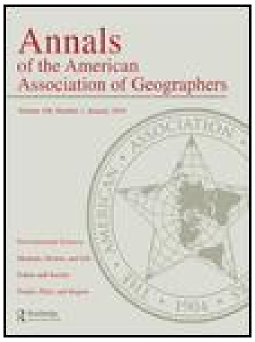

Annals of the American Association of Geographers

ISSN: 2469-4452 (Print) 2469-4460 (Online) Journal homepage: https://www.tandfonline.com/loi/raag21

Interannual Effects of Early Season Growing Degree Day Accumulation and Frost in the Cool Climate Viticulture of Michigan

Steven R. Schultze, Paolo Sabbatini & Lifeng Luo

To cite this article: Steven R. Schultze, Paolo Sabbatini & Lifeng Luo (2016) Interannual Effects of Early Season Growing Degree Day Accumulation and Frost in the Cool Climate Viticulture of Michigan, Annals of the American Association of Geographers, 106:5, 975-989, DOI: 10.1080/24694452.2016.1171129

To link to this article: https://doi.org/10.1080/24694452.2016.1171129

Interannual Effects of Early Season Growing Degree Day Accumulation and Frost in the Cool Climate Viticulture of Michigan

Steven R. Schultze,[*] Paolo Sabbatini,[†] and Lifeng Luo[‡]

[*]*Department of Earth Sciences, University of South Alabama*
[†]*Department of Horticulture, Michigan State University*
[‡]*Department of Geography and Center for Global Change and Earth Observation, Michigan State University*

Michigan daily climatic data and seasonal vine performance and phenological data (budburst timing) were analyzed to establish relationships between temperature (e.g., growing degree days or GDD) and juice grape yield and quality in *Vitis labrusca* grapevines. In viticultural regions such as Michigan, early season vine growth is highly important: Vines coming out of their winter dormancy need to withstand any potential bud-killing frosts after budburst. The temperatures during the months of March, April, and May are highly variable from year to year in Michigan, however. The average GDD accumulation at the time of budburst (average date is 27 April) from 1971 to 2011 was 158 (base 10°C) with a coefficient of variation of 45 percent. Seasonal GDD deficit or surplus at the midpoint of a growing season (as compared to an average year) was correlated to grapevine performance and the accumulation of GDD on a yearly basis was found to occur at a highly variable rate. Early season GDD accumulation was found to be a relative indicator of the end season total, where an early season deficit (or surplus) was able to predict whether the season would still be in deficit (or surplus) at the end of 80.5 percent of all seasons studied. Finally, a statistical model based on historical temperature data was created to calculate the date of budburst. Michigan's warming trend will likely continue in the future, which should bring positive effects to the region. Early season variability and post-budburst frosts are likely to still be a concern in the near future, however. *Key Words: budburst, climate, early season variability, GDD, viticulture.*

本文分析密西根的每日气候数据及季节性葡萄表现和生物气候数据 (萌芽时间点), 以建立气温 (例如生长度日或GDD) 和美洲葡萄的酿酒葡萄产量与质量之间的关联性。在诸如密西根的葡萄栽植区域中, 季节初期的葡萄成长具有高度重要性：从冬眠中甦醒的葡萄, 在萌芽之后, 必须能抵抗任何可能何杀死芽苞的寒霜。但在密西根, 每年三月、四月及五月份的气温却具有高度变异。自1971年至2011年, 萌芽期 (平均日期为四月二十七日) 的平均GDD累积为一百五十八日 (基于摄氏十度), 并有百分之四十五的变异係数。在成长季 (相较于平均年) 中点的季节性GDD不足或过剩, 与葡萄产量相关, 而年度的GDD累积, 则发现具有高度的变异。研究发现, 季节初期的GDD累积, 是季末总数的相关指标, 而在所有的研究季节中, 百分之八十点五的季节初期不足 (或过剩) 能够预测该季最终是否仍然不足 (或过剩)。最后, 本研究创造了根据历史温度数据的统计模型, 以计算萌芽的日期。在未来, 密西根的暖化趋势将很有可能继续, 并会对该区域带来正向影响。但季节初期变异性和萌芽后的寒霜, 在不久的未来中, 仍将有可能是重要的考量。 *关键词： 萌芽, 气候, 季节早期变异性, 生长度日, 葡萄栽植。*

Los datos climáticos diarios de Michigan y el desempeño estacional de la vid y datos fenológicos (el tiempo de brote o apertura de las yemas vegetativas) fueron analizados para establecer las relaciones entre temperatura (e.g., grados días para crecer, o GDD) y el rendimiento en jugo de uva y calidad de las vides *Vitis labrusca*. En regiones vitícolas como las de Michigan la temporada temprana de crecimiento de la vid es muy importante: Las vides que despiertan de su latencia invernal deben resistir cualquier helada potencialmente mortífera para los capullos después de que estos han brotado. Pero las temperaturas durante los meses de marzo, abril y mayo son altamente variables de año en año en Michigan. El promedio de acumulación de los GDD en el momento del brote de las yemas (la fecha promedio es el 27 de abril) de 1971 a 2011 fue de 158 (base de 10°C), con un coeficiente de variación del 45 por ciento. El déficit o el excedente estacional de los GDD en el punto medio de una temporada de crecimiento (al compararla con un año promedio) se correlacionó con el rendimiento del viñedo, y se descubrió que la acumulación de los GDD con base anual ocurría a una tasa altamente variable. Se encontró que la acumulación de los GDD de comienzo de la temporada eran un indicador relativo del total al final de la temporada, donde un déficit (o excedente) de temporada temprana estaba en capacidad de predecir si la temporada todavía estaría en déficit (o en excedente) al final del 80.5 por ciento de todas las temporadas estudiadas. Finalmente, se creó un modelo estadístico basado en datos históricos de temperatura para calcular la fecha del brote de las yemas. La tendencia climática al calentamiento en Michigan presumiblemente

Annals of the American Association of Geographers, 106(5) 2016, pp. 975–989 © 2016 by American Association of Geographers
Initial submission, March 2015; revised submission, December 2015; final acceptance, December 2015
Published by Taylor & Francis, LLC.

continuará, lo cual debería traer efectos positivos para la región. No obstante, la variabilidad en el comienzo de la temporada y las heladas posteriores al brote de yemas de seguro seguirán siendo una preocupación en el futuro cercano. *Palabras clave: Palabras clave: brote de yemas, clima, variabilidad en el comienzo de temporada, GDD, viticultura.*

The state of Michigan is a cool climate viticulture region in the United States, defined as having a growing season temperature average of 13°C to 15°C (Jones et al. 2010). The presence of the Great Lakes around Michigan regulates temperatures and precipitation throughout the year. This allows for considerable production of grapes along with a number of other specialty crops including cherries, apples, and apricots, despite the state's location in the center of the North American continent. The region's growing season, defined as the period between budburst and the first fall frost (temperature ≤ -1°C) is approximately 165 days in length on average in the northwestern Lower Peninsula and 180 days in the southwest corner of the state (Andresen and Winkler 2009). Vines in these regions can be subjected to frost events in the early season and they can also be limited during the fruit ripening stage at the end of the season by the occurrence of early fall frost (Zabadal and Andresen 1997). Frosts occurring in the early weeks and last days of the growing season effectively bound a vineyard's time scale wherein vine growth and fruit maturation can be achieved consistently every year. Although Michigan's climate has warmed during the last sixty years, frost persistence has not dissipated; frost events are a major cause of production failure for grape growers in Michigan's cool climate viticulture (Schultze et al. 2013).

Michigan viticulture is mixed; it is comprised of juice and wine grapes. Concord and Niagara (*Vitis labruscana* B.) are the major juice grape cultivars and Riesling and Pinot noir (*Vitis vinifera* L.) are the most planted wine grape cultivars (U.S. Department of Agriculture-NASS 2012). As a result of Lake Michigan's ability to regulate temperatures in the winter months, Michigan experiences two "fruit belts" that are both located in the Lower Peninsula: one in the Traverse City area in the northwest and the other in the southwest corner of the state. These areas were designated as American Viticultural Areas (AVAs) in the 1980s, which led to the creation of the Fennville (1981), Leelanau Peninsula (1982), Lake Michigan Shore (1983), and Old Mission Peninsula (1987) AVAs (Hathaway and Kegerreis 2010).

Vinifera production requires specific climatic conditions, and long-term changes in climate can accommodate or prevent production. With global climates continually fluctuating over time with such events as the Medieval Warm Period, Little Ice Age, and the recent increase in global temperatures since the mid-1800s, regional agriculture has responded accordingly. During the Medieval Warm Period, wine grapes were grown as far north as the Baltic Sea coast and southern England. The ensuing Little Ice Age and its associated consistently colder and shorter growing seasons effectively ended *vinifera* production in these areas, however (Pfister 1988; Gladstones 1992; Jones et al. 2005). Currently, as global climates continue to change, areas that have not been able to support *vinifera* production are gaining the ability to support the species of grape. These areas could be considered zones of transition for *vinifera* grape production and cultivation, and Michigan is one of these zones. As recent as the early 1960s, *vinifera* production was effectively nonexistent, as the region's climate posed too many threats to the reliable, consistent production of wine grapes. The growing season was too short, the growing season temperature was not reliably warm enough, and precipitation was too prevalent at inopportune times during an average vine's phenologic cycle. Beyond that, *vinifera* grapes are less cold-hardy than *labrusca* grapes. Extremely cold winter temperatures can kill off *vinifera* wines, whereas *labrusca* grapes easily survive (Zabadal et al. 2007). Global climates are shifting warmer in the coming decades and therefore plant phenology will respond accordingly (Cleland et al. 2007) along with several other ecological responses (Walther et al. 2002). As global temperatures continue to rise, several studies have established that grapevine phenology will be affected with earlier budburst, later fall frosts, and generally shorter phenological stages (Bindi et al. 1997; Jones and Davis 2000; Webb, Whetton, and Barlow 2007; Molitor et al. 2014).

Since the 1970s, though, there has been a considerable shift to the production of wine grapes in southwest and northwest Michigan. This is primarily the function of a climate that has warmed and has brought a reliably longer growing season to the region (Schultze et al. 2013). It is likely that more of these zones of transition will appear globally as climate continues to change. As such, these regions will likely face issues similar to those that Michigan viticulture is currently experiencing. This includes large interannual variation of temperature, especially in the early season and associated frosts.

Temperatures, precipitation, and frost occurrence can all vary on a year-to-year basis, leading to vastly different growing seasons, which in turn lead to different outcomes in vine growth, yield, and fruit quality (van Leeuwen et al. 2004; Santos et al. 2011). One way to quantify the interannual variation of the climate during growing season is through the use of thermal time. The calculation of thermal time over a growing season has been used in a number of methods to model plant growth and phenology (Gladstones 2000). Growing degree days (GDD) is an approximation of the time and magnitude of temperature during a given day over a defined base temperature and can be used for the calculation of thermal time. Comparing GDD accumulation in one season versus all other seasons can display whether a season is in GDD deficit or surplus. Swan et al. (1990) showed the GDD deficit was partly responsible for corn yield variability. No literature appears to exist examining the topic of the relationship between GDD deficit or surplus and grapevine response.

Early season weather in cool climate viticulture is critical to any year's potential success, and interannual variability of the early season can be a substantial limitation in the success of a sustainable cool climate viticultural region. In the early portion of the growing season, GDD accumulation determines vine budburst and flowering time. Accumulation and rate of accumulation of GDD are both linked to vine phenological development (McCarthy 1999). Understanding these connections could lead to a more accurate prediction of when budburst could occur, which is important for growers to prepare for the oncoming season.

Interannual variability of early season temperature can also lead to large variation in frost occurrence from year to year. Subfreezing temperature can occur frequently in the months of March, April, and May. Frost after the budburst stage can cause severe damage to the year's potential crop and can even damage the vine itself. One such example is the spring frosts of 2010 in Michigan, where grape production across the southern part of the state for juice grapes was approximately 0.75 tons/ha, a little more than one third of the long-term average of 2.05 tons/ha. An abnormally warm early spring followed by a return to climate normals can also devastate an entire region's crop. This happened in Michigan in the spring of 2012. The 2012 spring was 3.7°C warmer than the previous thirty-year average in the region, featuring some days as much as 22°C warmer than their climatological average. Many of the state's perennial plants accelerated their phenological development only to experience devastating frosts in early April. According to the U.S. Department of Agriculture, losses to some fruit varieties were as high as 95 percent (tart cherries) and losses were 75 percent and 40 percent for juice and wine grapes, respectively. One way to protect the vines in the early growing season against frost is through cold air drainage. Topographic influences allow for the flow of denser cold air to drain downhill, which minimizes the frequency of frost in the microclimate, thus decreasing the potential fruit and crop damages (Andresen and Winkler 2009). The inability to drain cold air in this region would make viticulture prohibitively hazardous on a year-to-year basis. During the 2012 spring, areas where cold air drainage potential was the highest suffered the least amount of damage, and these nonaffected areas were able to take advantage of the extraordinarily warm and dry summer of 2012 to produce high-quality grapes.

There has been extensive research on the effects of climate change and the vulnerability and risks of growing specialty crops in the Great Lakes and Northeastern United States. In 2009, 80 percent of all tart cherries produced in the United States came from Michigan, New York, Pennsylvania, and Wisconsin. In these states, spring frost damage is naturally part of the risk of growing cherries. Years like 2002 and 2012 where there was crop failure highlight this concern. Warmer early spring temperatures coupled with temperatures returning to climatological averages can lead to specialty crops entering their phenological cycles earlier than normal, only to encounter frost when the plant is at its most vulnerable (Winkler et al. 2012; Winkler et al. 2013). Apples in New York might see a benefit from warmer spring temperatures but, overall, these warmer temperatures could bring other problems, including higher water stress and higher stress from insects (Wolfe et al. 2008). In both specialty crops, it is apparent that change in climate over the recent past has caused new challenges for growers. These new challenges are likely to intensify in the near future and will likely be joined by even newer challenges that will add to the significant risk already associated with specialty crops.

The goal of this research is to examine the impact of interannual GDD accumulation on grapevines in Michigan's cool climate, which can serve as an analog to other similar climates that are transitioning in to regions that can support *Vitis vinifera*, as these regions are likely to grow in viticultural importance as climate continues to change. The main objectives are to link meteorology-based variables to vine phenological parameters of the similar grapevine cultivar *Vitis labrusca* in a cool climate viticultural region. This is being done to find connections between these variables and to establish the relationship between these variables as well as quantify the variability of the early season weather in a cool climate region. Of particular interest to this study was the fact that budburst is occurring earlier in cool climate viticultural regions and the link between budburst and frost occurrence in these regions is critical to their potential success on a yearly basis. As such, this article also attempts to develop a simple budburst model using temperature as an indicator of potential budburst several weeks in advance.

Data and Methods

Site Description

Western Michigan along the shore of Lake Michigan experiences a moderate climate due to the Great Lakes' effect on temperatures in the region. Southwest Michigan's climate is classified as a *Dfa* Köppen Humid Continental Climate class (Köppen 1900; Geiger 1965). Whereas most *D* Köppen class climates pose risks for grape and other specialty crop production, the effects of the lake and land breezes off of the waters of Lake Michigan tend to limit large temperature fluctuations in the summer, and the spring and fall positions of the jet stream can greatly influence the region's temperatures by bringing in polar or subtropical air (Moroz 1967; Andresen and Winkler 2009). Regular lake-effect snows during the winter allow for a more consistent snow cover on the ground, which can aid in the protection of roots and the lower parts of vines from exposure to extremely low temperatures that could potentially damage or kill the plants (Zabadal et al. 2007; Filo et al. 2013).

The Lake Michigan Shore AVA, located in southwest Michigan (see Figure 1), was chosen for this study because of numerous climate stations and availability of long-term crop statistical data from the National Grape Cooperative (J. Jasper and T. Holloway, personal

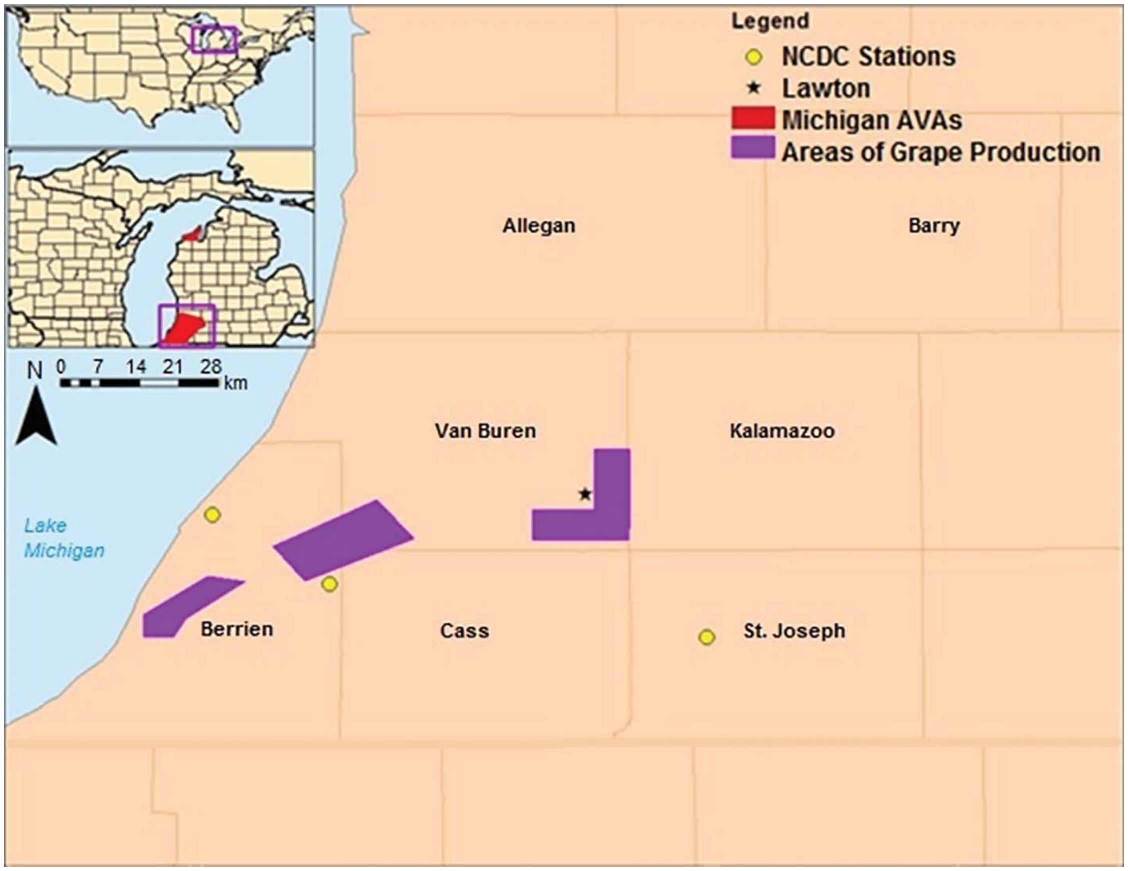

Figure 1. Map of Michigan, Michigan American Viticultural Areas, and southwestern Michigan with areas of interest for this study. *Note*: NCDC = National Climatic Data Center; AVA = American Viticultural Areas. (Color figure available online.)

communication). The Lake Michigan Shore AVA runs for 115 km along the Lake Michigan shoreline in southwest Michigan bounded by the Indiana–Michigan border, which serves as the southern boundary, to the terminus of the Kalamazoo River into Lake Michigan. The AVA runs east along the Kalamazoo River and into the interior of the state and includes the cities of Kalamazoo, Paw Paw, Lawton, and Dowagiac. It is delineated by two major railroad lines running south and southwest to the Indiana–Michigan border (Bureau of Alcohol, Tobacco, Firearms, and Explosives 1987). The region is 5,180 km^2 in area and contains a number of Michigan's oldest vineyards and wineries, as well as a grape juice processing plant in Lawton, where the National Grape Cooperative data were obtained.

Data

Temperature data were obtained from the National Climatic Data Center (NCDC)'s network of climate stations within the Lake Michigan Shore AVA using the NCDC online mapper tool (see http://gis.ncdc.noaa.gov). Data from three stations are used in this study for analysis and to develop a budburst model. The three stations used were Benton Harbor (42.1256°N, 86.4284°W), Eau Claire 4E (42.0147°N, 86.2409°W), and Three Rivers (41.9299°N, 85.6385°W). These stations were selected because they have long-term, continuous data availability and are located along an east–west axis that gives a good approximation of the average of GDD accumulation on a season-to-season basis across the AVA and gives an average approximately over Lawton. In comparing the three stations' total seasonal GDD accumulation with a larger data set from 1971 to 2011 (from Schultze, Sabbatini, and Andresen 2013), we found that the three stations had an average r^2 value of 0.92; in comparison, at an hourly station at Lawton installed in 2006, the r^2 was found to be 0.97.

The National Grape Cooperative contributed with annual viticultural data (1971–2011) on dates of budburst, yield, and fruit quality (sugar concentration, measured as soluble solids or °Brix via refractometer) for *Vitis labrusca* grapevines. Viticultural data were collected from twenty-five vineyards of members of the National Grape Cooperative located in southeastern Van Buren County, near Lawton, where a grape processing plant is located (42.16°N, 85.83°W). The crop statistics are the average of the twenty-five vineyard plots on a seasonal basis. These statistics include the dates of first fall frost (1961–present), budburst (1971–present), and yield (1975–present). Budburst was recorded as the date when 50 percent of the buds reached phenological stage 4 (Eichhorn and Lorenz 1977) in all of the experimental plots.

Methodology

The simplest method of calculation of GDD includes adding the maximum temperature of a given day ($T_{\max}$) and the minimum temperature ($T_{\min}$), and dividing the result by two and subtracting from that value a threshold temperature below which plant growth and development is halted (McMaster and Wilhelm 1997). Aggregation of all of the GDD over the course of a complete growing season allows for one growing season to be compared directly to another. Another method of GDD calculation is the Baskerville–Emin, or single sine, method. This method assumes that the daily temperature cycle can be approximated to be a single sine wave where the highest point on the curve is the highest temperature ($T_{\max}$) and the lowest point is the lowest temperature ($T_{\min}$). The area under this curve is integrated above a given base temperature (Baskerville and Emin 1969). This methodology was applied to the early season (1 April–20 May), season midpoint, and entire growing season. Additionally, GDDs were calculated from 1 March to 31 March for the creation of a simple budburst model.

Early season GDDs were calculated at three NCDC stations (Table 1) using the Baskerville–Emin single sine method (Baskerville and Emin 1969) using the stations' $T_{\max}$ and $T_{\min}$ variables. The early season is considered to be from 1 April to 20 May, with the latter date being the "frost-free" date (according to the National Grape Cooperative), a climatologically defined day after which no occurrences of frost have been recorded. These three stations had their early season GDDs averaged, as their average gives a more representative cross section of the spatial variation experienced within the region (Schultze, Sabbatini, and Andresen 2013). The midseason point was calculated as the midpoint between budburst and the first fall frost. GDDs were calculated from the date of budburst to this date for each season. An average date for all years was also calculated to give the midseason average date. This date was important for determining whether a season was in surplus or deficit of GDD at the midseason point.

Potential occurrences of frost were also calculated from these data. An occurrence of frost was considered

Table 1. Data sources, variables, and period of records for the different variables included in this study

Data	Source	Variable	Period of record
GDD	National Climatic Data Center	GDD (single-sine) with base 10°C	1950–2011
Frost occurrence	National Climatic Data Center	Number of < –1°C events between budburst and frost-free date	1971–2011
Vine budburst	National Grape Cooperative	Date of budburst	1971–2011
First frost (< –1°C)	National Grape Cooperative	Date of first fall frost	1961–2011
Vine yield	National Grape Cooperative	Tons/hectare	1971–2011
Fruit quality at harvest	National Grape Cooperative	Soluble solids (°Brix)	1975–2011

Note: GDD = growing degree days.

to be a day with a daily minimum temperature reading of –1°C or lower, where vine buds could be damaged or killed during their early stages of development (Zabadal and Andresen 1997). Potential frost days were counted from 1 April to 20 May. These occurrences were summed up for each station averaged for each year. As with the GDD calculation for this study, the potential frost occurrence calculation for the three stations was a more reliable representation of the average conditions in the region. The climatic data were correlated with data from the National Grape Cooperative (J. Jasper and T. Holloway, personal communication). Such data include the date of budburst, harvest soluble solids concentration (°Brix), and yield (tons/ha; Table 1).

A statistical model for the date of budburst of *Vitis labrusca* grapes was also developed. Prediction of budburst had been performed before (Wermelinger, Baumgärtner, and Gutierrez 1991; Bindi et al. 1997; Nendel 2010) but using different methods and different objectives. These papers use either deterministic models (Wermelinger, Baumgärtner, and Gutierrez 1991; Bindi et al. 1997) or were used in a number of regions (Nendel 2010). The goal of creating this "historical" model in this article is to establish a potential method for the calculation of budburst using readily available temperature data either in a predictive setting or in a historical setting wherein the model is used to calculate the date of budburst in years past where there is no direct observation. The need for such a model arose from the lack of success of a "rule of thumb" approximation proposed by Amerine (1980) and Mullins, Bouquet, and Williams (1992) where budbreak was assigned to a date after five days of GDD accumulation. This statistical model is a multilinear regression model developed using historical heat accumulation in the month of March. GDD calculations were made daily from 1 March to 31 March. This allowed for the creation of the five variables used in the equation: GDD total on 31 March (X_1), slope of GDD accumulation from 1 March to 31 March (Y_1), GDD total on 15 March (X_2), slope of GDD accumulation from 1 March to 15 March (Y_2), and total days of accumulation (Z), which was calculated as days from 1 March. The variables X_1 and Y_1 represent the total accumulation and rate at which the accumulation took place over the entire month of March. Variables X_2 and Y_2 are performed similarly but only for the dates of 1 March to 15 March. This is done because not all years have accumulations starting after 15 March, and the slopes could be misrepresented as being exceptionally high. Variable Z, total days of accumulation, is the total number of days of accumulation, which is important as it signifies the amount of time GDDs have been accumulating and because the date at which GDD accumulation begins varies from year to year in March in this region. The period of 1 March to 31 March was used, as it is both in a time of yearly GDD accumulation and still sufficiently prior to the date of potential budburst.

Results

Connections between Climate-Based Variables and Crop Statistics

Climate-based variables and crop statistics from the National Grape Cooperative (J. Jasper and T. Holloway, personal communication) were correlated to see which weather variables appear to have the largest effect on yield and fruit quality. The total number of frost events that occur after budburst has a negative impact on yield for a given season (Figure 2). The date of the first frost in the late season (September or October) has a positive correlation with vine yield. Season length, bounded by budburst in the early season and the first frost in the fall, is also positively correlated with vine yield. As for the soluble solids concentration

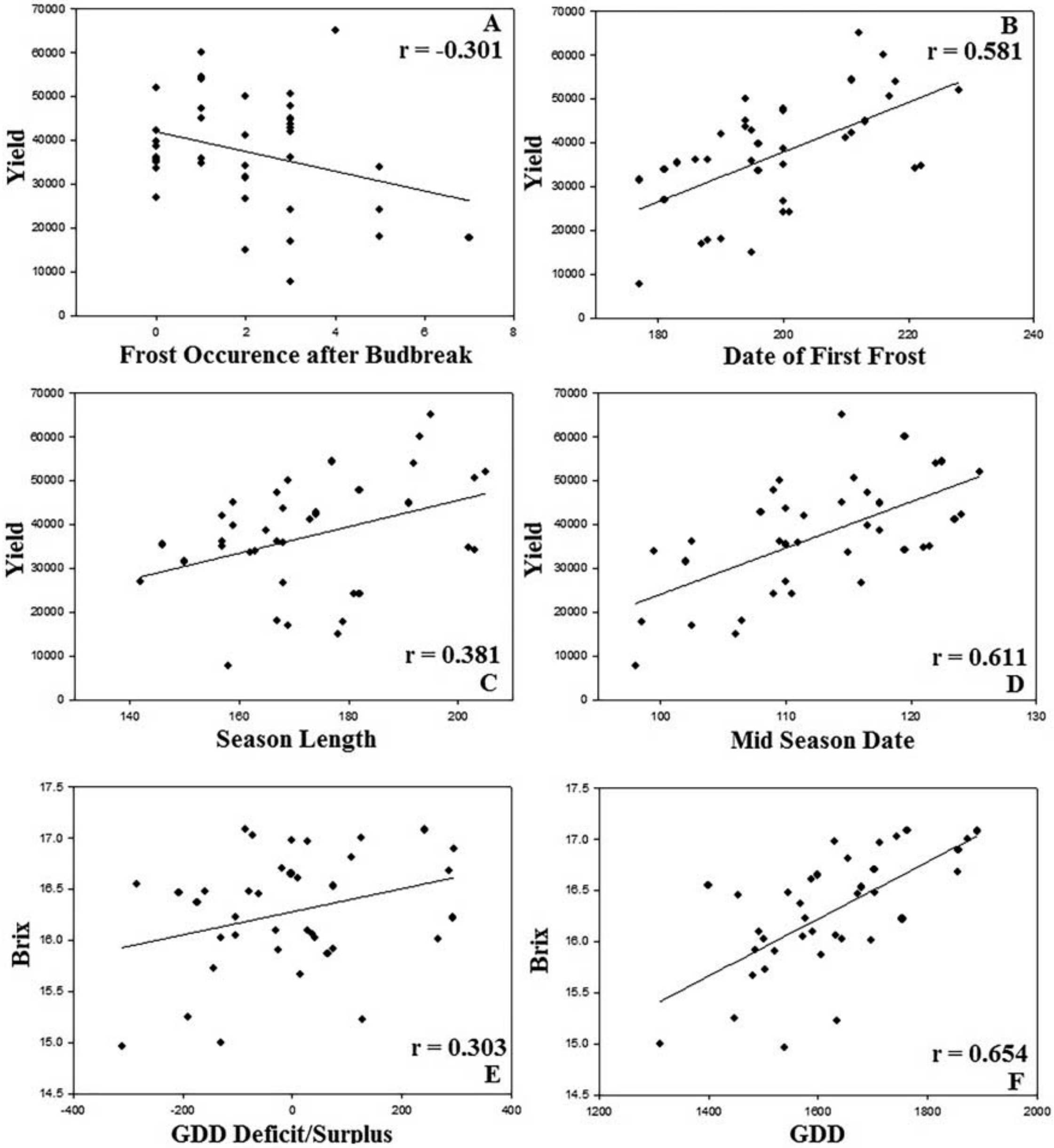

Figure 2. Pearson's r correlations at $p < 0.05$ significance levels for averaged climate-based variables versus crop statistics averaged over twenty-five plots collected by the National Grape Cooperative. Yield is calculated as total tons harvested, °Brix is calculated as grams of sucrose per 100 grams of grapes, and GDD deficit or surplus is defined as the amount of GDD on the average midseason date of the given year versus the average GDD accumulation on that day. GDD = growing degree days.

on a seasonal basis, there is a positive correlation between GDD accumulation and the relative quantity of GDD deficit or surplus that the specific season experienced. Significant correlations between yield, °Brix, and other variables are also reported (Figure 2).

Overall, the average GDD accumulation for the date of budburst (average = 27 April) from 1971 to 2011 was 158 (base 10°C). This average encountered a considerable amount of variability, however. The standard deviation of the long-term average was 71, with a coefficient of variation of 45 percent. This is reflected in the fact that some years had budburst occur with as little accumulation as 35 GDD in 1983 and as much as 304 in 1985.

Trends in Budburst and Frost

The nine-year moving average of the amount of frosts that occur after budburst in *Vitis labrusca* grapes and the seasonal total GDD along with the date of budburst are

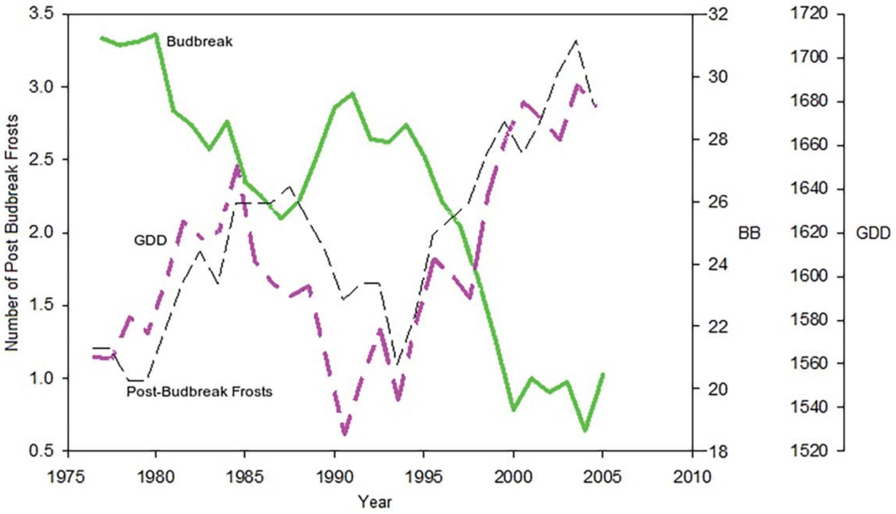

Figure 3. Nine-year moving averages of days of post-budburst frost (solid line), seasonal GDDs (dashed-dotted line), and date of budburst (dashed line). GDD = growing degree days. (Color figure available online.)

reported in Figure 3. There are strong, long-term trends in frost occurrence and the date of budburst in southwest Michigan. This increase is nearly parallel with the increase in total seasonal GDD ($r^2 = 0.7$). Earlier budburst has had a strong correlation on the end season total of GDD ($r^2 = 0.7$). If a season has an earlier budburst, GDDs are likely to be accumulating at an earlier date and thus are likely to achieve a higher total than years with a later budburst date. The connection between earlier budburst and the amount of post-budburst frost is different. An earlier budburst exposes a vine to more days where frost can potentially occur. Frost occurrence and budburst are independent variables, though, so an early budburst does not imply that frost occurrence will be a certainty. It should be noted that the calculations are from nine-year moving averages (Figure 3). This was done to gain the overall status of the changes in the seasonal data and also to remove "noise" from the data set, such as the 1992 year where GDD levels fell to their lowest level and budburst occurred on its latest dates in 1992 and 1993. When added to the data set, though, these years are visible even with the nine-year moving average.

Replacing these years (1992 and 1993) with "average values" changes the trends considerably. For example, total GDD accumulation increases in the first decade but decreases for the first few years of the 1990s decade. The inverse is true for the date of budburst, where it gets earlier, then delayed, then begins the trend of occurring earlier that it is currently on. This "reversal" of the trends is due partly to 1992 and 1993 having such low GDD values and late budburst dates. This is likely a remnant of the Mt. Pinatubo volcanic eruption, an event that caused cooler temperatures across the planet for a short time after the explosion (Robock and Mao 1995), which affected plant phenology on a global scale in the ensuing years (Cleland et al. 2007).

GDD Deficits, Surpluses, and Grapevine Performance

GDD accumulation occurs at a different rate each season. Figure 4 shows the distribution of GDD accumulations for each season including the average rate and the distribution of GDD surpluses and deficits as the season progresses. In an effort to establish whether the persistence of a season being in a deficit or a surplus had any effect on end-season quantity or quality, daily GDD accumulation was calculated for each day from 1971 to 2011 and averaged to give an average season. In the forty-one years of this study, most seasons (thirty-three of forty-one) that began in a surplus or deficit from 1 April to the date of long-term average of last spring frost (20 May) stayed in a surplus or deficit until the end of the season, meaning that if a year started with an early season in deficit or surplus, the season was likely to remain in deficit or surplus for the rest of the season 80.5 percent of the time. This suggests that early season GDD accumulation can statistically be used as a good indicator of the total season GDD.

GDD accumulation is a function of maximum and minimum temperatures; thus, the peak of daily accumulation should occur in mid-July, when surface temperatures are climatologically at their highest. Using GDD calculation, combined with data on the length of season

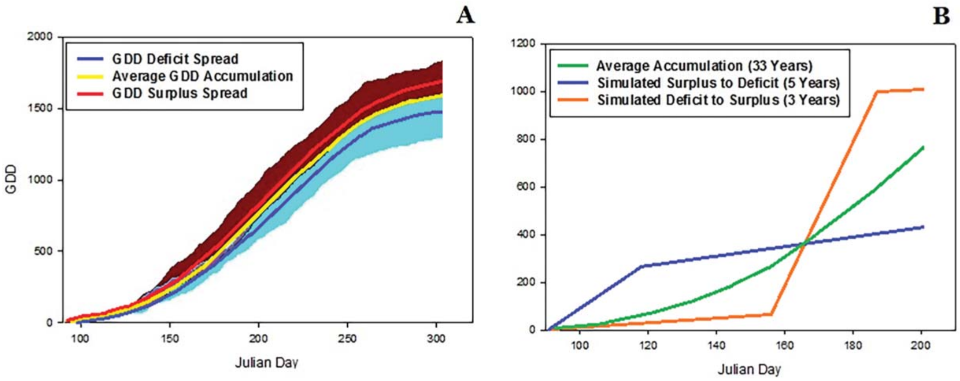

Figure 4. (A) Average GDD accumulation (1971–2011; in yellow) and spread of GDD deficits (blue) and surpluses (red). (B) Occurrences of accumulations in early season with the average accumulation (1971–2011) and hypothetical years where a season goes from deficit to surplus or surplus to deficit. GDD = growing degree days. (Color figure available online.)

(bounded by budburst and the first fall frost), the GDD at the average midseason point (20 July) was calculated and correlated to that season's yield and soluble solids (°Brix). There was a positive relationship between yield and midseason deficit or surplus level (Figure 2), but the relationship between °Brix and midseason GDD was not statistically significant. By knowing the total number of units that a season was behind average accumulation at its midseason point, we calculated the number of days of season delay in comparison to an average season's accumulation. In "deficit" years, there is a positive correlation between the number of days a season is behind schedule and °Brix ($r = 0.48$) but a negative correlation with yield ($r = -0.24$). The "surplus" years have a poor correlation with °Brix and yield.

A Simple Budburst Model

The recommendation from Amerine (1980) and Mullins, Bouquet, and Williams (1992) and used by Jones and Davis (2000) that budburst is linked to five consecutive days of GDD accumulation is adequate for a wide range of locations worldwide but, in hindsight, this "five days of accumulation" approximation was proven correct in two out of forty-one years in predicting the date of budburst in our study area. In some of the years, using this assumption would place budburst nearly a month earlier than its actual value and on average it set Michigan's approximated budburst more than sixteen days early. Figure 5 displays the comparison between observed budburst and the approximated date using the "five-day" methodology.

It should be noted that this could be due to Michigan's complex climatology in the winter and spring months. To supplant the five-day methodology, a simple model based on GDD accumulation was created as a means to predict the date of budburst using simple and readily available meteorological variables. The simple historical budburst model is composed of five variables, all pertaining to GDD accumulation. When combined into a multilinear regression, this equation was calculated:

$$\begin{aligned}\text{Date of Budburst} = {} & 71.486 + (0.129 * X_1) \\ & + (1.068 * Y_1) + (0.675 * X_2) \\ & - (11.173 * Y_2) - (0.722 * Z),\end{aligned} \tag{1}$$

where X_1 = GDD total on 31 March, Y_1 = slope of GDD accumulation from 1 March to 31 March, X_2 = GDD total on 15 March, Y_2 = slope of GDD accumulation from 1 March to 15 March, and Z = total days of accumulation calculated as days from 1 March.

The budburst model achieved a Pearson's r value of 0.6 when comparing the approximate date of budburst

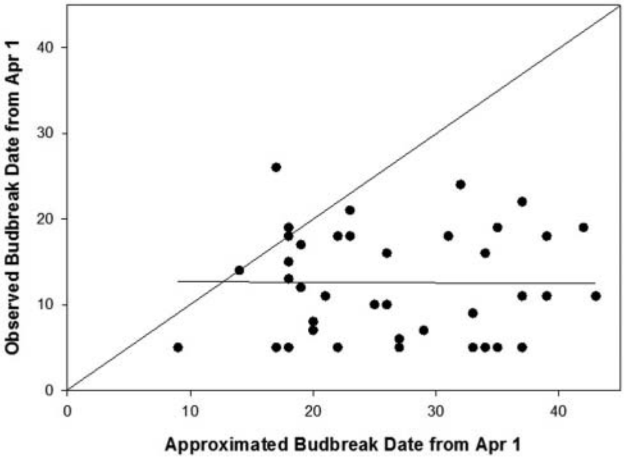

Figure 5. Comparison of the five-day approximation with observed data (trendline included) from southwest Michigan from 1971 to 2011.

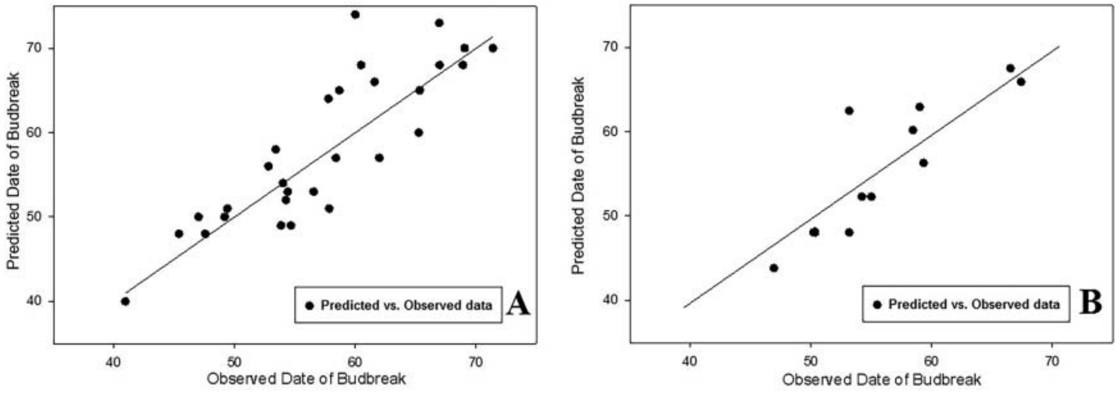

Figure 6. Predicted date of budburst versus actual date of budburst in (A) historical model ($R = 0.60$, $p < 0.05$) from 1971 to 1999 and (B) validation phase from 2000 to 2011.

versus the actual day of budburst from 1971 to 1999 (Figure 6). The mean average error (MAE), calculated as the number of days difference between the observed and predicted date of budburst, was 3.5. The model did underpredict the date of budburst, and in two of the twenty-nine years it was off by more than ten days. The general average, however, is sufficiently accurate and the model was typically off between two and five days. To validate the model, the equation calculated from 1971 to 1999 was then used to estimate the date of budburst for the years between 2000 and 2011. In those years, the model was off by an error of approximately seven days. This was deemed acceptable because the years since 2000 in this region have seen the date of budburst become more variable on a year-to-year basis compared to the previous decades. The model was validated by using the cross-one-out validation method. One season was randomly removed from the model and predicted using the regression and in ten reconfigured runs, the MAE was less than four days, indicating a similar accuracy to the nonadjusted model.

Discussion

Trends in Frost, GDD, and Budburst

Since 1971, budburst is occurring much earlier in the last few years (Figure 3) in *Vitis labrusca* grapevines. This follows the long-term trend of a warming occurring in spring in the northern hemisphere (Schwartz, Ahas, and Aasa 2006). An earlier budburst implies that vines in this region are beginning their phenological development earlier than before. Also following the long-term trend of warming is the increase in GDD, and GDD and budburst appear to be strongly related (Figure 3). The earlier budburst increased the number of post-budburst frost events in southwest Michigan (Schultze, Sabbatini, and Andresen 2013). Consequently, early budburst has the potential to expose buds to more days where frost could potentially occur. The average GDD accumulation at budburst from 1971 to 2011 was 158.43. The average date of budburst is 27 April, with an average GDD accumulation of 156, which shows good agreement with the long-term average. Some years experienced budburst as early as 9 April (2010) with an accumulation of 50.3 GDD or as late as 13 May (1993) with an accumulation of 262 GDD. GDD accumulation thus cannot be the only controlling factor in the timing of budburst. The simple budburst model of counting five days of GDD accumulation (days where the mean temperature is above 10°C as the assumed day of budburst; Amerine 1980; Mullins, Bouquet, and Williams 1992; Jones and Davis 2000), although useful for approximations in areas with less intensive data records, is not sufficient for a climate such as the *Dfa* Köppen Humid Continental Climate found in southwest Michigan (Köppen 1900; Geiger 1965). The temporal trend indicates that the risk of frost will continue to be a major issue even as global temperatures continue to rise. Global temperatures had already risen 1.3°C in a number of large-scale wine-producing areas worldwide (Jones et al. 2005), and Michigan is on the same trend. Because Michigan's frost persistence is not decreasing along with earlier budburst, however, the frost risk will still exist and could become a crucial cultural issue. Entire crops can be destroyed by a single frost event, and this research suggests a high probability that the event will occur.

Crop Statistics and Climate Data Relationships

Several climatic data parameters affect harvest (Figure 3). Correlations were performed over thirty different combinations of data, but only six were found to be statistically significant. This demonstrates that other environmental and physiological variables not considered in this study might be necessary to better understand vine performance in different climates. In this study, GDD and soluble solids (°Brix) appear to have a good correlation, likely due to higher temperatures affecting photosynthetic carbon production and allocation to the fruit (Figure 2). Each season's midseason date has a strong positive correlation with yield likely because the date of the midseason suggests whether a vine experienced a good or bad spring. It must be considered, however, that anthropogenic activities also influence yield (e.g., pruning, training, and time of harvest).

Deficits, Surpluses, and Accumulations

GDD accumulation is a function of temperature, and whether a season is in a deficit or surplus of heat accumulation is based accordingly. This study found that whether a season is in a deficit or surplus does influence soluble solids and vine yield at harvest. The calculation of a season's deficit or surplus can be useful to grape growers to modify viticultural practices during the growing season and specific cultural practices could be applied in a vineyard when it is too far in a deficit.

The Hövmoller diagram (Figure 7) displays how each season accumulated GDDs from budburst to the first fall frost date, which effectively ends the Michigan growing season. The amount of variability in GDD accumulation at the beginning of the season is far higher than the variability at the end of the season. Almost all seasons eventually end with at least 1,300 to 1,400 GDD (deep orange-red), and the few examples where this is not the case are clearly seen. The early season, though, is where the most variability occurs. The shift from blue to yellow begins at different times throughout every season and occurs at an irregular rate. In some years, the shift begins as early as mid-May to early June, but in others, the shift does not occur until nearly the midseason point. The black cells, representing post-budburst frost, are more present in years where budburst occurs earlier. The result is the potential cost of having an earlier budburst as the climate continues to warm up in Michigan.

Simple Budburst Model

Budburst and other phenological events are difficult to predict in grapevines. The relative accuracy of the model ($r = 0.6$) shows that the prediction of budburst using the historical data is a reliable method. If used as a predictive model, the date of prediction could be made as early as 1 April, which is nearly four weeks earlier than the long-term mean date of budburst. A four-week lead time with an MAE of 3.5 days shows that this method could be beneficial to growers. The model was only off by more than ten days in years where conditions were highly abnormal. This methodology will need to be tested in a new region to see if the variables used are adequate. If used as a historical model, 1 April can still be used as the date from which budburst can be based. Starting the date on 1 February was also attempted and had virtually no effect on the model, as there is very little to no accumulation on average in the month of February. We feel that although this model still has room to be improved, it is certainly an improvement over the five-day approximation. We do believe, however, that this statistical model might be a

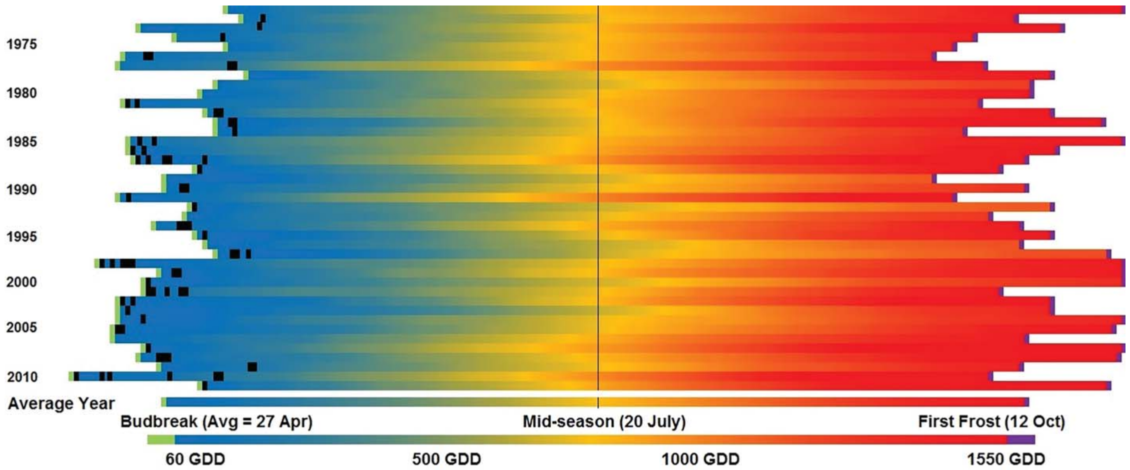

Figure 7. Growing degree days (GDD) accumulation for southwest Michigan from 1971 to 2011 along with average date of budburst (green), midseason and first frost (purple), and frost events after budburst (black). (Color figure available online.)

start to predicting accurately, and reliably, the date of budburst in Michigan's highly variable climate. The implications of being able to predict budburst are pivotal when using passive and active frost protection methods. Budburst prediction is also important in any pest and disease control model. Another implication is that a proper deterministic model for grapes can be performed in cool climates where variables like yield and quality can be predicted under different scenarios. The creation of such a model could allow for future climate change scenarios to be considered allowing for long-term predictions for areas that are currently undergoing expansion of the grape industry. The creation of this statistical model, and the validated accuracy, is encouraging. This model has proven to accurately predict the date of budburst based solely on climate variables. This could lead to a long-range forecast model that could be used in real time adding in constantly updated forecast data. Having such a system would allow users to predict the date of budburst weeks or months prior to the actual date of budburst, allowing for growers to make informed decisions on how to manage their vines in the early season. Using the same forecast data to predict the date of budburst, users could also predict the severity of frost after budburst, perhaps creating an index of frost risk based on the number of potential frosts after the predicted date of budburst.

Michigan and the Future

This research attempted to describe the importance of the early season in cool climate viticulture. The data set here was limited to *labrusca* grapevines, but the implication for *vinifera* are clear. *Vitis vinifera* grapes are less cold-hardy than *Vitis labrusca* grapes and thus are more susceptible to early season frosts. Considering Michigan is transitioning to *vinifera* production from *labrusca*, it is logical that the implications of Michigan's evolving climate on the state's viticulture industry are large. Risks for *labrusca* vines are not exactly the same as the risks for *vinifera*, but they are similar in many ways, including the response to their buds in the presence of frost. Thus, these results go beyond *labrusca* production and continue into the production of *vinifera*.

The early season climate is important to viticulture, but GDDs, their rate of accumulation, and the occurrence of frost appear to be of particular interest in Michigan's cool climate. The goal of this article, though, was not solely to demonstrate such importance; it was also intended to bring attention to the climate of a location that several decades ago was deemed unsuitable for wine grape production. Michigan's *vinifera* production only began in the 1970s and has increased in size since that time due to warmer growing seasons. This is due to Michigan being located within a zone of transition, as the climate is now moving toward being more accommodating for *vinifera* cultivation. Schultze, Sabbatini, and Andresen (2013) demonstrated that since 1980, average GDD values in southwest Michigan have increased by 3.7 base 10°C. It is our belief that as global climate warming continues, there will be areas previously unsuitable for wine grapes that will be able to begin production. This idea comes from Jones (2007), who mapped the shift of the global 12–22°C isotherm from the year 1999 to 2049. In this study, it was clear that a number of areas in both hemispheres will fall between that isotherm, which is regarded as the optimal maximum and minimum average growing season temperature levels for wine grapes (Gladstones 2005; Jones 2007). Jones (2007, 3–13) described how the planetary warming trend has been more visible and "largely beneficial" in the poleward fringes, bringing in "more consistent ripening climates" to "once forgotten regions again." We agree with that assertion, as it is both logical and inferential that as the 12–22°C isotherm shifts poleward, new areas will mirror Michigan's transition into becoming viable for wine grape production. Consequently, we believe that Michigan can be considered a Petri dish of the world's changing climate for wine grape production on the poleward fringes. As these new regions begin to plant vines and experience successes and failures, growers could evaluate the trials and errors in Michigan between 1980 and 2010. Areas such as northern Germany, southern Russia, southern Canada, England, southern Argentina and Chile, and other zones of transition will be able to use the original research done in Michigan to see how to navigate a variable climate, where frost occurrence and the date of budburst are intricately linked to the success of the production of an annual crop. Each new region will likely have unique challenges, but almost all will need to consider the early season as the most critical.

In contrast, Jones (2007) did mention that the warming trend has been beneficial due to longer and warmer seasons "with less risk of frost." We disagree with that assertion based on evidence from Schultze, Sabbatini, and Andresen (2013) and from data presented in this article. Frost is not decreasing in occurrence commensurate with the rate of warming in this region (Figure 3). Budburst is occurring earlier on average in Michigan, but frost still occurs at approximately the same rate up until the frost-free date. This increases the risk to growers, as an earlier budburst means there is a greater chance of frost post-budburst, which could severely affect an annual crop in both quantity and quality. Currently, we are limited to our own data set, but it is logical to infer that this will also occur in the regions that will soon fall within the 12–22°C isotherm. Frost occurrence is not as likely to dissipate in the short-term future in Michigan as in warmer regions such as Napa Valley or Australia, which are likely the regions Jones (2007) referred to in his research. Thus, earlier budburst in these cool climates makes frost risk an even bigger concern for wine grape production as global temperatures continue to warm.

There has been research using climate models in cool-climate viticulture (Molitor et al. 2014) suggesting that frost occurrence will dissipate in the future, but this decrease in spring frosts will not likely be as pronounced as the decrease in fall frosts. Molitor et al. (2014) also found that spring frosts are not likely to completely disappear. We agree with those findings, focused in Luxembourg, as they show that spring frosts will still pose a challenge for growers in the coming decades in cool-climate viticulture. The histories of Luxembourg and Michigan's wine grape industries are quite different, however, as Luxembourg has produced wine for centuries, whereas Michigan has been able to do so for only a few short decades due to climatic restrictions. It can be inferred from Molitor et al. (2014) that post-budburst frost might become less of a problem, but our research stated that post-budburst spring frosts will still be a primary concern in cool-climate viticulture as it only takes one frost event after budburst to alter a growing season's potential success.

In summation, we strongly agree with Jones (2007) about the shifting of the poleward fringes of wine grape production and we believe that Michigan's current research will be a cornerstone of those future areas' production. We believe that in cool climates, though, frost risk will persist over the next decades as earlier budburst dates will expose vines in the early season to potentially ruinous frosts.

Conclusions

The importance of early season GDD accumulation and frost and their connections with end-season variables in a cool climate was displayed in this research. Michigan's grape industry faces particular risk in this critical part of the growing season. Interannual variations in the climate variables examined in this study have been shown to affect yield and quality. GDD surpluses and, particularly, deficits show a clear connection with end season variables. In the creation of a budburst date prediction model, growers might be able to better prepare for the potential risk of a post-budburst frost. Having such a model might lead to increases in yield and quality on a seasonal basis.

Like most climate and agriculture studies, data availability is still an issue for this study. More spatial coverage, and thus more information, on the grape phenology would make this study stronger. As mentioned before, the assumptions taken on the phenological data are based on the average of twenty-five vineyards. Data from the individual plots would potentially allow for more analysis to be done, particularly in a spatial context. We also acknowledge that GDD is one of several methods that can be used as a metric for comparing interannual variability. Other methods include using the Huglin Index (Huglin 1978) or biologically effective degree days (Gladstones 1992), which are excellent methods for comparison and yield very similar results to GDD.

Post-budburst frost events still pose a major risk for growers in cool climates, but data on frost occurrence are not readily available; in the absence of such data, frost must be calculated remotely or indirectly. Cool climates will uniformly need to continue to battle frost, and prediction of the date of budburst can be pivotal. As global climates continue to rise in temperature and more areas become viable for grape production, though, frost will invariably be a factor. This means that the importance of the early season, climatically, and thus phenologically, cannot be overstated.

References

Amerine, M. A. 1980. *The technology of wine making*. Westport, CT: AVI.

Andresen, J. A., and J. A. Winkler. 2009. Weather and climate. In *Michigan geography and geology*, ed. R. J. Schaetzl, J. Darden, and D. Brandt, 288–314. Boston: Pearson Custom.

Baskerville, G. L., and P. Emin. 1969. Rapid estimation of heat accumulation from maximum and minimum temperatures. *Ecology* 50:514–17.

Bindi, M., F. Miglietta, B. Gozzini, S. Orlandini, and L. Seghi. 1997. A simple model for simulation of growth and development in grapevine (*Vitis vinifera* L.): II. Model validation. *VITIS* 36:73–76.

Bureau of Alcohol, Tobacco, Firearms, and Explosives. 1987. Code of Federal Regulations: §9.79 Lake Michigan Shore. Title 27: Alcohol, Tobacco and Firearms; Part 9: American Viticultural Areas; Subpart C: Approved American Viticultural Areas. Washington, DC: Bureau of Alcohol, Tobacco, Firearms, and Explosives.

Cleland, E. E., I. Chuine, A. Menzel, H. A. Mooney, and M. D. Schwartz. 2007. Shifting plant phenology in response to global change. *Trends in Ecology and Evolution* 22 (7): 357–65.

Eichhorn, K. W., and D. H. Lorenz. 1977. *Phänologische Entwicklungsstadien der Rebe* [Phenological development stages of the vine]. *Nachrichtenblatt des Deutschen Pflanzenschutzdienstes*.

Filo, A., P. Sabbatini, G. W. Sundin, T. J. Zabadal, G. R. Safir, and S. R. Cousins. 2013. Grapevine crown gall suppression using biological control and genetic engineering: A review of recent research. *American Journal of Enology and Viticulture* 64 (1): 1–11.

Geiger, R. 1965. *The climate near the ground*. Cambridge, MA: Harvard University Press.

Gladstones, J. 1992. *Viticulture and environment*. Adelaide, Australia: Winetitles.

———. 2000. Past and future climatic indices for viticulture. *Australia and New Zealand Wine Industry Journal* 15:67–73.

———. 2005. Climate and Australian viticulture. In *Viticulture 1—Resources*, ed. P. R. Dry, and B. G. Coombe, 90–118. Adelaide, Australia: Winetitles.

Hathaway, L., and S. Kegerreis. 2010. *The history of Michigan wines: 150 years of winemaking along the Great Lakes*. Charleston, SC: History Press.

Huglin, P. 1978. Nouveau mode d'évaluation des possibilités héliothermiques d'un milieu viticole [New method of assessment of possibilities in solar thermals (in the) middle of a vineyard]. *Comptes-rendus des Seances de l'Academie d'Agriculture de France* 64:1117–26.

Jones, G. V. 2007. Climate change and wine: Observations, impacts and future implications. *Wine Industry Journal* 21 (4): 21–26.

Jones, G. V., and R. E. Davis. 2000. Climate influences on grapevine phenology, grape composition, and wine production and quality for Bordeaux, France. *American Journal of Enology and Viticulture* 51 (3): 249–61.

Jones, G. V., A. A. Duff, A. Hall, and J. W. Myers. 2010. Spatial analysis of climate in winegrape growing regions in the western United States. *American Journal of Enology and Viticulture* 61:313–26.

Jones, G. V., M. A. White, O. R. Cooper, and K. Storchmann. 2005. Climate change and global wine quality. *Climatic Change* 73 (3): 319–43.

Köppen, W. 1900. Versuch einer Klassifikation der Klimate, vorzugsweise nach ihren Beziehungen zur Pflanzenwelt [Attempted classification of climates, preferably to its relation to the plant world]. *Geographische Zeitschrift* 6:593–611, 657–79.

McCarthy, M. G. 1999. Weight loss from ripening berries of Shiraz grapevines (*Vitis vinifera* L. cv. Shiraz). *Australian Journal of Grape and Wine Research* 5 (1): 10–16.

McMaster, G. S., and W. W. Wilhelm. 1997. Growing degree-days: One equation, two interpretations. *Agricultural and Forest Meteorology* 87:291–300.

Molitor, D., A. Caffarra, P. Sinigoj, I. Pertot, L. Hoffmann, and J. Junk. 2014. Late frost damage risk for viticulture under future climate conditions: A case study for the Luxembourgish winegrowing region. *Australian Journal of Grape and Wine Research* 20 (1): 160–68.

Moroz, W. J. 1967. A lake breeze on the eastern shore of Lake Michigan: Observations and model. *Journal of Atmospheric Science* 24:337.

Mullins, M. G., A. Bouquet, and L. E. Williams. 1992. *Biology of the grapevine*. Cambridge, UK: Cambridge University Press.

Nendel, C. 2010. Grapevine bud break prediction for cool winter climates. *International Journal of Biometeorology* 54 (3): 231–41.

Pfister, C. 1988. *Variations in the spring–summer climate of central Europe from the High Middle Ages to 1850*. Berlin: Springer.

Robock, A., and J. Mao. 1995. The volcanic signal in surface temperature observations. *Journal of Climate* 8 (5): 1086–1103.

Santos, J. A., A. C. Malheiro, M. K. Karremann, and J. G. Pinto. 2011. Statistical modelling of grapevine yield in the Port Wine region under present and future climate conditions. *International Journal of Biometeorology* 55 (2): 119–31.

Schultze, S. R., P. Sabbatini, and J. A. Andresen. 2013. Spatial and temporal study of climatic variability on grape production in southwest Michigan. *American Journal of Enology and Viticulture* 65 (2): 179–88.

Schwartz, M. D., R. Ahas, and A. Aasa. 2006. Onset of spring starting earlier across the northern hemisphere. *Global Change Biology* 12 (2): 343–51.

Swan, J. B., J. A. Staricka, M. J. Shaffer, W. H. Paulson, and A. E. Peterson. 1990. Corn yield response to water stress, heat units, and management: Model development and calibration. *Soil Science Society of America Journal* 54 (1): 209–16.

U.S. Department of Agriculture–National Agricultural Statistics Service. 2012. Fruit inventory results for grapes. News release NR 12–53, Michigan Field Office, MI: East Lansing, MI.

van Leeuwen, C., P. Friant, X. Choné, O. Tregoat, S. Koundouras, and D. Dubourdieu. 2004. Influence of climate, soil, and cultivar on terroir. *American Journal of Enology and Viticulture* 55 (3): 207–17.

Walther, G. R., E. Post, P. Convey, A. Menzel, C. Parmesan, T. J. Beebee, J. M. Fromentin, O. Hoegh-Guldberg, and F. Bairlein. 2002. Ecological responses to recent climate change. *Nature* 416 (6879): 389–95.

Webb, L. B., P. H. Whetton, and E. W. R. Barlow. 2007. Modelled impact of future climate change on the phenology of winegrapes in Australia. *Australian Journal of Grape and Wine Research* 13 (3): 165–75.

Wermelinger, B., J. Baumgärtner, and A. P. Gutierrez. 1991. A demographic model of assimilation and allocation of carbon and nitrogen in grapevines. *Ecological Modeling* 53:1–26.

Winkler, J. A, J. A. Andresen, J. M. Bisanz, G. Guentchev, J. Nugent, K. Piromsopa, N. Rothwell, et al. 2013. Michigan's tart cherry industry: Vulnerability to climate variability and change. In *Climate change in the Midwest: Impacts, risks, vulnerability, and adaptation*, ed. S. C. Pryor, 129–46. Bloomington: Indiana University Press.

Winkler, J. A., J. Andresen, J. Black, G. Bujdoso, F. Chmielewski, D. Kirschke, . . . and S. Zhong. 2012. Climate change impact assessments for international market systems (CLIMARK). In *AGU fall meeting abstracts*. Vols. 1, 2. American Geophysical Union, San Francisco, CA, December 3–7.

Wolfe, D., L. H. Ziska, C. Petzoldt, A. Seaman, L. Chase, and K. Hayhoe. 2008. Projected change in climate thresholds in the northeastern U.S.: Implications for crops, pests, livestock, and farmers. *Mitigation and Adaptation Strategies for Global Change* 13 (5): 555–75.

Zabadal, T. J., and J. A. Andresen. 1997. *Vineyard establishment I: Site selection, vineyard design, obtaining grapevines, and site preparation*. Extension bulletin E-2644. Michigan State University, East Lansing, MI.

Zabadal, T. J., I. E. Dami, M. C. Goffinet, T. E. Martinson, and M. L. Chien. 2007. *Winter injury to grapevines and methods of protection*. Extension Bulletin E2930. East Lansing: Michigan State University.

STEVEN R. SCHULTZE is an Assistant Professor in the Department of Earth Sciences, University of South Alabama, Mobile, AL 36688. E-mail: schultze@southalabama.edu. His research interests include the effects of climate change on regional agriculture, GIS applications in agriculture, and sports statistics.

PAOLO SABBATINI is an Associate Professor in the Department of Horticulture, Michigan State University, East Lansing, MI 48824. E-mail: sabbatin@msu.edu. His research interests include identifying environmental, physiological, and cultural factors that limit vine growth and development, fruit maturity and quality, and a focus on Michigan's cool climate.

LIFENG LUO is an Associate Professor in the Department of Geography, Michigan State University, East Lansing, MI 48824. E-mail: lluo@msu.edu. His research interests include land–atmosphere interaction, predictability and prediction of hydroclimatic extremes, and the impacts of global climate changes.