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G [illegible] -Y [illegible] C [illegible]

A K. a B , T D. P , Ma L. I a , a T R. W

[illegible] 1. (± 0.2) [illegible] 10- [illegible] 3. (± 0.3) [illegible] 1.4 [illegible] 10- [illegible] 2. [illegible] 3 % [illegible]

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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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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 113.7 (±5.9) 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).

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 i 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

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 ($BAI_t = (R_t^2 - R_{t-1}^2)$, 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 Rate

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.

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 × [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, [illegible] 80a6-.94prTcrease)-228vious)-2501year's ly2(in240.950(

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

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