# Spatial and Temporal Study of Climatic Variability on Grape Production in Southwestern Michigan

Steven R. Schultze,[1] Paolo Sabbatini,[2]* and Jeffrey A. Andresen[1]

**Abstract:** Daily climatic data were obtained from several sources to calculate growing degree days (GDD) for multiple sites in southwest Michigan, which contains the Lake Michigan Shore American Viticultural Area. The data were examined for spatial and temporal (1950 to 2011) patterns and trends over the region in order to better quantify the role of Michigan climate on juice grape production. The occurrence and severity of frost and freezing temperatures were also considered in this study, as subfreezing temperatures in late spring and early fall can have severe impacts on the region's juice grape production and fruit quality at harvest. Michigan's cool-cold climate has warmed in recent decades, particularly since 1980, with an average increase over the region of more than 3.7 GDD (base 10°C) per year. Southwestern Michigan was also found to have higher seasonal temperature variability when compared with Napa Valley (California). Since 1980, the season-to-season variability in Michigan has increased at a more rapid pace. The impacts of the increasing GDD have been positive for fruit quality, with a strong positive correlation between seasonal GDD and fruit maturation, indexed as total soluble solids (Brix). The growing season has also increased by 28 days in length since 1971. However, despite warmer temperatures, the number of days of potential frost and their seasonal variability in southwestern Michigan have remain unchanged, which continues to pose a risk for grapegrowers in the region. While it has become warmer in Michigan, and the spring warm-up is typically arriving earlier in the year, the number of days with damaging frost still has a profound impact on overall climate-related risk for grape production.

**Key words:** American Viticultural Area, growing degree days, frost, cool-climate viticulture

The state of Michigan ranks fifth in the nation for grape production and thirteenth in the country for wine production (USDA-NASS 2012). Concord and Niagara (*Vitis labruscana* Bailey) are the most widely cultivated juice grape varieties in Michigan, accounting for 64% and 24% of the total area dedicated to grapes, respectively. Nearly half (49%) of the total Niagara grape crop in the United States is produced in Michigan. Unfortunately, the cost of juice grape production has increased in recent years and current juice grape prices are below the economic break-even point for many Michigan growers. In general, grapegrower revenues are maximized when the crop produces high yields with Brix levels above an acceptable minimum for industry standards (Bates and Morris 2009).

Under cool-climate conditions, the interaction between grapevine and environment often limits yield and challenges the grower to maintain high production with optimal fruit quality without compromising the health of the vine (Howell 2001). Although the total area planted with *Vitis vinifera* is increasing within the state, Concord (*V. labruscana*) remains the largest portion of the grape crop acreage in Michigan and in the eastern United States. Michigan's designation as a cool-cold climate viticulture region of the Great Lakes for grape and wine production has historically been characterized by harsh winters and difficult spring frosts, inducing wide variations between yield and fruit quality over the years (Sabbatini and Howell 2011).

The calculation of heat summations is one method of determining weather seasonal variation in a region. The estimation of thermal time, a heat summation, over a given period of time has been used widely for modeling plant growth and phenology (Gladstones 2000). The most common method of approximating thermal time is the calculation of growing degree days (GDD), a temperature-derived index, which approximates the time and magnitude of the temperature during a given day above some defined base temperature. The simplest method of calculating GDD, given daily maximum and minimum temperatures, is the average method where $T_{max}$ is the maximum temperature of a given day, $T_{min}$ is the minimum temperature of a given day, and $T_{base}$ is the threshold temperature below which plant growth and development ceases (McMaster and Wilhelm 1997):

$$GDD = \left(\frac{T\max + T\min}{2}\right) - Tbase \qquad \text{Eq. 1}$$

All daily GDD totals less than zero are set equal to zero. There have been many improvements and modifications to this method (Gilmore and Rogers 1958, Yang et al. 1995),

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but the basic equation capitalizes on its simple computation and reliable accuracy and the goal is to quantify the amount of thermal units a viticultural area has received over a given time, such as a growing season.

The method known as the Baskerville–Emin (1969), or single sine, calculates GDD by assuming that the daily temperature cycle can be approximated by a simple sine wave, with the observed maximum temperature of a given day set to the highest point of the sine wave and the minimum temperature set to the lowest point in the curve. The GDD for the day is then obtained by integrating the area under the sine curve and above the base temperature (Baskerville and Emin 1969). This curve is generally considered more accurate than the simple average GDD calculation or a different method where temperatures are cut off (Roltsch et al. 1999). Studies on the impact of GDD have ranged from the growth of corn through a season (Swan et al. 1987) and the phenology of sunflowers (Robinson 1971) to the indirect calculation of evapotranspiration of different crops (Sammis et al. 1985) and the prediction of available nitrogen in livestock manures (Griffin and Honeycutt 2000).

Winegrape phenology has also been analyzed through GDD studies. In 1944, five regions of grape production in California were defined, together with associated winegrape cultivars appropriate for characteristic climate conditions, including GDD, and, consequently, potential wine styles (Amerine and Winkler 1944). Regions I and II produced excellent, delicate table wines, region III featured full-bodied wines, and region IV developed dessert wines that were too sweet for large-scale, table wine production. Region V was considered too hot for anything other than table grapes or raisins. This approach was later reworked for the Australian wine industry (Olmo 1956). The studies stimulated by the original research were groundbreaking in their predictive power, resulting in the dissemination of what has become a trusted guideline for future vineyard development using only a simple, temperature-based index.

In the early 1990s, it was concluded that daily variation in heat can affect wine quality (Gladstones 1992). Moreover, GDD were used recently to perform a spatial analysis of climate in the western United States (Jones et al. 2010) and as a metric to analyze how climatic variability affected wine quality in Napa Valley, California (Jones and Goodrich 2007). Similar studies have also been carried out for southern Ontario, Canada (Shaw 2005) and Australia (Hall and Jones 2010).

The presence of macro- and mesoscale climates (Geiger 1965) makes the choice of vineyard location more complex, although critical to sustainable quality and economic success. In the Great Lakes region, extreme minimum winter temperatures are, in general, used as a key factor in describing sites for their grapegrowing potential (Howell et al. 1987). Temperatures that do not drop below -12°C characterize “excellent” sites and they are suitable for tender *vinifera* grapes. In contrast, “poor” sites have winter temperatures that can reach -23°C five or more times in 10 years and are generally deemed unsuitable for sustainable commercial viticulture. “Acceptable” sites are characterized by winter temperatures that reach –20°C not more than three to four times over a period of 10 years and in which the long-term minimum temperature does not fall below -23°C. These temperatures are acceptable for most of the commercial juice grape cultivars but detrimental to very tender wine cultivars (e.g., *V. vinifera*), which would suffer severe damage at least once in 10 years (Zabadal et al. 2009).

In terms of site choice, the slope and aspect can also influence vine performance. Cooler northern slopes may delay spring budburst, reducing the potential of spring frost. For example, in 2012 Michigan was subjected to strong spring frosts after an unprecedented warm period in late winter (mid-March), with temperatures rising as high as 30°C. According to the USDA, these frosts destroyed 85% of *V. labruscana* crop. By contrast, southern-facing slopes are warmer and promote earlier fruit ripening, which is very important in Michigan and other cool-climate growing regions. In such cool regions, grape production is limited by a relatively short frost-free growing season (140 to 160 days) and by low heat accumulation (1000 to 1200 GDD, base 10°C, calculated from 1 Apr to 31 Oct). Such environmental constraints may reduce the ability of vines to fully ripen the fruit, especially when vines are overcropped and vine canopy management (e.g., shoot positioning, hedging, cluster zone leaf removal) is not performed in a timely manner. In addition, vines cultivated in cool climates can begin growth late in the spring and be subject to early fall frosts (sometimes in September), collectively resulting in both an unfavorably short growing season and a premature end to photosynthesis, hindering fruit ripening.

The goal of this research was to begin the process of establishing trends in year-to-year climatic variability and associated effects on juice grape production in Michigan. Our most critical objective required the quantification of the effects of climatic variability on the Michigan grape industry. By using daily temperature data obtained from the National Climatic Data Center, from observing sites in southern Michigan, GDD were calculated and summed for each year from 1950 to 2011. For comparative reasons, the same process was applied for the renowned Napa Valley region. Frost was also considered in this study, as it can have profound limiting effects on both yield and fruit quality.

## Materials and Methods

**Site description.** Michigan’s primary grape-producing areas are located on the west coast of the Lower Peninsula of the state, along the eastern shore of Lake Michigan. There are four American Viticultural Areas (AVA) in Michigan: Fennville, Leelanau Peninsula, Lake Michigan Shore, and Old Mission Peninsula established in 1981, 1982, 1983, and 1987, respectively (Hathaway and Kegerreis 2010). These four AVAs take full advantage of the Great Lake’s climate-moderating effect and topographic influences, which enhance the flow of cold air drainage down the sides of hills to minimize the frequency and severity of frost (Andresen and Winkler 2009).

Southwestern Michigan was selected for the study due to the availability of long-term meteorological data and the location of the Lake Michigan Shore AVA. Data were collected from a number of sites and the size of the area allowed for the study of differences in microclimates, which are the main drivers behind Michigan's juice grape industry. The Lake Michigan Shore AVA runs for 115 kilometers along the shoreline, extending from the Indiana–Michigan border, which serves as the southern boundary, to the terminus of the Kalamazoo River (Figure 1). The AVA extends east along the Kalamazoo River and into the interior of the state to include the cities of Kalamazoo, Paw Paw, Lawton, and Dowagiac and is delineated by two major railroad lines (BATF 1987). The region covers ~5,200 $km^2$ and is home to several of Michigan's oldest vineyards and wineries and a grape-juice processing plant in Lawton.

The town of Benton Harbor is located in largely agricultural Berrien County, southwestern Michigan. This agriculturally important area has numerous weather stations, most of which are operated through the Michigan State University (MSU) Enviro-weather network. The Southwest Michigan Regional Airport, which contains a long-term climate-observation station with records dating back several decades, is also located in Benton Harbor. While the community is located in a *Dfa* Köppen Humid Continental Climate class (Köppen 1900, Geiger 1965), the ebb and flow of lake and land breezes due to the city's proximity to Lake Michigan tend to limit temperature extremes (Moroz 1967).

**Data collection.** The primary source of climate data was the National Climatic Data Center (NCDC) station mapper (ncdc.noaa.gov). Daily temperature data were obtained from stations within and around southwestern Michigan and Napa Valley. Data were also collected from the MSU Enviro-weather network (Andresen et al. 2012a), which has 17 stations located across the seven counties of southwest Michigan (Berrien, Van Buren, Cass, St. Joseph, Kalamazoo, Barry, and Allegan). The National Grape Cooperative Association (NGCA) contributed annual viticultural data (1970 to 2011) on dates of budburst, spring frost, and harvest and data on yield and fruit quality. Viticultural data was collected from 25 vineyards of NGCA members in southeastern Van Buren County, near Lawton (42.16ºN, 85.83ºW). The age of the vineyards was between 15 and 30 years old. Own-rooted Concord vines were trained to 1.8-m high bilateral cordons with a north-south row orientation. Vines were spaced 2.38 m in row and 3.05 m between row (Jasper and Holloway, personal communication, 2012).

**Experimental design.** In order to obtain an accurate description of climatic variability in southwestern Michigan, it was necessary to consider both spatial and temporal aspects, which help quantify how climate fluctuates on a year-to-year basis as well as over space. Climatic normals or averages are typically defined as a mean or median of conditions over a 30-year period (WMO 1989). However, given a monotonic trend of increasing temperatures (~1.0°C between 1980 and 2011) in the Great Lakes region since 1980 (Andresen et al. 2012b), two separate time frames reflecting conditions before and during this period were selected: 1950 to 2011 and 1980 to 2011. The 1980 to 2011 period better reflects the current climate while the 1950 to 2011 time frame also includes a period of relative cooling between 1950 and 1980 and is generally more representative of regional long-term historical climate. Data for the temporal study were obtained from six well-established NCDC observation stations within the local areas: Benton Harbor, Eau Claire, Bloomingdale, South Haven, Holland, and Three Rivers. Seasonal GDD totals were calculated at the six stations with the Baskerville-Emin method (Baskerville and Emin 1969) from 1950 to 2011, using the daily high and low temperatures from 1 Apr to 31 Oct each year, which is generally regarded as the approximate grapegrowing season in Michigan based on historical dates of budburst and first frost (Jasper and Holloway, personal communication, 2012). Averages were calculated at the six stations over the study time frame.

A similar calculation procedure was performed with daily climate data from California, which was collected for the same 1950 to 2011 time frame from NCDC stations at St. Helena and Napa State Hospital. The general status, trends, and yearly totals of GDD in southwestern Michigan and Napa Valley grapegrowing regions were compared.

Potential frost days for southwestern Michigan were also summed each season for the same time frames. Defined as a daily minimum temperature of -1°C or lower, such frost conditions can kill or seriously injure the buds during their early stages of development (Zabadal and Andresen 1997). Potential frost days were computed from 1 Apr to 20 May, which is considered the "frost line" day in the region. (This computation was not considered for Napa Valley, where frost is much less of an issue.) These are days of "potential" frost and not days of confirmed frost, since operational minimum temperatures are observed at a height of 1.5 m aboveground and there is no confirmed frost observations data at actual vineyard locations where the conditions may have been different. However, potential frost days still highlight the risk of highly damaging frosts to Michigan's grape industry. These seasonal totals are actually a combination of radiation- and advective-type frost events. The vast majority of spring and fall frost events in Michigan are of the radiative variety, under which relatively clear, calm weather conditions allow temperatures near the surface to fall to or below freezing (Andresen and Winkler 2009). Growers typically reduce the impacts of radiative frosts by planting vineyards on relatively high topographical features, improving cold air drainage patterns around their vineyards, or by operating wind machines during the events, which take advantage of surface temperature inversions and warmer air just above the surface. In contrast, the region also experiences occasional advective frost conditions in which subfreezing air temperatures are accompanied by surface winds, turbulent mixing near the surface, and more homogeneous temperatures across a given area. These events, while much less common, may have much greater negative impacts and are more difficult to protect against (Winkler et al. 2013). Data obtained from the NGCA (Jasper and Holloway, personal communication, 2012) were used to analyze the timing of budburst relative to spring frost events (1971 to present) as well as the first fall frosts (1961 to present). The use of these data would allow for study of the status and trends of the start and stop dates of each growing season.

A Pearson correlation coefficient with a one season time lag (meaning one season is compared to its previous season) was performed to calculate temporal autocorrelations. These autocorrelations, where a value of +1.0 suggests that variability is low and a value of -1.0 suggests the variability is high, were calculated for each time series with the goal of calculating the persistence of the season-to-season trend in the region. Lastly, by considering both the budburst day and the last spring frost day, we were able to calculate the length of the grapegrowing season for each year from 1971 to 2011.

For the spatial component of this study, data were gathered from 17 observation stations within the MSU Enviro-weather network for the period 2000 to 2011. The six long-term NCDC stations were also added to this data set, combining for 23 stations across the area. In a cross-validation, the root mean square error (RMSE) for the GDD accumulation was 5.8 and for the frost was 0.03. Seasonal totals from these data were analyzed using the ArcGIS platform (Esri, Redlands, CA) and spatially interpolated using the kriging method, creating maps of spatially continuous data throughout southwest Michigan. These maps allow identification of spatial trends and patterns that occur across southwest Michigan's grapegrowing region.

## Results

**Spatial trends: GDD and frost.** There are several trends and patterns evident in the maps generated in the spatial component of this study. For GDD, there was a pronounced influence of the proximity of Lake Michigan and its associated lake effect on Michigan's climate (Andresen and Winkler 2009). The temperature-moderating effects of Lake Michigan can be seen in higher GDD farther inland and away from the lakes. There was also a south-north trend with GDD summations higher in the south than in the north. For example, in central Van Buren County there was a visible ridge of higher GDD totals (1650 to 1700 GDD) protruding north from Berrien and Cass Counties (Figure 2A). The south area is likely warmer because it is located inland of the lake breeze fronts of the summer season, which bring cooler

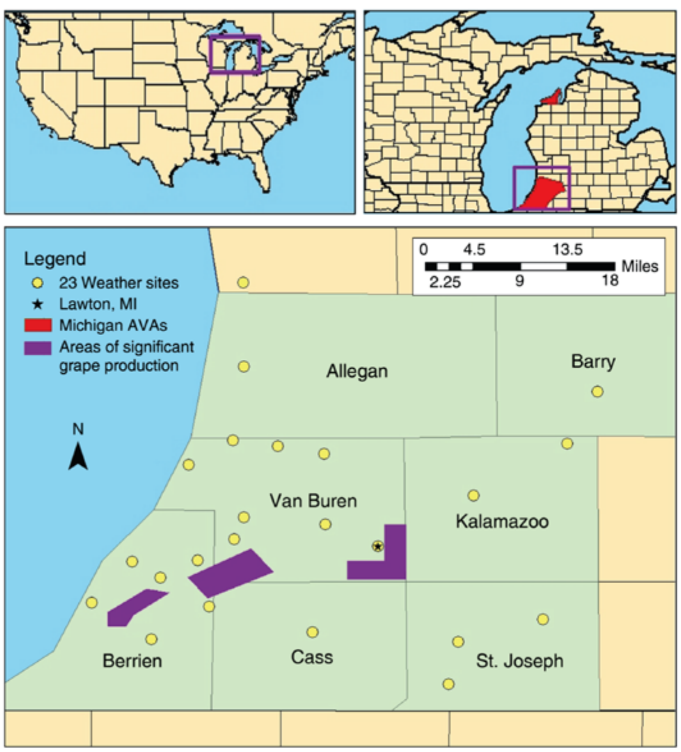


**Figure 1** Regional map of grapegrowing areas in southwestern Michigan, including weather stations and areas of significant grape production. The star represents the region where National Grape Cooperative Association data was collected from 25 vineyards.

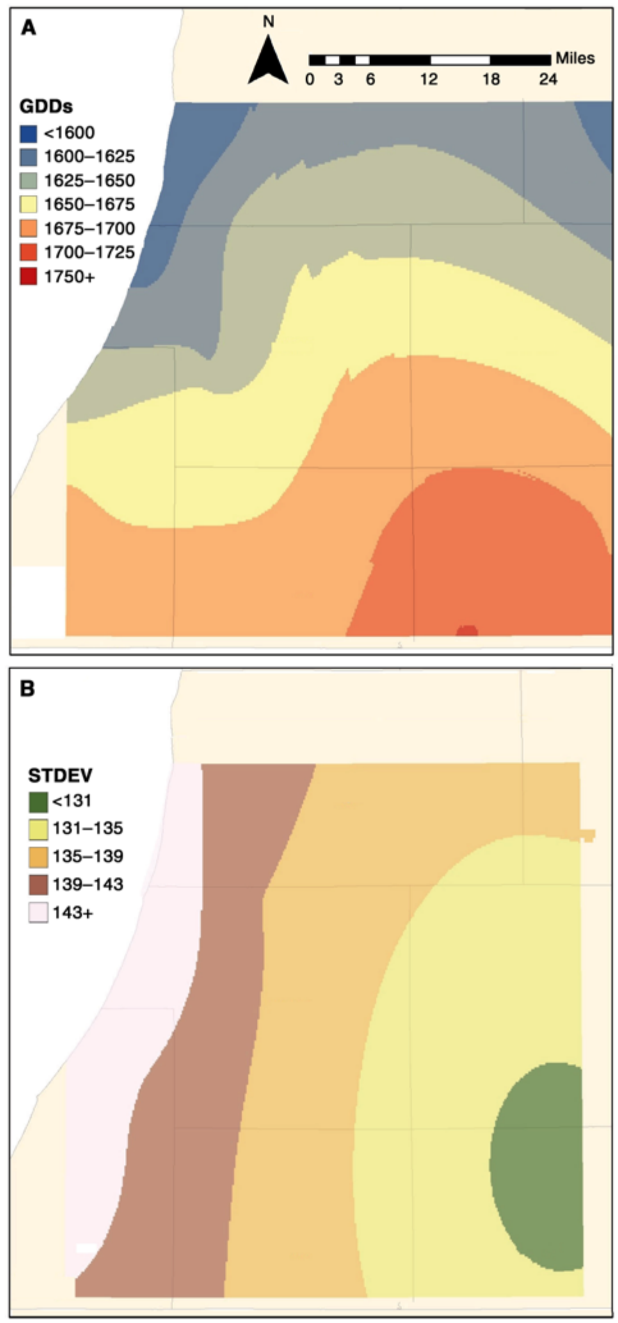


**Figure 2** Spatial interpolation of growing degree days (GDD) and standard deviation of GDD in southwestern Michigan: (**A**) average GDD and (**B**) average standard deviation of GDD.

water-modified temperatures to coastal areas. It also remains relatively warmer than the more inland areas during the end of the growing season when warmer lake temperatures and enhanced cloud cover slow the rate of seasonal cooling.

The map of the standard deviation (SD) of GDD indicates a strong pattern of decreasing variability as distance from the lake increases, where higher SD values indicate more variability over the study time frame (Figure 2B). Locations along the lake to a distance of ~1.5 miles have the highest values, at >143 SD. The values drop on a near-even gradient from west to east over the entire study area, at <135 SD for the majority of the eastern boundary of the region. Some areas in St. Joseph and Kalamazoo Counties drop below 130 SD.

The number of frost days is lowest in southern sections of the grapegrowing region and along Lake Michigan and highest in the north and areas farther from the lake (Figure 3A). The lake's moderating effect on temperatures can be seen in the map, but the trend was not as strong as it was in the GDD study. This is especially significant because of the geographical distance between high and low values, most likely the result of topographical differences and site microclimate. Areas with a relatively low number of frost days (between 3 and 4 days on average) are often within 20 miles of areas with between 7 and 8 days of potential frost in the early portion of the growing season. Given such a short distance between these areas, the variation in frost-day frequency on a year-to-year basis suggests that vineyard site remains a primary consideration, particularly for a variety characterized by early budburst and susceptible to frost. The SD of frost days was highest in the northeast corner in the region in Allegan and Barry Counties. The lowest frost variation was along the southeast boundaries in Cass and Kalamazoo Counties (Figure 3B).

**Temporal trends: GDD.** Temporal trends from the GDD data suggest that GDD have increased over time, but at different rates depending on the year in which the study begins. The data show two distinct trend lines and we examine both periods: 1950 to 2011 and the subset of 1980 to 2011.

From 1950, the yearly GDD trend for southwestern Michigan was effectively flat over the full 61 years of the study (Figure 4). The overall trend is a relatively modest 0.691 GDD gain per year (Table 1). However, the variation from year-to-year was very pronounced. Michigan had a minimum of 1310 GDD (1992) and a maximum of 1890 GDD (2007), a relative overall difference of 30.7%. The interannual variability was substantially greater than that of the Napa Valley (Table 1), which had more GDD, yet far less interannual variation (22.4%) with a minimum of 1656 GDD (1980) and a maximum of 2133 GDD (1997) (Figure 4). The standard deviations (SD) for both regions were substantially different, with 126 GDD SD for southwestern Michigan and 111 GDD SD for Napa Valley over all 61 years. The overall size of the range and SD of both regions suggest that Michigan is significantly more variable from year-to-year (Table 1). This analysis was repeated with the start date of 1980 in order to specifically reflect recent and current regional warming trends (Andresen et al. 2012). Following slowly decreasing temperatures from 1950 through the 1970s in Michigan, a temporal discontinuity was evident near 1980 followed by gradually increasing temperatures (Figure 4), gaining >3.68 GDD per season (Table 1). This trend was enhanced in the 2000 to 2010 decade, which had the highest GDD counts overall.

Another pivotal trend was the increase in GGD variability between years in southwestern Michigan, which rose from 126 GDD SD for the period 1950 to 2011 to 138 GDD SD for 1980 to 2011 (Table 1). However, this variability was spread over six stations throughout the region. The change was more dramatic

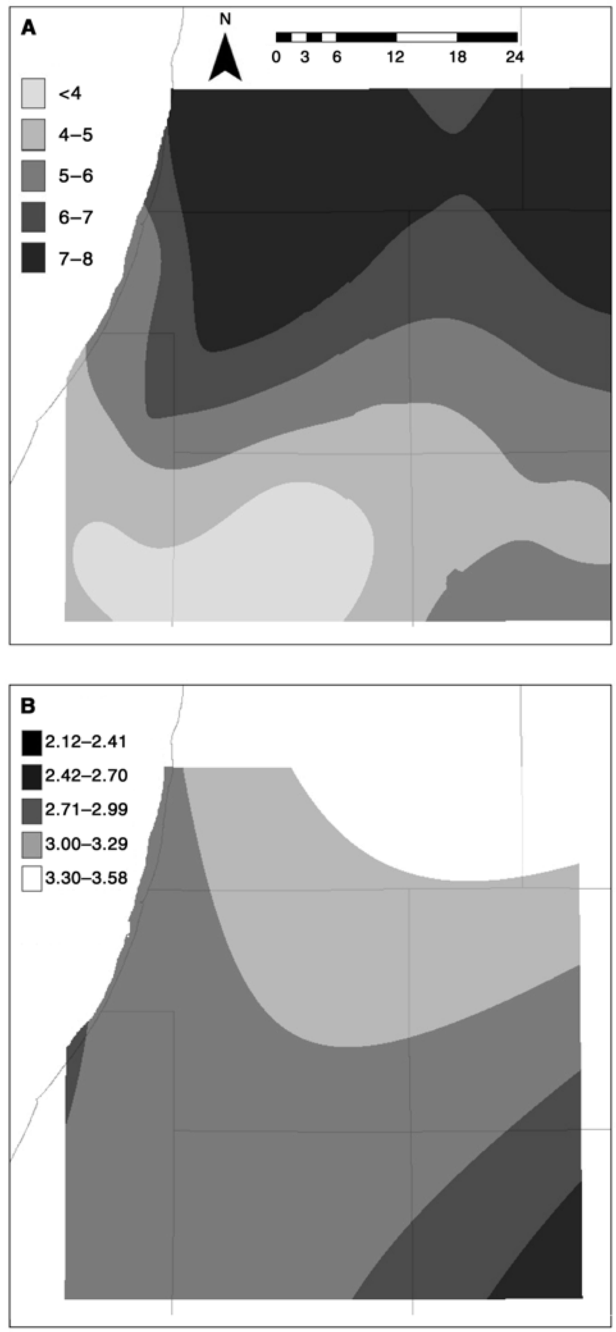


**Figure 3** Spatial interpolation of days of potential frost (**A**) and standard deviation (SD) of days of potential frost (**B**) in the southwestern Michigan grapegrowing region. Frost is calculated as daily minimum temperature of -1°C or less from 1 Apr to 20 May.

at some individual stations, such as 180 GDD SD during the 1980 to 2011 period at Benton Harbor Airport NCDC station. The variation in Napa Valley actually decreased during the same period, with a slight decreasing trend of GDD gain per year (Table 1). In summary, the trend since 1980 in both regions suggests warming temperatures, with increasing interannual variability in southwestern Michigan. One potential factor influencing the impressive increases and decreases may be the relatively shorter time frame; however, with 31 years of data comprising the 1980 to 2011 study, there is a trend. Another factor is the difference in Köppen climate classifications. Napa Valley features a Mediterranean (*Csb*) climate, whereas southwest Michigan has a humid continental (*Dfa*) climate. *C* level climates typically have mild winters and warm to hot summers while *D* level climates typically have cold winters and mild to warm summers. Napa Valley's *C* climate has a monthly high of 28.3°C in August and a monthly low of 4.1°C in January. Southwestern Michigan's climate has a monthly high of 27.2°C in July and a monthly low of -8.1°C in January. Michigan clearly has more variation. At the beginning (April) and end (October) of the seasons, Napa Valley has monthly average temperatures of 21.8°C and 24.8°C, respectively (Western Regional Climate Center 2013), much higher than temperatures of 13.4°C and 16.2°C for Michigan in the same months (Midwest Regional Climate Center 2013). The cooler start and end to the seasons in Michigan, combined with the irregular pattern of when spring "begins" and fall "ends," lends more variability and uncertainty to southwestern Michigan. While both regions are located on large bodies of water, Lake Michigan does not nearly have the same impact as the Pacific Ocean.

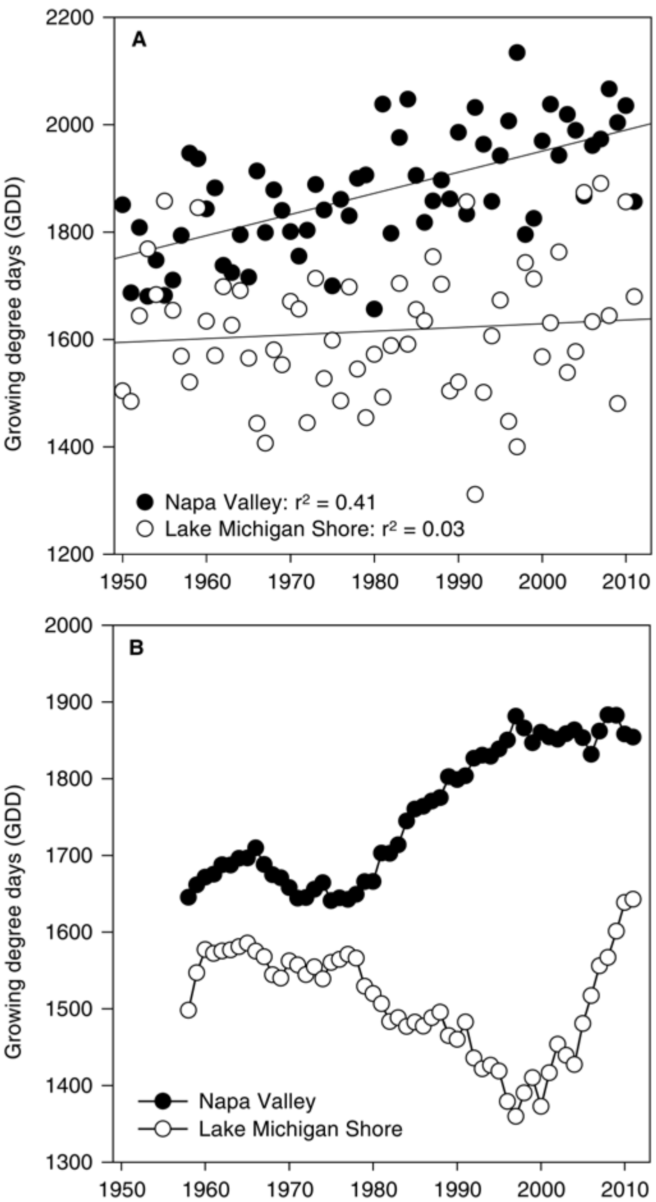


**Figure 4** Growing degree days (GDD) accumulation for Napa Valley and Lake Michigan Shore from 1950–2011 (**A**) and 9-year moving average (**B**).

**Frost risk.** Similar to the temporal changes in GDD over time, trends in the frequency of potential frost days within the boundaries of the growing season in southwestern Michigan are evident (Figure 4). From 1950 to 2011, there was very little change with a small gain of frost days over time (0.0163/year) (Table 2). However, from 1980 to 2011 there was a more pronounced counter trend, with a loss of 0.074 potential frost days per year. The SD values for both time frames are effectively the same, but the average was slightly

**Table 1** Growing degree days (GDD) in southwestern Michigan and Napa Valley (California) from 1950 to 2011 and from 1980 to 2011.

| Parameter[a] | Southwestern Michigan | Napa Valley |
|---|---|---|
| **1950–2011** | | |
| Long-term mean GDD | 1615.8 | 1874.1 |
| Standard deviation | 127.0 | 111.5 |
| Autocorrelation | 0.001 | 0.373 |
| Regression | 0.03 | 0.66 |
| GDD gain x year | 0.7 | 3.9 |
| **1980–2011** | | |
| Long-term mean GDD | 1628.0 | 1935.7 |
| Standard deviation | 138.4 | 101.8 |
| Autocorrelation | -0.10 | -0.12 |
| Regression | 0.42 | 0.27 |
| GDD gain x year | 3.7 | 3.6 |

[a]Autocorrelation: Pearson's R; regression: measure of variability within a time series from year-to-year.

**Table 2** Average days of potential frost risk in southwestern Michigan from 1950 to 2011 and 1980 to 2011.

| Parameter[a] | 1950–2011 | 1980–2011 |
|---|---|---|
| Long-term mean | 7.63 | 8.25 |
| Standard deviation | 3.68 | 3.66 |
| Coefficient of variance | 13.54 | 13.42 |
| Autocorrelation | 0.23 | 0.11 |
| Regression | 0.08 | 0.19 |
| Frost day gain per year | 0.016 | 0.074 |

[a]Autocorrelation: Pearson's R; Regression: measure of variability within a time series from year-to-year; frost day gain: frost calculated as daily minimum temperature of -1°C or less from 1 Apr to 20 May.

higher in the 1980 to 2011 study, likely due to the occurrence of the highest values for both time frames in 1989 and 1990 at 16 and 17, respectively. An average SD of ~3.7 frost days for both periods of study shows that variation from year-to-year has held relatively steady over the long-term. The coefficient of variance for both time frames was ~13.5 (Table 2), which underscores that finding.

**Seasonal trends: Growing season changes.** For seasonal trends, data were obtained from the NGCA and included the date of budburst from 1971 to 2011 and the date of the first fall frost from 1961 to 2011 (Figure 5). Budburst in the seasonal growth cycle of a grapevine is crucial to the development of the crop and typically occurs in April for juice grape varieties in Michigan. If this stage occurs either earlier or later than normal, it can lead to wide variation in fruit quality and crop yield. The same variation can occur depending on the date of the first frost of the fall season. The first frost, typically in October in Michigan, can either extend or shorten a season by several days to a few weeks.

According to NGCA, the latest frost-free day (date of last freezing temperatures) for the region has been 20 May and the earliest frost day in the fall season was recorded as 13 Sept. Because the Michigan growing season is bounded by budburst and the first frost of the fall, it is possible to calculate the length of each growing season for which data were obtained. From the linear trend line of the 1971 to 2011 period, the average length of the growing season has increased by 28.8 days (Figure 6). These four weeks at the end of the growing season are pivotal for late-ripening grape varieties to reach fruit technological maturity.

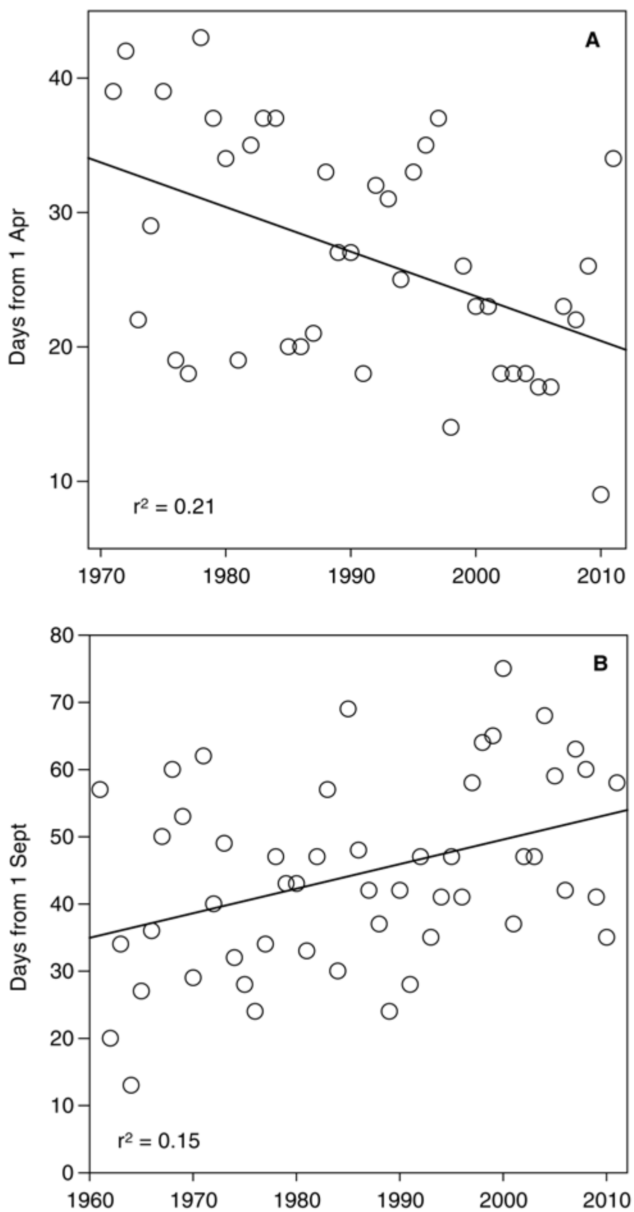


Figure 5 Date of budburst for Concord grapes in southwestern Michigan from 1971 to 2011 (**A**) and date of first fall frost in Lake Michigan Shore AVA from 1961 to 2011 (**B**) (significant at $p < 0.01$ level).

## Discussion

**Temporal trends.** GDD data over time generally reflect a warming trend during the study period, particularly from 1980 to 2011 in Michigan and California. While GDD trends in the southwestern Michigan region remained effectively flat from 1950 to 2011, there was a gain of more than 3.68 GDD per year from 1980 to 2011 (Figure 4), largely due to the last decade of the study, when some of the warmest growing seasons have occurred. Variability has also increased greatly between the two time frames. Compared to Napa Valley, there is general agreement in the trend of increasing total annual GDD, but the year-to-year variability in Michigan significantly exceeds that of Napa Valley over both time frames (Table 1). The warming trend, if it continues in the future, could allow for the introduction of alternative grape varieties to the Michigan region, given greater confidence that the higher seasonal GDD totals could be reached on a consistent basis. However, the amount of variability would almost certainly limit that

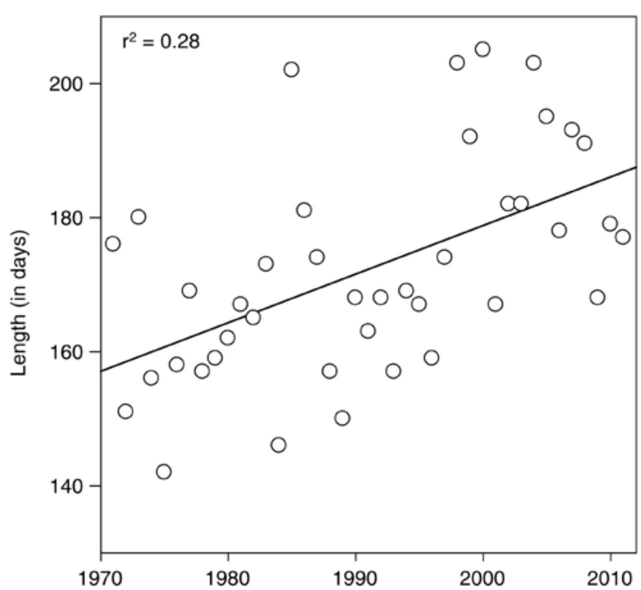


Figure 6 Length of the growing season (from last spring frost to first fall frost) for southwestern Michigan from 1971 to 2011 (significant at $p < 0.01$ level).

confidence because variability between seasons could greatly affect yield and fruit quality at harvest due to irregular spring and fall temperature patterns. For new vineyards, site selection is pivotal to manage this variability, although site selection alone would not completely overcome the risks presented by late spring freezes. The explanation for the greater variability in Michigan is unclear, but likely linked to the relatively high year-to-year variations in mean temperature during the transitional spring season. This phenomenon, associated with periodic changes in the location of the polar jet stream across North America, is relatively more common in Michigan at its higher latitude and more continental location. Observations of the persistence of early season GDD surpluses or deficits resulting from abnormally mild or cool temperatures throughout the remainder of the growing season support this hypothesis. For example, in the 1980 to 2011 Michigan GDD series, 71% of the GDD surpluses that have developed by 1 July of each year remained at the end of October, where a surplus is defined as a sum of GDD +1 standard deviation of the long-term normal mean or greater on the given day. For the California GDD series the percentage was 82%.

In terms of spring frost frequency, there was a slight rate increase during the broad 1950 to 2011 time frame, while a slight decrease was observed during 1980 to 2011 (Table 2). However, the variability was nearly the same with a SD of 3.68 and 3.66 GDD for the 1950 to 2011 and 1980 to 2011 scales, respectively. With variability of this magnitude, grapes can still be affected in terms of quantity and quality. Frost during the early portion of the season, particularly in and around the time of budburst, is an obvious threat to grape crops in Michigan. However, even though trends suggest that potential frost days may be decreasing, frost will never truly "disappear" from the area and will likely remain an issue for growers for the foreseeable future. Indeed, given regional trends toward an increasingly earlier onset of the seasonal spring warm-up (and an associated earlier onset of bud growth and development), the overall risk of frost-related damage appears to have increased in recent decades despite relative decreases in the number of frost days and earlier dates of the last frost of the spring season (Winkler et al. 2013). In fact, earlier budburst combined with a flat frost trend over the study time indicates that frost vulnerability has been increasing in the southwestern Michigan grapegrowing region, of major concern for Michigan growers. While frost damage and occurrence can in many cases be mitigated through both active and passive methods, Michigan growers will need to continue to consider frost as a potential threat every year as only one or two events may harm the entire grape industry.

**Spatial trends.** The average GDD follow the expected pattern of higher levels in the south of the study area and lower levels in the north. However, Lake Michigan's moderating effects are evident with areas of cooler temperatures south along the lakeshore into Van Buren County (Figure 2). The warmest temperatures are in St. Joseph and Cass Counties, in the southeastern portion of the region. There are also strong spatial patterns in the standard deviation of GDD: variability is higher in locations that are closer to the lake (Figure 2B). While this pattern may seem counter-intuitive, it is due to varying frequencies and strength of the lake breeze, which may differ considerably from year-to-year depending on larger, synoptic-scale weather patterns (Changnon and Jones 1972).

In a comparison with other wine-producing regions in the world and their respective GDD, the Lake Michigan Shore AVA is positioned among regions of high reputation. According to one study (Jones et al. 2010), the Lake Michigan Shore AVA average of 1468 GDD (base 10°C) from April to October from 1970 to 2000 places it between the Coonawarra region in Australia (1457 GDD) and the Walla Walla region in Washington State (1528 GDD). However, it should be cautioned that the Michigan calculation was calculated through the Baskerville–Emin method heat accumulation calculation of observed data and not by deriving GDD from daily temperature averages. The difference should be considered marginal, as these heat accumulation calculation methods do not typically have large differences between them.

Potential frost days, both in terms of long-term average and standard deviations of the long-term average, follow the expected pattern. Frost occurs most frequently in the northern portion of the region and least frequently in the southern portion (Figure 3). However, no area within the region registered a long-term average of less than 3.0 frost days, placing all areas in southwestern Michigan in at least some risk of frost in any given year. There is a small section in the north-central portion of the study area where frost days appeared to drop. This is likely an error in the methods of calculation due to the lack of stations in that area. The standard deviation of frost days over the study time period indicates higher levels in the north and northeast and lower levels in the southeast. The highest standard deviations coincide with the highest levels of frost days, indicating that viticultural areas with the highest frost frequency year after year are also subjected to the highest interannual variation in frost potential (Figure 3).

**Seasonal data.** Data obtained from NGCA (Jasper and Holloway, personal communication, 2012) illustrate the change in trends on an average seasonal scale, as well as the associated viticultural impacts (Table 3) in relation to yield and soluble solids accumulation. GDD was strongly positively

**Table 3** Correlation values of growing degree days (GDD) and potential frost days versus soluble solids (Brix) and yield (T/acre) in southwestern Michigan from 1990 to 2011 for Concord grapes.

| Parameter[a] | Correlation coefficient (r) | Equation | Coefficient signf[b] |
|---|---|---|---|
| GDD vs Brix | 0.80 | $y = 0.0018x + 11.001$ | ** |
| Frost vs Brix | -0.40 | $y = -0.0825x + 16.972$ | ** |
| Frost vs yield | 0.04 | $y = 0.0162x + 4.485$ | ns |
| Vulnerable frost vs yield | -0.46 | $y = -0.3862x + 5.532$ | ** |

[a]Frost calculated as daily minimum temperature of -1°C or less from 1 Apr to 20 May. Vulnerable frost versus yield calculated by obtaining number of potential frost days during the days from budburst to frost line (20 May) versus harvest season yield.
[b]Coefficient significance: *, **, and ns indicate significance at $p > 0.5$, 0.01, and not significant, respectively. Coefficients for linear (L) or polynomial (P) best fit analysis.

correlated with fruit quality (indexed as soluble solids) at harvest, likely due to the higher heat accumulation, a favorable condition for better fruit maturation in cool-climate viticulture. Conversely, potential frost days and soluble solids were negatively correlated, most likely due to frost days shortening the season length. Potential frost days versus yield do not display a strong correlation, likely due to the counting of potential frost days starting at 1 Apr, which will include days before budburst. However, potential frost after budburst is negatively correlated to yield, as these events are prone to damage severely vines at early stage of growth (Table 3). Michigan's climatic variability is clearly visible through GDD and potential frost days. Nonetheless, over time, there have been changes in growing season phenology for grapes (Figure 6). The increase of 28.8 days in the growing season since 1971 shows that southwest Michigan has gained nearly an entire month of potential favorable grapegrowing conditions. These extra days are from the beginning (spring) and ending (fall) of the season, which has implications for yield and fruit quality. While the data is for only one point within the study area, the trend is clear: Michigan's climate is evolving rapidly in a warmer direction.

## Conclusion

Several temporal and spatial trends were found for southwestern Michigan's grapegrowing region in terms of climatic variability during the 1950 to 2011 and 1980 to 2011 periods. Temperatures and seasonal GDD accumulations are increasing and the year-to-year variability is also increasing, especially during recent decades. Compared to the Napa Valley in California, Michigan's season-to-season variation is significantly higher and on average much cooler. Although Michigan's heat summations will likely never reach California's averages, recent trends suggest that differences between southwestern Michigan and Napa Valley have been decreasing. Trends in frost day frequency in the early part of the season are effectively flat overall, but the variation in frost from one year to another is relatively high, increasing risk for growers in the region. Spatially, a clear trend emerges, with the lake effect moderating temperatures closer to the lake. However, the strength of the lake's effect on heat summations is much stronger compared to its effect on potential frost days. Frost day frequency follows the same trend, but the effect of north-south location is stronger than the moderating effect of Lake Michigan. Lastly, seasonal trends with the dates for spring budburst and the first frost of the fall, which bound the grapegrowing season in the region, indicate a gain of slightly more than 28 days from 1971 to 2011. Such a lengthening of the season has implications that run through all levels of the industry, especially the potential to plant alternative grape varieties.

Data availability, while not an overall major concern for this study, was still an issue at some levels. More station data would lead to more accurate and continuous results, particularly in the spatial and seasonal portions of this research. In the future, the topic of frost vulnerability should be further addressed. Michigan's warm seasons in 2010 and 2012 were severely limited in terms of yields by late spring frosts, with the late April 2012 frost destroying 85% of *V. labruscana* juice grapes and impacting severely winegrape varieties. These warm seasons in terms of GDD, however, were some of the highest on record for the region and resulted in improved fruit quality. This juxtaposition of events displays the primary concern for Michigan's future growth: as Michigan's industry continues to grow it should always consider the risk of frost regardless of gains in GDD over the years. The increasing trend of GDD shows that Michigan's viability as a major grape producer in the Great Lakes region will increase in the future; however, frost risk is not decreasing, confining the state's grape industry in the foreseeable future.

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