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Growth Rates of Sugar Maple Trees Tapped for Maple Syrup Production Using High-Yield Sap Collection Practices

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The amount of sap that can be extracted annually from trees for maple syrup production using current equipment and practices is more than double the typical yields achievable when current maple industry tapping guidelines were developed. The growth rates of trees tapped with these "high-yield" practices at 18 sites in Vermont were measured and evaluated to determine whether they were sufficient for the replenishment of conductive wood to remain at sustainable levels when current tapping guidelines are followed. The basal area increments of healthy codominant or dominant trees across the sites ranged from 1.8 (± 0.2) in.^{2}/year in 10-in. diameter trees, to 3.5 (± 0.3) in.^{2}/year in 18-in. diameter trees. The estimated minimum growth rates required ranged from 1.4 in.^{2}/year in 10-in. trees to 2.6 in.^{2}/year in 18-in. trees. These results suggest that the growth rates of many trees tapped with high-yield sap collection practices are sufficient for this activity to remain sustainable when current tapping guidelines are followed. However, an average of 35% of sampled trees had growth rates below the estimated minimums. This indicates that tapping practices must be modified for some trees to ensure that adequate replenishment of conductive wood is maintained and that growth rates must be measured to be certain sustainable tapping practices are implemented.

Keywords: tapping guidelines, sap extraction, maple sap, basal area increment, radial growth.

Maple syrup production is practiced widely throughout the forests of the northeastern and northcentral United States and eastern Canada, with more than 11.4 million taps reported in the United States alone in 2014 (US Department of Agriculture 2014). The practice relies on repeated annual tapping and sap collection from mature maple trees, and thus the health of individual crop trees is vitally important to the long-term viability of maple production operations.

Tapping a tree for sap collection involves removing a portion of the stem wood where a small hole is drilled each year to place a spout. The tree's response to this wound results in the development of a column of compartmentalized wood extending above and below the taphole (Figure 1) (Walters and Shigo 1978, Shigo 1984). This column remains permanently nonconductive to water transport as well as unavailable for future sap collection (Mulhern et al. 1979, Houston and Fagan 1997). In addition, sap collection annually removes a portion of the tree's nonstructural carbohydrate reserves (Hills 1904, Isselhardt et al. 2014). Despite these impacts, the practice is generally considered sustainable when best practices are followed (Allen et al. 1999, Chapeskie et al. 2006). Radial growth adds new conductive wood to the stem each year, and photosynthesis during the subsequent growing season provides additional carbon capture (Hills 1904, Walters and Shigo 1978). Thus, generally speaking, for annual maple sap collection to be sustainable, the volume of nonconductive wood (NCW) generated by tapping over the long-term in the area of the stem used for sap collection must not exceed the volume of conductive wood added by radial growth, and, likewise, the portion of carbohydrate reserves extracted must not be large enough to reduce growth rates and hinder the replenishment of conductive wood (Houston et al. 1990, Chabot 2005).

Recent advances in the equipment and practices used in maple production have resulted in substantial increases in the amount of sap that can be extracted annually from trees. Pumps capable of propagating vacuum levels of ≥25 in. Hg throughout the tubing collection system, coupled with current spout technology and equipment sanitation strategies, routinely facilitate yields of >0.4 gallons of syrup equivalent per tree (Perkins and van den

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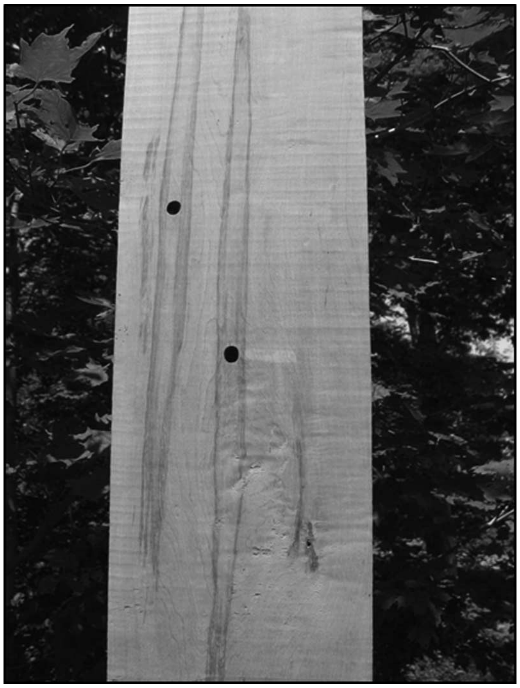

Figure 1. Illustration of columns of NCW generated by tapholes in a sugar maple stem. (Photograph courtesy of Mark Isselhardt.)

Berg 2009, Wilmot 2011a). This is approximately double the typical yields from systems using moderate levels or no vacuum and less current equipment and practices (Perkins and van den Berg 2009). Previous research has demonstrated that these higher vacuum and carbohydrate extraction levels do not increase the volume of NCW generated by taphole wounds (Wilmot et al. 2007). However, the availability of carbohydrate reserves strongly influences annual radial growth (Wargo 1977, Gregory 1980, Wong et al. 2005), and it remains unknown whether these higher levels of extraction are substantial enough to affect growth rates and have an impact on the sustainability of annual sap collection. Thus, the objective of this work was to determine the growth rates of trees tapped with these "high-yield" sap collection practices and assess whether they are sufficient for the use of these practices to be sustainable.

Methods

Site, Stand, and Tree Selection

Eighteen maple production operations throughout Vermont that had used high-yield sap collection practices for at least the previous 5 years were identified. For this study, we defined high-yield operations as those that used vacuum levels from 21 to 28 in. Hg and that had production yields of >0.4 gallon of syrup equivalent per tap (Perkins and van den Berg 2009). Operations were located in nine counties across Vermont and represented a range of stands typically tapped for maple production.

At each of the 18 operations, a single stand with uniform site characteristics and history, including site quality, elevation, aspect, stand density, and past management activities, was selected. To avoid confounding effects on growth rates, only stands that had not been thinned in the previous 10 years were selected. Stands with histories of stress or large-scale disturbances, such as multiple years of insect outbreaks, were excluded. Stand basal area was measured with a 10-factor prism in a representative location in each stand. The selected stands were of varying size and ranged from 260 to 2,000 ft in elevation and had an average basal area of 113.9 (± 5.7) ft^2/acre (range, 75–150 ft^2/acre), and the site quality was generally average to good as evaluated by site characteristics and indicator plants (Wilmot and Perkins 2004).

Table 1. Mean, SE, minimum, and maximum dbh of sugar maple trees selected for study at each of 18 sites in Vermont.

Site	*n*	Mean dbh (in.)	SE	Minimum dbh (in.)	Maximum dbh (in.)
A	21	9.8	0.2	8.2	11.6
B	47	12.8	0.5	8.0	19.9
C	49	13.5	0.4	9.2	19.0
D	34	14.4	0.5	9.2	19.7
E	20	12.8	0.6	9.0	16.6
F	17	14.8	0.7	10.5	19.2
G	39	14.1	0.5	8.8	19.9
H	41	13.5	0.5	8.0	19.7
I	49	13.2	0.4	9.0	17.8
J	46	11.8	0.3	8.1	15.4
K	44	13.9	0.5	8.2	19.7
L	38	13.5	0.4	8.2	18.6
M	27	15.5	0.4	12.2	19.4
N	40	12.3	0.4	8.0	15.6
O	37	14.3	0.6	8.1	19.8
P	42	13.5	0.5	8.0	19.5
Q	36	12.8	0.6	8.0	19.6
R	48	14.8	0.4	10.3	19.0

n is the number of trees. See the text for descriptions of site and tree selection.

Within each selected stand, healthy codominant or dominant sugar maple (*Acer saccharum* Marsh.) trees that had been tapped annually with a single tap for at least the past 10 years were selected. "Healthy" was defined as meeting the criteria for a North American Maple Project vigor rating of 1: the tree appears in reasonably good health with normal crown, no major branch mortality, <10% twig mortality, and no defoliation or discoloration present (Cooke et al. 2001). Five size classes in the diameter range specified by the "traditional" and "conservative" tapping guidelines in the *North American Maple Syrup Producers Manual* as suitable for tapping with a single annual tap (10.0–11.9, 12.0–13.9, 14.0–15.9, 16.0–17.9, and 18.0–19.9 in. dbh) were the primary focus (Chapeskie et al. 2006). As many maple trees as were present in these size classes in each stand were selected and included in the study. It should be noted that trees in all diameter classes were not present in every stand. The average and range of dbh of the trees selected for study in each stand are presented in Table 1. All selected trees met the basic criteria for tapping under current best practices for maple syrup production, including no obvious signs of insects, disease, physical damage, or stress (Chapeskie et al. 2006).

In addition, if dominant or codominant tapped trees near the lower limit of the size range (8.0–9.9) were present and met all other selection criteria, these were also included in sampling. However, these data were excluded from the primary analyses as this is below the minimum dbh specified by most current tapping guidelines (Chapeskie et al. 2006). The focus of the study was limited to the effects of a single annual taphole.

Increment Core Collection and Growth Rate Measurement

In late summer and autumn 2010, increment cores were collected from the north and south sides of each selected tree in each stand. Cores of 2–3 in. in depth were collected using a 5-mm increment borer (Haglöf, Långsele, Sweden) from a height approximately 2.5 ft. from the ground parallel to the slope contour to avoid areas of

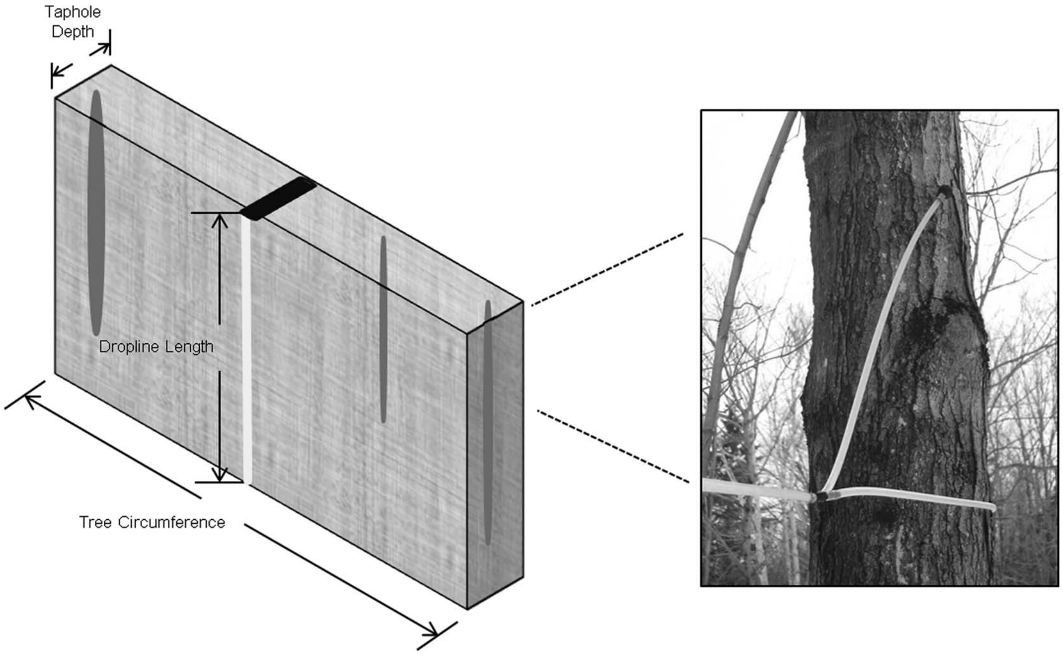

Figure 2. Generalized illustration of the tapping zone of a tree tapped for sap collection. The dimensions of the tapping zone are defined by the circumference of the tree, the length of the dropline, and the depth to which the taphole is drilled. At any point, the total amount of NCW (dark gray) within the tapping zone is the total volume of NCW within the zone's boundaries from all previous tapholes. The remainder of wood in the zone is the portion of conductive wood (light gray) available for tapping. The proportion of the tapping zone comprising conductive wood is equivalent to the probability of tapping into conductive wood annually.

the trunk affected by previous tapping. Dbh and the diameter at the height of core collection were recorded for subsequent calculations. After collection, cores were glued into wooden blocks, air-dried, and prepared for analysis by sanding to enhance the visibility of annual rings. With use of a dissecting microscope, the widths of each core's annual rings were measured to the nearest 0.001 mm using a digital micrometer linked to a measuring sledge. These data were used with the diameters at core height to calculate the mean annual basal area increment (BAI) over the previous 5 years (2005–2009) for each core using standard formulas ($\text{BAI}_t = \pi(R_t^2 - R_{t-1}^2)$, where R is the radius of the tree at time t (Long et al. 2009). North and south cores were averaged to calculate the mean BAI for each tree, which was used to calculate the mean BAIs of trees in each diameter class at each site. From these data, the mean BAIs of trees in each diameter class across all sites were calculated to express overall mean annual growth rates.

Minimum Growth Rates

To evaluate whether the measured growth rates of trees tapped with high-yield sap collection practices were sufficient for annual sap collection to be sustainable, a set of calculations to estimate the proportion of NCW in the tapping zone of an individual tree over time was developed. The calculations were combined into a spreadsheet "model" of the tapping zone, which was used to determine the minimum BAI required to ensure adequate replenishment of conductive wood.

The "tapping zone" of a maple tree is the area around the circumference of the stem that can be used for sap collection (Figure 2). For sap collection with tubing, its dimensions are defined by the depth of the taphole, the length of the sap dropline (tubing that connects the spout to the tubing system), and the circumference of the tree (Figure 2). Each year, tapping for sap collection generates a column of NCW proportional to the volume of wood removed for the taphole, while radial growth also adds conductive wood to the outside of the stem and functionally shifts the tapping zone outward so that some of the NCW generated by previous tapping is embedded deeper into the tree and thus no longer exists within the tapping zone boundaries. The total amount of NCW within the tapping zone at any time is equal to the sum volume of all NCW columns present from previous tapholes (Figure 2). Thus, the volume of the tapping zone and the relative proportion of NCW within it over time depend on the tree's diameter, growth rate, and tapping practices used: tapping depth, spout size, and dropline length. The tapping zone model was developed based on these premises and estimates the proportions of conductive and nonconductive wood in the tapping zone of an individual tree over time. For each year, the model calculates:

1. *The volume of NCW generated by the new taphole.* This is calculated as Taphole depth (in.) × Spout area (in.^{2}) × 75. The volume of NCW generated by each taphole is proportional to the size of the wound, and it can vary extremely widely among trees due to differences in diameter, growth rates, or other factors (Bauch et al. 1980). Previous research has shown that the volume of visibly stained wood can range from approximately 20 to 200 times the size of the taphole (average 50.3 ± 5.7) and that NCW can encompass an area up to 1.5 times larger than the area of visibly discolored wood (Wilmot et al. 2007, A.K. van den Berg, Univ. of Vermont, unpubl. data, 2014). Seventy-five (1.5 times the average visible stain volume observed in previous studies) was chosen as a conservative estimate for a multiplier based on these observations, so that the model was unlikely to underestimate the volume of NCW generated by taphole wounds (Wilmot et al. 2007).

2. *The total volume of NCW present in the tapping zone.* This is calculated as the sum volume of NCW remaining from each taphole present. The volume of each NCW column is reduced annually [(Taphole depth [in.] − Width of new ring [in.]) × Spout area (in.^{2}) × 75] to account for the outward shift of the tapping zone resulting from new radial growth. The volume of each taphole is eventually reduced to zero after sufficient radial growth occurs so that it is no longer within the tapping zone boundaries.
3. *The total volume of wood in the tapping zone.* For smaller trees for which the dropline length is greater than or equal to the circumference, this is calculated as Tree circumference (in.) × Dropline length (in.) × Taphole depth (in.) (Figure 2). For larger trees, for which the dropline cannot reach fully around the tree's circumference, the boundaries of the tapping zone are constrained to a smaller area of the tree's trunk. In these cases, the tapping zone is limited to the half-circle made by the dropline, and its volume is calculated as [π × Dropline length (in.)^2] ÷ 2 × Taphole depth (in.). The model also increases the tree circumference annually to incorporate radial growth, so that the volume of the tapping zone is increased concomitantly. To account for the increase in BAI with tree diameter, the average growth rates and dbh of trees sampled in this study were used to generate a best-fit regression equation to estimate the relationship between dbh and BAI ($y = -0.0024x^2 + 0.2534x - 0.6546$, $r^2 = 0.99$, where y = BAI and x = dbh). Each year, the model uses this equation to calculate the BAI for the tree at its current diameter. This increment is added to the tree's current diameter to calculate the new diameter (and circumference) after annual radial growth.
4. *The total percentage of the tapping zone occupied by NCW.* This is calculated as (Total NCW volume [in.^{3}] ÷ Total tapping zone volume [in.^{3}]) ×100.

The model was used to estimate the minimum growth rates required for sap collection to be sustainable when current tapping guidelines are followed. To accomplish this, model inputs were set to values specified by current tapping guidelines: maximum taphole depth, 2 in.; spout size, 5/16 in.; and minimum sap dropline length, 30 in. (Chapeskie et al. 2006). For each diameter class, the growth rates used in model calculations were then systematically adjusted to determine the minimum BAI required for the proportion of NCW in the tapping zone to remain below 10% over the next 100 years with the tapping practices specified. This level is equivalent to a <10% chance of encountering NCW when tapping each year and was selected through consultations with researchers, maple syrup producers, and extension personnel as the maximum amount of NCW acceptable.

The model provides a general approximation only and has assumptions and limitations that should be noted. It does not account for decreases in growth rates that might occur as the result of tree aging, changes in site conditions or management practices, or events such as drought or disease. It assumes that no preexisting NCW is present within the tapping zone. The model is also not spatially explicit and assumes annual tapping follows standard guidelines for taphole placement (4 in. laterally and 6 in. vertically from the previous year's taphole) (Chapeskie et al. 2006).

Table 2. Overall mean growth rates of sugar maple trees tapped with high-yield sap collection practices across 18 sites in Vermont.

Diameter class	No. of sites	Basal area increment (in.^{2}/yr)	SE	Radial growth (in.)
8 in.	5	1.5	0.3	0.06
10 in.	16	1.8	0.2	0.06
12 in.	16	2.1	0.2	0.05
14 in.	17	2.7	0.2	0.06
16 in.	14	2.8	0.2	0.05
18 in.	13	3.5	0.3	0.06

Trees had codominant or dominant canopy positions and had been tapped annually with a single spout for at least 10 years. The equivalent radial growth rates are also included.

Results and Discussion

Growth Rates of Tapped Trees

The mean growth rates for trees in each diameter class both across all sites and within each individual site are presented in Tables 2 and 3. As expected, growth rates increased with increasing diameter, and the values for overall means are comparable to those reported for sugar maple in other stands not managed for maple syrup production in the northeastern United States (Long et al. 2009). A prominent feature of the data was the large amount of variation observed in the growth rates of diameter classes both within and across sites. The variation across sites is likely attributable to differences in growth conditions, including soil properties, stand density, and local climate factors. Variations between trees at the same site could be attributable to individual tree factors, such as crown size or localized variations in stand density or soil quality. This observation emphasizes that even in the same stand, growth rates of individual trees can vary widely from one another.

Minimum Growth Rates Required

A model of the tapping zone was used to determine whether the measured growth rates were likely to be sufficient for annual tapping and sap collection to be sustainable. The model developed estimates the proportion of NCW within the tapping zone of an individual tree over time depending on tapping practices of spout size, sap dropline length, and tapping depth. The proportion of NCW is functionally equivalent to the probability of tapping into NCW each year and provides an estimate of the sustainability of tapping practices, since excessive accumulation negatively affects both tree physiological function and sap collection activities (Walters and Shigo 1978, Houston et al. 1990, Houston and Fagan 1997). A large buildup of NCW can lead to an increased incidence of decay and reduces the conductive sapwood available for future tapping (Walters and Shigo 1978, Houston et al. 1990, Houston and Fagan 1997). It can also cause columns of NCW to coalesce and result in even larger volumes of NCW within the tapping zone (Walters and Shigo 1978, Houston et al. 1990). In addition, tapholes drilled into NCW yield little or no sap and can increase the spread of discolored wood and decay within the xylem (Walters and Shigo 1978, Houston et al. 1990, Houston and Fagan 1997). Thus, it follows that the proportion of NCW within the tapping zone (and the probability of tapping into NCW) must remain low for sap collection practices to be both physiologically and economically sustainable (Houston et al. 1990, Chabot 2005). The model was used to determine the minimum growth rates required for the proportion of NCW in the tapping zone to remain below 10% over the next 100 years when current tapping guidelines are followed. The current guidelines

Table 3. Mean growth rates (BAI) of sugar maple trees tapped with high-yield sap collection practices within each of 18 sites in Vermont.

	Diameter class																	
	8 in.			10 in.			12 in.			14 in.			16 in.			18 in.		
Site	Mean	SE	*n*	Mean	SE	*n*	Mean	SE	*n*	Mean	SE	*n*	Mean	SE	*n*	Mean	SE	*n*
	(in.^{2}/yr)																	
A	2.6	0.2	12	2.8	0.2	9												
B	1.2	0.04	2	1.4	0.1	11	1.7	0.1	8	3.0	0.3	5	2.8	0.4	9	3.4	0.8	3
C				1.5	0.2	4	1.7	0.2	18	2.7	0.3	7	2.9	0.3	6	4.1	0.7	4
D				2.1	0.1	2	2.9	0.3	7	3.5	0.7	5	4.0	0.4	8	5.6	0.7	5
E				1.8	0.3	2	0.8	0.1	4	2.1	0.2	4	2.9	0.8	3			
F										2.4	0.3	6	2.2	0.5	3	3.8	0.6	3
G				1.0	0.1	3	1.4	0.2	5	2.0	0.2	10	2.6	0.3	6	3.2	0.8	5
H				1.9	0.4	2	2.7	0.2	7	3.8	0.4	10	3.7	0.8	4	3.7	0.8	5
I	1.3	0.03	2	1.8	0.2	8	2.0	0.2	14	2.5	0.3	6	2.9	0.4	12			
J				1.4	0.2	13	2.0	0.3	12	1.9	0.2	7						
K				1.3	0.2	8	2.1	0.3	4	2.9	0.3	14	3.6	0.5	7	4.3	1.1	4
L				0.9	0.2	5	1.4	0.2	11	1.1	0.2	6	1.5	0.1	7	1.9	1.0	2
M							2.3	0.6	3	2.6	0.4	8	2.0	0.5	9	1.6	0.03	3
N				4.1	0.9	3	3.0	0.2	9	3.9	0.4	13						
O				1.9	0.5	2	1.2	0.1	3	2.8	0.9	6	1.9	0.2	4	2.2	0.3	9
P	1.0	0.3	3	0.9	0.1	3	2.7	0.3	9	2.7	0.4	9	3.3	0.4	7	3.5	0.6	3
Q	1.3	0.2	7	3.0	0.4	8	3.6	0.5	5	2.2	0.3	6				2.8	0.3	6
R				1.1	0.2	2	1.9	0.2	14	3.7	0.5	8	3.2	0.4	10	5.3	0.7	8
Total no. of trees			26			85			133			130			95			60

Trees had codominant or dominant canopy positions and had been tapped annually with a single spout for at least 10 years. *n* is the number of trees.

specify a minimum tree diameter of 10 in. and the use of 5/16-in. spouts, 30-in. droplines, and a maximum tapping depth of 2 in. (Chapeskie et al. 2006).

The estimated minimum BAI required ranged from 1.4 in.^{2}/year in 10-in. trees, to 2.6 in.^{2}/year in 18-in. trees (Table 4). These estimates are for trees tapped with a single tap only and assume that no changes in tapping practices are made, and no major events that substantially affect growth rates, such as drought, ice damage, significant incidences of insects or disease, or alterations in stand structure, occur over time. The overall mean growth rates measured in trees tapped with high-yield practices were substantially higher than these estimated minimum levels, ranging from 1.8 in.^{2}/year in 10-in. trees to 3.5 in.^{2}/year in 18-in. trees (Table 2). This generally suggests that the growth rates of many healthy dominant or codominant trees are sufficient for tapping with current practices to result in sustainable outcomes when current tapping guidelines are followed. However, although the overall mean growth rates exceeded the estimated minimums, many of the mean growth rates within the stands were below these levels (Table 3). Indeed, between 27 and 47% of individual sampled trees had growth rates that were below the minimum rates needed when current tapping guidelines are followed (Table 4). In trees with these growth rates, tapping following current guidelines would be more likely to result in an accumulation of NCW in the tapping zone, reduced sap yields, and negative impacts on tree health. Although slow taphole closure, poor crown condition, branch dieback, and other visual factors can be indicative of lower growth rates (Heiligmann et al. 2006), the only way to be certain the growth rate of an individual tree is above the minimum rate needed is through direct measurement.

Practices to Increase Sustainability

It is possible, however, to improve the sustainability of sap collection from trees with subminimum growth rates by adjusting tapping and management practices. First, the length of sap droplines strongly influences the sustainability of tapping practices because it determines the extent of the trunk area available for tapping each year: longer droplines access a larger portion of the tree, and the proportion of the tapping zone occupied by the NCW generated by each taphole is thereby reduced (Figure 2 and model calculations 1–4 above). Thus, in some cases simply increasing the length of sap droplines above the minimum recommended 30 in. is sufficient to increase the likelihood of sustainability. For example, increasing dropline length to 36 in. lowers the minimum required growth rates to 1.1 in.^{2}/year in 10-in. trees and to 1.6 in.^{2}/year in 18-in. trees (Table 5). With this change in practice, the percentage of sampled

Table 4. Estimated minimum growth rates required when trees are tapped following current tapping guidelines and the numbers and percentages of sampled trees with growth rates lower than these minimum levels.

	Results for current tapping guidelines: spout size, 5/16 in.; dropline length, 30 in.; tapping depth, 2 in.				
Diameter class	Minimum basal area increment (in.^{2}/yr)	Minimum radial growth (in.)	Total no. of trees sampled	No. of trees below minimum	% of trees below minimum
8 in.	1.3	0.05	26	10	38
10 in.	1.4	0.04	85	35	41
12 in.	1.7	0.04	133	53	40
14 in.	2.0	0.04	130	35	27
16 in.	2.3	0.04	95	34	36
18 in.	2.6	0.04	60	19	32

Table 5. Estimated minimum growth rates required when tapping practices are altered from current guidelines and the numbers and percentages of sampled trees with growth rates below these minimum levels.

		Results for increased dropline length: spout size, 5/16 in.; dropline length, 36 in.; tapping depth, 2 in.				Results for increased dropline length and reduced tapping depth: spout size, 5/16 in.; dropline length, 36 in.; tapping depth, 1.5 in.			
Diameter class	Total no. of trees sampled	Minimum basal area increment (in.^{2}/yr)	Minimum radial growth (in.)	No. of trees below minimum	% of trees below minimum	Minimum basal area increment (in.^{2}/yr)	Minimum radial growth (in.)	No. of trees below minimum	% of trees below minimum
8 in.	26	1.0	0.04	5	19	0.8	0.03	1	4
10 in.	85	1.1	0.03	23	27	0.8	0.03	9	11
12 in.	133	1.1	0.03	21	16	0.9	0.02	7	5
14 in.	130	1.1	0.02	11	8	0.9	0.02	6	5
16 in.	95	1.4	0.03	9	9	0.9	0.02	1	1
18 in.	60	1.6	0.03	7	12	1.2	0.02	2	3

trees with growth rates below the required minimums is reduced to between 8 and 27% (Table 5).

Reducing the depth of tapping can also increase the likelihood of sustainability. For sap collection with vacuum, current tapping guidelines recommend tapping to a depth between 1 and 2 in. Tapping to the maximum depth is advantageous, as it is likely to result in higher sap yields (Wilmot 2011b). However, because this benefit would be offset if tapping practices resulted in an excess accumulation of NCW and reduced sap yields, choosing a shallower tapping depth in trees with subminimum growth rates could be a cost-beneficial strategy. For example, if tapping depth is decreased to 1.5 in. in addition to using 36-in. droplines, the estimated minimum growth rates are further reduced to 0.8 in.^{2}/year for 10-in. trees, and 1.2 in.^{2}/year for 18-in. trees (Table 5). With these tapping practices, the percentage of sampled trees with growth rates below the estimated minimum levels is reduced to between 1 and 11% (Table 5).

Silvicultural treatments can also help increase the likelihood that tapping practices will be sustainable. In particular, periodic thinning is recommended in stands managed for maple production to promote vigorous radial growth and tree health (Heiligmann et al. 2006). Indeed, thinning and other intermediate cutting has been demonstrated to significantly increase the diameter growth rates of sugar maple trees (Voorhis 1990, Pothier 1996, Miller 1997) and thus could be used to increase the growth rates of trees that have growth rates below the estimated minimum levels. The best approach for thinning to promote radial growth in trees tapped for sap collection will depend on the specific conditions of the stand in question, but general guidelines and recommendations can be found in Heiligmann et al. (2006). The stands examined in this

Table 6. Mean growth rates (BAI) of sugar maple trees with intermediate or suppressed canopy position that had been tapped using high-yield sap collection practices and the numbers and percentages of these trees with growth rates below the estimated minimum rates required when current tapping guidelines are followed (Table 4).

	Diameter class								
	8 in.			10 in.			12 in.		
Site	Mean	SE	*n*	Mean	SE	*n*	Mean	SE	*n*
					(in.^{2}/yr)				
Overall	1.0	0.1	14	1.4	0.1	15	1.7	0.4	5
A									
B	1.2	0.2	9						
C	0.9	0.1	5	1.7	0.3	5			
D	2.1	0.7	3	1.2	0.4	4			
E	0.9	0.2	3	1.2	0.2	4			
F				1.2	0.1	5			
G	0.8	0.2	4	1.2	0.2	6			
H	0.9	0.1	6	1.8	0.4	7			
I	1.0	0.2	5	1.5	0.1	2			
J	0.7	0.1	8	1.0	0.2	6			
K	0.8	0.2	4	0.9	0.3	3			
L	0.7	0.2	3	0.7	0.1	2	0.6	0.0	2
M							1.6	0.7	4
N	1.3	0.2	10	2.0	0.1	3	3.0	1.0	2
O	0.7	0.2	6	1.4	0.5	3	1.6	0.6	4
P	0.7	0.2	5	1.7	0.2	3			
Q	1.9	1.0	2	2.2	0.7	2			
R				2.0	0.4	4	1.9	0.7	2
Total no. of trees		73			59			14	
No. of trees below minimum		60			31			7	
% of trees below minimum		82.2			52.5			50.0	

Trees were sampled from 18 sites in Vermont and had been tapped annually with a single spout for at least 10 years. Trees that met these criteria were found only in 8-, 10-, and 12-in. diameter classes. *n* is the number of sites for overall means and the number of trees for means within each site.

study had not been thinned in at least 10 years, and some had not been thinned ever or for more than 20 years. It is likely that the growth rates of trees in some of these stands were lower than those in stands that are more regularly thinned, which could account for the relatively large number of trees sampled that had growth rates below the minimum levels necessary under current tapping guidelines.

In addition, any activities or practices that increase the effective size of the tapping zone, such as raising or lowering the lateral tubing due to yearly variations in snow depth, can also increase the likelihood that tapping practices will be sustainable. Experiments have recently been initiated to examine the sap yields and efficacy of placing tapholes below the lateral tubing. If found to be effective, this practice could also increase the effective size of the tapping zone and the likelihood that sap collection will be sustainable in the long term.

Smaller and Subcanopy Trees

Although not the primary focus of the study, tapped codominant or dominant trees in the 8.0- to 9.9-in. diameter class, as well as trees with intermediate or suppressed canopy position, were included in sampling if they were present in study stands and met all other selection criteria. The data obtained from these trees are limited, but they do provide information that should be considered when these types of trees are evaluated for inclusion as crop trees for sap collection. First, the growth rates of 38% of the trees sampled in the 8-in. size class were below the minimum rates required when current tapping guidelines are followed (Tables 2 and 4). This is a particularly important observation, since alternative sets of tapping guidelines that currently exist across the maple industry specify 9 in., rather than 10 in., as the minimum diameter for tapping (Northeast Organic Farming Association of Vermont 2012). Likewise, the growth rates of intermediate and suppressed trees were substantially lower than those of most codominant and dominant trees, and 50–82% of sampled trees had growth rates below the minimums needed when current tapping guidelines are followed (Table 6). Together these observations indicate that apparently healthy trees that are smaller than the diameter range recommend by current tapping guidelines or underneath the primary canopy cannot be presumed to have sufficient growth rates for sustainable tapping.

Conclusions

The results of this study indicate that the growth rates of many healthy dominant or codominant trees in sugarbushes are probably sufficient for sap collection with high-yield practices to be sustainable when current tapping guidelines and best practices are followed. However, the results also demonstrated that the growth rates of some trees might require that tapping practices be adjusted from the minimum specifications of current tapping guidelines to prevent an excess accumulation of NCW. The results also indicated that many smaller diameter or subcanopy trees often do not have growth rates sufficient for tapping and sap collection to be sustainable in the long term. In addition, the large amount of variation observed in the growth rates of trees in the same size class both within and across sites indicates that to be certain that appropriate and sustainable sap collection and tapping practices are used for a particular tree or stand, growth rates must be measured and tree and stand conditions carefully assessed. The results also reinforce the importance of regular thinning in maple sugarbushes to promote vigorous growth of crop trees to maintain the sustainability of annual tapping and sap collection. Foresters, maple producers, and landowners can use this information to help inform management planning activities and can use the minimum growth rates determined in this study to help guide assessments and decisions regarding the sustainability of sap collection and tapping practices in particular trees and stands. Additional information, guidance, and recommendations on appropriate tapping guidelines and practices, selection of crop trees, and management activities to promote radial growth in stands managed for maple syrup production can be found in the *North American Maple Syrup Producers Manual* (Chapeskie et al. 2006, Heiligmann et al. 2006). In addition, a version of the tapping zone model designed for producer use that can be used to assess the sustainability of input tapping practices and help guide management decisions is available[1] and is described in van den Berg and Perkins (2014).

This study did not address the potential fundamental impact of tapping and sap collection on the growth rates of trees and whether the practice itself results in a decrease in growth rates relative to those of trees not tapped for maple production. A long-term experiment was recently initiated with trees previously untapped for maple production to address this question.

Endnote

1. The tapping model is available for downloading at www.uvm.edu/~pmrc.

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