Yields from Early Tapping and Taphole "Rejuvenation" Strategies

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There is currently substantial interest in early tapping, with or without subsequent treatments to "rejuvenate" the taphole, as a means to potentially increase overall annual yields and net revenues in general, and also as a mitigation strategy for losses due to production seasons with poor or unusual conditions for sap flow, such as fewer than usual sap flow days due to warmer or colder than average temperatures, and shortened seasons due to the occurrence of earlier than typical warm temperatures that result in premature reductions in sap flow and season end. These "unusual" conditions are increasingly common with changes in weather patterns and climate caused by changing global climate conditions (Jay *et al*. 2018). It is believed that tapping earlier than the standard spring sap flow season might be able to mitigate potential losses that result from these occurrences, and increase yields in general, by capturing sap flows during the brief autumn sap flow period and/or thaw periods in the early-winter (e.g. late-December and January for areas like northern Vermont) (Wilmot 2008, Orefice 2018). "Rejuvenation" strategies are thought to possibly be able to further augment this by extending the standard sap flow season or increasing overall yields through the enlargement of existing tapholes. It is believed that by exposing new vessels these strategies might increase sap flow and yields by overcoming the tree's response to the taphole wound and microbial effects (Childs 2019, Childs 2020, Wild 2020). Because the impacts on yields of these early tapping strategies, with or without subsequent rejuvenation, are likely to be affected by weather conditions which can vary widely from year to year, controlled experiments over multiple years are required in order to more fully assess whether any of these strategies result in greater yields than tapholes made during the standard spring sap flow period, or whether any increases in yield would be sufficient to compensate for the increased costs associated with implementing them. Thus, we conducted a multi-year, controlled experiment to assess the yields of several early tapping strategies, with and without subsequent rejuvenation, relative to the yields of standard spring tapholes.

Materials and Methods

Eighty healthy trees with codominant or dominant canopy position in a single stand at the UVM Proctor Maple Research Center in Underhill, Vermont were stratified into eight treatment groups of equal diameter (Table 1). Each tree was connected to a single, 30-gallon collection chamber (Figure 1). A separate 15-gallon collection container was placed into the collection chamber, allowing removal and replacement with an empty container to facilitate yield measurements during extended periods of below-freezing temperatures (Figure 1). Vacuum was applied to the system using a Busch 1142 rotary claw vacuum pump equipped with a variable frequency drive maintained between 25-27"Hg throughout the experiment each year.

Treatments
Seven different early tapping and taphole rejuvenation treatments were studied (Table 2). All treatments were compared to that of a taphole drilled during the standard spring sap flow season (**Spring Control**). Standard taphole depth was 1.5” in Year 1 of the experiment, and 2” in Years 2 and 3; standard taphole diameter was 5/16”. New polycarbonate spouts were used for all treatments, including all rejuvenation treatments. All droplines and lateral tubing were new in Year 1, and not replaced over the course of the experiment.

Four “Fall Tapping” treatments were studied; for these treatments, tapholes were drilled after leaf drop and the initial occurrence of below-freezing temperatures in autumn (Figure 2).

- One fall treatment was drilled to standard depth and diameter, with no subsequent rejuvenation treatment (**Fall Control**).
- One fall treatment was drilled to standard depth and ¼”-diameter, then enlarged to 5/16” wide and 2.5” deep on the same day that Spring Control tapholes were drilled (**Fall Wider and Deeper**).
- One fall treatment was drilled to standard depth and diameter, then deepened to 2.5” on the same day that Spring Control tapholes were drilled (**Fall Deeper**).
- One fall treatment was drilled to standard depth and diameter, then on the same day that Spring Control tapholes were drilled, a second taphole of standard depth and diameter was drilled 2” immediately above the first taphole (**Fall Second Hole**). The spout of the first hole was plugged to eliminate vacuum leaks (Figure 3). This treatment was studied in Years 1 and 2 of the experiment only.

Three “Early-Winter Tapping” treatments were studied. For these treatments, tapholes were drilled between late December and mid-January, depending on the occurrence of temperature conditions for sap flow.

- One early-winter treatment was drilled to standard depth and diameter, with no subsequent rejuvenation treatment (**Early-Winter Control**)
- One early-winter treatment was drilled to standard depth and ¼”-diameter, then enlarged to 5/16” wide and 2.5” deep on the same day that Spring Control tapholes were drilled (**Early-Winter Wider and Deeper**)
- One early-winter treatment was drilled to standard depth and diameter, then deepened to 2.5” on the same day that Spring Control tapholes were drilled (**Early-Winter Deeper**)

An eighth taphole rejuvenation treatment was studied in Year 3 only. For this treatment, an initial taphole was drilled on the same day as Spring Control tapholes, then was deepened to 2.5” after the occurrence of four days with air temperatures above 50°F (**Late-Season Rejuvenation**). This treatment replaced the Fall Second Hole treatment in Year 3.

During each year of the study, each tree was tapped, and subsequently rejuvenated as appropriate, with its respective treatment. Each tree received the same treatment in each year of the study. The total volume and sugar concentration of sap produced by each tree was measured periodically until the conclusion of the sap flow season (Figure 1) as determined by when either sap flow ceased, or late-season off-flavor was detected within the UVM PMRC maple operation, whichever arrived first. Sap volume was measured by weight with a digital scale, and sugar concentration with a handheld digital refractometer (Misco PA203). These data were used to calculate the total syrup equivalent produced by each tree, and the average yield for each treatment. The average yield for each treatment was also expressed as a percentage of the average yield of standard spring tapholes (Spring Control). The experiment was repeated for three sap flow seasons: 2017-2018, 2018-2019, and 2019-2020. The data for the three individual years were used to calculate the overall average yield for each treatment in gallons of syrup per tree, and as a percentage of Spring Control trees for the three years of the study.

Statistical analyses
A repeated measures linear model with main effects for tree diameter, year, treatment, and a random effect for tree, was used to determine if any significant difference existed in yields of treatments across the three study years. Multiple paired comparisons were used to explore if any of the early tapping or rejuvenation treatments resulted in yields significantly different from those of standard spring tapholes (Spring Control). "Fall Second Hole" and "Late-Season Rejuvenation" treatments were not included in statistical analyses, as they were not repeated in all three study years.

Results and Discussion

Although some patterns may seem evident from the average yields of the treatments for the individual years of the study (Figure 4), assessing the performance of early tapping or rejuvenation practices from any single year is not optimal, as the effect of these treatments will be strongly impacted by the weather conditions in that year, which can substantially impact the number and intensity of sap flow days in each sap flow period (Fall, Early-Winter, Spring; Figure 2). For this reason, it is necessary to compare the average performance of the treatments across the three years of the study. Figure 5A shows the overall total average syrup yield per tree for each treatment, and 5B their average yields as a percentage of the yield of Spring Control tapholes. None of the treatments had yields significantly different statistically from yields of Spring Control tapholes (Table 3).

One factor which, in other research studies, would have influenced the ability to detect differences between treatments is the high level of variation in yields between the trees within each treatment. This variability is evident in Figure 4, which depicts the means of yields within each treatment each year with an error bar calculated as the standard error of the mean (the standard deviation of measurements divided by the square root of the sample size). However, much of this variability is due simply to differences in tree diameter within each treatment – while mean diameters were equal in all the treatments, tree size ranged between approximately 9 and 20 inches within each treatment group (Table 1). Indeed, diameter is a highly significant predictor variable of yield in the model (estimate 0.058, p-value < 0.0001). However, because the statistical model used accounts for the impacts of tree diameter on yields, it did not impact the ability to detect differences between the treatments. On the other hand, a consequence of the relatively small sample size for each treatment is that there was possibly insufficient statistical power to detect true differences between the treatments. So, while general patterns in yields between the different treatments can be discussed, it must be done with the caveat that, from a strictly statistical perspective, there are no differences in yields between any of the treatments.

Early Tapping Without Rejuvenation

Looking at general patterns, over the three years of the study, tapholes drilled early without subsequent rejuvenation had lower yields than standard spring tapholes. Fall and Winter Control tapholes yielded an average of 84 and 92% of Spring Control tapholes, respectively (Figure 5B). This suggests that despite good sanitation practices and high levels of vacuum there can be some loss in yield with earlier tapping, which increases the earlier the taphole is drilled. This is not surprising, as the tree's response to compartmentalize or "wall-off" the taphole wound begins immediately – as early as five days after wounding depending on weather conditions and other factors (Rier and Shigo 1972, Shigo and Hillis 1973, Figure 6). For some larger operations, this might be an economically balanced tradeoff of early-winter tapping to ensure that all trees are tapped by the time the primary spring sap flow season begins. On the other hand, these data indicate that tapping in early-winter to capture early sap flows is not an effective strategy to *increase* yields, at least in the weather conditions that occurred during the three years of this study. The size of the yield reduction observed with fall tapping, coupled with the numerous practical challenges of the practice, are substantial enough to indicate that the practice is not an effective strategy to increase yields in a climate with a standard spring sap flow season in mid-February through April. It remains possible that tapping in the fall season could be beneficial in areas where the standard spring sap flow period occurs earlier than in the study area, or is characterized by numerous warm periods, however that cannot be determined from the results of this study. Whether fall tapping is a cost-effective means to increase revenues by reducing the proportion of the annual crop with late-season off-flavors in regions where the standard spring sap flow season occurs *later* in the year (e.g. mid- to late-April), also cannot be determined from the results of this study, which did not assess the flavor of syrup produced in the fall, and was not performed in such a climate. Both possibilities indicate a need for similar experiments to be done in areas with different sap flow seasons. However, any future studies of early tapping practices should take into account and examine potential impacts on tree health and sustainability of extracting sap throughout the tree's dormant period, during which the carbohydrate resources in the sap are critical for tree function and survival.

Early Tapping with Rejuvenation

The yields of tapholes treated with rejuvenation practices had varying results relative to standard spring tapholes.

<u>Second Complete Taphole</u>

Tapholes that were drilled in the fall and later had a second taphole drilled immediately above it (Fall Second Hole) averaged approximately the same yields as Spring Control tapholes (103%, Figure 5B). The second taphole treatment was envisioned as a way to potentially maximize the potential sap yield gain of rejuvenation, while minimizing the overall amount of nonconductive wood (NCW) generated, by tapping within the area already encompassed by the column of NCW that would develop from the first taphole. This hypothesis was incorrect in several ways. First, if that thinking had been correct, we should have observed a significantly higher yield than a standard spring taphole – these trees received a "fresh," complete taphole in the spring, in addition to the taphole initially drilled in the fall. However there was no gain in yield from this second hole relative a single spring taphole. This strongly suggests that compartmentalization from the first taphole wound had already proceeded enough to result in reductions in vessel conductivity within the area adjacent to the initial wound. Second, a simultaneous study of NCW generated by rejuvenation treatments (van den Berg *et al*. 2021) showed that the amount of NCW generated in response to the second hole treatment was *more than double that of a single taphole of the same size*, and moreover that two, completely distinct columns of NCW were generated, one from each taphole wound (Figure 7). Together these results demonstrate that drilling a second taphole vertically proximate to the first does not enhance yields, and is disproportionately more detrimental to sustainability than a single taphole. For these reasons, a second taphole drilled vertically proximate to the first is not a recommended practice.

Increased Depth and Depth+Diameter

Across the 3 years of the study, ¼"-diameter tapholes drilled in the fall and subsequently enlarged to 5/16" diameter and 2.5" depth (Fall Wider and Deeper) averaged approximately the same yields as Spring Control tapholes (97%, Figure 5B). However, 5/16" tapholes drilled in the fall and subsequently deepened to 2.5" (Fall Deeper) averaged 116% the yield of standard spring tapholes. Similarly, ¼"-diameter tapholes drilled in early-winter and subsequently enlarged to 5/16"-diameter and 2.5" deep (Early-Winter Wider and Deeper), and 5/16"-diameter tapholes drilled in early-winter and subsequently deepened to 2.5" (Early-Winter Deeper), had average yields 20 and 21% higher, respectively, than Spring Control tapholes (Figure 5B).

Tapholes that were drilled at the same time as Spring Control tapholes and deepened after four days of temperatures above 50°F (Late-Season Rejuvenation) yielded 18% more sap than the standard spring tapholes in the single year this treatment was studied (Figure 8A). However, an examination of the yields of these two treatments before and after rejuvenation shows that the two treatments had similar yields after the Late-Season Rejuvenation tapholes were enlarged (Figure 8B). This indicates that any difference in yield was not due to the rejuvenation treatment.

The first important note to make with respect to the yield data for rejuvenation treatments is the final taphole depth – the final depth of rejuvenation treatments was 2.5", 0.5" deeper than the Spring Control tapholes. It is possible that simply the greater tapping depth contributed to some of the higher yields observed in the rejuvenation treatments. The relative extent to which greater depth versus the rejuvenation of partially compartmentalized vessels contributed to any yield improvements observed cannot be assessed from this study, as a control (non-rejuvenated) taphole of the same final depth (2.5") was not studied. However, in a study of the impacts of taphole depths on yield at PMRC, the difference in yields from tapholes at 2.0 and 2.5" depth was negligible (Perkins *et al.* 2021). This suggests that the gains observed in this study might be attributable more to the rejuvenation treatments than simply the greater depth.

The most important factor to take into account with respect to the yield data from the rejuvenation treatments is the amount of nonconductive wood generated by these practices. In a simultaneous experiment, we observed that rejuvenation treatments result in proportionally more NCW than single, undisturbed tapholes of the same final volume (van den Berg *et al*. 2021, Figure 9). In other words, taphole rejuvenation practices did not result in more NCW simply because of the greater size of the hole, but rather they generated *more* NCW than single tapholes of the same volume. This indicates a disproportionately greater general impact on the tree in terms of sustainability, relative to any potential short-term gain in yield. Moreover, greater accumulation of NCW increases the likelihood of reduced yields and economic returns over the long-term, further negating any short-term gains. For these reasons, we strongly advise against implementing taphole rejuvenation practices.

Conclusions

Tapping in the fall and early-winter without subsequent rejuvenation resulted in reductions in yield relative to tapholes drilled in the standard spring sap flow season in northern Vermont (~mid-February through April). If early tapping strategies are employed, these reductions must be balanced with the potential economic or other gains of the strategies for each individual operation. It remains possible that the strategies could result in lower (or greater) reductions in yields or net economic benefits in regions with different climate conditions or for seasons with greatly differing sap flow timing.

Taphole rejuvenation practices resulted in varying impacts on yield, however the disproportionate impacts of these practices on the development of NCW render their cost to tree health and long-term economic returns and sustainability more significant than any short-term gains attainable, and therefore are not recommended. The levels of yield improvement observed from rejuvenation treatments in this study can be achieved through other, less damaging methods, such as optimization of vacuum levels and taphole and tubing sanitation, and reducing losses throughout syrup processing operations. These other methods, which do not pose risks to tree and economic sustainability, should be used as the first line options when yield improvements are desired.

Acknowledgements

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Table 1. Mean, standard error, minimum, and maximum diameter at breast height (DBH) of trees in each treatment group. Mean diameter was not significantly different between the treatment groups (*p* < 0.9822, Wilcoxon Rank Sums test of the hypothesis that the means were equal).

Treatment	Number of Trees	Mean DBH (in)	Std. Error	Minimum DBH (in)	Maximum DBH (in)
Fall Control	10	12.9	1.1	9.2	20.1
Fall Wider+Deeper	10	12.9	0.9	9.5	19.5
Fall Deeper	10	12.9	0.7	9.0	16.2
Fall 2nd Hole/Late-Season Rejuv.	10	12.9	0.6	10.8	16.4
Winter Control	10	12.9	1.2	9.6	22.3
Winter Wider+Deeper	10	12.9	0.7	9.7	15.9
Winter Deeper	10	12.8	0.9	9.3	17.8
Spring Control	10	12.9	1.3	9.0	23.2

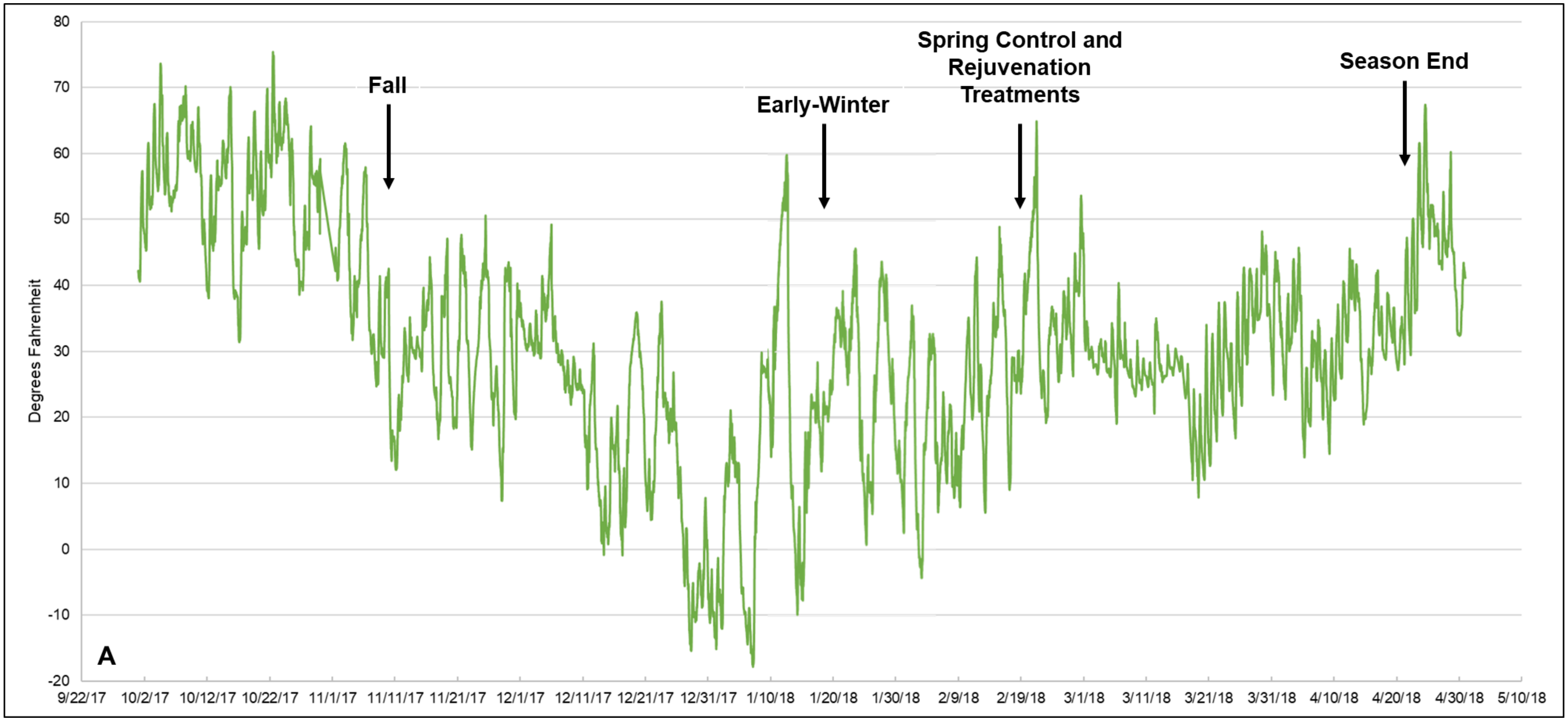
Table 2. Early tapping and rejuvenation treatments in the 3 study years. The "Fall Second Hole" treatment was replaced with "Late-Season Rejuvenation" after Year 2.

			Year 1: 2017-18		
Description	**Initial Spout Diameter**	**Initial Taphole Depth**	**Date First Tapped**	**On Same Date as Spring Control**	**Season End**
Fall Control	5/16"	1.5"	11/10/2017	-	
Fall Deeper	5/16"	1.5"	11/10/2017	Drilled Deeper (2.5")	
Fall Wider+Deeper	1/4"	1.5"	11/10/2017	Enlarged to 5/16" and Deeper (2.5")	
Fall 2nd Hole	5/16"	1.5"	11/10/2017	Drilled 2nd hole 2" Higher (1.5")	4/23/2018
Winter Control	5/16"	1.5"	1/18/2018	-	
Winter Deeper	5/16"	1.5"	1/18/2018	Drilled Deeper (2.5")	
Winter Wider+Deep	1/4"	1.5"	1/18/2018	Enlarged to 5/16" and Deeper (2.5")	
Spring Control	5/16"	1.5"	2/19/2018	(First tapped)	
			Year 2: 2018-19		
Fall Control	5/16"	2"	10/24/2018	-	
Fall Deeper	5/16"	2"	10/24/2018	Drilled Deeper (2.5")	
Fall Wider+Deeper	1/4"	2"	10/24/2018	Enlarged to 5/16" and Deeper (2.5")	
Fall 2nd Hole	5/16"	2"	10/24/2018	Drilled 2nd hole 2" Higher (2")	4/18/2019
Winter Control	5/16"	2"	1/3/2019	-	
Winter Deeper	5/16"	2"	1/3/2019	Drilled Deeper (2.5")	
Winter Wider+Deep	1/4"	2"	1/3/2019	Enlarged to 5/16" and Deeper (2.5")	
Spring Control	5/16"	2"	2/13/2019	(First tapped)	
			Year 3: 2019-20		
Fall Control	5/16"	2"	10/31/2019	-	
Fall Deeper	5/16"	2"	10/31/2019	Drilled Deeper (2.5")	
Fall Wider+Deeper	1/4"	2"	10/31/2019	Enlarged to 5/16" and Deeper (2.5")	
~~Fall 2nd Hole~~	------		----------	-----------------	
Winter Control	5/16"	2"	12/17/2019	-	4/8/2020
Winter Deeper	5/16"	2"	12/17/2019	Drilled Deeper (2.5")	
Winter Wider+Deep	1/4"	2"	12/17/2019	Enlarged to 5/16" and Deeper (2.5")	
Spring Control	5/16"	2"	2/12/2020	(First tapped)	
				On 3/30/2020:	
Late-Season Rejuv.	5/16"	2"	2/12/2020	Drilled Deeper (2.5")	

Table 3. P-values for the overall statistical model to determine if any significant difference existed in yields of treatments (early tapping, rejuvenation, standard spring tapholes) across the 3 study years, and for pairwise comparisons to determine if any of the early tapping or rejuvenation treatments resulted in yields significantly different from those of standard spring tapholes (Spring Control).

Treatment	*p*-value
Overall Model	0.13
Versus Spring Control:	
Fall Control	0.43
Fall Wider+Deeper	0.96
Fall Deeper	0.31
Winter Control	0.65
Winter Wider+Deeper	0.20
Winter Deeper	0.22

Figure 1. A portion of the sap collection chambers (*top*) and internal removable containers (*bottom*) used to quantify yields.



Degrees Fahrenheit
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70
60
50
40
30
20
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-10
-20
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10/2/17
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10/22/17
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12/1/17
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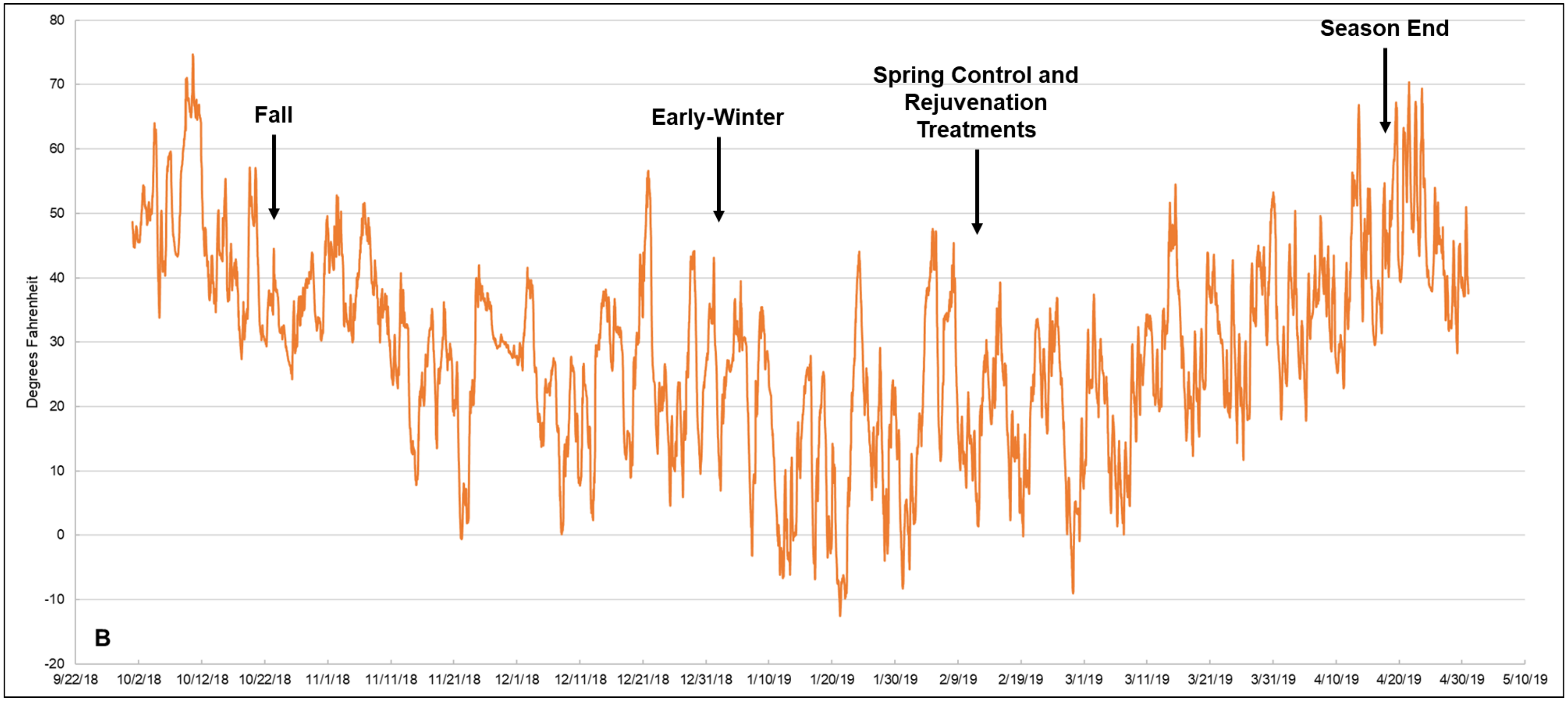
Fall
Early-Winter
Spring Control and Rejuvenation Treatments
Season End
A



Season End
Spring Control and Rejuvenation Treatments
Fall
Early-Winter
Degrees Fahrenheit
80
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60
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10
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-10
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B
9/22/18
10/2/18
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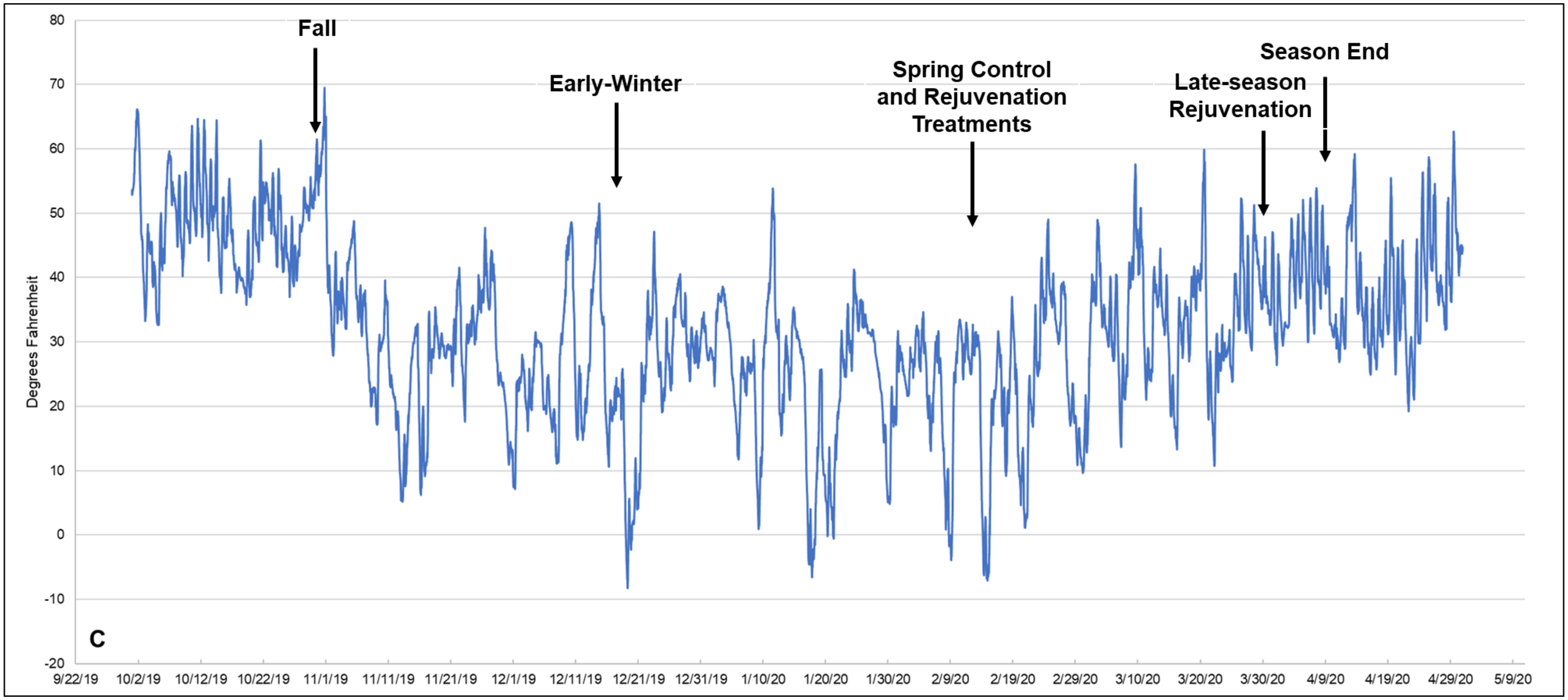

Figure 2. Temperature and timing of study treatments in study years 1 (A), 2 (B), and 3 (C). Data from UVM Forest Ecosystem Monitoring Cooperative Forest Canopy Tower at UVM PMRC, proximate to the study area. Duncan J., and C. Waite. Raw Forest Canopy Meteorological Tower Data. University of Vermont. FEMC. Data can be retrieved: https://www.uvm.edu/femc/data/archive/project/forest-environmental-monitoring-canopy-tower/dataset/raw-forest-canopy-meteorological-tower-data

Figure 3. "Fall Second Hole" treatment. Spout was left in the initial taphole when the second hole was tapped, but was plugged with a dead-end tee to prevent air leaks.

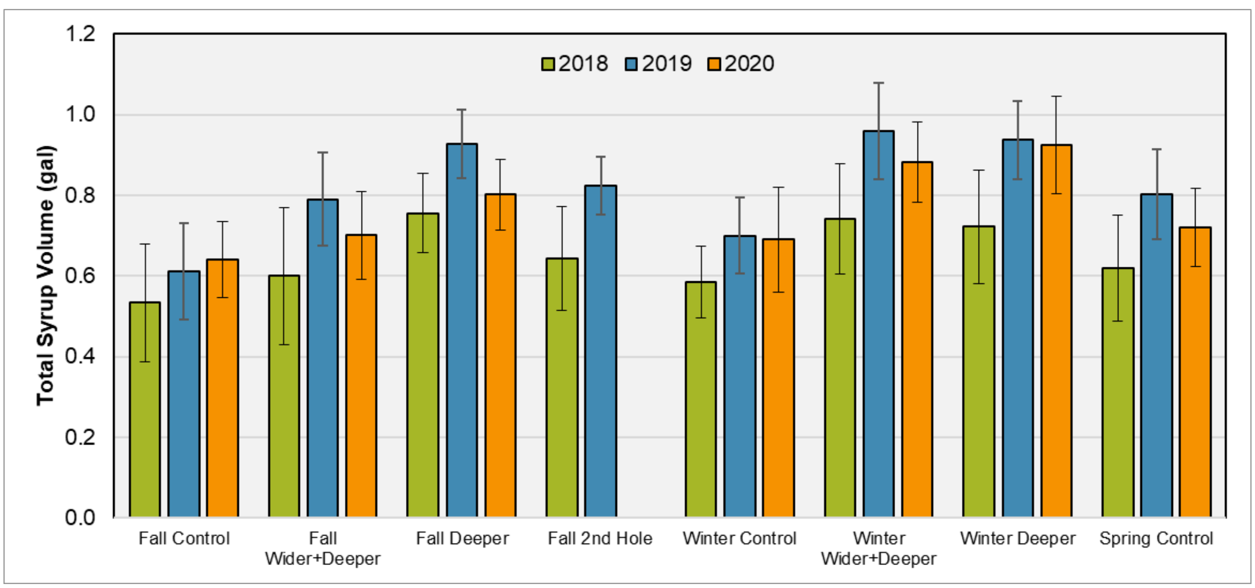

Figure 4. Average total yields (gallons of syrup equivalent per tree) for early tapping and taphole rejuvenation treatments and standard spring tapholes during 3 sap flow seasons (green 2017-18; blue 2018-19; orange 2019-20) at UVM PMRC. Error bars represent standard error of the mean, n = 10 trees for each treatment.

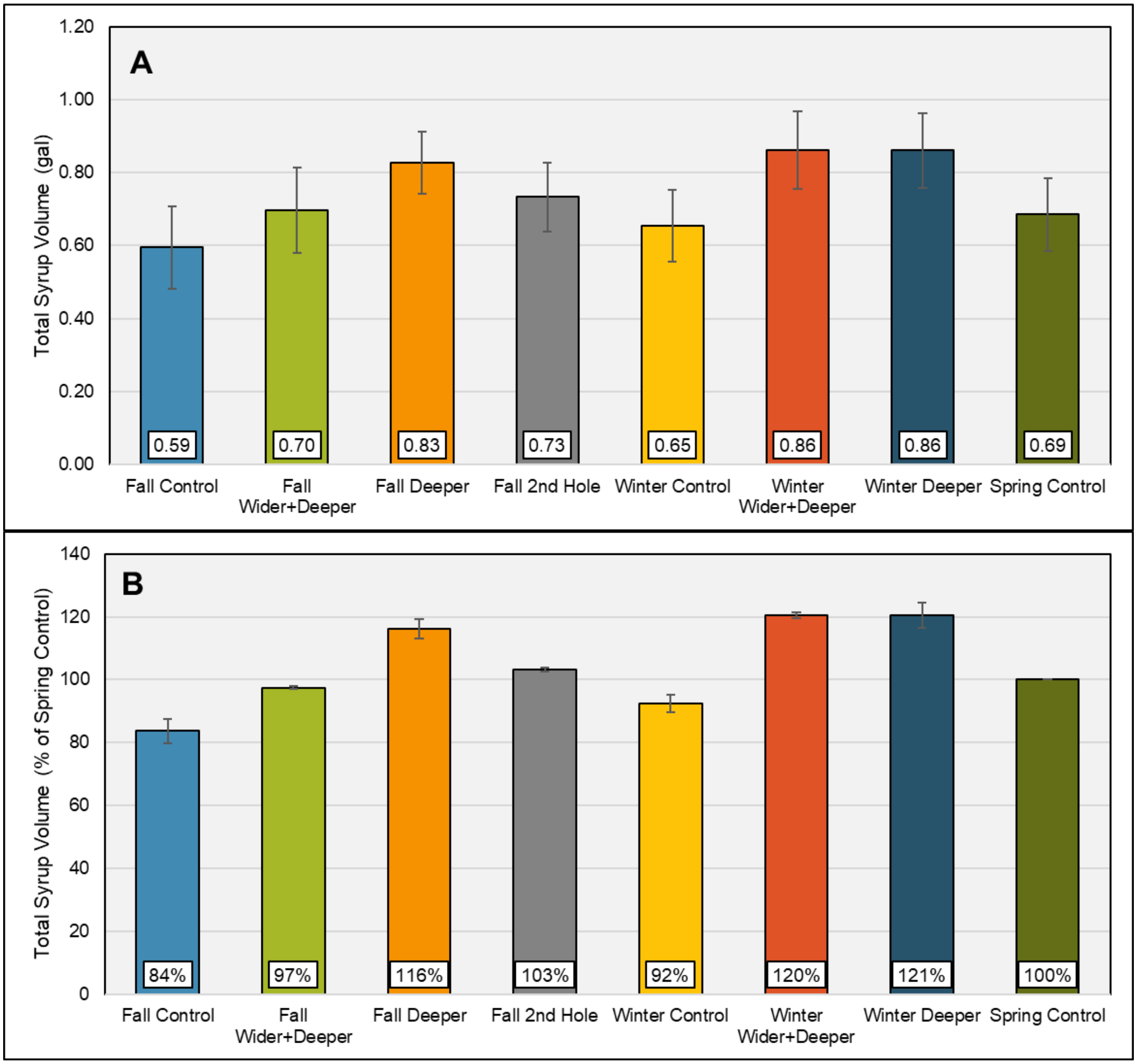

Figure 5. Overall average annual total yields of early tapping and taphole rejuvenation treatments for the 3 years of the experiment in gallons of syrup equivalent per tree (**A**), and as a percent of the yields from Spring Control tapholes drilled during the standard spring sap flow season (**B**). Error bars represent standard error of the mean, *n* = 10 trees for each treatment each year.

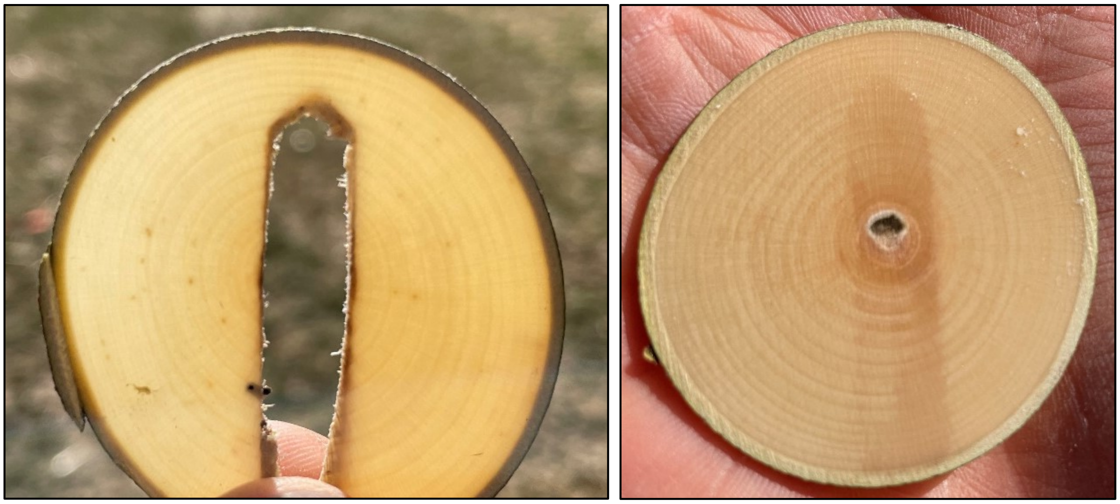

Figure 6. The tree's response to the taphole wound begins immediately. In these stem segments made through a taphole (left) and 0.5" above the taphole (right), substantial discoloration from the wound response is already visible 2 weeks after the taphole was drilled. Photos and data courtesy of Mark Isselhardt, University of Vermont Extension.

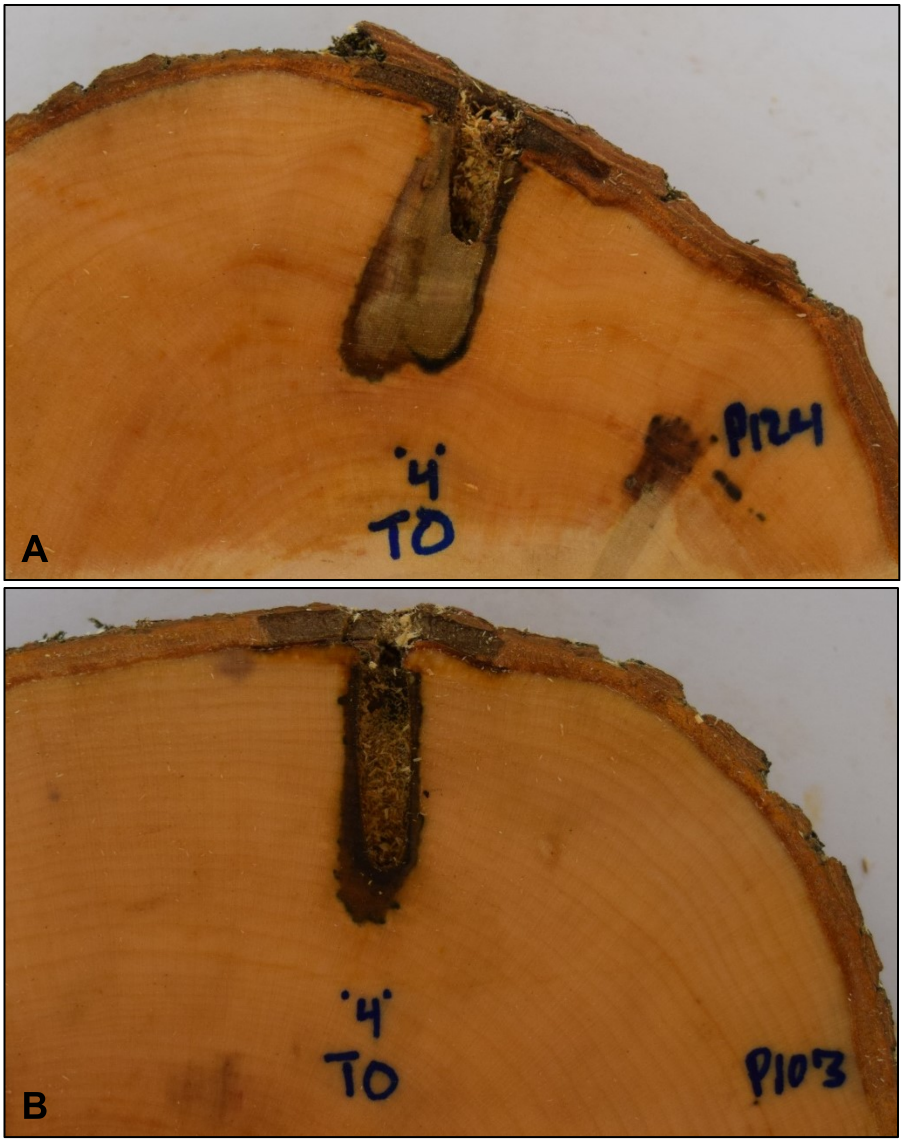

Figure 7. Two examples of stem segments cut through the center of the initial taphole in "Fall Second Hole" treatments. If the initial and subsequent tapholes were not perfectly horizontally aligned, it is easier to see two distinct areas of NCW development from the two different tapholes, as shown in the upper photo (**A**). However even when the two tapholes were well-aligned, two distinct areas of compartmentalized wood are still visible (**B**), and the total volume of NCW generated was more than double that from a single Control taphole of the same size.

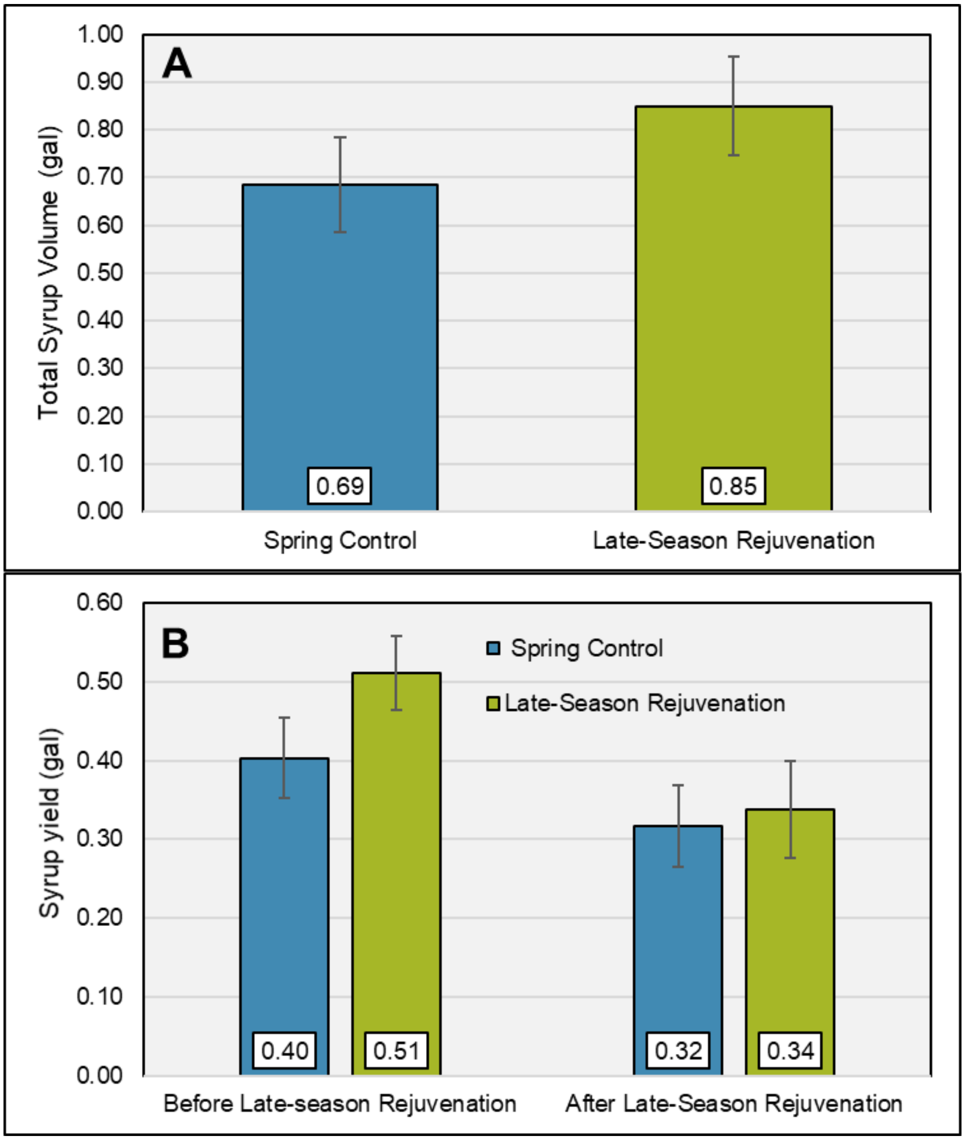

Figure 8A. Average total yields (gallons of syrup equivalent per tree) for standard spring tapholes (Spring Control) and tapholes that were initially tapped on the same date, then deepened to 2.5” after 4 days of temperatures above 50°F (Late-Season Rejuvenation) in Year 3 of the experiment. **B.** Average yields of the Spring Control and Late-Season Rejuvenation tapholes before and after the Late-Season Rejuvenation tapholes were deepened. Error bars represent standard error of the mean, *n* = 10 trees for each treatment.

Figure 9. Cross-section through the center of “Spring Control” and “Fall Wider and Deeper” tapholes.

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