severe crown damage after events such as ice storms can alter the short-term allocation of NSC to ensure survival. Recent evidence has indicated the potential for reduction in radial stem growth in certain trees tapped for maple syrup production (Copenheaver et al. 2014).

The current study sought to identify the impacts of sap extraction on late-dormant-season xylem tissue NSC concentrations and twig and stem growth in sugar maple trees under two levels of NSC removal (gravity sap extraction [GSE] and vacuum sap extraction [VSE]) compared with trees with no NSC removal (control [CTL]). The study objectives were as follows: to investigate whether VSE of xylem sap would increase the removal of NSC compared with GSE; to determine whether high-yield NSC extraction would reduce the residual NSC concentrations in twig and stem xylem tissue relative to those of trees subjected to low yield or no sap extraction; to determine whether twig and stem growth is reduced in trees exposed to high-yield extraction compared with that in trees exposed to low-yield and no-extraction treatments.

Methods

Study Site

The pilot study was conducted at the University of Vermont, Proctor Maple Research Center, in Underhill Center, VT (44°31′N, 72°53′W) at 435 m above sea level on a 10% slope with a generally westerly-facing aspect. Soils are a Marlow (Coarse-loamy, isotic, frigid Oxyaquic Haplorthods) with a pH of 3.7 ± 0.1. Sugar maple represents more than 50% of the tree canopy. A more detailed site description can be found in Wilmot et al. (1995).

Sample Collection

Twelve previously untapped and visually healthy sugar maples were identified, and the dbh was measured (1.4 m above ground

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Table 1. Sugar maple (*Acer saccharum*) mean diameter, sap yield, sap sweetness, and sugar yield from vacuum sap extraction, gravity sap extraction, and no sap extraction (CTRL) trees.

	No. of trees	Dbh (cm)	Sap yield (L)	Sap (°Brix)	Sugar yield (kg)
VSE	4	19.3 (3.5)	69.8 (19.9)	1.5 (0.2)	1.19 (0.46)
GSE	4	20.0 (3.5)	24.9 (7.6)	1.8 (0.1)	0.48 (0.14)
CTRL	4	19.8 (3.3)	NA	NA	NA

Data are means (SE). NA, not applicable.

level). All trees were growing in the same stand and therefore experienced the same climate conditions throughout the study period. Four trees were randomly assigned to each of three experimental treatments and had similar stem diameters (Table 1). GSE and VSE trees were fitted with sap extraction chambers consisting of 1.5-m sections of 15.2-cm-diameter clear polyvinylchloride pipe capped at each end (Figure 1). The GSE treatment was open to ambient air pressure (77 cm Hg), whereas the VSE chambers were evacuated to 60 cm Hg. The tree-to-chamber connection was accomplished with standard 0.8-cm diameter maple spouts and polyethylene tubing and allowed exuded sap from tapholes to collect into the chamber.

Trees were tapped on Feb. 26, 2010, to a depth of 5 cm. All tapholes faced west approximately 2 m above ground level.

Daily sap depth was measured with a graduated rule, converted to sap volume, and totaled for the season. A digital refractometer (PA202X; Misco, Cleveland, OH) was used to measure the sap sugar concentration to the nearest 0.1°Brix on three dates (March 19, March 29, and April 1). Sap collection ceased when the adjacent maple syrup operation ended production.

Twig and stem samples were collected to determine NSC concentrations before the initiation of spring growth. Three sun-exposed twig samples were collected from all study trees on Apr. 6, 2011 using a shotgun, placed in plastic bags, and put in a cooler with ice. Samples were transported immediately to an ultralow freezer (−70° C) and kept until carbohydrate analysis.

Two stem samples (1.9 cm in length and 0.6 in diameter) were collected from each study tree on Apr. 8, 2011, using an increment hammer (Haglof, Inc., Madison, MS) at approximately 1.2 m above the ground from the north and east face of the stems, transported immediately to the laboratory, and stored with twig samples in the ultralow freezer.

Twig and stem samples were subsequently analyzed (enzymatically for starch and by high-performance liquid chromatography for soluble sugars) at the US Department of Agriculture Forest Service laboratory in South Burlington, VT, as described in detail in Wong et al. (2003).

Growth Analysis

Stem growth and twig length were measured on June 12, 2011, 1 year after the sap extraction experiment. Twig samples were collected from the upper crown with a shotgun. Internode length from terminal twigs was measured to the nearest mm for segments and averaged for each the 2009 and 2010 growth seasons. Stem cores were collected using a 5-mm increment corer (Haglof, Inc.) on May 21, 2011, air-dried, glued into wooden blocks, and sanded using 320-grit sand paper. Ring widths from 2010 were measured to the nearest 0.01 mm using a digital micrometer linked to a computerized measuring sledge.

Figure 1. Xylem sap extraction chamber for gravity or vacuum extraction attached to sugar maple (*Acer saccharum*) stem.

Statistical Analysis

Treatment differences in total sugar removed and total sap yield (gravity versus vacuum) were analyzed via Student's *t*-tests after verification of the underlying statistical assumptions (GraphPad Prism 5.04). The effects of sap extraction treatment (gravity, vacuum, or control) on residual NSC concentrations within twig and stem xylem tissues were analyzed via one-way analyses of variance (ANOVAs). Treatment differences in radial stem growth and twig length the year after sap extraction were also analyzed via ANOVAs. Effects were considered significant at $P \leq 0.05$.

Results

Extraction of NSC-Enriched Xylem Sap

VSE trees produced more than 2.5 times the volume of sap than GSE trees (Table 2) ($P = 0.04$). GSE sap sweetness did not differ statistically from that of VSE sap (Table 1) ($P = 0.114$). Total sugar extraction was statistically greater ($P = 0.03$) in VSE trees than in GSE trees (Table 1).

Stem Sapwood NSC

Starch was the dominant NSC in stem sapwood tissue (Table 2). VSE trees had a greater residual mean stem starch concentration than GSE and CTL trees, although these values were not statistically different ($P = 0.47$). A similar pattern of increasing total soluble sugar (TSS) concentration with increasing NSC extraction was observed for stem tissues (Table 2).

Twig Sapwood NSC

Starch concentrations in twigs were nearly twice that of stems (Table 2). Observed values were consistent with previously published values of twig starch (Wong et al. 2003). The mean concentration of TSS in twigs was highest in VSE followed by CTL and GSE, respectively. Unlike stem sapwood samples, no indication of increasing TSS concentration with increasing NSC extraction was observed in twigs.

Table 2. Late dormant season starch and TSS concentrations in sugar maple (*Acer saccharum*) twig and stem xylem tissue.

	No. of trees	Stem TSS (mg/g)	Stem starch (mg/g)	Twig TSS (mg/g)	Twig starch (mg/g)	Twig growth (2010/2009 ratio)	Stem radial growth (mm)
VSE	4	16.05 (1.35)	28.56 (4.28)	11.72 (2.08)	54.87 (4.66)	0.84 (0.04)	1.99 (0.44)
GSE	4	13.40 (2.24)	26.71 (2.92)	4.93 (0.45)	38.16 (7.49)	0.88 (0.06)	1.67 (0.12)
CTRL	4	12.53 (1.12)	22.73 (2.38)	10.69 (3.10)	37.96 (9.81)	0.92 (0.05)	2.93 (0.58)

Data are means (SE).

Twig and Stem Growth

The mean ratio of twig internode length after sap extraction treatments (2010) to that of the year preceding the sap extraction experiment (2009) was greatest in the untapped control, compared with that in GSE and VSE (Table 1). Compared with that of CTL trees, radial stem growth was reduced 43% in GSE and 32% in VSE trees, respectively. However, this result was not statistically significant ($P = 0.35$).

Discussion

The results of this study agree with previous work (Wilmot et al. 2007), which showed an increase in sap yield of trees tapped using vacuum.

The mean NSC concentrations in sugar maple stem xylem tissue just before budbreak did not differ statistically between the two methods of spring sap extraction. The pattern of increasing starch concentration with increasing NSC extraction observed in stem samples was less clear in twig samples. Within-treatment variability was noticeably greater in twig samples (up to 4 times that of stem starch samples) (Table 2). The rapid physiological and metabolic changes corresponding with spring twig development could help explain the high degree of variability in twig NSC concentrations. Measured NSC concentrations were consistent with previous studies of sugar maple (Jones and Bradlee 1933, Wong et al. 2005).

Radiocarbon estimates of the mean age of NSC in the outermost 3 cm of red maple stems indicate that these pools can be relatively old, averaging 7–14 years (Richardson et al. 2013). Furthermore, it is estimated that the age of NSC supporting stump sprout growth after tree harvest can be even older, up to 17 years old (Carbone et al. 2013). The ^{14}C age of tree ring cellulose is only 0.9 year older than direct ring counts, suggesting that the carbon here is derived primarily from NSC stored during the previous growing season (Carbone et al. 2013). The question as to what portion of a trees total NSC budget is available during spring sap extraction remains unanswered. The answer to that question will strongly influence the long-term sustainability of modern maple sugaring practices.

The ratio of twig length in the year immediately after sap extraction to the year preceding sap extraction did not differ among the treatments, although there was a trend toward reduced twig length with increasing levels of sap extraction (Table 2). This could indicate that the sink for twig elongation and radial stem growth are weaker than the sink for NSC storage or that the two sinks draw from different sources within the tree.

Mean stem growth values for both sap extraction treatments tended to be lower in the year after sap extraction than in the control treatment. Chantuma et al. (2009) found that in rubber trees (*Hevea brasiliensis*), increased latex extraction was accompanied by a reduction in radial stem growth. The largest reduction in radial stem growth was observed in the year immediately after latex tapping. Copenheaver et al. (2014) observed impacts on stem growth in three stands tapped for maple syrup production compared to the reference (untapped trees) of −26, −36, and +23%, respectively, and attributed the impacts to altered NSC allocation. The magnitude of reductions in radial stem growth observed in our study was similar to that seen by Copenheaver et al. (2014).

Stem xylem tissue samples taken from trees not tapped and from those tapped at two levels of sap extraction (GSE and VSE) appeared to have a pattern of increased NSC concentrations with increasing sap extraction. The pattern raises the possibility of altered late dormant season NSC allocation within sugar maple trees. These trends were not significant, probably due to the small sample size and corresponding low statistical power.

The timing of NSC extraction coincides with the exit of trees from winter dormancy. The areas within a tree that extracted NSC originates from spatially, or for that matter, the age of the carbon that is being extracted are not clear from our results. Our results failed to identify significant differences in residual NSC concentrations among sap extraction treatments. The functional size of NSC pools is influenced by the storage capacity of woody roots, stems, and twigs and the temporal duration during which these stores remain accessible. Although it is reasonable to assume that the age of NSC in sap is also dominated by recent sources, this awaits verification and could vary over space and time, depending on factors including physiological stress mechanisms within trees that could trigger access to long-stored carbon pools. Our pilot study had a limited temporal scale, focusing on short-term impacts after one season of sap extraction. These results provide limited but useful insight into sugar maple growth and NSC dynamics.

Conclusions

The results of this study show that more NSC can be extracted using VSE than GSE. We did not detect a significant impact of increased sap extraction on the residual NSC pool in stems or twigs during the period immediately after sap extraction. The observed reduction of radial growth must be considered along with other factors that contribute to the long-term sustainability of maple sap extraction. Thousands of syrup producers continue to produce maple syrup annually without reports of widespread dieback or mortality in crop trees. Managers should consider that long-term sap extraction coupled with additional stresses (biotic and abiotic) might result in a greater risk to the health and growth of sugar maples.

Investigations into the age and spatial origin of carbon compounds that are removed through the process of xylem sap extraction will be needed to establish the true extent of available NSC and answer the question of whether current practices are indeed sustainable.

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