5-2018

Developing a Localized Predictive Model for Sugar Maple Sap Production Season Termination

Benjamin S. Taylor

Developing a Localized Predictive Model for Sugar Maple Sap Production Season Termination

by

Benjamin S. Taylor
Candidate for Bachelor of Science
Environmental Resources Engineering
With Honors

May 2018

APPROVED

Thesis Project Advisor: ______________________
Christopher Somerlot, P.E.

Second Reader: ______________________
Charles Kroll, Ph.D.

Honors Director: ______________________
William M Shields, Ph.D.

Date: 5/12/2018

Table of Contents

Abstract

For thousands of years, humans have been extracting the sap of the sugar maple tree for use in many areas of life. The ability to predict, as a function of environmental conditions, the critical events, like the change in the flavor of maple sap, can be critical for the success and profitability for modern maple syrup production. Four models are developed to correlate the accumulation of heating and cooling over specified periods of time with the change in maple sap flavor at a maple operation in Attica, NY. Growing degree days and cooling degree days are used to simulate this heating and cooling accumulation. After testing the four models with varying date ranges, threshold/base temperatures, cooling accumulation thresholds, and heating start dates, the data suggests there is no significant correlation between heating and cooling accumulation and the flavor change of maple sap at this location.

Keywords: Maple, phenology, trees, heating, cooling, GDD

Developing a Localized Predictive Model for Sugar Maple Sap Production Season Termination

by

1.0 Introduction

1.1 Maple Syrup Production

This study is an in-road to further studies regarding sugar maple phenology and the prediction of maple syrup quantity and quality. The maple syrup industry, spanning the Northeastern United States and Southeastern Canada, has traditionally been an industry without a culture of consistent data collection. Because of this, maple producers do not fully understand the controlling factors of the maple season. “Maple season” refers to the length of time, traditionally in January through April, where a sugar maple tree, *Acer saccharum,* transports sap throughout the organism, and can be harvested. Maple sap is extracted from the tree by drilling a 1-3 inch deep hole, with a diameter from 3/16th inch to 3/8th inch, which allows sap to drip into a bucket or tubing system. This is called “tapping” and occurs in December-March, depending on the location and technology available. The maple sap will flow from the tree until bacteria enter the hole, which triggers an immune response in the tree to close the hole and block sap flow. Before this, however, the sap may change flavor, which is correlated to the chemistry of the tree and bud break. Sap collected after bud break (which is concentrated into “buddy” syrup) is generally inferior in quality. After the sap exits the tree, it is collected and water in the sap is removed via reverse osmosis and boiling, which results in the product of maple syrup. To produce one gallon of maple syrup, a producer needs 40-50 gallons of maple sap.

This study analyzes the cooling and heating degree day requirements for the sap and syrup flavor to change from the common maple flavor to the undesirable “buddy” flavor. This change to “buddy” flavor is a controlling factor every year in how much syrup can be produced.

The intent of this study is to lay the groundwork for the development of a localized model that will be able to predict the season end date for an individual maple operation. If a relationship between the local cooling and heating degree days and the time to "buddy" sap are known, one can use temperature data and forecasts to determine how "long" the maple season will last. The bud-out dates for the trees is not used based on data limitations and the relative practicality of bud break versus season end date. Maple producers care when the flavor will change, as this determines how much syrup they can produce and sell, not necessarily when the trees will bud.

1.2 Growing Degree Days

In this study, growing degree days (GDD) and cooling degree days (CDD) will be used to quantify and model the accumulation of cooling and heating units in sugar maple trees. GDDs and CDDs are the accumulation of temperature units above or below a certain threshold temperature for a specific amount of time. GDD is frequently used to describe the timing of biological processes in agriculture and horticulture operations (McMaster & Wilhelm, 1997). GDDs have allowed for the prediction of phenological events such as maturation, pest emergence, or flowering. Accumulated growing and cooling values will be calculated for a variety of start dates and thresholds, and then used in multiple methods to investigate the relationship between cooling and heating accumulation and sugar maple sap production season.

The heat accumulation in the spring may be intuitively seen as the sole factor controlling bud break and changes in the tree biology. Multiple studies on woody plants, though, have shown that cooling also has some relationship on the heating required to trigger phenological events (bud break, leaf out) in the spring (Cannell & Smith, 1983; Raulier & Bernier, 2000; Hunter & Lechowicz, 1992)

1.3 Biology

The fundamental question behind the ability to create a predictive model is: What causes trees to undergo significant spring biological changes (i.e. budding)? The literature is not clear on the exact factors that lead a tree, specifically sugar maple, to bud or undergo change. There are various phases of dormancy, regulated by chilling, photoperiodic responses, nutrients, and water availability (Kozlowski & Pallardy, 1997). It is also known that temperature has an influence on the development of buds and shoot growth, and that there is significant variation among species in response to temperature factors (Zimmermann & Brown, 1971). Taylor and Dumbroff make a strong case for the inverse relationship between chilling and number of heating days required for bud break. They also claim that sugar maple trees from northern regions fulfill their chilling requirement at 2500-3000 hours below 5ºC, but that some trees could reach bud activity at as low as 1500 hours (Taylor & Dumbroff, 1975). To our knowledge, a relationship between bud break and growth has not previously been correlated to the change in flavor of maple sap. Based on this research, the exact mechanisms that drive a sugar maple tree to bud are not clear; temperature most likely has an important effect.

1.4 Other Work

The most significant study that has been conducted on the prediction of sugar maple phenological events was conducted by Raulier and Bernier in 1999. Two years of data from two sugar maple stands were used to relate the amount of cooling and heating to the timing of leaf emergence. The use of leaf emergence instead of bud break was intentional, as that is an easier event to observe and record than bud break. Raulier and Bernier used an exponential model that relates the number of cooling days with the accumulation of heat, and achieved a high correlation between the number of cooling days with the accumulated heat required for leaf emergence. This method is described further in the methods section of this work. Additionally, Raulier and Bernier note that their model does not account for any other factor like soil temperature or photoperiod, and that it relies on a constant threshold temperature for accumulation calculations (Raulier & Bernier, 2000).

Another study that is significant is the work of Hunter and Lechowicz in 1992. They provide a comprehensive overview of 4 methods of accumulating growing and cooling degree days, which include the spring warming, parallel chill, sequential chill, and photoperiod methods. Three of these methods are used in this study and will be described in subsequent sections. Their results indicate that the spring warming and sequential chill model were the most accurate in predicting budburst from historical datasets. They identified challenges of the models and indicated that in their testing of artificial datasets that replicated biological responses, there seems to be little correlation between the "predictive ability of a model and the biological basis of phenological responses" (Hunter & Lechowicz, 1992).

With the present study, a combination of the models presented by Raulier and Bernier (1999) and Hunter and Lechowicz (1992) will be tested with season end date data from Attica, NY. Heating and cooling accumulation will be tested solely, as the body of literature indicated that temperature has a significant effect on the development of trees in the spring season. Additionally, temperature data is easy to collect, which allows this model to be widely distributed and improved upon.

2.0 Methods

2.1 Data

2.1.1 Season End Dates

Season end dates were obtained from a maple operation in Attica, NY. The family has kept season end date records since the 1960s. The dates from 1982-2017 will be used for this analysis based on availability of temperature data. The season end dates are based on the flavor of the syrup changing, as confirmed by the current owner and his father, who continue to produce syrup until the syrup becomes off-flavored. Technology has changed in the maple syrup industry since 1982, including the installation of a vacuum system as well as the implementation of using sanitized spouts. These technologies, though, would have changed sap flow, but not sap flavor. Therefore, from 1982 to 2017, the metric used to determine season end date is flavor change.

2.1.2 Temperature

Average hourly temperature data was obtained from the PRISM Climate Group, of the Northwest Alliance for Computational Science & Engineering, based at Oregon State University (PRISM Climate Group, 2017). This tool allows for the extraction of daily historical temperature data at a single location or 500m gridded location. The grid that overlays the Attica, NY maple operation's oldest section of woods was used. This data extends back to 1981, which was the limiting factor in the amount of years that could be analyzed.

2.2 Calculations

The GDD and CDD calculations performed in this study followed the modified sine wave method (Equation 1, Appendix) (Allen, 1976). This is based on the assumption that daily temperature fluctuations generally follow the path of a sine wave. This was chosen over the simple averaging method, or the rectangle method, as it can employ a lower and upper threshold temperature, and has been shown to not exceed 5% error of the actual heat accumulation (Baskerville & Emin, 1968). Pruess (1983) also suggests that the sine wave method is most effective in the spring for degree day calculations. The following three methods describe the usage of the daily degree day accumulation in this study, based off of the budburst timing study done by Hunter and Lechowicz (1992).

To calculate heating or cooling accumulation, one must define a base threshold temperature. Heating is accumulated above this threshold, and cooling accumulated below. Across the literature, there is no set base temperature for tree phenological research. Commonly, 32ºF or 50ºF are used (Crimmins, et al., 2017). To create a model that describes the phenology as accurately as possible, multiple thresholds will be tested in the following models. 32ºF is an important temperature in the maple industry, as the maple sap flows from the trees when the air temperature is above 32ºF. Note that the sap does not immediately flow, but will after the tree temperature adjusts with the air temperature. If a base temperature of 50ºF is used, all days that do not surpass 50ºF in temperature will have a recorded GDD of zero. This seems to lose valuable data on the days where the temperature is over 32ºF and the trees are undergoing nutrient and sugar transport. Therefore, multiple thresholds will be tested.

The following four sections describe various ways to calculate growing and cooling accumulation.

2.2.1 Spring Warming

The spring warming model used in this study is adapted from Hunter and Lechowicz (1992). GDD calculations are performed on each historical day using the modified sine wave method (Calculation 1). The daily growing degree days accumulate until a specified end date, which is represented as "aGDD". In this study, the end date is defined as the season end date, received from the historical data at the Attica maple operation. Base temperatures of 0, 10, 32, 40, and 50°F were tested with start dates beginning on January 1st, in 10-day increments. This yields a start date and base temperature combination, with the aGDD values from 1982-2017. The relative precision of each combination was measured by fitting an ordinary least square (OLS) regression line to the data over time. The coefficient of determination (R^2) of the regression models are reported in the results.

2.2.2 Parallel Chill

The parallel chill model used in this study is adapted from Hunter and Lechowicz (1992). GDD and CDD calculations are performed on each historical day using the modified sine wave method (Calculation 1). GDD and CDD are accumulated, noted as aGDD and aCDD, respectively. This model has three parameters to vary: fall start date for cooling accumulation, spring start date for heating accumulation, and base temperature. Fall start dates for cooling were in 20 day intervals beginning on October 1st. Spring start dates for warming were in 7 day intervals starting on January 1st. Tested base temperatures were 0, 10, 20, 32, 40, 50, and 60. For each combination, the linearly regressed R^2 value is calculated using the aGDD yearly values as the dependent variable, with the aCDD yearly values as the independent variable. The highest R^2 combinations are reported in the results.

2.2.3 Sequential Chill

The sequential chill model used in this study is also adapted from Hunter and Lechowicz (1992). GDD and CDD calculations are performed on each historical day using the modified sine wave method (Calculation 1). In sequential chill, the start date for heating accumulation depends on reaching a "cooling threshold." Because the required cooling for sugar maple trees has not been found in the literature, empirical methods are used. Cooling is accumulated from October, November, or December 1st. The cooling thresholds tested range from 1-3000 (cooling degree days) in even increments in a log fashion. The cooling thresholds vary significantly because the base temperatures are also varied at the same increments as the parallel chilling model, which creates magnitude differences. The R^2 values of the yearly aGDD values versus time are calculated for each combination of cooling start date, threshold temperature, and base temperature.

2.2.4 Raulier Method

The Raulier Method model is based on the work of Raulier and Bernier (2000). This method calculates the accumulation of heat and cooling from December 1st. The accumulated cooling and heating are modeled against each other using an exponential function (modified from Raulier and Bernier, 2000):

$$Sw = \beta e^{\alpha d_c}$$

Where β and α are estimated parameters from the exponential (nonlinear) regression. This exponential is meant to make a prediction on the heat accumulation required for leaf emergence based on the number of days of cooling. To develop a local model, the Sw (growing degree days) and corresponding d_c (number of days that the average temperature falls below the threshold temperature) are calculated from 1982 and fit with an exponential function, which yields the β and α parameters for a prediction model. Raulier and Bernier found that a base temperature of 50ºF yielded the most accurate predictions, so 50ºF as well as 32ºF will be tested in this study.

3.0 Results

3.1 Spring Warming

The spring warming model, with inputs of different base temperatures and starting dates (50 different combinations), yields no significant results of any combination. The highest R^2 value was .22, which corresponds to a February 10th heat accumulation start date, and a base temperature of 10ºF.

3.2 Parallel Chill

The parallel chill model, with 525 different combinations of base temperatures, cooling accumulation starting dates, and heating accumulation starting dates, yields no significant linear correlation between the accumulation of cooling and heating. The highest R^2 value was .35, which corresponds to a December 20th cooling accumulation start date, a January 1st heat accumulation start date, a base temperature of 10ºF.

3.3 Sequential Chill

The sequential chill model, with 399 different combinations of base temperatures, cooling accumulation starting dates, and threshold cooling values, yields no significant linear correlation between year to year accumulated growing degree days after the threshold is reached. The highest R^2 value was .24, which corresponds to an October 31st cooling accumulation start date, a base temperature of 20ºF, and a cooling threshold of 1 cooling degree day.

3.4 Raulier Method

The Raulier method, tested at base temperatures of 32ºF and 50ºF, yields no significant exponential relationship between the cooling day accumulation and growing degree day accumulation. There is also no significant linear relationship, with exponential R^2 values of .034 and .105 for 32ºF and 50ºF, respectively.

4.0 Discussion

This study offers further insight into the complexities of trees and our inability to predict nature. The results of this study indicate that there may be more significant factors influencing the change in flavor of maple syrup. Although bud break was loosely used as a baseline to understand the correlation, this was only because of the generally accepted theory of maple production in the maple industry, that has not been scientifically tested. The results are only indicative of one location. The historical temperature data from PRISM has an unknown accuracy, because of the lack of true localized temperature data at the Attica, NY location. If the sample size was expanded to other maple producers, there may be a higher chance of developing a model that would be able to predict the season end date based on temperature. Although this would be advantageous, the variation among producers must be considered in the analysis. If the season end date is based on the last time a producer makes syrup, that has the potential to vary greatly from year to year and producer to producer, even those in the same location. Further data is beginning to be collected from producers across NY state.

The other factors potentially influencing the spring phenology of trees, namely soil temperature, photoperiod, region, genetics, or soil moisture have been intentionally overlooked in this study, but may need to be entered back into the model. The composition of a sugar bush, or sugar woods, could also be skewing the results. The stand density, canopy height, and basal area could all be factors in the ambient temperature that effects the trees. Also, since red, green, black, and sugar maples (sugar maples are still predominant) are all tapped for sap, the inter-species differences could be having an influence on the phenology.

The assumptions in the models of constant temperature threshold, a linear regression, and the sine wave method can all contribute to the lack of uncertainty in the results. In addition, the PRISM daily temperature was recorded for a 24-hour period ending at 7am EST on the day that was reported, which would slightly adjust the results, but not on the level that would correct the low correlation of these results.

5.0 Conclusion

After the testing of four models of heating and cooling accumulation with the goal of making a step towards a localized predictive model for sugar maple sap production season termination, it can be concluded that further studies will have to be conducted. The uncertainty in the biology of the trees, the selection of the models, the temperature data contributing to the model, the timing around the season end date, and the lack of replicability at other maple operations all contribute to an open-ended question of whether or not the maple season end date can be predicted using solely temperature. At this point, the data would suggest that there are other factors that would need to be included in a model. In order to achieve widespread usage and practicality, the model has to be developed in a simple, communicable way that maple producers can replicate at their own operations.

References

Allen, J. C. (1976, June). A Modified Sine Wave Method for Calculating Degree Days. *Environmental Entomology, 5*(3), 388-396.

Baskerville, G. L., & Emin, P. (1968, April 27). Rapid Estimation of Heat Accumulation from Maximum and Minimum Temperatures. *Ecology, 50*(3), 514-517.

Cannell, M. G., & Smith, R. I. (1983). Thermal Time, Chill Days and Prediction of Budburst in Picea sitchensis. *Journal of Applied Ecology, 20*(3), 951-963.

Crimmins, T. M., Marsh, R. L., Switzer, J. R., Crimmins, M. A., Gerst, K. L., Rosemartin, A. H., & Weltzin, J. F. (2017). *USA National Phenology Network Gridded Products Documentation.* Open-File Report 2017-1003, U.S. Geological Survey.

Hunter, A. F., & Lechowicz, M. J. (1992). Predicting the Timing of Budburst in Temperate Trees. *Journal of Applied Ecology, 29*(3), 597-604.

Kozlowski, T. T., & Pallardy, S. G. (1997). *Physiology of Woods Plants* (2nd ed.). San Diego, California: Academic Press.

McMaster, G. S., & Wilhelm, W. W. (1997). Growing degree-days: one equation, two interpretations. *Agriculture and Forest Meteorology, 87*, 291-300.

Melaas, E. K., Friedl, M. A., & Richardson, A. D. (2016). Multiscale modeling of spring phenology across Deciduous Forests in the Eastern United States. *Global Change Biology, 22*, 792-805.

PRISM Climate Group. (2017). PRISM Climate Data. Oregon, USA.

Pruess, K. P. (1983). Day-degree methods for pest management. *Environmental Enomology, 12*, 680-686.

Raulier, F., & Bernier, P. Y. (2000). Predicting the date of lead emergence for sugar maple across its native range. *Canadian Journal of Forest Research, 30*, 1429-1435.

Taylor, J. S., & Dumbroff, E. B. (1975). Bud, root, and growth-regulator activity in Acer saccharum during the dormant season. *Canadian Journal of Botany, 53*, 321-331.

Zimmermann, M. H., & Brown, C. L. (1971). *Trees, Structure and Fuction.* New York, New York: Springer-Verlag.

Equations

Equation 1. Modified Sine Wave Method Daily Growing and Cooling Degree Days

$avT = Average\ daily\ temperature$ *(ºF)*

$baseT = Selected\ base\ temperature\ for\ which\ heat\ accumulates\ above\ (ºF)$

$\alpha = Value\ (used\ in\ another\ equation, for\ simplification)$ *(ºF)*

$maxT\ or\ \min T = Daily\ maximum\ or\ minimum\ temperature$ *(ºF)*

$arg = Value\ (used\ to\ modify\ the\ calculations\ based\ on\ the\ value)$ *(unitless)*

$\theta = Constant$ *(used in the sin wave GDD equation) (radians)*

$GDD =$ Growing degree days $in\ one\ 24hr\ time\ period$ *(unitless)*

$CDD =$ Cooling degree days $in\ one\ 24hr\ time\ period$ *(unitless)*

$$avT = \frac{maxT + minT}{2}$$

$$\alpha = \frac{(maxT - minT)}{2}$$

$$arg = \frac{(baseT - AvT)}{\alpha}$$

if arg>1, arg= 1

if arg<-1, arg= -1

$$\theta = \sin^{-1}(\text{arg})$$

$$GDD = \frac{1}{\pi}\left[(avT - baseT)\left(\frac{\pi}{2} - \theta\right) + \alpha\cos(\theta)\right]$$

if GDD<0, GDD=0.0

$$CDD = \frac{1}{\pi}\left[(baseT - avT)\left(\frac{\pi}{2} + \theta\right) + \alpha\cos(\theta)\right]$$

if CDD<0, CDD=0.0