SECTION 1. ADMINISTRATIVE INFORMATION

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SECTION 2. PUBLIC SUMMARY

Maple syrup is produced from the sap of sugar maple trees collected in the late winter and early spring. Native American tribes have collected and boiled down sap for centuries, and the tapping of maple trees is a cultural touchstone for many people in the northeast and Midwest. Because the tapping season is dependent on weather conditions, there is concern about the sustainability of maple sugaring as climate changes throughout the region. At the same time the demand for this natural sweetener and the production of maple syrup are increasing rapidly.

Our research addressed the impact of climate on the quantity and quality of maple sap used to make maple syrup. We examined yields coupled with the sugar and biochemical composition of sap collected throughout the geographic range of sugar maple in the northeastern USA and Canada, and related this to historical and projected variation in climate. This is the first study to document potential climate related changes in sap production and sap quality across the full geographic range of sugar maple. Declines, as well as increased variability, in sap flow near the southern range limit and increased sap flow at the northern range limit suggest long term range shifts toward the north, as well as geographic variation in expected syrup production over the next several decades. Survey results highlighted that producers do perceive changes in climate variables and concomitant shifts in sap production. Many producers are willing to shift sap harvesting practices in response to changing climate scenarios, but producers are split in their perceptions about the importance of individual variables and their level of concern about future impacts on the industry. Overall, our results can be applied to design more effective extension programming and adaptation plans to mitigate the risk of climate in maple systems.

SECTION 3. PROJECT SUMMARY

Sugar maple (*Acer saccharum*) is a key cultural and ecological resource of the northeast and Midwest and could be a flagship species for the Northeast Climate Adaptation Science Center (NE CASC). We worked to quantify how climate change is affecting sugar maple syrup quality, and the potentially less climate-sensitive alternative of red maple. We sampled over 100 trees (15-20 mature sugar maple trees at six sites from Virginia to Quebec). We observed that the sap collection season shifted earlier with warmer March temperatures, that total sap collection was highest when March temperature was near 0°C, and that warmer growing seasons (as measured by July temperature) had a negative effect on sap sugar content in the following tapping season. Using these relationships to project future tapping seasons based on an ensemble of climate projections, we predicted that by the end of the century the tapping season will be 2-3 weeks earlier with more change toward the north and that the optimal region for maple sap production will shift northward with a decline in production in most areas, especially within the U.S. range of sugar maple. We also conducted surveys on maple syrup producer perceptions of climate change patterns as well as their effects on maple syrup yields and quality. In addition, we conducted a semi-structured survey to elicit responses of maple syrup producers to climate change. Survey findings highlight that producers have perceived changes in climate patterns over the course of their lifetimes including increased variability of temperatures, snowfall, snowpack, and suitable conditions for maple production. Producers perceive these climate variables have impacted maple production including an earlier start date to the production season. In addition, producers perceive multiple climate variables impact maple syrup quality including temperatures, snowfall, rainfall, tree density, and herbivory. Survey results highlighted that sap harvesting practices are the management response that producers are most willing to shift in response to various climate scenarios. Findings further highlight the climate variables and socio-economic factors which producers are willing to respond to. Results can be applied to design more effective extension programming and adaptation plans to mitigate the risk of climate in maple systems.

Analyses leveraged downscaled climate data to make projections of future harvests. We worked with LCCs, States, Tribal Members, and other producers through remote and in-person meetings to elucidate and adapt the resulting linkages to livelihoods, ecological knowledge and adaptive management practices. We coupled these ecological data with surveys to gauge traditional ecological knowledge, perceptions of climate risk, and existing adaptive management strategies. Products from the research include: (i) two highly successful stakeholder workshops, (ii) an interactive project website, (iii) a glossy illustrated management document, (iv) a peer-reviewed journal article in revision and another in preparation, (v) strengthened connections with tribal communities, (vi) more than 20 students, including a tribal member who was integral to the project, trained in ecological sampling and analysis in the field and lab, (vii) high-level USGS interest leading to a value of information analysis, and (viii) maps displaying annual and estimated future variation in syrup yield and quality. These products are being disseminated to stakeholders with the aim to facilitate adaptation to climate change and aid in preserving the cultural and economic values of maple sugaring in the northeast and Midwest United States.

SECTION 4. REPORT BODY

Purpose and Objectives:

Sugar maple (*Acer saccharum*) is a key cultural and ecological resource contained almost entirely within the Northeast Climate Adaptation Science Center boundary and as such could be considered one of the flagship species for the NE CASC. Maple syrup production has been expanding across the region, despite predictions that sugar maple may be particularly sensitive to climate change. Given these trends, projections of the direct impacts of climate change on maple syrup production are needed to guide regional stakeholders to adapt to future climate variability and change. This study examined the effects of climate variation on sugar maple syrup quality and corresponding socio-economic responses to address NE CASC Science Theme 6: Impacts of climate variability and change on cultural resources, Priority 3 - Effects of climate change on the sustainability of cultural resources. Our primary goal was to provide quantitative data on how sugar maple syrup quality is vulnerable to changing climate conditions and the resulting linkages to producer livelihoods, ecological knowledge, and adaptive management practices. In addition, we planned to evaluate whether including red maple (*A. rubrum*), a less climate-sensitive species, may increase the adaptive capacity of maple syrup production.

The specific objectives accomplished by this study include:

1) **Evaluate Climate Effects on Maple Syrup Quality and Yield:** Across a latitudinal gradient in the northeastern U.S., we quantified the effects that climate has on sugar maple sap yields and quality, via changes in secondary metabolite chemistry and sensory properties. We hypothesized that sap yields and quality would vary according to climatic conditions
2) **Elucidate Feedbacks among Producer Livelihoods, Ecological Knowledge and Management Practices:** We documented how producer knowledge of climate effects on maple syrup quality and yield feedback into adaptive management of cultural resources in the face of changing climate conditions.
3) **Work with LCCs, States, Tribal Members, and other Producers in order to Adapt Maple Syrup Culture to 21st Century Climate Change:** We held workshops at the outset and conclusion of the project to guide research questions, engage stakeholders in data collection, and disseminate results.

Organization and Approach:

The project was conducted through intensive field sampling and ethnoecological surveys. The field sampling focused on measuring impacts of climate variability and change on productivity and quality through analysis of sap yield, sugar content, and concentrations of tannins and other compounds that contribute to the flavor of maple syrup. Samples were collected from 6 sites located across the native range of sugar maple in the northeastern United States and southeastern Canada, including sites in southwest and central Virginia, Indiana, Massachusetts, New Hampshire, and Quebec (Figure 1). This includes two private maple producers, University owned sites, and a collaboration with the Great Lakes Research and Education Center at the Indiana Dunes National Lakeshore. At each site, 15-25 mature sugar maple trees and an additional 10 red maple trees were sampled from mid-February through late April, depending on the site, on all days of sap flow (generally when the diurnal temperature range crosses 0°C) in 2014, 2015, and 2016 (Figure 2). Sap volume and sugar content were recorded for each tree during each collection. In addition, 45 mL samples of sap were collected for biochemical analysis every day for 5 trees of each species per site and weekly for the remaining trees at each site. Sap quality was quantified at Selena Ahmed's lab at Montana State University by measuring concentrations of different plant chemicals produced by sugar maple.

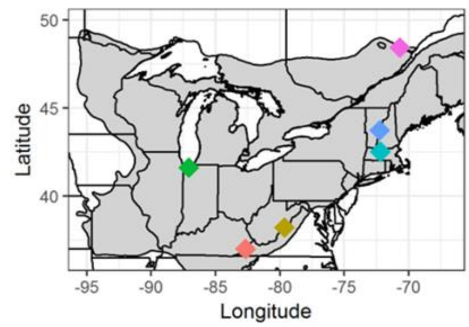

Figure 1: Sap collection study sites (diamonds) were distributed across the range of sugar maple (gray area).

Ethnoecological surveys were carried out with sugar maple producers within and outside of tribal communities to examine perceptions, experiences, traditional ecological knowledge, and practices associated with sugar maple management and production in the context of climate change. Research in communities began with rapport building and participant observation coupled with focus groups with interested producers. With these focus groups we used a community-based participatory research approach to collectively identify challenges and opportunities related to sugar maple resources, and collaboratively designed qualitative and quantitative surveys that were administered in person and online through a SurveyMonkey Tool. Data from ethnoecological surveys were analyzed using cultural consensus analysis to identify and

Figure 2: Sap collection for the study was conducted by placing collection bags beneath taps placed into small holes drilled directly into the tree trunk.

understand similarities between and within communities, including socio-ecological and management variables that encourage adaptation to climate variability.

Project Results, Analysis and Findings:

Relationship of Sap Sugar Content and Climate Variables

We predicted that climate conditions in the previous summer would influence nonstructural carbohydrate storage and thus affect sap quality. We established statistical relationships between sap quality based on sugar content and climate variables to understand how maple sap quality may change with projected climate change. We then used the observed relationships between climate and sap quality along with downscaled general circulation models to project future sap sugar content, sap flow, and syrup production on a per tap basis.

We found that mean March temperature influenced the timing and number of freeze/thaw cycles and sap collection days, as well as the amount of sap collected per collection day (Figure 3). Conversely, sap sugar concentration was negatively and linearly related to the previous July mean temperature. These relationships suggest present spring and prior summer climate conditions both impact syrup production.

The timing of the spring freeze-thaw period was linearly and negatively related to mean March temperature (i.e., the warmer mean March temperature, the earlier the freeze-thaw period). However, sites and years with a mean March temperature greater than 0°C (i.e., southern sites, warmer years) had much more variability in the timing of the optimal freeze-thaw period suggesting it is harder for producers to anticipate the optimal freeze-thaw period based on average temperatures when these temperatures are warmer. Interestingly, much more of the variance in the timing of sap collections was explained by mean March temperature than was explained for the timing of the optimal freeze-thaw period, even though the mean trend of the relationship was similar. A hump-shaped relationship was observed between mean March temperature and the number of days with freeze-thaw cycles in the spring (March, April, May), the number of sap collections, and the total sap collected per tap at a site, suggesting the existence of an optimal climate for syrup collection.

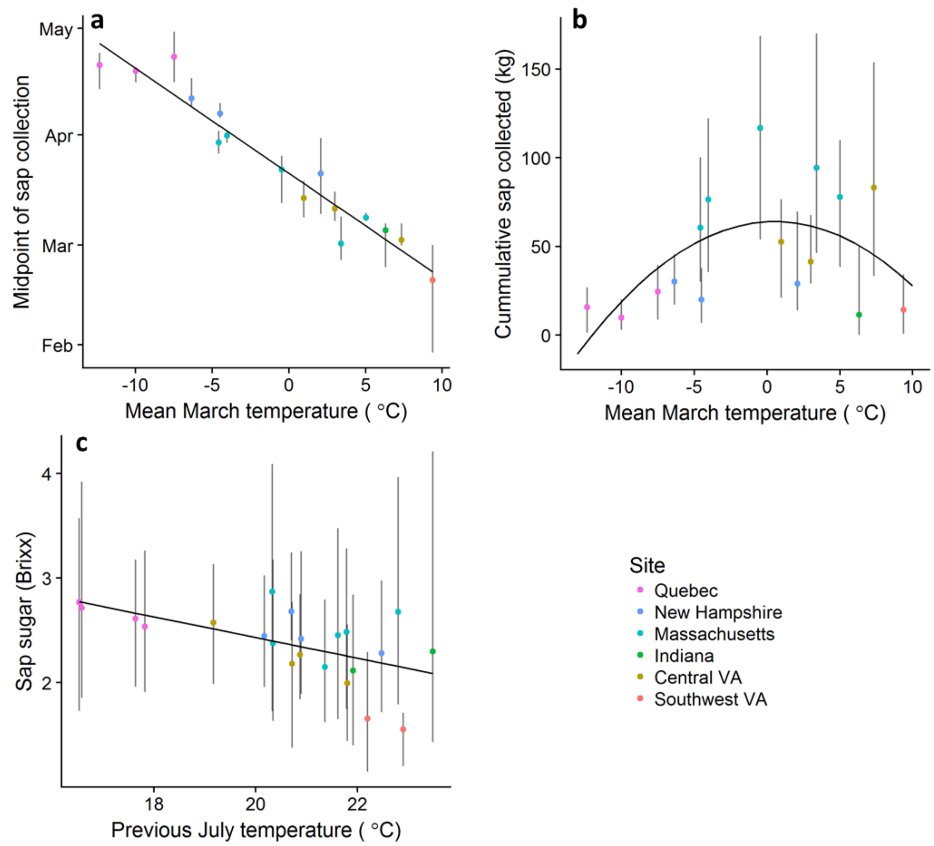

Figure 3. Tapping season metrics are predicted by monthly mean climate. a) Mean March temperature predicts day when 50% of sap is collected. b) Total season sap collected per tap has a hump-shaped relationship with mean March temperature. c) Sap sugar concentration has a negative relationship with previous July mean temperature. Points represent means for each site in each year of sampling, while vertical lines depict the range of values observed across trees within each site and year.

Using historical climate data and future climate projections, we estimated the timing of the tapping season, sap sugar content, total sap volume and total syrup volume per tap over the periods 1950-2016 and projected it for 2017-2100 (Figure 4). Linear regression of hindcasted sap variables at individual sites revealed that only sites in New England experienced linear trends in sap metrics over 1950-2016. At the New Hampshire site, the tapping season midpoint, sap sugar content, and only total syrup volume declined over time using our model. For the Massachusetts site, total syrup volume declined over time (Figure 4). With respect to our future projections, we found that projected tapping season midpoints showed a clear trend toward an earlier timing by the end of the century for all sites, with more change toward the north. The midpoint of the tapping season at the Quebec site was projected to be 20 days earlier by the end of the century while our site in southwest Virginia near the southern range limit of sugar maple was projected to be only 12 days earlier. Total sap production per tap was projected to shift substantially at all sites by 2100. Sites in Virginia and Indiana were projected to see decreases of 28–52% in total sap collected, while the most northern site in Quebec was projected to see an increase of 57%, further evidence of a northward-shifting climate optimum. Sites in New Hampshire and Massachusetts were projected to have the smallest change in total sap collected. With respect to sap sugar concentration, future projections showed a clear trend toward lower and more variable sugar content by the end of the century (21-27% lower across sites). We found that inter-annual variability in projected total syrup production was greater for sites in the warm and cold extremes of sugar maple's range, rather than more moderate sites. Projections indicated dramatic and mostly negative changes in syrup production per tap by the end of the century. At every site, aside from Quebec, syrup production was projected to decrease (Figure 4). Estimates for Quebec indicated that production would remain relatively stable with a slight increase until the middle of the 21st century. Declines in projected syrup production ranged between 0.79 L/tap in southwest Virginia to 0.44 L/tap in New Hampshire.

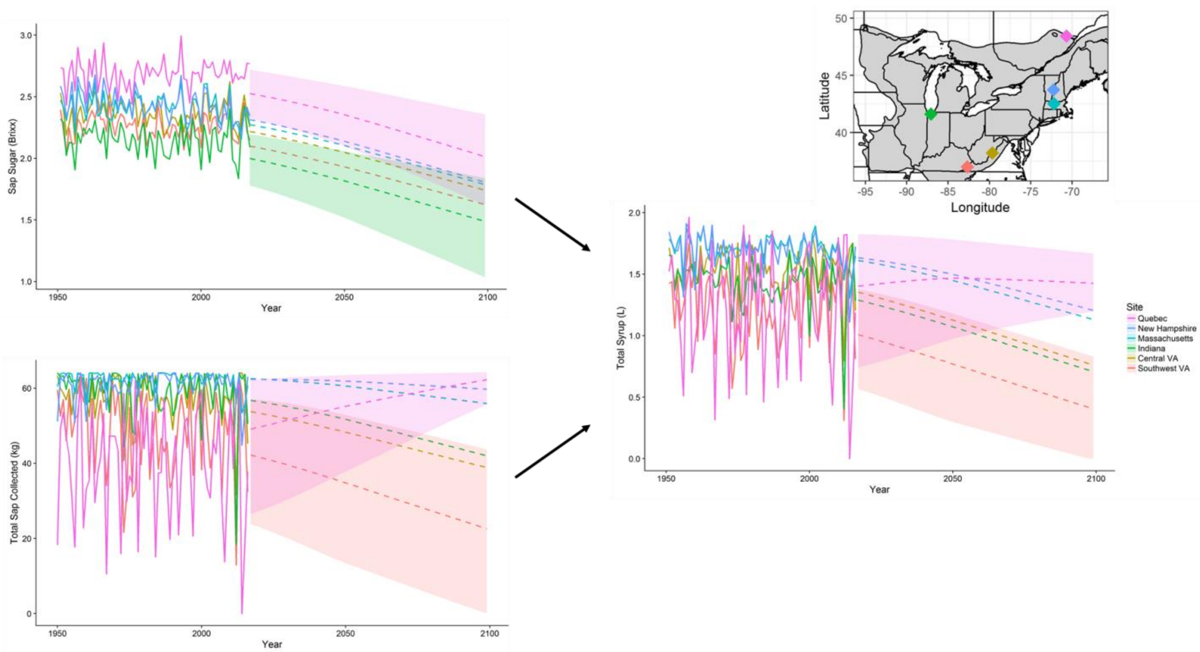

Figure 4. Historical and future projections of total sap collected per tap based on mean March temperature, sap sugar content based on mean previous July temperature, and total syrup produced per tap calculated from projections of total sap collected and sap sugar content. Projections from 1950–2016 are based on historical temperature data (solid lines), while projections from 2017–2099 are based on future climate projections from 14 statistically downscaled climate models. Dotted lines show the smoothed mean of projections using all 14 climate models, while the bands show the 95% prediction interval for selected sites.

Our models indicated that optimal syrup production conditions in the historical period stretched from Wisconsin, across the Great Lakes, through New York and New England and southern

Ontario and Quebec. This area is projected to shift northward by the end of the century, with lower average production overall across all latitudes (Figure 5). Our projections indicate that the amount of maple sap collected per tap is expected to decline in much of the United States and that future tapping seasons will occur between two to three weeks earlier in most of sugar maple's range in North America. Concurrently, maple sap sugar content is projected to decline across much of sugar maple's range in the United States, leading to a decline in total syrup production per tap in most areas because a higher sugar concentration yields more syrup overall. However, maple sap volume is projected to have moderate increases in northern Maine and along the northern range limit of sugar maple in Canada. As a result, maple syrup production is expected to decline over most of the U.S. range of sugar maple, but hold steady in the northern Great Lakes, mountainous areas of New England and New York, and much of the Canadian range of sugar maple. These findings indicate that climate change will drive a northward shift in the optimal conditions for maple syrup production that is likely to have profound implications for the maple syrup industry and for communities that culturally value sugar maple trees, especially in the United States.

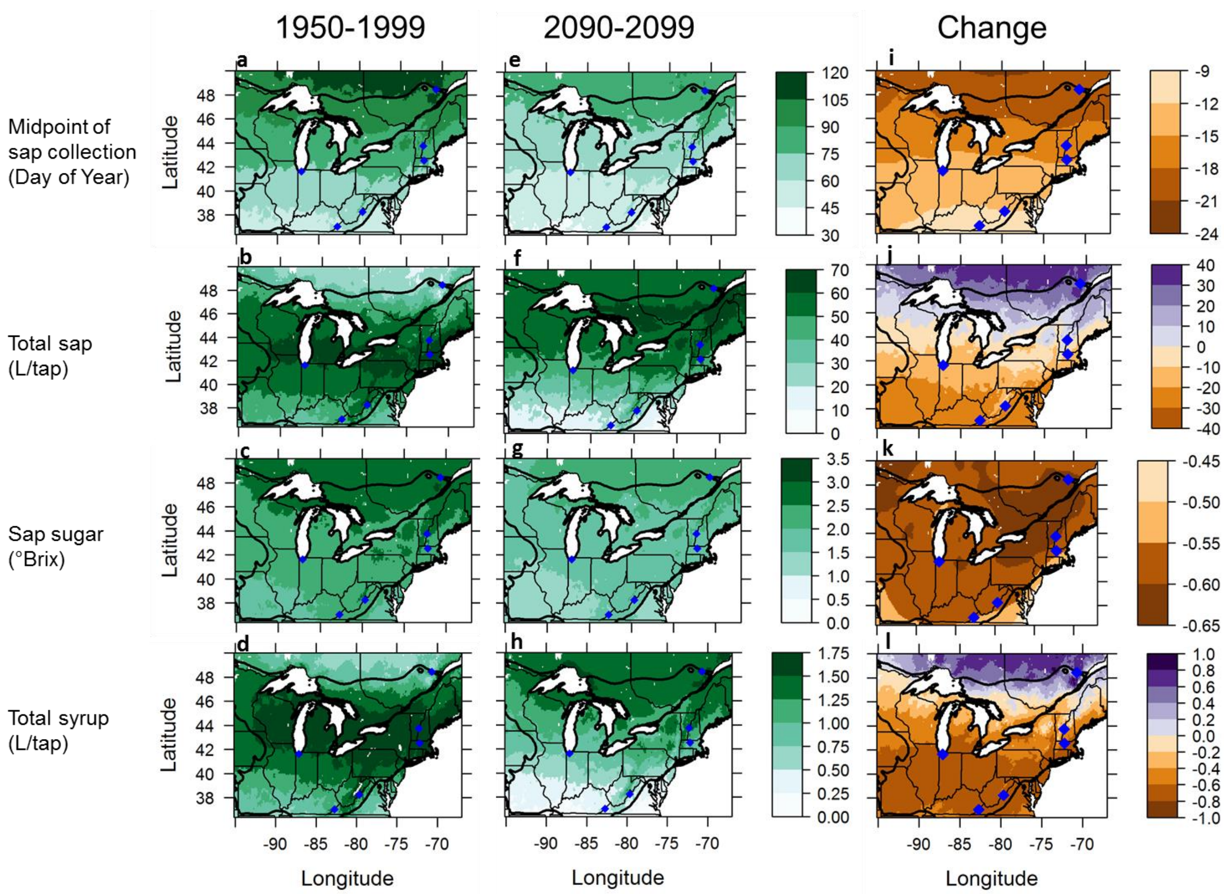

Figure 5. Projections of mean values for sap metrics for the historical period (a–d) and the end of the century (e–h), and the change in mean value between the historical period and the end of the

century (i–l). Blue diamonds show the locations of ACERnet sampling sites, while the thick black line shows the current range limit for sugar maple.

Relationship of Sap Chemical Content and Climate Variables

Findings show that sap quality as measured by Total Phenolic Content (TPC) significantly varies on the basis of geographic location (Figure 6), collection year (Figure 7), and maximum temperature (Figure 8). The most southern site, Virginia, had the lowest levels of TPC while the northern site of Quebec had amongst the highest TPC along with Indiana. These geographic findings suggest an inverse relationship between temperature and TPC and are confirmed by the statistical significance of the inverse relationship between Tmax and TPC (Figure 4). As expected temperatures increase with climate change, the TPC of maple syrup quality and its' health and quality attributes may decrease. This calls for climate mitigation and adaptation strategies to protect potential detrimental effects of climate change on maple quality. Within sites, Total Phenolic Content also significantly varied based on vapor pressure for the Virginia and Indiana sites.

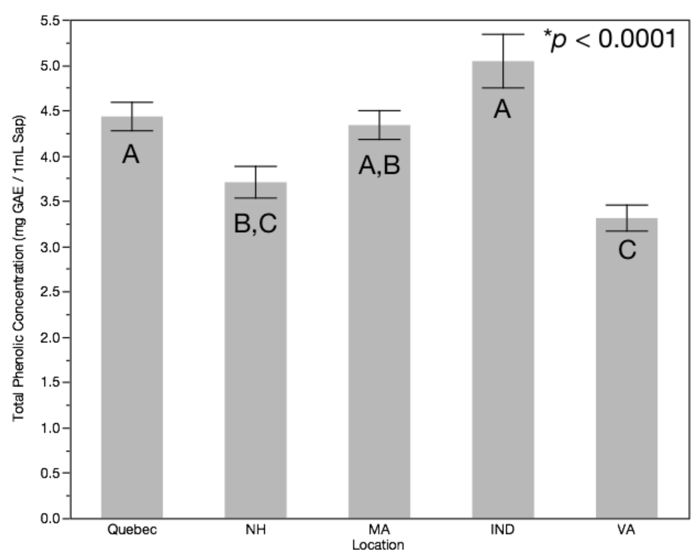

Figure 6. Variation of Total Phenolic Concentration of sap samples by study sites (Quebec, NH, MA, IN, and VA) across sampling years (2014-2016).

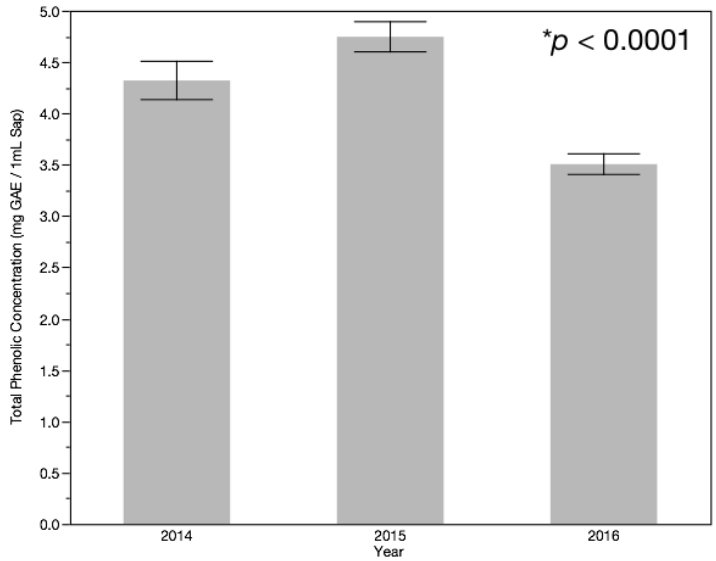

Figure 7. Variation of Total Phenolic Concentration of sap samples for the study sites (Quebec, NH, MA, IN, and VA) across sampling years (2014-2016).

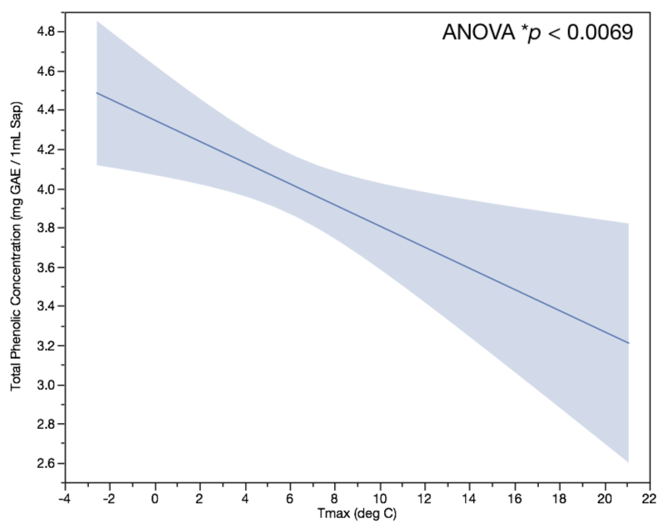

Figure 8. Relationship of maximum temperature with Total Phenolic Concentration of sap samples for the study sites (Quebec, NH, MA, IN, and VA) across sampling years (2014-2017).

We measured the concentrations of different natural chemicals produced in maple sap. A total of 95 individual secondary metabolites were quantified in the sap samples (Appendix Supplementary Table 1).

Construction of a heat map showing the top 25 secondary metabolite features (based on presence and concentrations) based on geographic location, demonstrated that the Quebec samples were significantly different (Figure 9). These differences suggest that multiple factors influencing maple trees and maple syrup are different in Canada with notable placed-based differences for flavor. These chemical differences may be attributed to variation in a range of climate, environmental, and management factors including temperature, snowfall, soil, and population genetics of the maple trees themselves.

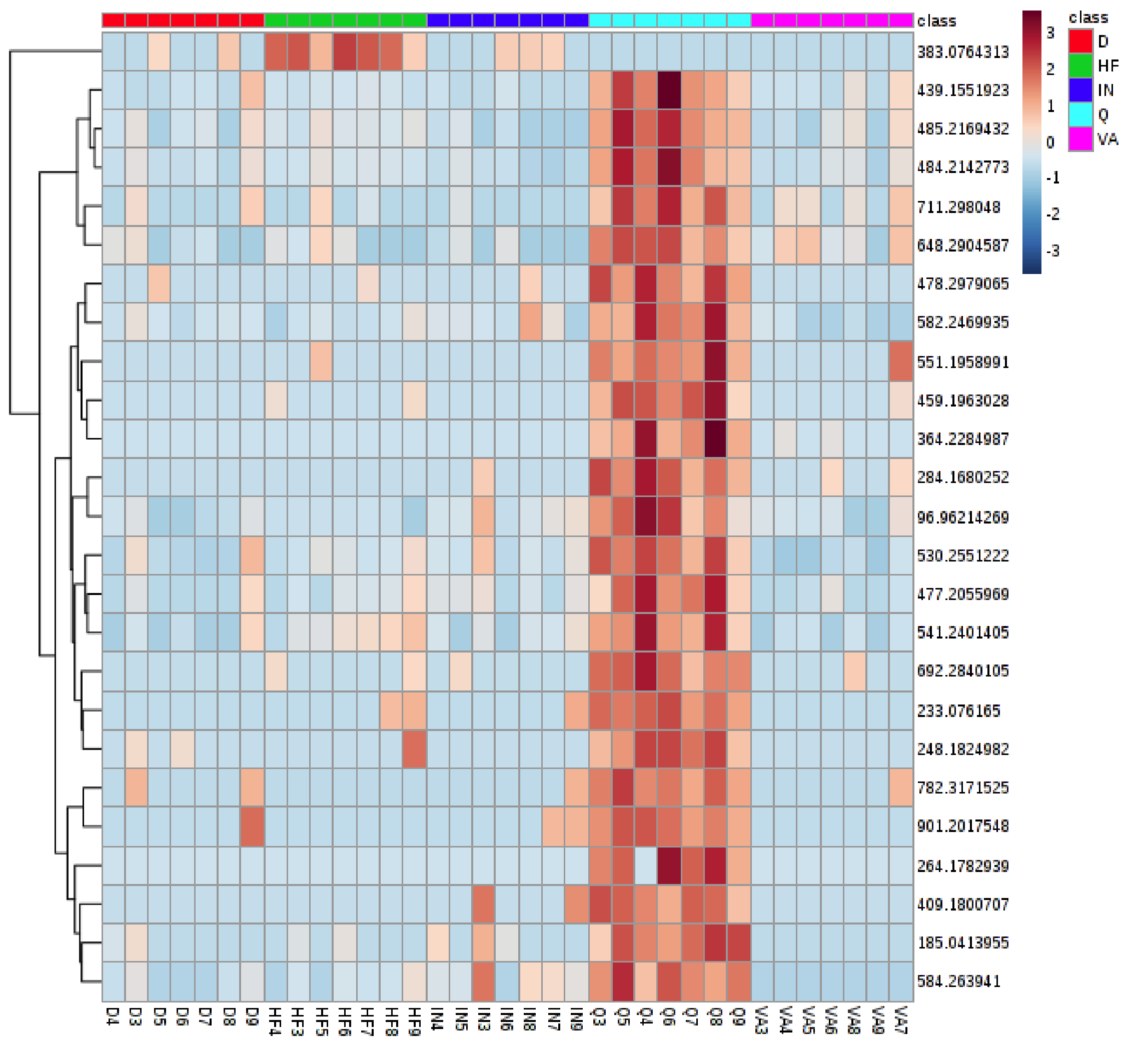

Figure 9. Heat map showing the top 25 secondary metabolite features (based on presence and concentrations) based on geographic location (D = Dartmouth, New Hampshire; HF = Harvard Forest, Massachusetts; IN = Indiana Dunes; Q = Quebec; VA = Virginia).

Principal component analysis of sap samples from the different geographic locations based on collection time (as a proxy for temperature) demonstrated clear groupings of metabolites (Figure

10). Overall, our findings indicate that there are geographic differences in makeup of maple syrup across its range that are dependent upon climate variables.

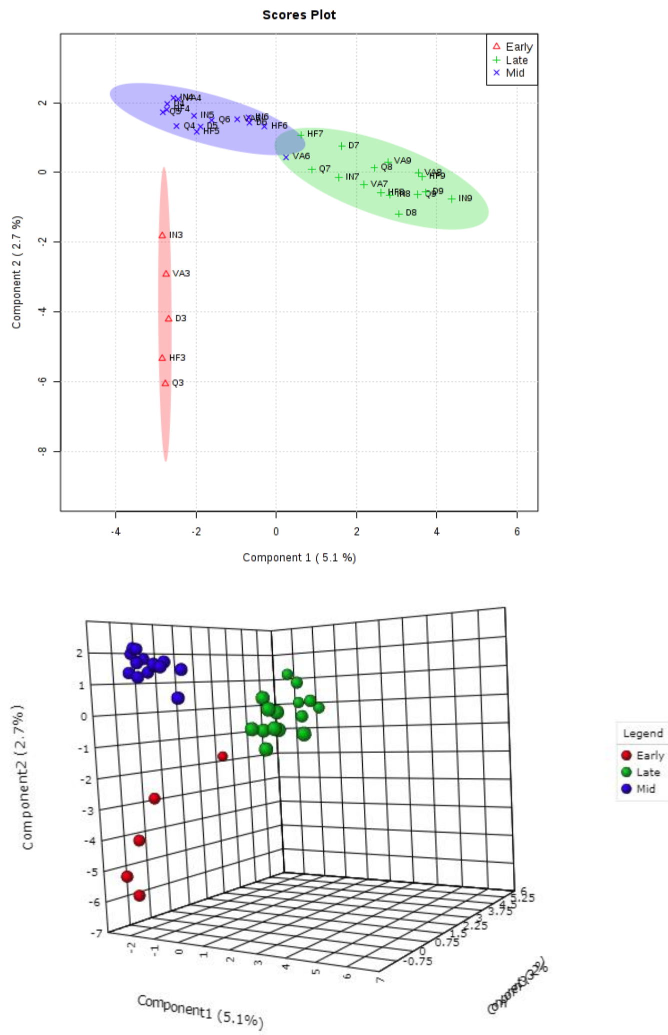

Figure 10. Principal component analysis of sap samples from the different geographic locations based on collection time (as a proxy for temperature)

Producer Perceptions of Climate Change

A total of 106 maple producers from NY (34 maple producers), MA (16 producers), VT (16 producers), NH (15 producers), PA (11 producers), ME (10 producers), VA (3 producers), and MD (1 producer) responded to our survey on maple producer perceptions of climate change (Appendix Supplementary Table 2). Almost all respondents surveyed produce maple syrup (98.04%) and a majority also produce maple candies (55.88%). Respondents listed a range of additional value-added maple products that they produce such as maple cream, maple sugar, spice mixtures, mustard, peanut butter, soda, fudge, cotton candy, jelly, granola, seasoning, and beer. Producers reported a range of techniques for tapping and processing maple sap. A total of 47.17% of producers reported using a system involving tubing while only a small group use more traditional techniques involving buckets (12.26% of producers). A very small group of producers uses both tubing and buckets for procurement of sap (5.66%). Over half of the producers reported using an evaporator as their primary processing technique while a notable number of producers use a combination of reverse osmosis coupled with an evaporator for processing maple syrup (27.36%). Wood is the primary source of fuel for maple syrup production for the majority of producers (66.04%) while oil and gas is used by others (26.42%).

The production sites of the respondents range notably on the basis of elevation, size, and amount harvested. The average elevation range of the sugar maple trees tapped by the producers surveyed is 1,141.27 ft (STDEV 631.57; range from sea level to 2,200 ft). Producers surveyed collect sap from an average of 4,153 taps (STDEV 11,380) with producers collecting from as few as 11 taps and others collecting from as many as 83,000 taps. Respondents harvest an average of 52,985 gallons of sap annually (STDEV 184,807) with producers collecting as little as 25 gallons and others as much as 1,320,000 gallons.

The majority of producers reported observing a change in several weather variables during their lifetime. Exactly half the producers stated that temperature has become more variable during their lifetimes while 26.92% of producers stated that they have observed that temperatures have increased. A total of 51% of producers reported that conditions suitable for sap flow have become more variable while 25% of producers stated that they have observed these conditions to stay the same. The majority of producers also noticed a change in the amount of snow pack. Specifically, 48% of producers observed that the amount of snowpack has become more variable, 22% observe that it has decreased, 23% observe it has stayed the same, and 5% observe it has increased. A notable percentage of producers observe that rainfall has stayed the same (45.10%) while others perceive it has become more variable (33.33%) or increased (17.65%). A bulk of producers perceive that snowfall has become more variable (43.69%) while others report it has decreased (25.24%) or stayed the same (22.33%). The majority of producers have perceived changes in the duration of snow cover on the ground as well as number of days of January thaw. Specifically, 34.95% of producers perceive duration of snow cover on the ground has decreased and 31.68% of producers perceive duration of snow cover on the ground has become more variable while 21.36% have not observed a difference. Likewise, 31.68% of producers perceive greater variability in the number of days of January thaw and 22.77% perceive the number of days have increased while 36.63% perceive no changes. In addition, producers also differ in perceptions regarding the occurrences of winds and storms. 44.55% of producers haven't noticed changes in wind patterns and 39.22% of producers haven' noticed changes in storm patterns while the rest are relatively spilt if these events have increased or become more variable.

The majority of producers share the observation that the start date of the sugar tapping season is coming earlier (75.76%). Many producers also perceive that the end date of the tapping season also occurs earlier than in the past (46.46%) while some think it's coming later (17.17%) or experienced no change (38.38%). In addition, many producers share that the budding of sugar maple trees has started earlier (52.53%) and others share budding has stayed the same (38.38%). Overall, producers report noticing changes in the maple-sugaring season over their lifetimes including the total duration of the sugar tapping season. A total of 33.33% of producers report the duration has become more variable and 26.47% report it has increased. Most producers report that daytime temperatures during the tapping season have become more variable (51.49%) or increased (21.78%) while others perceive these temperatures have stayed the same (19.80%). Nighttime temperatures during the tapping season are also perceived by many to have increased (45.00%) while others perceive these to have stayed the same (29.00%). A notable number of producers shared that the total number of days when syrup is produced has become more variable (44.55%) while others perceive this has stayed the same (29.70%). While the majority of producers have observed a change in the number of days of the January thaw, the direction of this is not clear with some reporting increased variability (25.74%), increased duration of the number of thaw days (23.76%), and decreased duration of the number of thaw days (12.87%).

Producers seemed to be aware of the effects of multiple environmental factors on the quality of maple syrup. The most prevalent factors noted by producers to impact maple syrup quality are: (1) outdoor temperatures (89.00%), (2) alternating periods of cold nights and warm days (83.00%), (3) duration of snow cover on the ground (snow pack; 69.00%), (4) Insect infestation during the previous autumn season (such as forest tent caterpillar, sugar maple borer and saddle; 69.70%), (5) size of sugar maple tree crown (68.37%), (6) amount of rainfall (66.34%), (7) soil type and quality (63.73%), (8) amount of snowfall (58.59%), (9) age of the tree (57.58%), (10) tree density (55.56%) and, (11) barometric pressure (51.58%). Days of the January thaw (36.73%), direction of the wind (43.88%), air pollution (43.88%), and altitude (45.45%) were recognized by less than half of the producers as variables to impact maple syrup quality, yet were still reported by a notable amount of producers (over one third of producers).

While the large majority of producers (89.32%) have experienced weather events that have negatively impacted their production of maple syrup, most producers are not aware of any growing practices that mitigate the impacts of weather events on maple production. The majority of producers have responded to changes in their sap yields and quality by intensifying their production through adding more taps, though a few mentioned adding vacuum to tubing systems, using disposable instead of metal spouts, changing location of taps and/or trees that are being tapped, and other measures to try to mitigate uncertainty in sap yield. Overall, producers are split between feeling concerned, hopeful, or neutral about the future of sugar maple trees and sugaring production.

Producer Management Responses to Climate Change Scenarios

We conducted a second survey (112 respondents) that assessed the existence and types of management responses to a variety of scenarios, i.e., potential impacts of global-scale warming for local maple syrup production (Appendix Supplementary Table 3). We examined the types of management practices that producers would change under various climate change scenarios in three broad categories: harvesting practices (e.g., time of harvesting, type of taps and droplines, use of a drill for tapping, etc.), stand management practices (e.g. thinning canopy, density of planting, and mulching around trees, etc.), and sap processing practices (e.g., use of an evaporator, reverse osmosis, wood for fuelwood, etc.). Of all the management practices, producers responded that they were most likely to change their harvesting practices compared to their stand management, processing, and marketing. The scenarios that the majority of producers were most likely to respond to were more variable and extreme weather conditions, warmer winter and spring seasons, shorter duration of the tapping season, and decreased sap quantity. The majority (over 50%) of the producers were not likely to respond to higher pest prevalence in maple stands, shifts in geographic range, decreased sap quality, shifts in consumer demand, policy and financial incentives, and higher prices for maple. According to survey results, only a change in the prevalence of pests in their stands would cause a large percentage (47.92%) of producers to change their stand management practices.

When presented with a scenario regarding more frequent and extreme weather events ("If you knew that there would be more variable weather patterns and more frequent extreme weather events such as warmer winters in the next 10 years, would you change the following practices? If so, how?), the majority of the producers (62%) stated they would change their sap harvesting practices. The majority of producers further stated that they would not change their sap stand management practices (54%) and sap processing practices (74%). When presented with the scenario regarding warmer weather ("If you knew that the weather was going to become notably warmer in the winter and spring during the next 10 years, would you change the following practices?"), the majority of the producers (73%) stated they would change their sap harvesting practices. The majority of producers further stated that they would not change their sap stand management practices (59%) and sap processing practices (70%).

Conclusions and Recommendations:

Findings from this study have the potential to inform maple producers and policy makers who need evidence-based management plans to mitigate climate risk in the sugar maple industry. A key insight from this research is that mean climate conditions are predictive of maple syrup production, at the site level. While previous research has reported links between climate and syrup production (Duchesne & Houle, 2014; Duchesne et al., 2009; Houle et al., 2015), these studies have used syrup production data aggregated at broad scales, and used more derived climate metrics such as accumulated growing degree days and the frequency of freeze/thaw events. These studies have also not included data from the warm edge of the sugar maple range, which is needed to understand how syrup production may be affected by the magnitude of warming predicted from climate models. While projections using more refined climate measures could be more accurate, forecasts are not available for metrics such as Growing Degree Days or the number of freeze thaw cycles, while 1-3 month forecasts of mean temperatures are available. Sugar makers could therefore use these long-term weather forecasts to gain insight into the timing of the sap collection season, and whether sap harvests are likely to be large or small. Producers may also use summer temperature as a predictor of sap sugar concentrations in the following year. Likewise, forest managers and policy makers could use climate projections with confidence to make decisions that could impact future maple sap harvests. This could include siting new maple production operations.

Our surveys revealed that the majority of producers perceive some change in weather variables that we have shown to affect sap quality and quantity, but producers are split in their perceptions about the importance of individual variables and their level of concern about future impacts on the industry. Many producers have altered and/or are willing to alter their harvesting techniques to try to mitigate uncertainty in weather patterns that appear to affect sap production. Further research is needed to identify additional management practices to mitigate climate risk in the sugar maple system. For example, demand for greater syrup products has led to the ubiquitous use of a wide variety of technologies meant to increase production, including vacuum tubing (Kelley & Staats, 1989) that mitigates freeze-thaw cycle controls on sap flow, and novel spouts to enhance sap collection (van den Berg, Perkins, Isselhardt, & Wilmot, 2016). But whether and how these practices affect overall tree physiology (Isselhardt, Perkins, van den Berg, & Schaberg, 2016; Wilmot, Perkins, & Van den Berg, 2007) and how climate affects sap quality and quantity require further study. In the Northeastern United States, large forested areas are being converted primarily for maple sap production, another practice that requires assessment. A variety of agroecological management strategies for climate adaptation have been proposed for other plant-based ecosystem services, ranging from species/ varietal substitution, to technological changes and post-harvest practices, as well as migration and relocating production systems to more suitable locations (S. Ahmed & Stepp, 2016). Given the rapid increase in maple syrup production and its expanded role in local economies in many rural places of northeastern North America (M. Farrell, 2013; National Agricultural Statistics Service, 2017), our work highlights a spatial and temporal focus for these adaptation activities, and allows better planning for maple syrup producers, large and small. Sugar maple producers and resource managers can apply these results to design plans and policies to minimize climate risk. In addition, our findings are relevant to indigenous communities of North America who have a long cultural history of tapping sugar maple trees before the arrival of Europeans (Keller, 1989; Turner & von Aderkas, 2012).

Outreach and Products:

1) Two workshops brought together states, tribal members, and producers concerned with maintaining the cultural and economic values of maple sugaring in the northeast and Midwest. The second, held in conjunction with the New England Forest Ecosystem Monitoring Cooperative's annual meeting, was especially well-attended, including by tribal members as well as stakeholders from the Midwest who joined remotely. Presentations from that workshop are posted online at the
2) interactive website (http://blogs.umass.edu/acernet/) produced through this grant; the outreach group, ACERnet - Acer Climate and Socio-Ecological Research Network (https://blogs.umass.edu/acernet/) was also formed. This group is focused on community needs assessment and stakeholder networking related to the project. ACERnet underscores the importance of regionally appropriate responses to climate change, enhances stakeholder engagement, and creates a space to share data and form collaborative partnerships.

The website provides stakeholders and the public with updates and results from the project, as well as general information about sugar maple and climate change. The site includes

3) maps displaying both intensive and extensive sample collection sites and annual variation in syrup yield across sugar maple's range. Maps depict areas (including uncertainty, projected from a range of scenarios) that are projected to be less or more viable for maple sugaring, leveraging NE CASC downscaled climate data and results from this research.
4) One manuscript is in revision, to be submitted to Ecological Society of America's Open-Access journal, *Ecosphere*. Another manuscript, focused on the sap quality, is in preparation.
5) A glossy manager-focused document was produced summarizing climate impacts on maple sugaring, designed to be easily accessible to LCCs, state agencies, tribes, producers, and the public. It can be found at the NE CASC website.
6) 20 undergraduate students, including a tribal member, were trained in sap analysis, climate impacts, and ethnoecology.
7) Nearly 40 volunteers as well as staff from the National Park Service were engaged and trained.
8) A number of media outlets interviewed collaborators and published articles referencing ACERnet and this study, including: the Christian Science Monitor, PRI, Science Friday, The Analytical Scientist, Chicago Post-Tribune, Climate Central, and Worcester Telegram.

SECTION 5. APPENDIX

Supplementary Table 1. Secondary Metabolites Identified and Quantified in Maple Sap Samples

Molecular formula	Name	Molecular formula	Name
C10H12N4O4	2'-Deoxy Inosine	C5H12N2O2	L-Ornithine
C10H13N5O3	2-Deoxy-Adenosine	C5H12O5	Adonitol
C10H13N5O4	2'-Deoxyguanosine	C5H4N4O1	Hypoxanthine
C10H13N5O5	Guanosine	C5H4N4O3	Uric Acid
C10H14N2O5	Thymidine	C5H5N5	Adenine
C11H19N1O9	N-Acetyl-D-Neuraminic Acid	C5H5N5O1	Guanine
C12H22O11	D-Cellobiose	C5H6O4	Citraconic Acid
C12H24O11	Lactitol	C5H7N1O3	L-Pyroglutamic Acid
C13H18O7	Salicin	C5H8O3	alpha-Keto Valeric Acid
C18H32O16	Maltotriose	C5H9N1O3	Hydroxy-L-Proline
C1H4N2O1	Urea	C5H9N1O4	D-Glutamic Acid
C1H6O6P2	Methylene Diphosphonic Acid	C6H10O6	D-Galactonic Acid-gamma-Lactone
C2H5N1O2	Glycine	C6H10O7	5-Keto-D-Gluconic Acid
C2H5O5P1	Phosphono Acetic Acid	C6H11N1O6	Glucuronamide
C2H7N1O1	2-Aminoethanol	C6H12N2O4S1	Lanthionine
C2H7N1O1	Ethanolamine	C6H12O5	L-Fucose
C2H7N1O2S1	Hypotaurine	C6H12O6	D-Tagatose
C3H2N2O3	Parabanic Acid	C6H12O6	D-(+)-Glucose
C3H4O3	Pyruvic Acid	C6H13N1O2	L-Isoleucine
C3H6O2	Propionic Acid	C6H13N1O5	D-Galactosamine
C3H6O3	Dihydroxy Acetone	C6H14N2O2	D-Lysine
C3H7N1O2	D-Alanine	C6H14O6	D-Mannitol
C3H7N1O2S1	D-Cysteine	C6H15O4P1	Triethyl Phosphate
C3H8O2	1,2-Propanediol	C6H6N2O1	Nicotinamide
C3H8O3	Glycerol	C6H8O6	Tricarballylic Acid
C3H9O6P1	D,L-alpha-Glycerol-Phosphate	C7H11N1O5	D-1-N-Acetyl-D,L-Glutamic Acid
C4H11N1	N-Butylamine	C7H12N2O3	Glycyl-L-Proline
C4H4O2	alpha-Hydroxy Glutaric Acid-gamma-Lactone	C7H12O6	Quinic acid
C4H4O4	Fumaric Acid	C7H12O6	Sedoheptulosan
C4H4O5	Oxaloacetic Acid	C7H12O6	Quinic acid
C4H5N3O1	Cytosine	C7H12O7	beta-Methyl-D-Glucuronic Acid
C4H6O2	2,3-Butanone	C7H14N2O4	Ala-Thr
C4H6O3	Acetoacetic Acid	C7H14N2O4S1	Cystathione
C4H6O4	Succinic Acid	C7H14O6	3-Methyl Glucose
C4H6O6	D-Tartaric Acid	C7H6O3	2-Hydroxy Benzoic Acid
C4H7N1O3	Succinamic Acid	C8H11N1	beta-Phenylethyl-amine
C4H8O2	Butyric Acid	C8H11N1O2	D,L-Octopamine
C4H8O2	3-Hydroxy 2-Butanone	C8H14O2S2	DL-alpha-Lipoic Acid (ox)
C4H8O2	Butyric Acid	C8H15N1O6	N-Acetyl-D-Galactosamine
C4H8O3	D-Lactic Acid Methyl Ester	C8H15N3O4	Ala-Gln
C4H8O3	alpha-Hydroxy Butaric Acid	C8H9N1O3	Pyridoxal
C4H8O3	D-Lactic Acid Methyl Ester	C9H11N1O2	L-Phenylalanine
C4H9N1O2	D,L-alpha-Amino-Caprylic Acid	C9H12N2O5	2'-Deoxy Uridine
C5H10N2O3S1	L-Cysteinyl-Glycine	C9H13N3O5	Cytidine
C5H10O4	2-Deoxy-D-Ribose	C9H18N2O3	Ala-Leu
C5H10O5	D-Arabinose	H3O3P1S1	Thiophosphate
C5H11N1O2	L-Valine		
C5H11N1O2S1	L-Methionine		
C5H11N1O4S1	L-Methionine Sulfone		

Supplementary Table 2. Maple Producer Survey Questions

Where is the location of your farm (name of county, township and state)?
How old are you?
How many years have you tapped sugar maple trees?
When was the last sugaring season that you tapped?
Did your parents tap sugar maple trees?
Did your grandparents tap sugar maple trees?
What best describes how you first learned how to produce maple syrup?
What is the approximate elevation or elevation range of your sugar maple trees?
Approximately how many taps do you collect sap from?
Approximately how many gallons of sap do you collect annually?
What do you value about producing sugar maple? Please describe everything you value about maple sugar production.
Do you produce maple syrup for commercial sales?
Overall, how does sugaring contribute to your household income?
Approximately what percentage of your income comes from sugar maple production?
Is sugar maple production your primary source of income?
What sugar maple products do you produce for sales?
What is the primary outlet for your maple syrup and sugaring sales?
Are sugar maple products an important component of agri-tourism in your area?
What tapping method do you primarily use?
What method do you primarily use to process your sap into syrup?
What kind of fuel do you use to boil sap?
Do you know of any medicinal or nutritional properties of maple sugar? If yes, what are these?
Do you tap sap from any species other than the sugar maple?
During your lifetime, have you noticed a change in any of the following weather variables?
During your lifetime, have you noticed a change in any of the following aspects of the maple-sugaring season?
During your lifetime, have you noticed a change to the start or end time to any of the following aspects of the maple-sugaring season?
How would you best describe high quality maple syrup?
How would you say the quantity and quality compared to previous years?
Do any of the environmental variables below impact the quality of the final maple syrup product?
Have you ever experienced weather events that have negatively impacted your production of maple syrup? If yes, what are these?
Are you aware of any growing practices or conditions that make sugar maple trees less threatened by weather events? If yes, what are these practices?
Have you ever changed your tapping or other production practices in response to changing sap yields and/or quality? If yes, how?
Are you concerned, hopeful, or neutral about the future of your sugar maple trees and sugaring production? Please describe why you feel this way.

Do you keep records of harvest dates?
Can we contact you about potentially sampling sap on your sugaring operation?
Please use this space for any additional observations that you have had on sugar maple and the environment that were not covered in the survey. You may also use this space for additional related comments or suggestions.

Supplementary Table 3. Survey to assess the existence and types of management responses by maple producers to a variety of scenarios

What state is your maple stand(s) located?
How many years have you tapped sugar maple trees?
Approximately how many taps do you collect sap from?
Scenario 1: If you knew that there would be more variable weather patterns and more frequent extreme weather events such as warmer winters in the next 10 years, would you change the following? If so, how?
Scenario 2: If you knew that the weather was going to become notably warmer in the winter and spring during the next 10 years, would you change the following? If so, how?
Scenario 3: If you knew that the duration of the tapping season would decrease during the next 10 years, would you change the following? If so, how?
Scenario 4: If you knew that there would be notably higher pest prevalence in maple stands during the next 10 years, would you change the following? If so, how?
Scenario 5: If you knew that the geographic area most suitable for tapping maple would notably shift north during the next 10 years, would you change the following? If so, how?
Scenario 6: If you knew that sap quantity would decrease during the next 10 years, would you change the following? If so, how?
Scenario 7: If you knew that sap quality would decrease during the next 10 years, would you change the following? If so, how?
Scenario 8: If you knew that there would be more consumer demand for maple syrup grown in an environmentally sustainable way (such as organic certification and / or diversification of stands) during the next 10 years, would you change the following? If so, how?
Scenario 9: If you knew that there would be financial policy incentives such as subsidies for organic certified maple production during the next 10 years, would you change the following? If so, how?
Scenario 10: If you knew that there would be higher prices for maple syrup during the next 10 years, would you change the following? If so, how? If so, how?