EFFECTS OF CLIMATE CHANGE AND CLIMATE VARIABILITY ON THE MICHIGAN GRAPE INDUSTRY

By

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ABSTRACT

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The purpose of this dissertation is to explore the effects of climate change on Michigan's grape industry from a historical, present-day and future perspective. The majority of the research concentrates on grapes grown on the western coast of Michigan, where the majority of grapes grown for wine purposes are produced. The impetus for this dissertation was the fact that in the 1960s, production of *Vitis vinifera* (sub varieties include Riesling, Cabernet Sauvignon, etc.) was non-existent yet by the decade of the 2000s, growth in terms of acreage was more than 300% and Michigan was expanding into a regional power for wine. Climate change, as is proved by this dissertation, was the main driver behind this shift.

The dissertation begins by discussing the general concept of *terroir*, or "land characteristics," which include an area's soils, topography, culture and climate. *Terroir* is a central theme in grape and wine production, as it can vary immensely over even the smallest of scales. Of the four main characteristics of *terroir*, climate is the most variable of over time, and thus should be considered tomerit the most focus of the four characteristics when considering grapes and wine from an agricultural perspective. Other concepts including microclimates and scale are also discussed.

The next chapters are composed of three papers written for publishing in scientific journals. The second chapter explores how climate change has impacted the grape industry in the past. Southwest Michigan's growing season has warmed up by an average of 3.8 growing

degree day (GDD) per year increase since 1980 and the growing season has grown by an average of 28.8 days since 1971. The third chapter looks at present day issues for the grape industry, particularly by looking at the importance of the early growing season (1 Mar – 20 May). It was found that the early season is of great importance to the potential success of any growing season and the issues such as the rate at which GDD accumulate and the occurrence of spring frosts are of significant concern. The fourth chapter used downscaled data from the CMIP5 suite of climate models to explore the potential impact of future climate change on Michigan's grapes in southwest and northwest Michigan. Some of the primary obstacles to the production of *vinifera* in the 1960s (prior to its introduction) are likely to diminish in scale as climate change continues in the Great Lakes region.

The dissertation concludes with a discussion chapter recapping the findings of the previous chapters. This discussion chapter also suggests the implications of the findings, which concern climate change and agriculture on a global scale. It is with some concern that a region like Michigan has been to shift to be able to reliably grow *Vitis vinifera* grapes in such a short amount of time, and questions regarding similar circumstances for other crops and other regions of the world are asked. Improvements for the studies and future research directions are also discussed.

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For Allie*
*pOo

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I would first like to thank my committee: Dr. Lifeng Luo, Dr. Jeff Andresen, Dr. Andrew Finley and Dr. Paolo Sabbatini. The guidance and assistance they offered was invaluable in making this dissertation a reality. They put in a number of hours to take a widely scattered idea and helped hone it in on a focused paper on "the climate of Michigan and its effects on wine," which was always the goal. I will always be in their debt for their time, their open doors and (most importantly) their patience and it was a true pleasure to work under them. I hope to continue to work with them as my career progresses.

Secondly, I must thank my wife, Allie. She helped keep my feet on the ground while my head was in a million places at once and she was always there when needed. Putting our life on hold for a few more years was difficult, but it will be worth it in the long run. I must also give thanks to my family, especially my Mother and Father. Their unconditional support helped me get through these last years. This dissertation is the culmination of a number of hope and dreams of mine since I was a child. I can still remember being four years old and watching the Weather Channel and falling in love with meteorology. Upon realizing my dream at the age of eight of playing shortstop for the Florida Marlins was unlikely to be achieved (being left handed was the first of many setbacks), I immediately set my sights on the backup plan: becoming a scientist. I owe this accomplishment to their great parenting and their unyielding support.

Finally, I would like to thank two of my Grandparents: Grandma Connie and Grandpa Walter. Though they were from different sides of my family, they were equally important in my decision to take this path and I wish they could be here to see this. Grandma Connie, after I started taking classes in climate, was fascinated by the lessons I had learned and always voiced

her concerns for future generations "because we are changing our planet so much." She regularly pointed out that she was unhappy that people like her were leaving the Earth in worse shape than when they came in to it. This seemingly inconsequential point has given me hope that all people regardless of age, nationality, race, religion or class inherently care about our planet. "Education," she regularly said, "is the key." If only our society had more Grandma Connies, this world would have far more grace, civility and intelligence and thus would be a far better place.

Grandpa Walter, despite having no formal college education, was one of the smartest people I knew, and he showed me that you can learn anything simply through the force of will. His life was a rolling comedy of errors and back-breaking work and despite having no reason to do so, he continued to educate himself until the day he died. Not only did he teach me the importance of math and science in everyday life, he also had a few pointers on what I may do in these fields. I remember being in eighth grade and him handing me a pamphlet for the University of Colorado's Atmospheric Sciences department that he had personally ordered from the school. He also had very strong feelings me going to Virginia Tech or Rensselaer Polytech, if engineering was my thing. I may have been 4 years off from knowing where I would go to college and really had no clue what I wanted to do with my life, but there he was steering me towards the sciences. I took a few turns and detours along the road, but here I am: a climate scientist. He would have loved this topic and would have loved talking about it, and he would be elated to find out that there is finally a "Dr. Schultze" in the family.

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CHAPTER 1 – SPRING THAW.

INTRODUCTION

Terroir is a term that means everything to winegrapes. This concept, developed by the French, assigns the set of special characteristics that all locations possess. It translates literally to the term "land," from the French word "*Terre*," but the characteristics that *terroir* refers to include a location's soils, topography, culture and climate. *Terroir* is the culmination of the experience of several millennia of growing grapes and finding differences between vines of the same variety in one location versus another location. These vines could be in a nearby vineyard or hundreds of miles away in another country. A Cabernet Sauvignon of one quality can be completely different than another grown further down a hillside with the differences in the vines' *terroir* being the logical explanation. The growth of the societal and economic importance of the product of wine over time led the study of *terroir* to be transformed in to a scientific paradigm, and not just limited to the growing of grapes, or Viticulture.

Considering that studying the component parts of *terroir* requires a highly multi-disciplinary approach (studies in soil, topography, culture and climate), it can be argued that this study falls directly under the jurisdiction of the field of Geography. Soil, topography and climate fall directly within the scientific boundaries of the field of Physical Geography, while the study of cultures is in line with Human Geography. Beyond that, these characteristics change over space and time, satisfying the requirements of a modern Geographic study. This could be interpreted to mean that the study of *terroir* and how it changes over space and time is as "Geographic" as a study could be, especially if one considers that soil, topography and climates are the pillars of a basic Physical Geography lecture class and that Cultural Geography is still, at minimum, a mandatory requirement for any Geography student in the modern University.

Of the four primary components of *terroir*, two remain effectively the same over time: soil and topography. The soil component is immensely important in terms of the characteristics of the types of grapes at a given location, and can vary greatly over a small area. One such example is in the Burgundy region of France where there is a large amount of limestone marl and alluvium. Vineyards on the marl portion traditionally produce wine at a high quality. Vineyards on the alluvium areas are typically lesser regarded. This change over a relatively small space is due to the differences in soil characteristics, where the vineyards located on the marls have more access to nutrients from the fossils of shellfish from another era (Wilson, 1998 and Dougherty, 2012). Topography is also an important part of any grape growing. Slope is important for cold air drainage, which takes advantage of the physical property of cooler air being more dense and heavier than warm air, allowing for this air to be "drained" out in times of cool weather which can prevent frost build-up in spring or fall. Aspect, or the orientation of the slope, is also something that must be considered in this field. Depending on hemisphere, a south facing slope can either maximize the amount of sun exposure or limit it. Control of the amount of sunshine hours in a season has consequences on a number of variables in the production of winegrapes.

However, soil and topography are two components of *terroir* that are effectively static over time. While change may occur to soils and topography, it is very slow and on the order of decades and even Centuries. Culture, another component of *terroir*, is also subject to very slow change. These changes come in the form of technology upgrades, access to better resources and even improvement to reputation. However, many parts of viticulture are rooted in tradition and in some cases, this tradition is "enforced" by an overarching government entity such as in the case of Italy's *Denominazione di origine controllata* or France's *Appellation d'Origine Contrôlée*. The culture part of *terroir* also deals the most of any component with subjectivity. This subjectivity especially comes in to play when considering wine ratings or reputations of various regions.

The fourth component of *terroir*, climate, incurs the most change over time. The role of climate is multi-scaled both spatially and temporally, and changes in climate on these scales can lead to very different results in winegrapes both in terms of what can be grown and the overall quality of a vintage. The variation within these scales makes the effects of climate vastly important to winegrapes. For this reason, climate's role in *terroir* is the focus of this dissertation.

1. Climate, Scales, and Wine

As mentioned previously, climate's role in winegrapes is multi-scaled both in a spatial and temporal sense. Spatially, climate affects winegrapes at three scales: the macro-, meso- and micro-scales. From a macroscale, climate is the primary determinant in where grapes can be successfully grown. Typically, climate governs whether a location can grow grapes or not. Southern France can grow fantastic grapes of innumerable variety, but a tundra in Svalbard, Norway cannot grow grapes at all. Typically, successful winegrape growing is limited to Köppen C class climates (Köppen 1990, Geiger 1961), where the typical climate conditions are both favorable and less variable on a yearly basis. Köppen D class climates can also grow these grapes, but special conditions are necessary and attention must be paid to the interannual climate variability that inherently comes with these climates, particularly in the spring and fall months. From a macroscale perspective, the question of grapes contains a binary answer of "yes" or "no."

Winegrapes are also affected on a mesoscale. If an area is suitable for grapes, then one must ask what kind of grapes can be grown. Typically, the best wines are produced from *Vitis vinifera* species of grapevine where many of the famous cultivars such as Cabernet Sauvignon, Chardonnay and Riesling come from. However, these varieties are not conducive to cold climates. Wine can be made from any type of grape, including the North American *Vitis labrusca* species, however these wines are regularly not considered to have the depth of flavor that *vinifera* grapes possess. Yet, these North American varieties are more cold hardy and can survive colder winter temperatures. A grower must consider climate on a mesoscale as to which type can be grown in a location. Questions of "*Vinifera* or *Labrusca*" must be asked, and then "Which cultivar?" For *vinifera* alone, there are five thousand varieties, each with its own climatic optimum where some are better suited for hot and dry climates where others are better for cooler, damper conditions. A grower does best to tailor a vineyard's inhabitants to the strengths of the *terroir*, which is why one may see strong Shirazes in hot, drier climates such as Australia's Hunter Valley and sweet Rieslings in cooler, damper climates such as Germany's Mosel Valley, but not the other way around. The question of viticulture on a mesoscale is answered by: "What kind of grape can I successfully and reliably grow in this location, or where can I reliably grow this variety of grape?"

Finally, winegrapes are affected at a microscale. As is typical with geographic studies, the greatest variation comes at the smallest scales. Microscale influences dictate such things as end season yields and quality of the crop as well as interannual variability of those variables. Differences over space on a microscale include changes in aspect and slope, which can create vast amounts of change over even a small distance. When combined, we can consider the summation of these variables to be the microclimates of a given area and this topic will be revisited later in this dissertation numerous times. The question of microscale can be answered by: "What will my yields and qualities be this year for this varieties, versus others in the surrounding area?"

The previous scales dealt with climate's role in *terroir* from a spatial perspective. But climate is not purely a spatial concern. Climate varies over time and that variation fluctuates at different scales: both short-term and long term. From a short-term temporal scale, for example an interannual scale, one must consider that no season is ever exactly the same as a previous season. This is due to differences in heat accumulation, precipitation intensity or the timing of atmospheric conditions between the years. Of course, different areas have different amounts of variability in climate on a yearly scale. Typically, a Köppen class C climate can be considered to be more "stable" than a Köppen class D climate, particularly in the spring and fall months. However, each region is subjected to different climate regimes and their numerous varieties of grapevines all respond differently to the same climate. This leads to a great deal of variability over a small space in a short time frame.

However, climate can have effects on a long time scale, too. This is evident in the long term fluctuations of climate and the response in the growing of grapes across the globe. Grapes have been harvested for at least the last 8000 years and the distribution of winegrapes has fluctuated over time. As civilization spread out across the Earth, grapes were brought to a number of places and they succeeded where the climate was accommodating. During and after the Medieval Warm Period (~900-1300), winegrapes were grown in England and Scandinavia (Pfister, 1988). However, the ensuing "Little Ice Age" limited these areas' ability to reliably sustain grapes. Grapes would follow the explorers, missionaries, soldiers and settlers from the Old World to the New World, but yet again winegrapes only succeeded where the climate allowed. The recent warming trend of the past 150 years has brought winegrapes to areas that had previously been unable to grow, but this process has been slow.

2. Microclimates, *Terroir* and Complexity

The variability of climate at numerous scales leads to an abundance of complexity in terms of its effects. For the purpose of this dissertation, climate will be considered to be atmospheric factors such as temperature, precipitation or solar radiation. Assuming appropriate soil, topographic and cultural conditions, these three variables are the primary controls in the photosynthetic rate of any plant, grapevine included. An increase in photosynthetic rate can lead in a greater rates of biomass accumulation which potentially increases yields in any crop (Santos et al., 2011). Since no two seasons are ever the same, seasonal alterations of the accumulation of precipitation, temperatures or sunshine hours lead to differences in yields and quality (Bindi et al., 1996, Jones, 2000).

Climate interacts with the other components of *terroir* to create extensive complexity, despite the fact that the other components are effectively fixed in place. Oke (1987) called the phenomenon that creates this complexity "spatial inhomogeneity," which is the term used to describe how climate interacts with the soils and topography of an area and how differences in the fixed components (soil and topography) can create different responses to effectively the same climate conditions. Spatial inhomogeneity can be considered to be a word related to the concept of *terroir*.

For example, soil characteristics and climate can combine for a wide distribution of site suitability for winegrapes. Climate's temperature and precipitation variables can have different responses in grapevines due to soil characteristics. Soil characteristics include such variables as soil moisture, thermal conductivity, drainage capacity, chemical concentrations and even soil color. Differences in these variables, among many others, contribute to the physical characteristics that make up the thousands of series of soil catalogued in the field of soil taxonomy. Soil type is an important consideration when planting winegrapes, as some grape require drier conditions while others need more available moisture. Depending on a regions climate regime, precipitation may or may not be a problem. If average precipitation is too abundant for a specific variety but average temperature is favorable, then a soil with good drainage capacity would be best to accommodate that variety. If no such soils exist in the given area, then another variety should be chosen. This Climate-Soil connection is something that shows up repeatedly in the field of Viticulture.

From a climate perspective, soils dictate water management in areas where irrigation is not necessary. Soils can also play a role in temperature over a very small area. Depending on such things as land cover, available soil moisture and incoming solar radiation rates, soils can greatly affect an area's radiation balance. An example would be the fetch effect and what it may do to a vineyard. The classical example is a vineyard situated next to a field that is covered with bare soil. In this example, the wind is blowing from the direction of the bare field to the vineyard. The radiation balance over the un-vegetated plot of land will be very different than over the vineyard. It will have virtually no shade, in direct sun, with very little soil moisture. Thus, most of the insolation over this bare plot will be converted to sensible heat and very little going toward latent heat, involving the amount of water vapor in the air. This air will be blown over the vineyard, leaving the first several meters of the vineyard on the bare plot facing side to be afflicted with much hotter, drier air. The vines in these first few meters will naturally experience a hotter average temperature and a lower humidity, and these vines likely will be subjected to more water stress (assuming no irrigation is present). As one were to progress across the vineyard and away from the bare plot, the vegetated land cover would have more shade and more available moisture and would be cooler and under less water stress. There would be a natural zone of transition from the leading edge of the vineyard in to the areas farther away from the bare plot and yields in this zone of transition would likely be different than areas away, and unaffected by the bare plot. This fetch effect is but one of a number of interactions between the Climate and Soil components of *terroir*.

The Climate and Topography components also interact to create a great deal of inhomogeneity across space. Consider aspect. The aspect of an area is the direction it faces: east, southwest, north, 105 degrees azimuth, etc. The aspect plays a large role in a microclimate because it determines how much energy an area will be getting, and when. An eastern facing slope receives its max insolation in the morning, the western facing slope receives max insolation in the afternoon. A south facing slope (in the non-tropical Northern Hemisphere) receives maximum sun at solar noon while a northern slope receives reduced insolation in comparison to the south face. As a result, a hill (or mountain or valley) will receive different amounts of insolation at different points at different times. If one were to also consider clouds, which vary over space and time, the issue of aspect becomes even more complex, and we must also remember that not all slope face exactly 0, 90, 180 or 270 degrees.

Beyond the question of aspect, we must also consider slope. A slope that is perpendicular to the angle of the incident solar radiation receives maximum insolation. As the angle of the sun travels away from the perpendicular, an area loses a portion of insolation equal to the cosine of the difference between the perpendicular and actual angle of direct insolation ($\cos 0 = 1$, $\cos 1 = 0$). This slope angle dictates how much insolation, of the total amount of potential insolation, will reach a grapevine to be converted through the process of photosynthesis in to biomass.

However, slope has another role that is central to cool climates. Slopes allow for the natural heavier colder air to "drain" away from an area to be pooled in a lower lying area. Ashcroft et al. (2012) displayed how cold air drainage capacity is the most important factor in controlling extreme cold conditions on a microscale. This cold air drainage is vital to cool climates, especially in the field of Viticulture. This allows for dangerously cold temperatures to be drained away from vines that are strategically placed on slopes and away from areas where cold air may pool. This is also prevents the formation of potentially damaging frosts in the spring and fall months. Frost will be discussed at length later in the dissertation, but the implications of cold air drainage and frost prevention are very important to viticultural regions in cool-cold climates. Even a slight slope (1-2% grade) can be viable for cold air drainage, but generally anything between 2-10% can be optimal for the prevention of cold air pooling. This means that cold air drainage can occur in nearly any location, as perfectly flat, 0% slopes are not common in many areas.

The combination of the Climate-Soil-Topography components of *terroir* can be combined to make microclimates. These microclimates are generally any location that are 1000 m^2, which if measured as a square would only be 33 by 33 meters on its perimeter. When one considers the spatial inhomogeneity of a land surface, it becomes evident that the variability even over a small area can be enormous. In the field of viticulture, one must consider these aspects of *terroir* when placing a vineyard and choosing which cultivars to grow. Failure to do so will result in a vineyard with inconsistent vintages and continued risk of losses to quality and quantity for as long as the vineyard exists. Microclimates speak directly to the concept of *terroir* because they are the physical manifestation of why a season's crop from one location has certain characteristics that a crop from another year did not have, and it explains why that crop is different than a location's crop of the same variety 1, 10, 100 or 1000 kilometers away.

Microclimates are also responsible for differences in end season results for a season's harvest. For the duration of this dissertation, "quantity" (defined as end season yields, measured as tons per acre (t/acre)) and "quality" (defined as end season suspended sugar concentrations, known as the Brix content, measured as the number of grams of sucrose per 100 grams of grapes) will be the primary metrics used to compare season-to-season harvest statistics. Due to the complexity presented by an area's spatial inhomogeneity, end season statistics can vary from vineyard to vineyard, and even from one part of a vineyard to another. The data used in this dissertation come from the National Grape Co-operative Association, and used data compiled for decades from 25 vineyards throughout southwest Michigan. It should be noted that the data presented within this dissertation areal averages (for example: the budbreak data discussed at length in Chapters 2 and 3 are the dates of budbreak averaged from the 25 sites), and that variability across the sites is a concern. However, as this dissertation will show (see Chapter 2), spatial variability for temperatures and frost follow a regular spatial pattern. Dates provided for such events as "budbreak" or the "first fall frost" would naturally have spatial variability, but not nearly enough to render the data useless.

Quantity and quality metrics are prone to vary spatially, but their variation over time is of bigger concern in this dissertation. These metrics are bound to a season's climate, and since no two seasons are ever the exact same, one would expect to see variability over time. Quantity in winegrapes responds to the amount of heat accumulation over a season as well as the amount of rainfall and sunshine hours. As we will see in Chapters 2 and 3, cool climate Viticulture relies heavily on the early season and the amount and timing of frost events. Growers can have a direct influence in an end season quantity. A grower is likely to prune the vines to achieve the "correct" amount of grapes per vine at various times throughout a season. However, the "correct" amount of grapes can vary on a number of outside influences ranging from water availability to the type of grapes being grown. Governmental controls can also play a part in yields, such as the imposed limit on tons per hectare of production in Portugal's Port wine producing Douro region.

Quality metrics in winegrapes are less beholden to human influences. Quantity is related to quality in Viticulture, where too many grapes per vine can lead to imbalanced chemistries within the grapes. But, overall one can consider quality to be largely controlled by climate influences.

One example comes from the timing of a vine's phenological events. The typical order of Budbreak → Floraision → Veraision → Maturity/Harvest in a vine's seasonal phenology is dictated by the vine's response to climatic conditions. Variables like heat accumulation and sunshine hours can have a strong influence on how a vine progresses through a season. The timing and length between each phenological stage differs every year and thus the biochemistry within the vines and fruit are different. Having shorter stages for a vine has shown mixed results (Jones, 2000 (positive), Bindi 1996 (negative)), but interannual variation in the length of these stages clearly changes the end season quality of grapes. Water availability also can have a role in quality. The amount of water is important, but the timing of water can be just as important. The timing aspect matters for the biochemistry within the fruit in terms of acid-sugar-water concentrations. Timing is also an issue for a vine's vulnerability to pests and disease.

Overall, one must not only consider the spatial distribution of the large number of variables that contribute to an area's *terroir*, as the temporal aspects of these variables also contribute to great diversity in winegrapes. Microclimates are the vehicle through which *terroir* operates. The intersection of Viticulture and Climatology requires a researcher to consider the large amount of variability over space and time, and the complexity involved for even one small region is significant.

3. Grapes, Climate and Michigan

The combination of climate and wine has been explored numerous times throughout history. The first modern groundbreaking paper is likely Amerine and Winkler's 1944 paper on the spatial distribution of heat accumulations throughout California and its relationship to the types of grapes that can be grown in different "regions" classified by the amount of growing degree days. Lower accumulations were in line with better suitability for high quality wines. Higher accumulations were in line with higher suitability for raisins. This methodology would be extended by Olmo to Australia (1956) and then built upon by a number of researchers, culminating in Gladstones 1992 book Viticulture and Environment. Numerous papers that focused on climatic conditions and their effects on winegrapes followed Amerine and Winkler (1944), but many were limited to static climatic conditions and the response from the vines and fruit. Studies in the 1990s and early 2000s focused on changing climates and the responses to vines either on a localized (Bindi 1996) or regional (Jones 2000, Schultz, 2000, van Leeweun, et al., 2004) scale.

While there were some papers before it, Jones (2005) kicked off the study of global climate change and its effect on regional wine producing areas either in the past, present or future. Jones (2005) explored the idea of temperature optimums for current grape production in 27 different areas using climatic conditions (past, present and future) and the effect on wine ratings. Many areas were found to near, or already at their optimums with the suggestion that surpassing their optimums would have detrimental effects to these regions assuming no change in practices. Jones (2007) delved deeper in to the matter and found change would also occur in the future within different regions. This idea was the foundation of his 2010 paper which explored the changes to the western United States' climate and its effects on wine production potential. The 2007 paper also considered the idea that climate models suggest that the 12-22˚C isotherm (considered to be the necessary bounds for necessary heat requirements for reliable winegrape production, from Gladstones 1992) would migrate poleward as the world continued to warm up in the 21st Century. This would allow for areas previously unable to grow winegrapes to once again partake in Viticulture.

However, Jones stopped at that point in the line of thought. Climate is intricately a part of the field of Viticulture and a changing global climate should obviously have consequences on wine production on a global scale. This is the justification for this dissertation. If climate is likely to change how winegrapes are produced, then a location that is currently in the midst of that change must be studied. Enter the State of Michigan.

The history of the State of Michigan's winegrape production will be discussed in the next chapter, but it should be noted that winegrape production in Michigan was unthinkable in before the late 1960s. Michigan was considered to be too cool during the summer, and the growing season was considered to be too short thanks to late-spring and early-fall frosts. The combination of these obstacles was too much for any reasonable grower to consider the region despite the tantalizing prospect of growing winegrapes along the shores of the largest freshwater network of lakes in the world. However, this dissertation starts in 1950 and expands in to a number of different analyses after 1970. In the past forty years, Michigan has gone from unthinkable for winegrape production to one of the largest producers in the United States. This is almost entirely due to a warming shift in climate in the Great Lakes region. The once inhospitable region is now a location for considerable production, and is likely to continue growth in the coming decades as temperatures continue to rise. This dissertation will continue out until 2100, and look at the potential landscape for winegrape production under a new climate regime. However, there are still risks. Frosts, inconsistent heat accumulations and season-to-season variability conspire to hurt the industry, still in its infancy. Michigan's industry, without the Great Lakes and without a warming shift in climate theoretically should not exist. Yet, it is one of the largest producers in the United States.

Michigan poses unique challenges that few other winegrape producing regions experience. Microclimates are the key to its success, as the industry's existence is hinged entirely on their presence. Jones 2007 discusses the potential idea that as global temperatures continue to rise in the next decades, frost will become less of an issue. This may be true for some of the largest producing regions in the world like Bordeaux or Barolo, but as Chapter 3 of this dissertation argues, cool climate Viticultural areas will see frost as an even bigger issue in the future. Expanding on the idea of Jones's poleward march of the 12-22˚C isotherm, this dissertation will seek to explain how Michigan's trials and tribulations since 1970 and in to the present make the region the "Petri-dish" of the future world's wine producing world. The experiences Michigan has had to endure will be what regions that will soon acquire the ability to grow *Vitis vinifera* will have to manage, and these areas will have to look no further than the Great Lakes State.

The goals of this research are as follows: (1) Establish Michigan's "place" on the winemaking globe by defining the viticultural climate of Michigan compared to other producing regions, (2) Explore the primary issues that have affected the region in the past decades and (3) Estimate the effects of climate change on the region and what potential effects could be felt in the wine industry in the coming decades. Ultimately, Michigan's changing climate and emerging wine industry is an excellent case study in discovering the direct effects of climate change in recent times. If this dissertation successfully accomplishes its goals, then one should be able to understand where Michigan's wine has come from and where it will go in the future. Understanding Michigan's unlikely industry will hopefully be a window in to future areas of winegrape production in the coming decades.

4. Review of Ensuing Chapters

The following chapters of this dissertation are as follows: Chapter 2 will include the text and figures from the paper "Spatial and Temporal Study of Climatic Variability on Grape Production in Southwestern Michigan," a paper published in the American Journal of Enology and Viticulture as well as additions to the "place" Michigan holds in the world of Viticulture. Chapter 3 will include the text and figures from the paper "Interannual Effects of Early Season GDD

Accumulation and Frost on Cool Climate Grape Production in Michigan," a paper submitted to Annals of the Association of American Geographers. Chapter 4 will include the paper "Effects of a Continual Warming Trend on Cool Climate Viticulture in Michigan, USA" on the effects of future climate change on southwest Michigan and its effects on potential winegrapes in the coming decades which was submitted to the Applied Geography Journal. Chapter 5 will include a summary of ideas, a discussion of the significance of the findings in the previous chapters and the potential implications on the field of Climate and Viticulture and some conclusions followed by appendices.

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CHAPTER 2 – BUDBREAK.
SPATIAL AND TEMPORAL STUDY OF CLIMATIC VARIABILITY ON GRAPE PRODUCTION IN SOUTHWESTERN MICHIGAN, USA

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 (AVA), located in the southwest corner of Michigan, USA. 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 grape production of the *Vitis labrusca* variety. The occurrence and severity of frost and freezing temperatures were also considered in this study, as sub-freezing 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 (CA). 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 Southwestern Michigan's number of days of potential frost and their seasonal variability have remained unchanged, which continues to pose a risk for grape growers in the region. It should be noted that 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 have a profound impact on overall climate-related risk for grape production.

Keywords: American Viticultural Area, Growing Degree Days, Frost, Cool Climate Viticulture

1. Introduction

The state of Michigan ranks fifth in the nation for grape production and number thirteen in the country for wine production (USDA-NASS 2012). Concord and Niagara cultivars (*V. 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 and 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, grape growers' 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). Despite the fact that total area planted with *V. vinifera* is increasing within the state, Concord (*V. labruscana*) remains the largest portion of the grape crop acreage in Michigan and in the eastern U.S. as well. Michigan's designation as a cool-cold climate viticulture region of the Great Lakes region for grape and wine production has historically been characterized by harsh winters and difficult spring frosts inducing large variations between yield and fruit quality over the years (Sabbatini and Howell 2011).

One method of determining seasonal variation in a region is through the calculation of heat summations. 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):

[1]
$$GDD = \left(\frac{T\max + T\min}{2} \right) - Tbase$$

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), 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 are then obtained by integrating the area under the sine curve and above the base temperature (Baskerville and Emin 1969). This curve is generally considered to be more accurate than the simple average GDD calculation or a different method where temperatures are cutoff (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).

Wine grape phenology has also been analyzed through GDD studies. In 1944, Amerine and Winkler produced a seminal paper that defined five regions of grape production in California. They also defined these areas in terms of wine grape cultivars appropriate for characteristic climate conditions, including GDD, and, consequently, potential wine styles. Regions I and II produced excellent, delicate table wines, while 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 (Amerine and Winkler 1944). This approach was then reworked for the Australian wine industry by Olmo (1956). The studies it stimulated 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 more recent times, Gladstones (1992) discussed improvements of Olmo's (1956) methods but also concluded that daily variation in heat can affect wine quality. Moreover, GDD were used recently to perform a spatial analysis of climate in the Western U.S (Jones et al. 2010) and as a metric to analyze how climatic variability affected wine quality in Napa Valley, CA (Jones and Goodrich 2007). Similar studies have also been carried out for southern Ontario (Shaw 2005) and Australia (Hall and Jones 2010).

The presence of macro- and meso-scale climates (Geiger 1965) makes the choice of vineyard location more complex, though critical to sustainable quality and economic success. In the Great Lakes region of US, extreme minimum winter temperatures are, in general, used as a key factor in describing sites for their grape-growing 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 3 to 4 times over a period of ten 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).

Regarding the site, the choice of the slope and aspect can also influence vine performance. Cooler northern slopes may delay spring budburst, reducing the potential of spring frost. In one example of spring frosts, the year 2012 in Michigan was subjected to strong spring frosts after an unprecedented warm period in late winter (mid-March) with temperatures rising in to as much 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 April 1st to October 31st). Such environmental constraints may reduce the ability of vines to fully ripen the fruit, especially when vines are over-cropped 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 is to begin the process of establishing trends in year-to-year climatic variability and its 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 Napa Valley region in California, a renowned grape growing region in the world. Frost was also considered in this study, as it can have profound limiting effects on both yield and fruit quality.

2. Materials and Methods

2.1. 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) currently 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 as well as topographic influences, which enhance the flow of cold air drainage down the sides of hills in order to minimize the frequency and severity of frost (Andresen and Winkler 2009).

For the study, southwestern Michigan was selected due to the availability of long term meteorological data and the location of the Lake Michigan Shore AVA in the region. 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 (Fig 1). The Lake Michigan Shore AVA runs for 115 kilometers along the Lake Michigan shoreline in southwestern Michigan extending from the Indiana-Michigan border, which serves as the southern boundary, to the terminus of the Kalamazoo River. 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 (ATF 1987). The region covers nearly 5,200 km^2 and is home to several of Michigan's oldest vineyards and wineries and a grape juice processing plant in Lawton, MI.

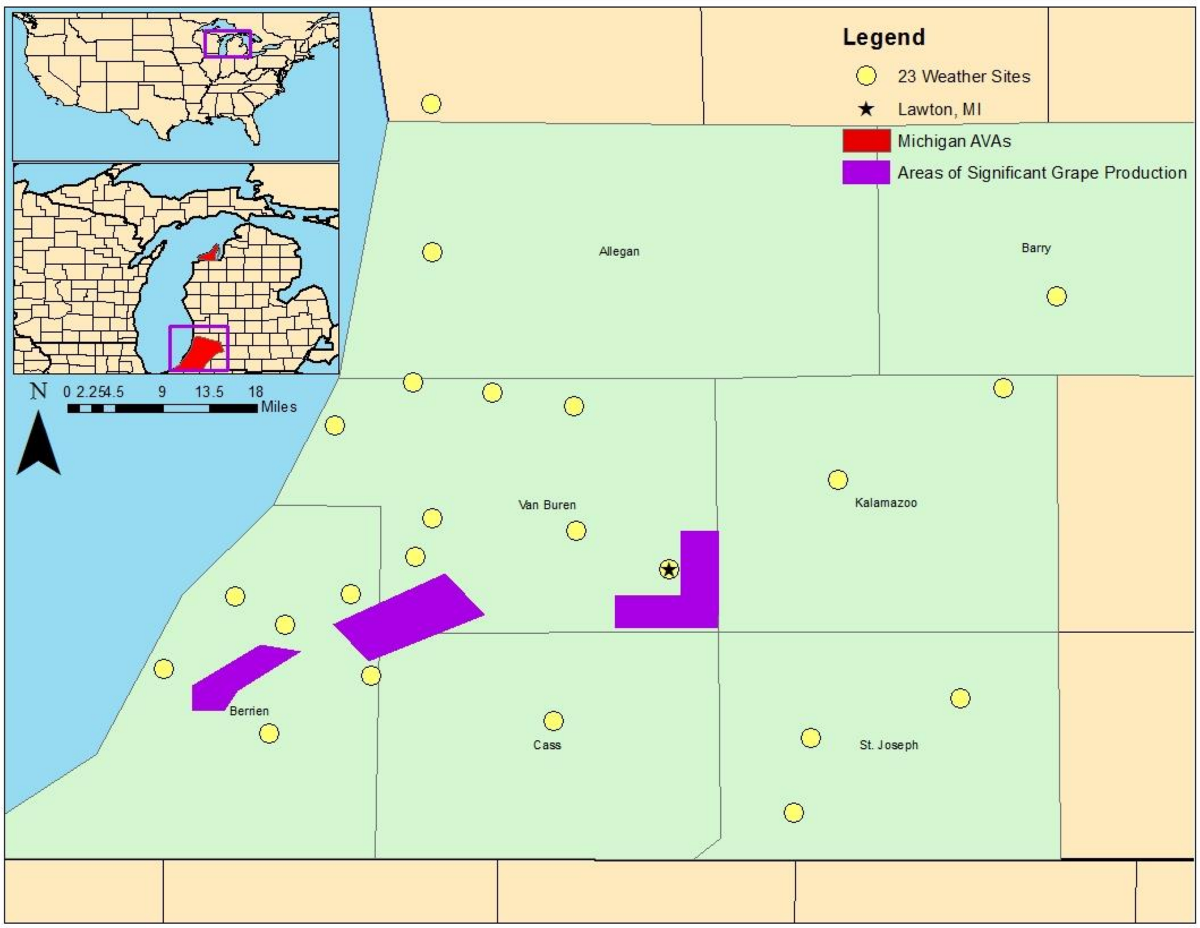

Figure 2.1. Regional map of grape growing areas in southwestern Michigan, US including weather stations, and areas of significant grape production. The asterisk represents the region were National Grape Coop data was collected from 25 vineyards.

Benton Harbor is a town located in largely agricultural Berrien County and is within southwest western Michigan. This agriculturally-important area has numerous weather stations, most of which are operated through Michigan State University's Enviro-weather system (formerly known as the Michigan Automated Weather Network, or MAWN). Benton Harbor is also home to the Southwest Michigan Regional Airport, which contains a long-term climate-observation station with records dating back several decades. While the community is located in a *Dfa* Köppen Humid Continental Climate class (Köppen 1900 and Geiger 1965), the ebb and flow of lake and land breezes caused by the city's proximity to Lake Michigan tends to limit temperature extremes (Moroz 1967).

2.2. Data Collection

Climate data were collected from several sources. The primary source of data was the National Climatic Data Center (NCDC) station mapper (http://gis.ncdc.noaa.gov). Daily temperature data were obtained from stations within and around southwestern Michigan as well as Napa Valley. Data were also collected from Michigan State University's Enviro-weather Automated Weather Station Network (Andresen et al. 2012a), which has seventeen stations located across the seven counties (Berrien, Van Buren, Cass, St. Joseph, Kalamazoo, Barry, and Allegan) of southwest Michigan. National Grape Cooperative contributed with annual viticultural data (1970 to 2011) on dates of budburst, spring frost and harvest. Also yield and fruit quality were provided. Viticultural data was collected from 25 vineyards of members of the National Grape Cooperative located in southeastern Van Buren County, in proximity of Lawton (Figure 2.1), were the Welch processing plant is located (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).

2.3. Experimental Design

In order to obtain a proper description of climatic variability in the southwestern Michigan region, 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. By convention, 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 (approximately 1.0°C between 1980 and 2011) in the Great Lakes region since 1980, two separate time frames reflecting conditions before and during this period were selected: 1950 to 2011 and 1980 to 2011. The 1980-2011 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 long-term historical climate in the region. Data for the temporal study were obtained from National Climatic Data Center (NCDC) observation sites within the local areas. Six stations in the region were utilized due to their long record of data and their location within or near the study area. They included Benton Harbor, Eau Claire, Bloomingdale, South Haven, Holland and Three Rivers. Seasonal GDD totals were calculated at the seven stations with the Baskerville-Emin method (Baskerville and Emin 1969) from 1950 to 2011 using the daily high and low temperatures from 1 April to 31 October each year, which is generally regarded as the approximate grape growing season in Michigan based on historical dates of budburst and first frost (Jasper and Holloway, personal communication). Averages were calculated at the seven NCDC stations over the study time period.

Following a similar calculation procedure with daily climate data from California, the southwestern Michigan grape producing region yearly GDD totals were compared with those of Napa Valley. Data were collected for the same 1950 to 2011 time frame as the seven stations in Michigan from NCDC stations at St. Helena and the Napa State Hospital, California. In addition to the comparison of the general status and trends of GDD between southwestern Michigan and Napa Valley, potential frost days were summed each season along the same time scale for southwestern Michigan. Defined as a daily minimum temperature of -1°C or lower, such conditions can kill or seriously injure the buds during their early stages of development (Zabadal and Andresen 1997). These days were computed from April 1st to May 20th, which is considered to be the "frost line" day in this region. This was done as an issue more central to Michigan's industry, and not considered for Napa Valley, as frost is much more of an issue for southwestern Michigan. It should be noted that 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 above ground level and we have 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. It is also important to note that 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 the operation of 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 much more homogeneous temperatures across a given area. These events, while much less common in number, may have much larger negative impacts and are more difficult to protect against (Winkler et al., 2013). Data obtained from the National Grape Cooperative (Jasper and Holloway, personal communication) were used to analyze the timing of budburst relative to spring frost events (1971-present) as well as the first fall frosts (1961-present). Using these data would allow for study of the status and trends of each growing season's start/stop dates.

A Pearson correlation coefficient with a 1 season time lag (meaning one season is compared to its previous season) was performed to calculate temporal autocorrelations of GDD accumulation. These autocorrelations, where a value of +1 suggests that variability is low and a value of -1 suggests the variability is high, were calculated for each time series with the goal of calculating the variability 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 grape-growing season for each year from 1971 to 2011.

For the spatial component of this study, data were gathered from seventeen observation sites within Michigan State University's Enviro-weather Automated Weather Station Network for the period 2000 to 2011. The six long term NCDC stations were also added to this dataset, combining for 23 stations across the area. In a Cross Validation, the root mean square error (RMSE) for the GDD accumulation was 5.8 while the Frost RMSE was .03. Seasonal totals from these data were fed into ESRI's ArcGIS 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 grape producing region.

3. Results

3.1. Spatial Trends: GDD and Frost

There are several trends and patterns evident in the maps generated in the spatial component of this study. In terms of GDD, there is 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 higher GDD summations in the south versus the north. For example, in central Van Buren County there is a visible ridge of higher GDD totals ranging from 1650 to 1700 GDD protruding north from Berrien and Cass Counties (Figure 2.2). The reason this area is warmer is likely the result of remaining just inland of the lake breeze fronts of the summer season, which brings cooler water-modified temperatures to coastal areas. It also remains relatively warmer than more inland areas during the ends of the growing season when warmer lake temperatures and enhanced cloud cover infiltrate enough to slow the rate of seasonal cooling.

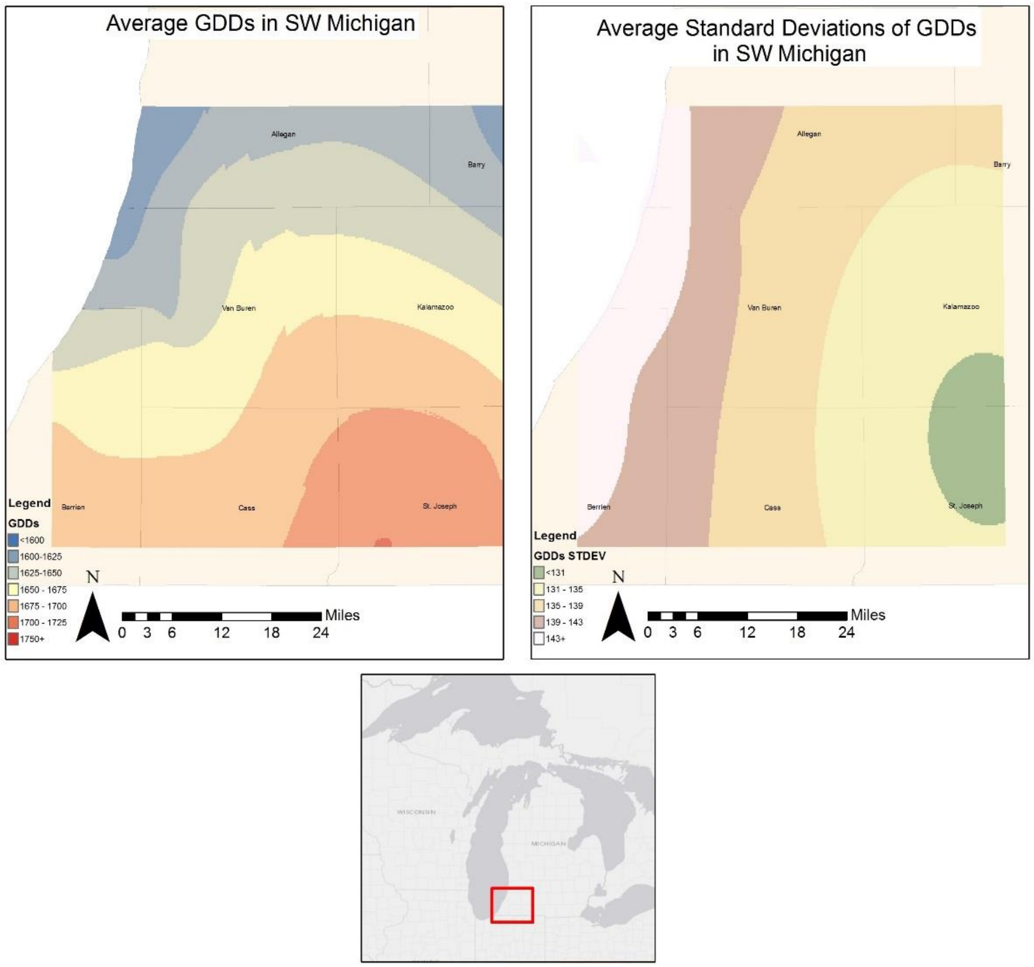

Figure 2.2. Spatial Interpolation of Growing Degree Days (GDD) and standard deviation (SD) of GDD in southwestern Michigan

The map of the standard deviation (SD) of GDD displays a strong pattern of decreasing variability as distance from the lake becomes greater, where higher SD levels indicate more variability over the study time period (Figure 2.2). Locations along the lake to a distance of approximately 1.5 miles experience the highest levels of SD, with a value of more than 143. The values drop on a near-even gradient from west to east over the entire study area, where SD levels are below 135 for the majority of the eastern boundary of the region. Some areas, in St. Joseph and Kalamazoo Counties drop below a value of 130 (Figure 2.2).

The number of frost days is lowest in southern sections of the grape producing region and along Lake Michigan and highest in the north and in areas farther from the lake (Figure 2.3). The lake's moderating effect on temperatures can be seen in the map, but the effect is not as strong as it is 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 that experience a relatively low number of frost days (between 3 and 4 days on average) are often within 20 miles of areas that experience 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 site selection of a vineyard remains a primary consideration, particularly if frost is an issue for a variety with early characterized by early budburst. The SD of frost days is highest in the northeast corner in the region in Allegan and Barry Counties. The lowest frost variation is along the southeast boundaries in Cass and Kalamazoo Counties (Figure 2.3).

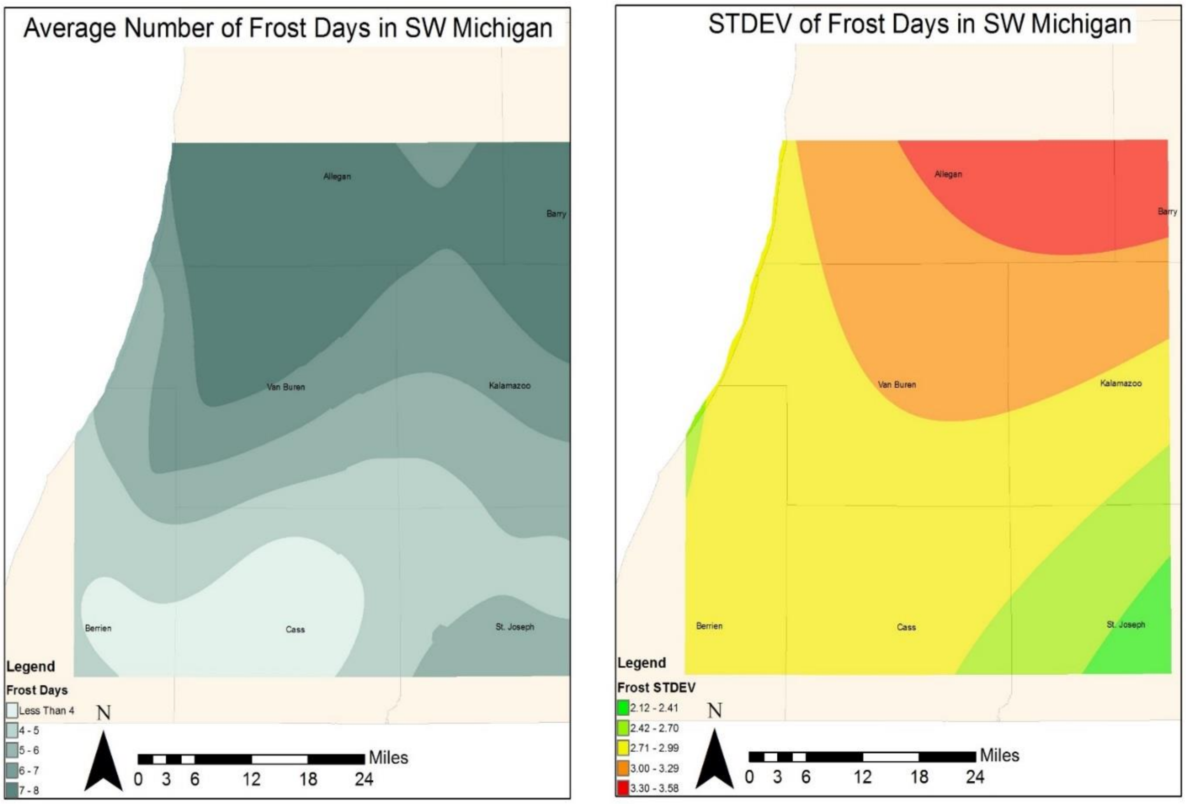

Figure 2.3. Spatial Interpolation of days of potential frost and standard deviation (SD) of days of potential frost in the southwestern Michigan grape producing region. Frost is calculated as daily minimum temperature of -1°C or lower from April 1st to May 20th.

3.2. Temporal Trends: Growing Degree Days (GDD)

Temporal trends from the GDD data series suggest that GDD have increased over time, but at different rates depending on what year the study begins. An examination of the data shows two distinct trend lines and we examine both periods, 1950 to 2011 and the subset of 1980 to 2011.

Starting from 1950, southwestern Michigan has a yearly GDD trend that is effectively flat over the full 61 years of the study (Figure 2.4). The overall trend is a relatively modest 0.691 GDD gain per year (Table 2.1). However, the variation from year-to-year is very pronounced. Michigan has a minimum of 1310 GDD (1992) and a maximum of 1890 GDD (2007), a relative overall difference of 30.7 %. The large amount of inter-annual variability is substantially greater than that of the Napa Valley (Table 2.1). Overall, Napa Valley experiences more GDD, yet far less inter-annual variation (22.4%) with a minimum of 1656 GDD (1980) and a maximum of 2133 GDD (1997) (Figure 2.4). The standard deviations (SD) for both regions are substantially different. The SD for southwestern Michigan is 127.0 GDD over all 61 years while the Napa Valley SD is 111.5 GDD over the same period. The overall size of the range and SD of both regions suggest that Michigan is significantly more variable from year-to-year (Table 2.1). This analysis was repeated with the start date of 1980 in order to specifically reflect recent and current regional warming trends (Andresen et al. 2012b). Following slowly decreasing temperatures from 1950 through the 1970's in the Michigan, a temporal discontinuity is evident near 1980 followed by gradually increasing temperatures (Figure 2.4) gaining more than 3.7 GDD per season (Table 2.1). This trend was enhanced by the 2000 to 2010 decade, which experienced the highest GDD counts overall.

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

[a]SD = Standard Deviation
[b]Pearson's R
[c]Measure of variability within a time series from year-to-year

Table 2.1. Growing Degree Days (GDD) of southwestern Michigan and Napa Valley (CA) from 1950 to 2011 and from 1980 to 2011

Another pivotal trend is the increase in GDD variability between years in Michigan. The SD rose from 127.0 GDD for the period 1950 to 2011 to 138.4 GDD for 1980 to 2011 (Table 2.1). However, this variability is spread over seven stations throughout the region. The change was more dramatic at some individual station sites. For example, the SD at the Benton Harbor Airport NCDC station was 180 GDD during the 1980 to 2011 period. Napa Valley's variation actually decreased during the same time frame with a slight decreasing trend of GDD gain per year (Table 2.1). In summary, the trend since 1980 in both regions suggests warming temperatures, with increasing inter-annual variability in the southwestern Michigan. One potential factor influencing the impressive increases and decreases may be the relatively shorter time frame; however, with 31 years of data behind the 1980 to 2011 study, a trend is present. Another factor is the difference in Köppen climate classifications. Napa Valley features a Mediterranean (*Csb*) climate while 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's *C* climate features a monthly high of 28.3°C in August and a monthly low of 4.1°C in January. Southwestern Michigan's climate sees a monthly high of 27.2°C in July and a monthly low of -8.1°C in January. Michigan clearly sees more variation. At the beginning and end of the seasons (in April and October), Napa has monthly average temperatures of 21.8°C and 24.8°C, respectively. This is much higher than Michigan's temperatures of 13.4°C and 16.2°C in the same months (MRCC 2013 and NRCC 2013). Michigan's cooler start and end to the seasons combined with the irregular nature of when spring "begins" and when fall "ends" lends more variability and more uncertainty to southwestern Michigan. It should also be noted that while both are located on large bodies of water, the size of Lake Michigan does not nearly have the same impact as the Pacific Ocean.

Parameter	1950-2011	1980-2011
Long-term mean	7.63	8.25
SD[a]	3.68	3.66
Coefficient of Variance	13.54	13.42
Autocorrelation[b]	0.23	0.11
Regression[c]	0.08	0.19
Frost Day Gain per Year[d]	0.016	0.074

[a]SD = Standard Deviation
[b]Pearson's R
[c]Measure of variability within a time series from year-to-year.
[d]Frost is calculated as daily minimum temperature of -1°C or lower from April 1st to May 20th.

Table 2.2. Average days of potential frost risk in southwestern Michigan from 1950 to 2011 and 1980 to 2011.

3.3. 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 the southwestern Michigan are evident (Figure 2.4). From 1950 to 2011, there is very little change with a small gain of frost days over time (0.016/year) (Table 2.2). However, from 1980 to 2011 there is a more pronounced counter trend, with a gain of 0.074 potential frost days per year (Figure 2.5). The SD values for both time frames are effectively the same, but the average is slightly higher in the 1980 to 2011 study. This is likely due to the occurrence of the highest values for both time frames in 1989 and 1990 at 16 and 17, respectively. A coefficient of variance for both time frames was found to be approximately 13.5 (Table 2.2) to underscore that finding.

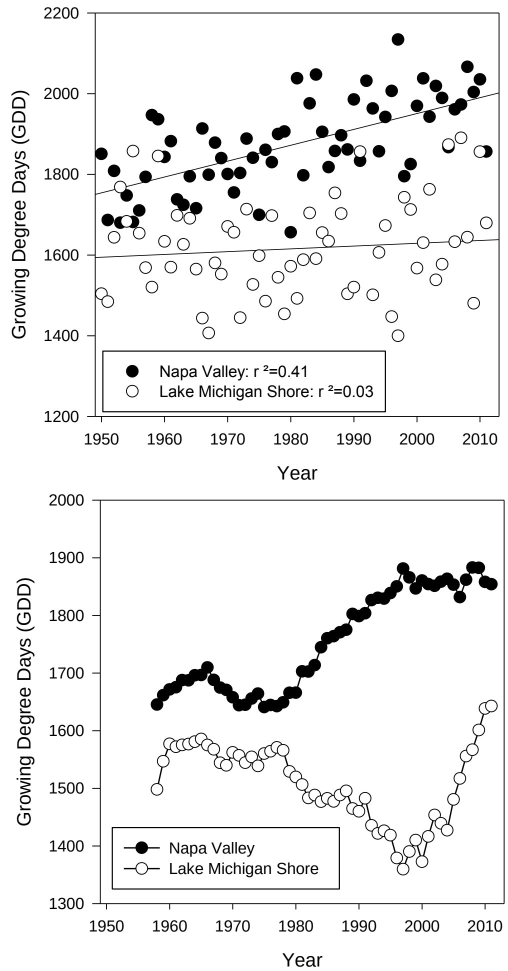

Figure 2.4. Growing Degree Days (GDD) accumulation for Napa Valley and Lake Michigan Shore from 1950-2011 (above) and 9-years moving average (below).

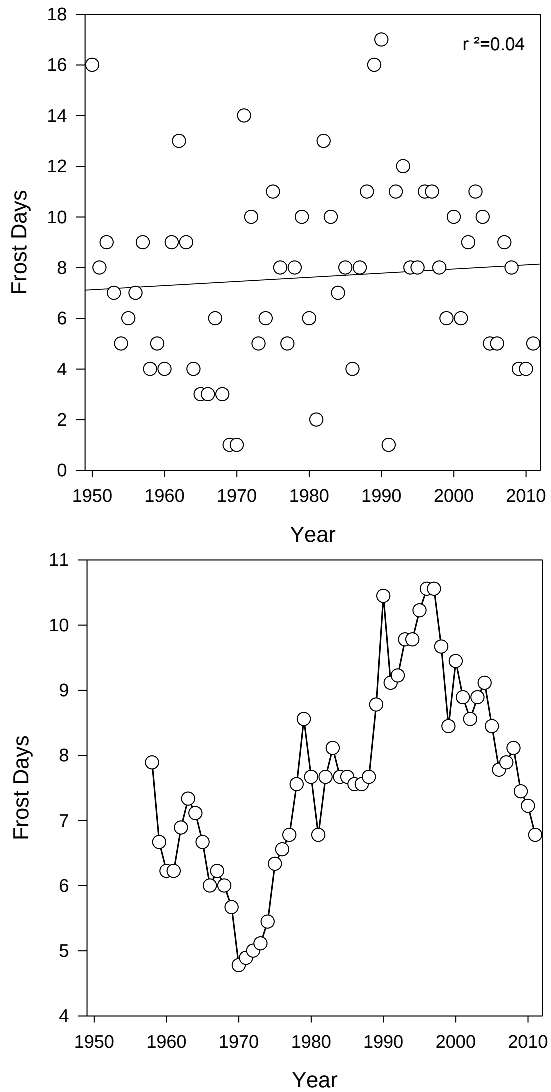

Figure 2.5. Days with risk of frost during early season in southwestern Michigan from 1950-2011 (above) and 9-years moving average (below).

3.4 Seasonal Trends: Growing Season Changes

For seasonal trends, data were obtained from National Grape Cooperative. Data included the date of budburst from 1971 to 2011 and the date of the first fall frost from 1961 to 2011. Budburst in the seasonal growth cycle of a grapevine is crucial to the development of the crop. Budburst typically occurs in April for juice grape varieties in Michigan. If this stage occurs either earlier or later than normal, it can lead to large amounts of variation in fruit quality and crop yield.

The same occurs with 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.

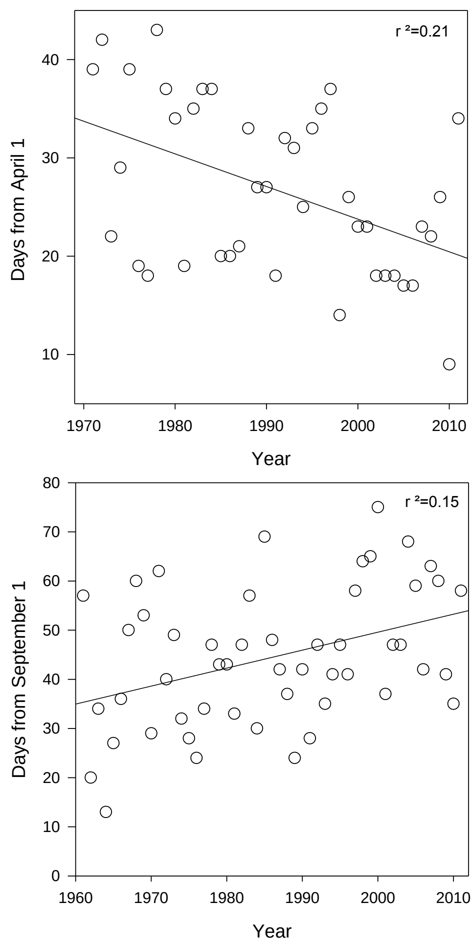

Figure 2.6. Date of budburst for Concord grapes in southwestern Michigan from 1971-2011 and date of first fall frost in Lake Michigan Shore AVA from 1961 to 2011 (Significant at $p < 0.01$ level)

According to National Grape Cooperative, the latest frost-free day (date of last freezing temperatures) for the region has been May 20th and the earliest frost day in the fall season was recorded as September 13th (Figure 2.6). 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 2.7). These four weeks at the end of the growing season are pivotal for late ripening grape varieties to reach fruit technological maturity.

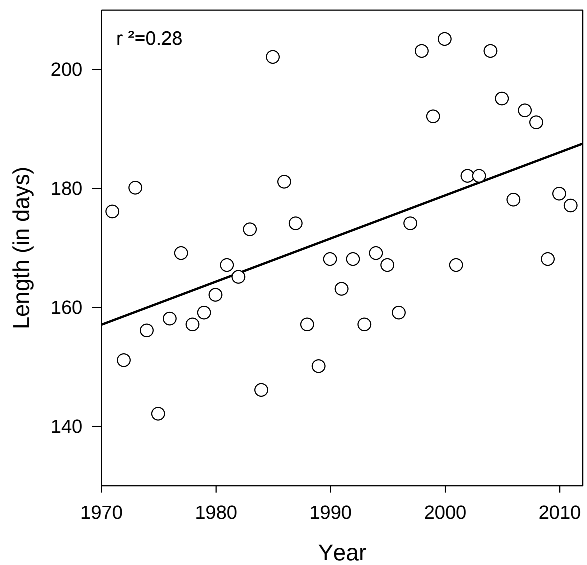

Figure 2.7. Length of the growing season (from last spring frost to first fall frost) for southwestern Michigan from 1971 to 2011 (Significant at $p < 0.01$ level).

4. Discussion

4.1. Temporal Trends

GDD data over time generally reflect a warming trend during the study period, particularly from 1980 to 2011 in Michigan and in 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 2.4). This is largely due to the last decade of the study, in which some of the warmest growing seasons have occurred. Variability has also increased greatly between those two time spans. Compared to Napa Valley, there is general agreement in the trend of increasing total annual GDD, but the year-to-year variability in Michigan far exceeds that of Napa Valley over both time scales by a significant amount (Table 2.1). 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 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 reasons for the greater variability in Michigan are still not clear, 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 notion. For example, in the 1980 to 2011 Michigan GDD series, 71% of the GDD surpluses that have developed by July 1st of each year remain 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 series the percentage is 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 (Figure 2.5). However, the variability was nearly the same with a SD of 3.68 and 3.66 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, it should be noted that 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 towards 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 grape producing region. This trend is a major concern for Michigan's grape producers. While frost damage and occurrence can in many cases be mitigated both through active and passive methods, Michigan growers will need to continue to consider frost as a potential threat every year as it only takes one or two events to harm the entire grape industry.

4.2. 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 on display with areas of cooler temperatures running south along the lakeshore into Van Buren County (Figure 2.2). 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 2.1). While this 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, located in the study area, is placed among regions of high reputation. According to Jones, et al. (2010), the Lake Michigan Shore AVA's 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 of Washington (1528 GDD). However, it should be mentioned that the Michigan calculation was done through the Baskerville-Emin method heat accumulation calculation of observed data and not by deriving the GDDs from daily temperature averages. The difference should only be considered to be 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 2.3). However, it should be noted that no area within the region registered a long-term average of less than 3.0 frost days. This places 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 appear to drop. This is likely an error in the methods of calculation due to the lack of stations in that area. An additional station in this area, or to the north would likely fix this issue. The standard deviation of frost days over the study time period indicates higher levels in the north and northeast, and less in the southeast. The highest levels of SD coincide with the highest levels of frost days. This indicates that viticultural areas experiencing the highest frost frequency year after year are also subjected to the highest level of inter-annual variation in frost potential (Figure 2.3).

4.3. Seasonal Data

Data obtained from National Grape Cooperative (Jasper and Holloway, personal communication) illustrates the change in trends on an average seasonal scale, as well as the associated viticultural impacts (Table 2.3) in relation to yield and soluble solids accumulation. GDD was strongly positively correlated with fruit quality (indexed as soluble solids) at harvest, likely due the higher heat accumulation, favorable condition for better fruit maturation in cool climate viticulture. Contrarily, 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 April 1st, which will include days before budburst. However, potential frost after budburst is negatively correlated to yield as these are prone to damage severely vines at early stage of growth (Table 2.3).

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 2.7). The increase of 28.8 days in the growing season since 1971 shows that southwest Michigan's viticultural area have gained nearly an entire month of potential favorable growing condition. These extra days come from the beginning (spring) and ending (fall) of the season which has implications on yield and fruit quality. While the data is averaged over the study area rather than at individual points, the trend is clear. These changes show that Michigan's climate is evolving rapidly in a warmer direction.

Parameter	Correlation coefficients (r)	Equation	Coefficient significance[a]
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[b] vs. Yield[c]	-0.46	y = -0.3862x + 5.532	**

[a]Coefficient significance: *, **, ***, ns indicate significance at $P < 0.05$, 0.01, 0.001 and not significant respectively. Coefficients for linear (L) or polynomial (P) best fit analysis.
[b]Frost is calculated as daily minimum temperature of -1°C or lower from April 1st to May 20th.
[c]Vulnerable Frost vs. Yield: Calculated by obtaining number of potential frost days during the days from budburst to frost line (May 20th) vs. harvest season yield.

Table 2.3. 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.

5. Conclusion

A number of temporal and spatial trends were found for southwestern Michigan's grape producing 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 year is relatively high. This increases 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 grape growing season in the region, show that there has been 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 frost in the 2012 season destroying 85% of *V. labruscana* juice grapes and impacting severely wine grape 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; or, *caveat emptor*. 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, leaving the state's grape industry confined in the foreseeable future.

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CHAPTER 3 – VERAISION.

INTERANNUAL EFFECTS OF EARLY SEASON GROWING DEGREE DAY ACCUMULATION AND FROST IN THE COOL CLIMATE VITICULTURE OF MICHIGAN

Abstract:

Michigan daily climatic data and seasonal vine performance and phenological data were analyzed to establish relationships between temperature (e.g. growing degree days or GDD) and juice grape yield and quality. 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 season-killing frosts after budburst. However, the months of March, April and May are highly variable from year-to-year in Michigan. The average GDD accumulation at the time of budburst (Avg date: 27 Apr) from 1971 to 2011 was 158 (base 10˚C) with a coefficient of variation for accumulation of 45%. Seasonal GDD deficit or surplus at the midpoint of a 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 irregular 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 likely to still be in deficit (or surplus) at the end of 80.5% of all seasons studied. Lastly, a statistical model based on historical temperature data was created to predict the date of budburst weeks in advance of the long-term average. Michigan's warming trend is likely to continue in the future, which should bring positive effects to this cool climate viticultural region. However, early season variability and post-budburst frosts are likely to still be a concern in the near future.

Keywords: Climate, Viticulture, Early Season Variability, Budburst, GDD

1. Introduction

The State of Michigan is a cool climate viticulture region in the United States, defined as having a growing season temperature average of 13-15˚C (Jones 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 southwestern corner of the State. Vines in these regions can be subjected to freezes in the early season and they can be also limited during the fruit ripening stage at the end of the season by the occurrence of early fall frost. 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 60 years, frost persistence has not dissipated (Schultze et al. 2014). Frost events are a major cause of production failure for grape growers in Michigan cool climate viticulture.

Michigan viticulture is mixed; it is comprised of juice and wine grapes. Concord and Niagara (*Vitis labruscana B.*) are the major juice grape cultivars while Riesling and Pinot noir (*Vitis vinifera L.)* are the most planted wine grape cultivars (USDA 2012). As a result of Lake Michigan's ability to regulate temperatures in the winter months, Michigan experiences two "fruit belts" which 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).

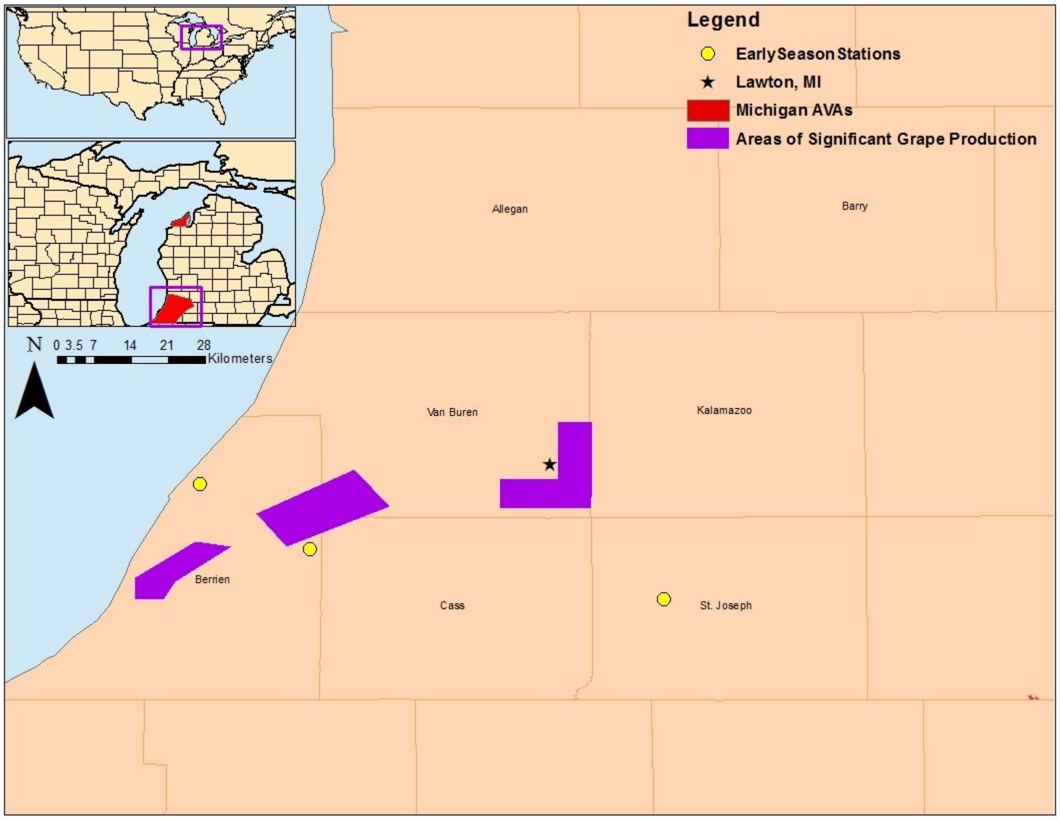

Figure 3.1. Map of Michigan, Michigan AVAs and southwestern Michigan with areas of interest for this study.

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. However, the ensuing Little Ice Age and its associated consistently colder and shorter growing seasons effectively ended *vinifera* production in these areas (Pfister 1988, Gladstones

1992 and Jones 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 as "zones of transition" for *vinifera* grapes production and cultivation, and Michigan is one of these zones. As recent as the early 1960s, *vinifera* production was effectively non-existent 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. Global climates are shifting warmer in the coming decades, 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 impacted with earlier budburst, later fall frosts and generally shorter phenological stages (Bindi 1997, Jones and Davis 2000, Webb et al 2007, Molitor et al 2014).

However, since the 1970s, there has been a considerable shift to the production 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. 2014). 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 similar issues 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 and 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 on the topic of GDD deficit/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 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 were approximately 0.75 t/ha, a little more than one-third of the long term average of 2.05 t/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 30-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 USDA, losses to some fruit varieties were as high as 95% (tart cherries) and losses were 75% and 40% 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 fronts in 2012 spring, areas where cold air drainage potential was the highest suffered the least amount of damage, and these non-affected areas were able to take advantage of the extraordinarily warm and dry summer of 2012 to produce high quality winegrapes.

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% 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 state may see a benefit from warmer spring temperatures, but overall, these warmer temperatures may 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 in a cool climate viticultural region. This is being done in order 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 paper also attempts to develop a simple budburst model using temperature as an indicator of potential budburst several weeks in advance.

2. Data and Methods

2.1 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. Southwestern Michigan's climate is classified as a *Dfa* Köppen Humid Continental Climate class (Köppen 1900; Geiger 1965). While 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 (Moroz 1967). 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 plant (Zabadal et al 2007; Filo et al 2013)

The Lake Michigan Shore AVA, located in southwestern Michigan, was chosen for this study because of numerous weather stations and availability of long-term crop statistical data from the National Grape Cooperative (Jasper and Holloway, personal communication). The Lake Michigan Shore AVA runs for 115 kilometers along the Lake Michigan shoreline in southwestern Michigan bounded by the Indiana-Michigan border, which serves as the southern boundary, to the terminus of the Kalamazoo River in to Lake Michigan. The AVA runs east along the Kalamazoo River and in to the interior of the state and includes the cities of Kalamazoo, Paw Paw, Lawton, and Dowagiac and is delineated by two major railroad lines running south and southwest to the Indiana-Michigan border (ATF 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, MI, the location of where the National Grape Cooperative data were obtained.

2.2 Data

Temperature data were obtained from the National Climatic Data Center (NCDC)'s network of weather stations within the Lake Michigan Shore AVA using the NCDC online mapper tool: (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 utilized 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 which 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, MI.

The National Grape Cooperative contributed with annual viticultural data (1971 to 2011) on dates of budburst, yield and fruit quality (sugar concentration, measured as soluble solids or Brix via refractometer). Viticultural data was collected from 25 vineyards of members of the National Grape Cooperative located in southeastern Van Buren County, near Lawton, MI., where a grape processing plant is located (42.16ºN, 85.83ºW). The crop statistics are the average of the 25 vineyard plots on a seasonal basis. These statistics include the dates of first fall frost (1961-pres), budburst (1971-pres) and yield (1975-present). Budburst was recorded as the date when 50% of the buds reached phenological stage 4 (Eichhorn and Lorenz 1977) in all the experimental plots.

3. 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 2 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, season mid-point and entire growing season.

Early season GDDs were calculated at three NCDC stations (Table 3.1) using the Baskerville-Emin single sine method (Baskerville and Emin 1969) using the stations' Tmax and Tmin variables. The "early season" is considered to be from 1 March to 20 May, with the latter date being the "frost free" date (according to the National Grape Co-operative), 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 et al. 2013). The mid-season point was calculated as the mid-point 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 mid-season average date. This date was important for determining whether a season was in surplus or deficit of GDD at the mid-season point.

Data	**Source**	**Variable**	**Period of Record**
GDD[x]	National Climatic Data Center	GDD (Single-Sine) with base 10˚C	1950-2011
Frost Occurrence	National Climatic Data Center	# 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

[x]*Growing Degree Days (GDD)*

Table 3.1. Data sources, variables and period of records for the different variables included in this study.

Potential occurrences of frost were also calculated from this data. An occurrence of frost was considered 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 both from 1 Apr to 20 May, and from the date of budburst to 20 May. The reason for the latter analysis was to assess the potential damage of frosts after budburst had already occurred. 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 was correlated with data from the National Grape Cooperative (Jasper and Holloway, personal communication). Such data include the date of budburst, harvest soluble solids concentration (Brix) and yield (t/ha) (Table 3.1).

A statistical model for the date of budburst was also developed. Prediction of budburst had been performed before (Wermelinger et al. 1991, Bindi et al. 1997, Nendel 2010), but using different methods and different objectives. The goal of creating this "historical" model is to establish a potential method for the prediction of budburst using readily available climatic data. The need for such a model arose from the lack of success of a "rule of thumb" approximation proposed by Amerine (1980) and Mullins (1992) where budbreak was assigned to a date after 5 days of GDD accumulation. This statistical model is a multi-linear regression model developed using historical heat accumulation in the early season. 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 Mar (X_1), slope of GDD accumulation from 1 Mar to 31 Mar (Y_1), GDD total on 15 Mar (X_2), slope of GDD accumulation from 1 Mar to 15 Mar (Y_2) and the 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 Mar to 15 Mar. This is done because not all years have accumulations starting after 15 Mar, 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. Using the variables between these dates allows for the model to make a prediction on 1 Apr, nearly four weeks prior to the long-term regional average for budburst (27 Apr). The period of 1 Mar to 31 Mar was used as it is both in a time of yearly GDD accumulation and it is sufficiently prior to the date of potential budburst.

4. Results

4.1 Connections between climate based variables and crop statistics

Climate based variables and crop statistics from the National Grape Cooperative (Jasper and 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 (Fig 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 on a seasonal basis there is a positive correlation between GDD accumulation and between the relative quantity of GDD deficit/surplus that the specific season experienced. Significant correlations between yield, brix and other variables are also reported (Fig 2).

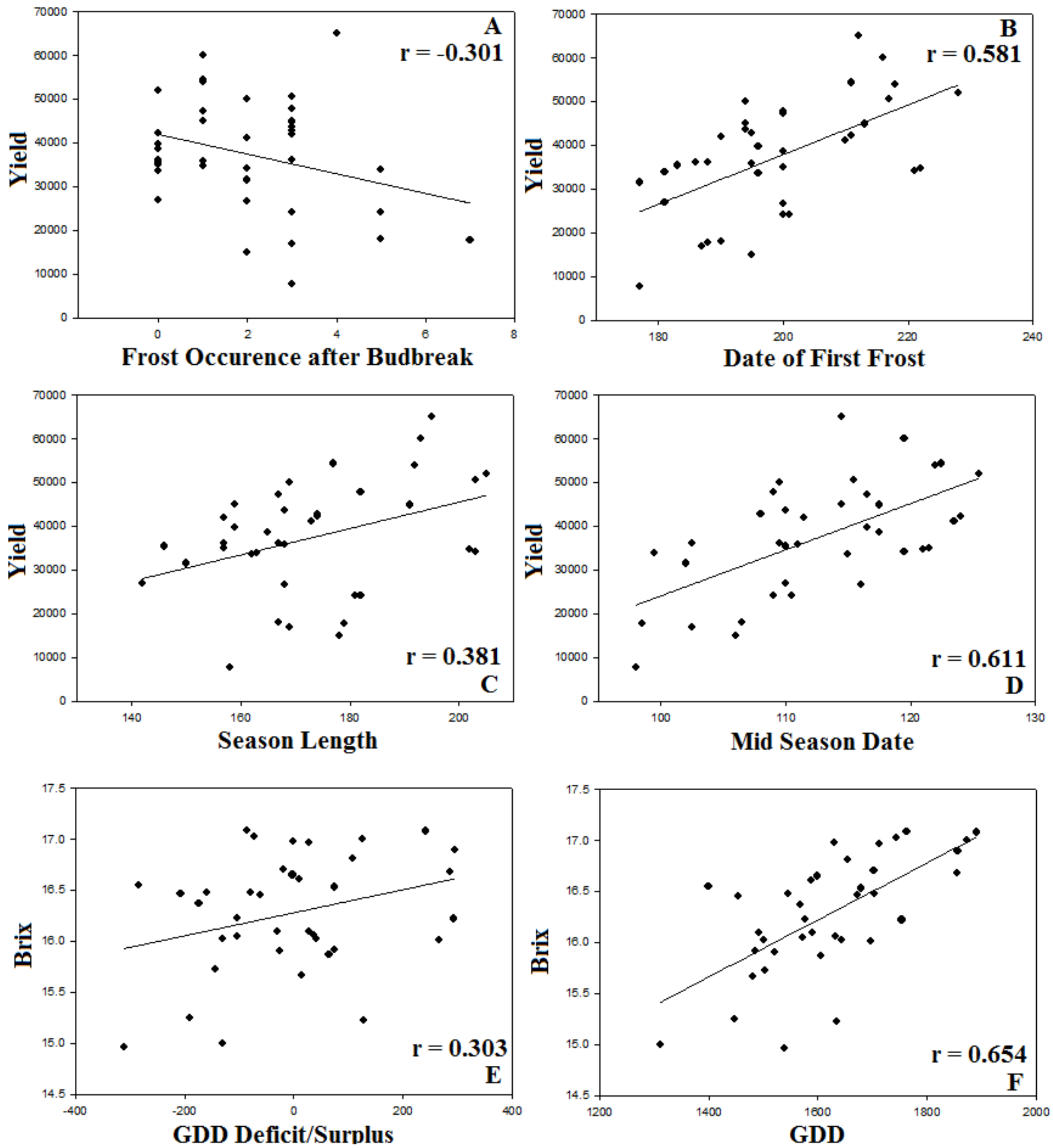

Figure 3.2. Pearson's R correlations at $p<0.05$ significant levels for climate based variables vs. crop statistics from National Grape Cooperative.

Overall, the average GDD accumulation for the date of budburst (Avg = 27 Apr) from 1971 to 2011 was 158 (base 10˚C). However, this average encountered a considerable amount of variability. The standard deviation of the long-term average was 71, with a coefficient of variation of 45%. 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.

4.2 Trends in budburst and frost

The 9-year moving average of the amount of frosts that occur after budburst and the seasonal total GDD along with the date of budburst are reported in Figure 3.3. There are strong, long-term trends in frost occurrence and the date of budburst in southwestern Michigan. This increase is nearly in 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. However, frost occurrence and budburst are independent variables, thus an early budburst does not imply that frost occurrence will be a certainty. It should be noted that the calculations are from 9-year moving averages (Figure 3.3). This was done to gain the overall status of the changes in the seasonal data and also to remove "noise" from the dataset, such as the 1992 year where GDD levels fell to their lowest level, and budburst occurred on its latest dates in 1992 and 1993.

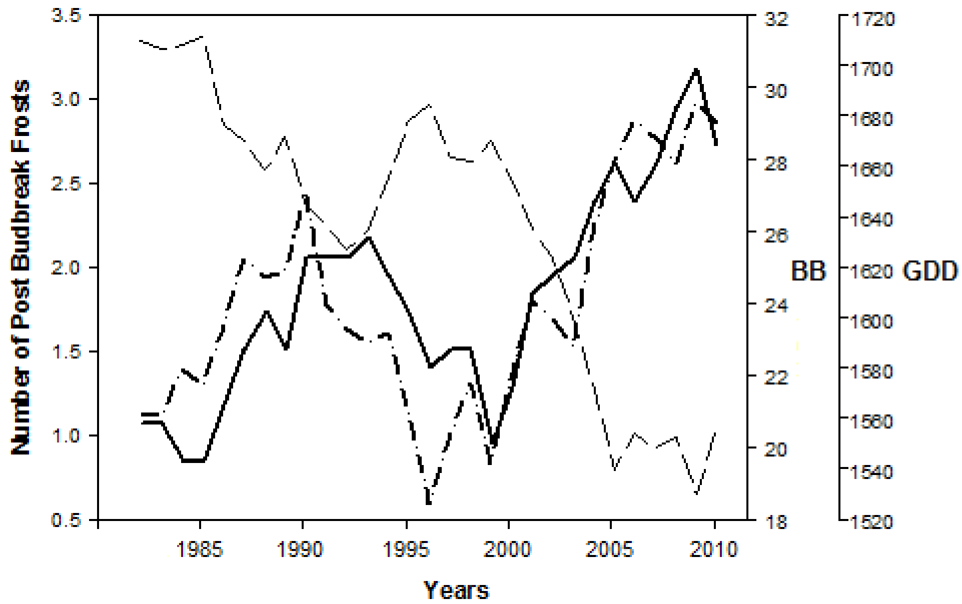

Figure 3.3. 9-Year moving averages of days of post-budburst frost (solid line), seasonal GDDs (dash-dot line) and date of budburst (dash line).

4.3 GDD deficits, surpluses and grapevine performance

GDD accumulation occurs at a different rate each season. Figure 3.4 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 if 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 41 years of this study, most seasons (33 of 41) that began in a surplus or deficit from 1 Apr to the date of long term average 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% of the time. This suggests that early season GDD accumulation can statistically be used as a good indicator of the total season GDD, although there is no clear physical process that is physically responsible for this.

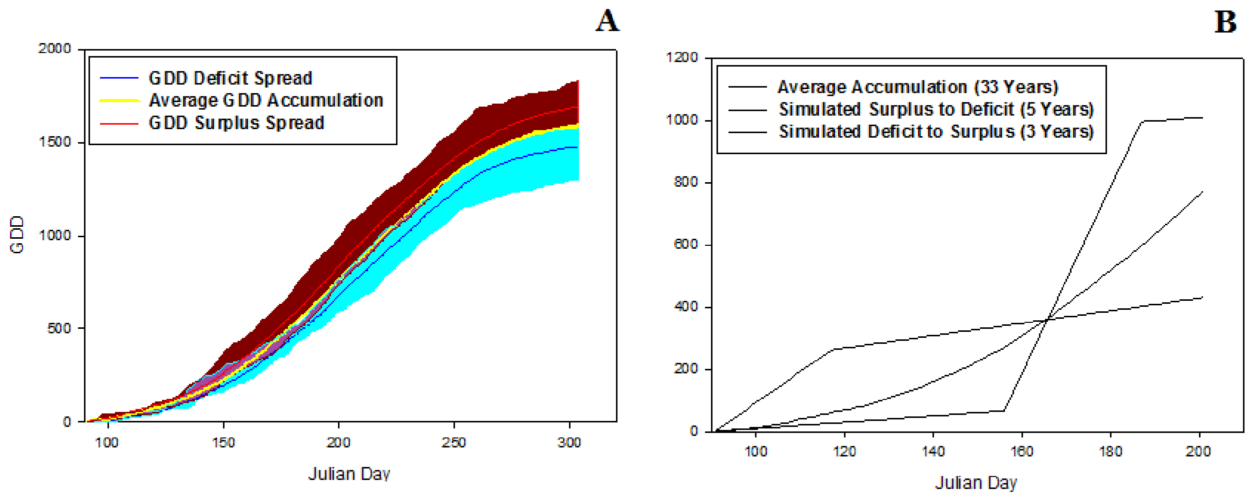

Figure 3.4. Average GDD accumulation (1971-2011) (in Yellow) and spread of GDD deficits (blue) and surpluses (red) (Panel A). Occurrences of accumulations in early season with the average accumulation (1971-2011) and hypothetical years where a season goes from deficit to surplus or surplus to deficit (Panel B).

GDD accumulation is a function of maximum and minimum temperatures, thus the peak off 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 (bounded by budburst and the first fall frost), the GDD at the average mid-season 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 3.2), 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 mid-season 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.

4.4 A simple budburst model

The recommendation from Amerine (1980) and Mullins (1992) and used by Jones (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 "5 days of accumulation" approximation was proven correct in 2 out of 41 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 16 days early. Figure 3.5 displays comparison between observed budburst and the approximated date using the "5-days" methodology.

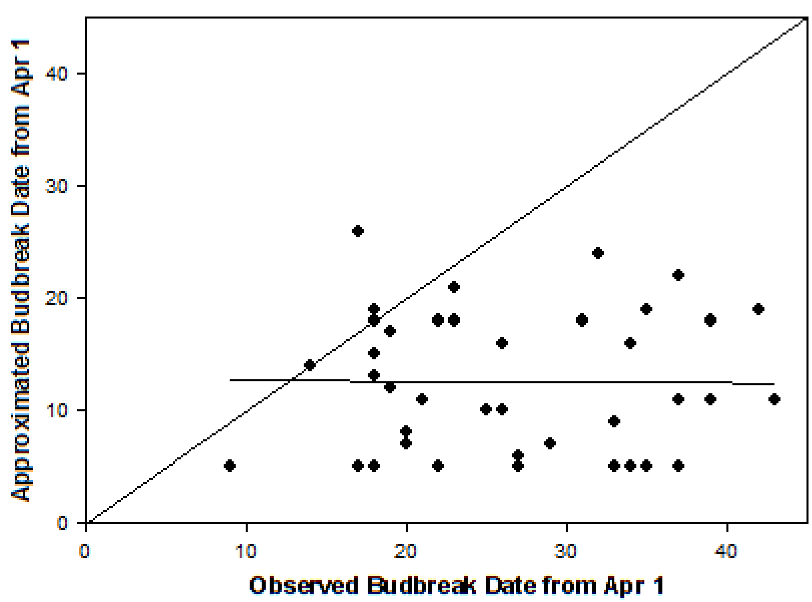

Figure 3.5. Comparison of the "5 days approximation" with observed data from southwest Michigan from 1971-2011.

It should be noted that this may be due to Michigan's complex climatology in the winter-spring months. In order to supplant the "5-days" 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 budburst prediction model is composed of five variables, all of which pertaining to GDD accumulation. When combined in to a multi-linear regression, this equation was calculated:

(1) Date of Budburst = 71.486 + (0.129 * X_1) + (1.068 * Y_1) + (0.675 * X_2) - (11.173 * Y_2) - (0.722 * Z)

Equation 1: Model for predicting the date of budburst using the variables GDD total on 31 Mar (X_1), slope of GDD accumulation from 1 Mar to 31 Mar (Y_1), GDD total on 15 Mar (X_2), slope of GDD accumulation from 1 Mar to 15 Mar (Y_2) and the total days of accumulation (Z). Calculated as Days from 1 March.

The budburst model achieved a Pearson's R value of 0.6 when comparing the approximated date of budburst versus the actual day of budburst from 1971 to 1999 (Figure 3.6). The mean average error, calculated as the number of days difference between the observed and predicted date of budburst, was 3.5. The model did under-predict the date of budburst, and in two of the 29 years, it was off by more than 10 days. However, the general average is sufficiently accurate and the model was typically off between 2 and 5 days while making a prediction four weeks prior to the average date of budburst in this region. 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 7 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.

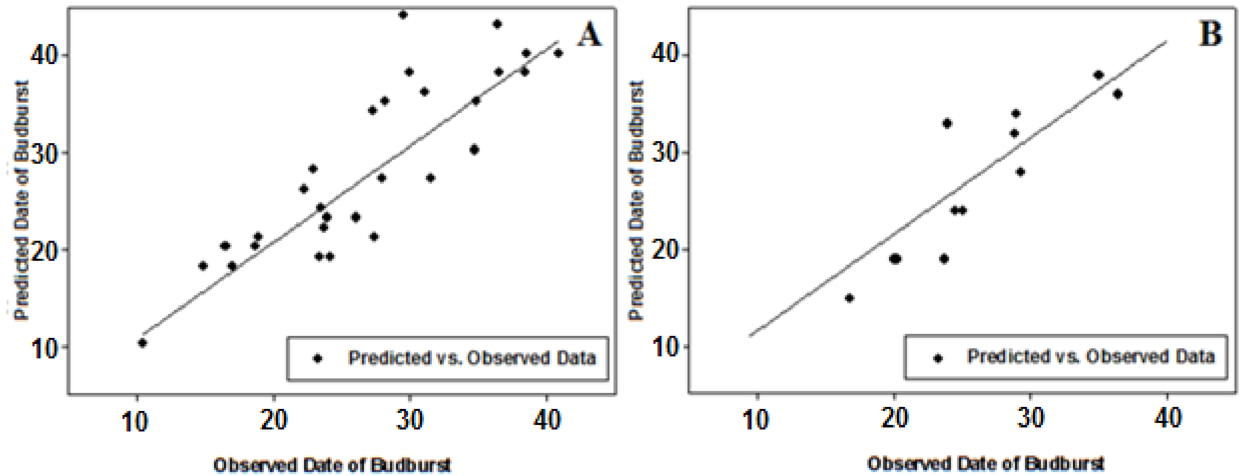

Figure 3.6. Predicted date of budburst vs. actual date of budburst in historical model (R = 0.60, p<0.05) from 1971-1999 (Panel A) and in validation phase from 2000-2011 (Panel B).

5. Discussion

5.1 Trends in frost, GDD and budburst

Since 1971, budburst is occurring much earlier in the last few years (Figure 3.3). This follows the long-term trend of a warming occurring in spring in the northern Hemisphere (Schwartz et al 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 3.3). The earlier budburst increased the number of post-budburst frost events in southwestern Michigan (Schultze et al. 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 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 1992; Jones 2000), while useful for approximations in areas with less intensive data records, is not sufficient for a climate such as the *Dfa* Humid continental Köppen climate found in southwestern 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. However, since Michigan's frost persistence is not decreasing along with earlier budburst, the frost risk will still exist and may 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.

5.2 Crop statistics and climate data relationships

Several climatic data affects harvest parameters (Figure 3.3). Correlations were performed over 30 different combinations of data set, but only six resulted significant. This demonstrates that other environmental and physiological variables not considered in this study may 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 impacting photosynthetic carbon production and allocation to the fruit (Figure 3.2). Each season's mid-season datehas a strong positive correlation with yield likely because the date of the mid-season suggests whether a vine experienced a good or bad spring. However, it must be considered that anthropogenic activities also influence yield (e.g. pruning, training and time of harvest).

5.3 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/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 3.7) is displaying 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 1300-1400 GDD (deep orange-red) and the few examples where this is not the case are clearly seen. But the early season 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 mid-season 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.

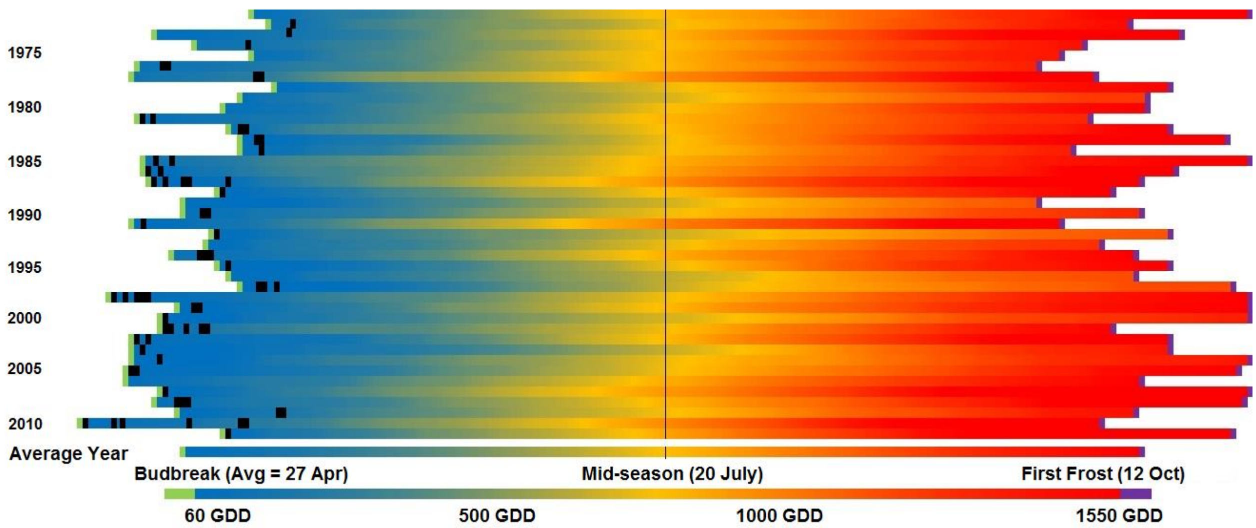

Figure 3.7. Diagram displaying GDD accumulation for SW Michigan from 1971 to 2011 along with average date of budburst (green), mid-season and first frost (purple), and frost events after budburst (black).

5.4 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. The date of prediction could be made as early as 1 April, which is nearly weeks earlier than the long term mean date of budburst. A four week lead time with a mean average error of 3.5 days shows that this method could be beneficial to growers. The model was only off by more than 10 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. Starting the date on 1 Feb was also attempted, 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 “5-days” approximation. However, we do believe that this statistical model may be a 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 utilizing 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-cold 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.

5.5 Michigan and the future

This research attempted to describe the importance of the early season in cool climate viticulture. 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. However, the goal of this paper was not solely to demonstrate such importance, it was also to bring attention to the climate of a location that several decades ago was deemed unsuitable for wine-grape production. The State of 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 towards being more accommodating for *vinifera* cultivation. Schultze et al. (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 winegrapes 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 winegrapes (Gladstones 2005 and Jones 2006). Jones (2007) describes 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 winegrape production. Consequently, we believe that Michigan can be considered the "petri-dish" of the world's changing climate for winegrape 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 and 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) does 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 et al. 2013 and from data presented in this paper. Frost is not decreasing in occurrence commensurate with the rate of warming in this region (Figure 3.3). Budburst is occurring earlier on average in Michigan while 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 risk post-budburst, which could severely impact an annual crop in both quantity and quality. Currently, we are limited to our own dataset, but it is logical to infer that this will also occur in the regions what 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) was referring to in his research. Thus, earlier budburst in these cool-cold climates makes frost risk an even bigger concern for winegrape 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 it shows that spring frosts will still pose a challenge for growers in the coming decades in cool climate viticulture. However, the histories of Luxembourg and Michigan's winegrape industries are quite different 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 may become less of a problem. However, 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, post 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 winegrape production and we believe Michigan's current research will be a cornerstone of those future area's production. However, we believe in cool climates, frost risk will increase over the next decades as earlier budburst dates will expose vines in the early season to potential ruinous frosts.

6. Conclusions

The importance of early season GDD accumulation and frost and their connections with end season variables in a cool-cold 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 may be able to better prepare for the potential risk of a post budburst frost. Having such a model may lead to increases in yield and quality on a seasonal basis.

Like most climate-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 25 vineyards. Data from the individual plots would potentially allow for more analysis to be done, particularly in a spatial context. We also acknowledge that using GDD is one of several methods to be used as a metric for comparing inter-annual 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-cold climates. However, data on frost occurrence is not readily available and in the absence of such data, frost must be calculated remotely or indirectly. Cool-cold climates will uniformly need to continue to battle frost, and prediction of the date budburst can be pivotal. However, as global climates continue to rise in temperature and more areas become viable for grape production, frost will invariably be a factor. This means that the importance of the early season, climatically, and thus phenologically, cannot be overstated.

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CHAPTER 4 – MATURITY.

EFFECTS OF A WARMING TREND ON COOL CLIMATE VITICULTURE IN MICHIGAN, USA

Abstract

Historically, Michigan has been considered a cool climate Viticultural region in the United States. Michigan's climate has mainly three challenges for grape production: it did not have reliably warm summers, the growing season was too short from spring frost to fall frost and there was much rain occurring at harvest time, which is very unfavorable for high quality grape production. However, since the 1960s, there has been a significant shift from *Vitis labrusca* (North American) grapes to *Vitis vinifera* (wine grapes) planting in the state of Michigan. This is due to the warming of Michigan's climate and several other factors that have created a climate more conducive for *vinifera* production in the region. The goal of this study is to analyze the historical shift in climate and its potential future effects. This paper obtained data from the NEX-DCP30 downscaled version of the CMIP5 suite of model experiments run in the RCP4.5 and RCP8.5 scenarios of greenhouse gas emissions in the ensuing decades of the 21st Century and focused on Michigan's future climate pertaining to grape production. First, a multi-linear regression model was built to predict future grape yields (t/ha) using data from the climate model projections. This model was found to have adequate accuracy ($r^2 = 0.66$, mean absolute error =0.59 t/ac) and found that the two RCP scenarios have very different future scenarios for grape production in terms of yield. Second, Michigan's issues with temperatures, season length and precipitation timing are analyzed with the climate projection data. In all three cases, Michigan's climate is likely to become more conducive for *vinifera* production as the three issues begin to diminish in severity in the coming decades.

Keywords: Viticulture, Climate Change, Climate Models, Wine, Great Lakes

1. Introduction

From a climate perspective, Michigan is considered a “cool-cold” climate viticulture region of the world: cool is referred to the summer and cold is referred to the winter temperature (Gladstones 1992; Zabadal and Andresen 1997). This classification is due to a combination of climate challenges that the grape growing industry has historically encountered. The first issue is the average growing season temperature. Michigan’s average growing season temperature in the 1950s and 60s was 14.1C in the northwest corner of the Lower Peninsula and 16.5C in the southwest corner of the State. Both areas experienced summers with appreciable variability on a yearly basis, with a 0.19 and 0.21 C standard deviation, respectively, in temperature during the twenty-year period. Michigan’s two potential regions for *Vitis vinifera* production were generally too cool, as any warm years would occur unreliably. The second issue centered on the distribution of monthly rainfall. Michigan’s west coast is classified as a *Dfa* Köppen climate classification (Köppen 1900, Geiger 1965), with consistent precipitation year-round. However, the peak of precipitation occurs in the months of August and September and October, which coincide with veraison (August), the vine phenological stage where the fruit begins to ripe and harvest (September and October). Rainfall after veraison and during harvest increases yield loss due to disease and poor fruit technological maturity (Gladstones 1992, Zhuang at al, 2014). Consequently, Michigan’s monthly rainfall distribution was considered to be a negative factor in the production of *vinifera* grapes. In addition to temperature and precipitation concerns, Michigan’s growing season was considered relatively short for several grape varieties commercially important in US (e.g. Cabernet Sauvignon, Cabernet Franc, Merlot). As of the early 1970s, Michigan’s growing season from budburst to first fall frost was approximately 160 days

(Schultze et al., 2014). The grape growing season was limited by late bud-bursts, potential hazardous frosts in the spring and an unreliable timing of the first fall frosts ranging from as early as 13 Sept to as late as 30 Oct (Jasper and Holloway, personal communication). Early and late season frosts can be particularly damaging to vines and are thus of concern in cooler climates. Exposure to air temperatures at or below -1C can significantly damage buds in the early season (Zabadal and Andresen 1997) and expose fruit to risk at the end of the growing season (Molitor et al., 2014). Data are limited to the southwest of Michigan, and we assume that the growing season in the northwest (not as extensively measured for grape production as in the southwest) was shorter due to even later bud-bursts and earlier fall frosts. When considering the three major concerns of the region were that Michigan was too cool, was too wet at the wrong time and had a short season, it is remarkable that *vinifera* production began in the late 1960s (Hathaway and Keggeris, 2011) and since its initial plantings, has grown into a considerable industry in a relatively short amount of time. Part of the reason this has occurred is almost certainly due to Michigan's climate becoming more favorable for *vinifera* production in recent decades.

The climate in the region of the Great Lakes has experienced warming commensurate with the global trend in higher temperatures with the region experiencing an approximate 1.0°C increase in temperatures since 1980 (Andresen et al. 2012). Schultze et al. (2014) found the shift in southwest Michigan's climate since 1980 contributed to a 3.7 GDD per year increase (base 10°C) in southwest Michigan; a trend likely to continue in to the near future. The research also found that GDD accumulations in the 1950s and 1960s were typically between 1300 and 1500 units, which is considerably lower than the long term mean from 1980 to 2011 of 1628 (Schultze et al. 2014). It should be noted that *Vitis vinifera* production in Michigan did not begin until the late 1960s, and did not expand beyond a few small plots until the 1980s. According to the USDA, from 2000 to

2011, Michigan underwent a nearly 300% increase in *vinifera* acreage (USDA-NASS 2012). GDD accumulations in the first decade of the 2000s were typically in the >1600 range, and never below 1400 units. This reflects the fact that Michigan's warming climate is becoming more conducive for *vinifera* production. Michigan's ability to go from incapable of supporting *vinifera* production to becoming a region of considerable production of wine grapes places Michigan in a "zone of transition"; from being able to support primarily one species of grape (juice grapes, V*itis Labrusca*) to being able to accommodate a wide range of wine grape varieties.

The goal of this research is to explore the possible direct and indirect effects of climate change on grape production in Michigan over the next decades up to the end of the 21st Century. A previous study (Schultze et al. 2014) was focused solely on the southwest portion of Michigan due to the availability of long-term yield data acquired from the National Grape Co-operative (Jasper and Holloway, personal communication). This study will discuss potential implications on yields for the southwest region of Michigan, but climate projections will still be addressed for the northwest, as it is likely to continue to be an important part of Michigan's wine grape industry. The aforementioned three primary obstacles will be addressed for the Michigan's potential *vinifera* industry and how shifts in climate will help the region overcome those problems. This work will use data obtained from a number of sources including; 1) the National Grape Cooperative, 2) the CMIP5 downscaled NEXDCP-30 dataset, 3) Michigan State University's Enviro-weather Mesoscale network and 4) National Climatic Data Center to evaluate potential trends in Michigan climate. By combining these sources, issues such as season length, growing season temperature, rainfall distributions, potential yields and potential new varieties of *vinifera* from 2012 to 2099 can be addressed. This study focuses on climate projection data for both the southwest and northwest of Michigan.

2. Methods and Materials

2.1 Site Description

The primary grape producing areas in Michigan are located in the west coast of the Lower Peninsula. There are four American Viticultural Areas (AVAs) within the state, two of which are located in the southwest corner (Fennville, Lake Michigan Shore) and two in the northwest portion of the lower peninsula (Leelanau, Old Mission) (Figure 4.1). The reasons for the location near the shores of Lake Michigan are: a) the climate moderating effects of the Lake and b) topographic influences, which allow for drainage of cold air during the spring and fall seasons. Growing *vinifera* grapes farther inland or in flat regions in Michigan is not recommended, as spring/fall frosts and harsh winter temperatures can combine to potentially damage or even kill vines (Zabadal and Andresen, 1997). These potentially dangerous temperatures still occur in the coastal areas where *vinifera* grapes are grown, but site selection and vineyard management are key to mitigating these potential damages. Thus, large-scale losses are less common in these regions as compared to areas as little as 30 miles inland.

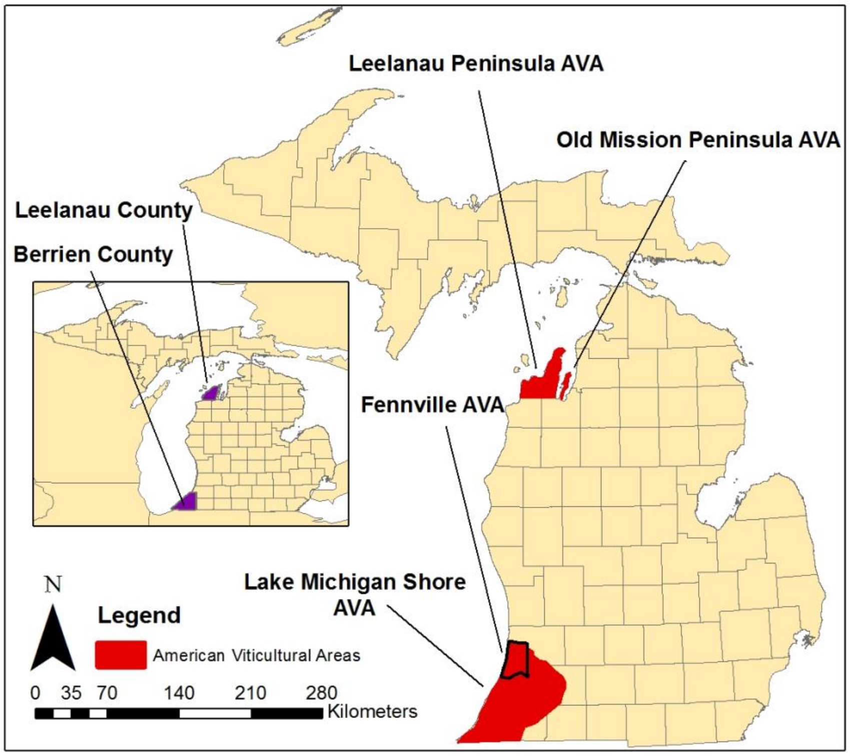

Figure 4.1. Map of Michigan's American Viticultural Areas (AVAs). Leelanau and Old Mission Peninsula AVAs will be referred to as "Northwest Michigan" and Fennville and Lake Michigan Shore AVAs will be referred to as "Southwest Michigan" in this paper. Both northwest and southwest Michigan will be compared in terms of current and future climate.

Southwest Michigan is classified as a *Dfa*, humid continental climate in the Köppen Climate Classification system (Köppen 1900, Geiger 1965). Northwest Michigan is classified as a *Dfb* climate with shorter summers and colder winters than areas to the south. However, the small areas that are located within the Leelanau and Old Mission AVAs are areas located on peninsulas (the AVAs are named for their respective peninsula) in Lake Michigan and Grand Traverse Bay. The ability to grow *vinifera* grapes in these regions is due almost entirely to the presence of favorable microclimates where the temperature during fall, winter and spring are much warmer than surrounding areas. It is likely that the microclimates in the northwest are much more similar to the *Dfa* climates found in the southwest Michigan AVAs. A combination of microclimates and the close proximity of the Lake help to limit temperature extremes compared to areas farther inland due to consistent lake and land breezes (Moroz 1967).

2.2 Data Collection

This research relies on future climate projections from the fifth phase of the Coupled Model Intercomparison Project (CMIP5) suite of climate models. CMIP5 was developed to answer the many questions posed by the Intergovernmental Panel on Climate Change (IPCC)'s fourth assessment report (Solomon, 2007). Among the many potential improvements to the experiments, one group of hypothetical scenarios is of particular interest to our research. Included in the model experiments were four different, transient greenhouse gas (GHG) scenarios wherein the amount of global emissions of GHGs followed different potential cases. These "representative concentration pathways" (RCP) scenarios would project global GHG emissions in the coming decades using different econometric and social models where the number following "RCP" represents the increase in radiative forcing values (measured in W/m^2) by the year 2100 relative to pre-industrial values (van Vuuren et al. 2010). In one such scenario (RCP4.5), GHG emissions are reduced on a global scale at a certain point in the future on the assumption of policy action by global leaders. In another scenario (RCP8.5), very little to no action is taken. As such, these scenarios involve different reactions by global temperatures to these hypothetical GHG emission scenarios (Taylor et al. 2012).

The results of many of the CMIP5 models were released in 2013. However, one of the limitations of such a large undertaking when creating such a large model projection dataset is that model resolution has to be sacrificed limited by computational power, storage space among other factors. Most model runs in the CMIP5 models have a resolution of ~100 km., Projections at such a resolution is useful for continental to global scale studies, but problematic for regional scale applications. This problem, according to CMIP5's executive summary, presents an issue with point observations and with the spatial areal issue, in that a spatially averaged value (one gridcell) is not representative of a point observation within the grid cell (Taylor et al. 2012). One method to manage this concern is through the downscaling of grid cells from a lower resolution to a higher resolution. The NASA Earth Exchange Downscaled Project (NEX-DCP30) is one project that downscaled a number of CMIP5 model runs down to a resolution of 800 meters for the entire contiguous 48 United States. Using the Bias Correction Spatial Disaggregation methodology established in Wood et al. (2004), NEX-DCP30 allows users to use future climate projections to perform environmental analysis at a manageable resolution. These projections are based on data obtained from the Parameter-elevation Relationships on Independent Slopes Model (PRISM) temperature data and this data transitions seamlessly into 32 different CMIP5 models until the year 2100 at a monthly time step for three variables: Temperature max (Tmax), Temperature min (Tmin) and Precipitation. This downscaled analysis of the climate models allows for a high-resolution analysis of future trends. It is of particular interest in an area like the Great Lakes Region, where the land-water interface is highly difficult to resolve in models where the resolution is bigger than 50 km.

The NEX-DCP30 downscaled data was compiled from the National Climate Change Viewer (http://www.usgs.gov/climate_landuse/clu_rd/apps/nccv_viewer.asp), managed by the United States Geological Survey (USGS). The downscaled data was downloaded on a county scale and averaged over the county in focus. The two counties focused on in this study were Berrien county (southwest MI) and Leelanau county (northwest MI). These counties, combined, account for a significant portion of Michigan's *vinifera* production and are likely to expand in acreage in the coming decades, potentially following the near 300% trend in *vinifera* acreage growth from

2000 to 2011 (USDA-NASS, 2012). The dataset, downscaled to a resolution of 800 meters and then averaged over the county area, does introduce uncertainty as the data was downscaled from the much larger climate model scaled projections. However, such a fine resolution is needed for studies where microclimates are a part of the study and is crucial in a region like the Great Lakes, where the land-water interaction is either idealized or roughly estimated due to the coarse resolutions of the models.Averaging the NEX-DCP30 data over a county is also reflective of the dataset for yields used in this study. The data obtained from the National Grape Co-operative was taken as the average from 25 plots from around the southwest portion of Michigan.

2.3 Experimental Design

In order to describe how the continual warming trend has affected and will continue to affect Michigan's wine grape industry, it was necessary to use data from historical sources in conjunction with future projections. First, temperatures (max, min and mean) were calculated for the growing season (1 Apr - 31 Oct) for both regions considered in the study. The NEXDCP30 dataset (future projections) has data obtained from 32 model runs plus one ensemble mean of all models run in the RCP4.5 and RCP8.5 greenhouse gas emission scenarios. However, these model simulations begin in the year 1950. The historical data from these models was developed by incorporating PRISM temperature and precipitation data when the creators were using the Bias Correction Spatial Disaggregation (BCSD) method of downscaling (Wood et al, 2004). This downscaled data was used as historical climate in SW and NW Michigan in this study from 1950 to 2005. From 2006 to 2099, there were 32 different model runs for each RCP scenario, and there was one ensemble mean for all models. This historical and future projection data was then used as the input for the analysis in this paper.

This analysis includes a multilinear regression based on past climate and grape yields in order to predict future trends for grapes. Similar concepts in methodology for the application of future climate projections in to statistical models for estimating future grape yields can be found in Lobell et al (2006) and Santos et al (2011). This multilinear regression is limited only to the SW of Michigan, as that is where the yield data has been recorded for decades by the National Grape Co-operative. This regression calculates potential yield in future years based on both historical data and monthly and seasonal climate projections in the RCP4.5 and RCP8.5 scenarios based on five variables: Average Growing Season Temperature (GST), Growing Degree Day totals (GDD), Potential Early Season Frost Occurrence (Frost), Total Season Precipitation (PPT) and Early Season GDD Accumulation (eGDD). NEXDCP30 data was used to directly obtain two data sources (GST, PPT, eGDD) and to indirectly obtain the other variables using regressions (Frost, GDD).

Variable	*Source*	*Equation*	*R^2*
GST	Historical Model Runs	Tavg of Apr-Oct months	
PPT	Historical Model Runs	Total Precipitation of Apr-Oct months	
Frost	Regression	-10.410 + (1.389 * MayTmin)	.52*
GDD	Regression	-996.347 + (118.021*JunTavg) + (237.501*JulTavg) - (298.855*AugTavg) + (67.267*SepTavg)	.61*
eGDD	Historical Model Run	Tavg of April	

Table 4.1. Table of variables used in regression model for yield data in southwest Michigan along with equations and accuracy of regressions for Frost and GDD variables. * = significant at p<.001

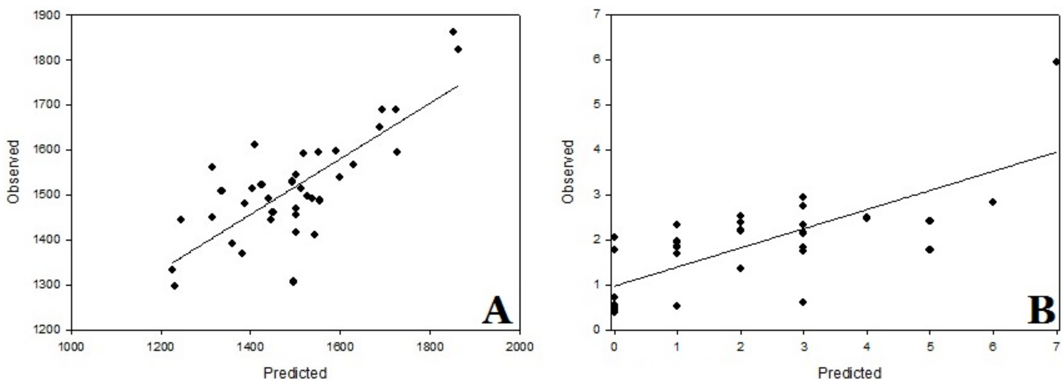

Figure 4.2. Table of variables used in regression model for yield data in southwest Michigan. Included is the scatterplots of the observed versus predicted results for the training of the GDD variable (Panel A) and Frost variable (Panel B).

Eq. 4.1. T/ac = -27.662 + (0.0778 * PPT) + (1.758 * GST) - (0.542 * Frost) + (0.00170 * GDD) - (0.0220 * eGDD)

Equation 4.1: Regression model for approximation of potential yield of *Vitis labrusca* where PPT = total season recipitation, GST = average growing season temperature, GDD = growing degree day total, Frost = potential early season frost occurrence, and eGDD = early season GDD accumulation.

This regression is prone to uncertainty, but the goal of using this model is to look at how the RCP4.5 and RCP8.5 scenarios potentially affects grape yields under future scenarios in southwest Michigan.

The study also includes analysis on the region's changing climate and how it affects the aforementioned three primary concerns for *vinifera* cultivation in Michigan. Future growing season temperature, monthly precipitation distributions and season length are all considered under the RCP4.5 and RCP8.5 scenarios in the future out to the year 2099 for southwest and northwest Michigan and the changes are discussed. Finally, there is a discussion of Michigan's potential future varieties using the future climate projections and known climate thresholds for a number of *vinifera* varieties. This section is meant as a hypothetical scenario for future decades where *vinifera* acreage in Michigan continues to expand and new varieties are considered for the region.

3. Results

3.1 Temperature Trends

Traditionally, Michigan's grape growing region is classified as a "cool climate". Table 4.1 displays the average temperatures over the course of two 30-year periods starting in the year 1950. The average growing season temperatures for both southwest and northwest Michigan suggest that Michigan's grape growing regions may not necessarily need to be combined as one homogenous region and southwest Michigan is, on the long term average, approximately 2.4˚C warmer than northwest Michigan. From a temperature perspective, these two regions have two different climates. This is represented by the fact that southwest Michigan is a *Dfa* Köppen climate class, while northwest Michigan is a *Dfb* class (Köppen 1900, Geiger 1965). The second issue is that southwest Michigan's average growing season temperatures should be seen as too warm to be classified as a "cool climate", at least from the perspective of growing season mean temperature. Michigan's growing season has traditionally been too short from spring to fall, and Michigan's winters would certainly classify the region as cool. However, from an average growing season temperature perspective, Michigan's *vinifera* production regions are not homogeneous and may not need to be classified as "cool climate viticulture."

	1950 – 1979	***1980 – 2009***	***Change in Temp***
Southwest Michigan	16.50˚C	17.05˚C	+0.55˚C
Northwest Michigan	14.13˚C	14.69˚C	+0.56˚C

Table 4.2. Comparison of historical average growing season temperatures (Apr-Oct) in both primary grape growing regions in Michigan (significant at $p<.001$).

3.2 Potential Future Yields

A statistical model was built to illustrate the effects of potential changes in climate on vine production for southwest Michigan. The reason for the model being built for SW Michigan, and not for NW Michigan, was that long-term historical yield data has only been compiled for the southwest corner of the state. The statistical model, a multi-linear regression, had an input of five independent X variables (Precipitation, Average Growing Season Temperature, Potential Frost Occurrence, GDD accumulation and Early Season GDD Accumulation) as predictors of yield (t/ha). The model was found to have good accuracy, with a Pearson's R = .81 (R^2 = 0.66) and a mean average error of 0.59 in the years from 1975 to 2011. The model was validated by using the cross-two out validation method. Two seasons were removed from the model and predicted using the regression and in both seasons, the error was less than 0.4, indicating good relative accuracy (Figure 4.2).

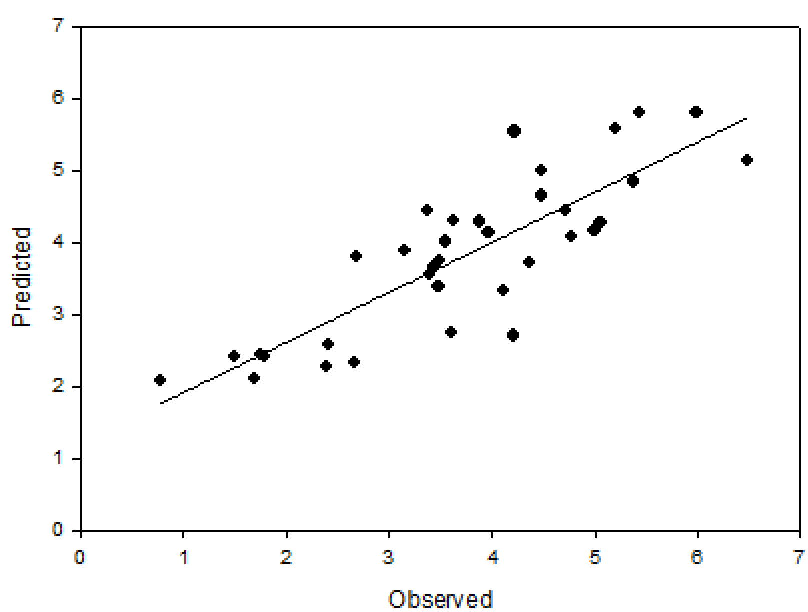

Figure 4.3. Predicted vs. Observed results in yields (t/ha) from 1975-2011 for southwest Michigan *Vitis labrusca*. (R = 0.81, R^2 = 0.66, MAE = 0.08).

Using the multilinear regression built from historical data, future climate projections (the five independent X variables) were included to the model to approximate hypothetical yields in future yields using the NEX-DCP30 dataset in the RCP4.5 and RCP8.5 scenarios (Figures 4.4 and 4.5). Included in the graph is yield according to the maximum, minimum and average model temperatures returned by the 32 model runs plus one ensemble mean that make up the NEX-DCP30 dataset. This dataset explores potential yields in a climate where the included variables appear to become more favorable for grape production in Michigan. As a downscaled projection, the NEX-DCP30 data should not be viewed as predictions for each exact year, rather it is the long-term trend from which analysis should be done. It is apparent that yields are likely to increase due to the expected change in Michigan's climate in the coming decades.

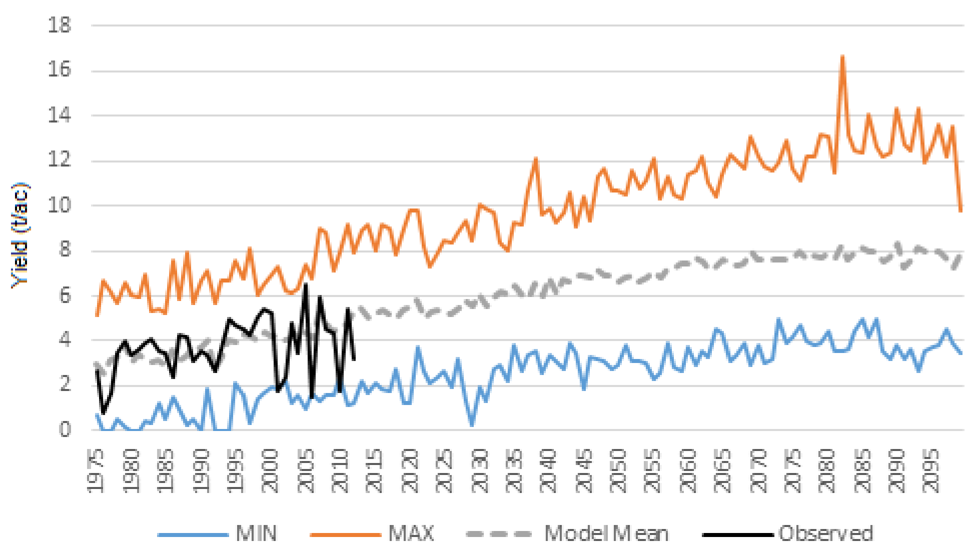

Figure 4.4. Minimum temperature, maximum temperature, model mean and observed potential yields for *Vitis labrusca* grapes in southwest Michigan from 1975 to 2099 with data from the RCP4.5 greenhouse gas emissions scenarios.

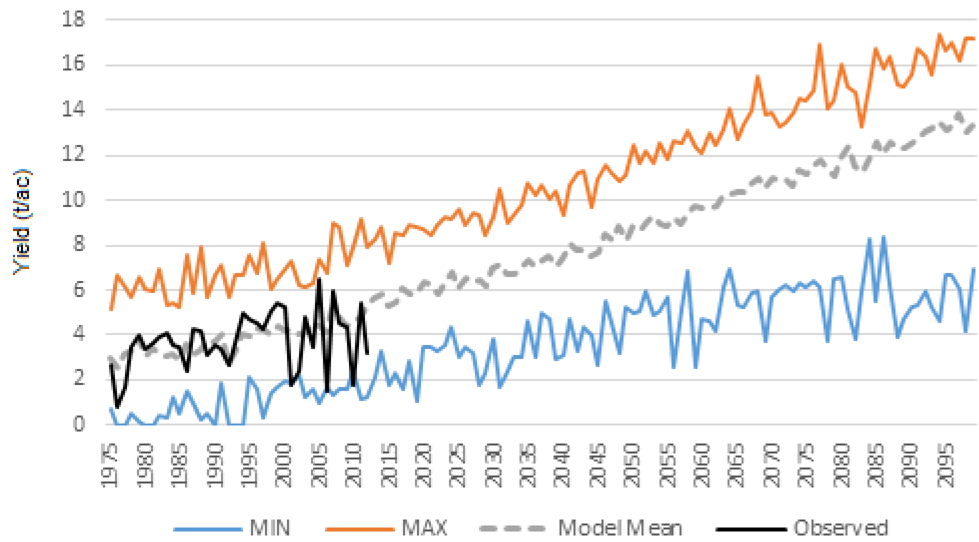

Figure 4.5. Minimum temperature, maximum temperature, model mean and observed potential yields for *Vitis labrusca* grapes in southwest Michigan from 1975 to 2099 with data from the RCP8.5 greenhouse gas emissions scenarios.

3.3 Michigan's Future Growing Conditions

As previously mentioned, there are three primary concerns for Michigan's *vinifera* production. Those include growing season low temperatures, a growing season that is not long enough (from spring to fall frost) and a disadvantageous monthly rainfall distribution. However, according to potential future projections, these issues are likely to become less of a factor in Michigan's future *vinifera* production. Figure 4.6 shows the average growing season temperatures for southwest and northwest Michigan. The average temperatures for both regions in both the RCP4.5 and RCP8.5 all show considerable warming out to the end of the 21st Century. For the RCP4.5 scenario, there is an increase of approximately 2.5˚C in the southwest, and a ~2.75˚C increase in the northwest. In the RCP8.5 scenario, the warming is even clearer. In this scenario, the southwest experiences temperatures nearly 5.5˚C warmer than previous decades, and the northwest registers warming of nearly 6˚C. These warmer temperatures, regardless of scenario or location, would almost certainly change the landscape of Michigan's *vinifera* industry.

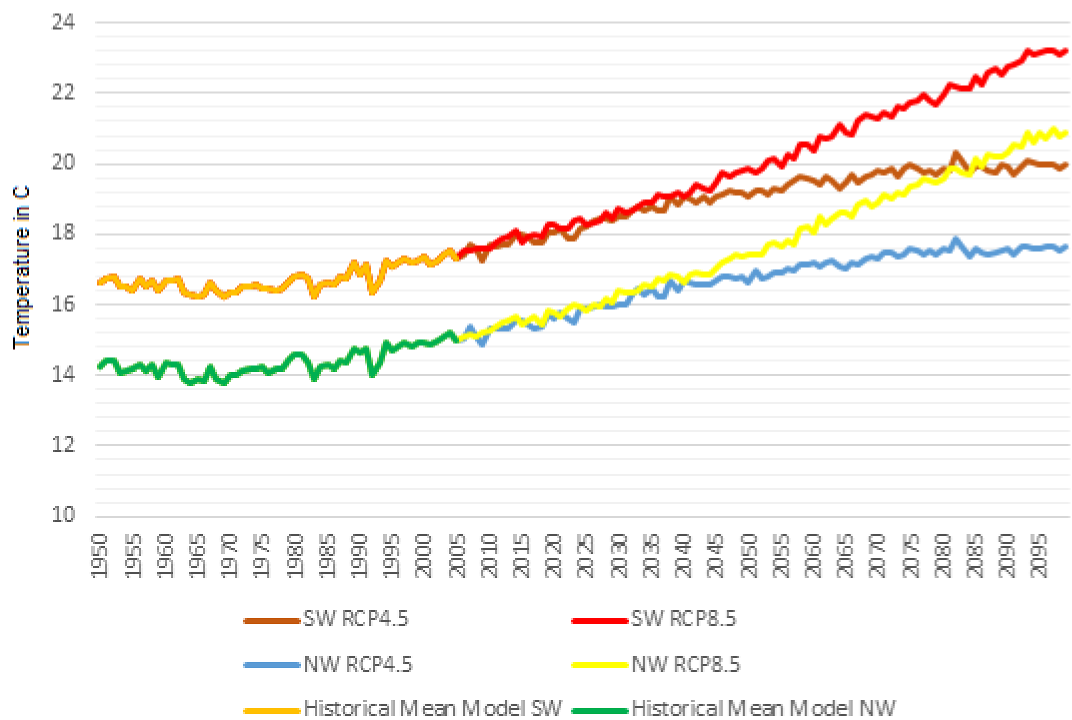

Figure 4.6. Average Growing Season Temperature (in C) Between SW and NW Michigan from 1950 to 2099 according to the Mean NEX-DCP30 Model Outputs.

Temperature is not the only climate variable to likely undergo change in the coming decades. Season length is very likely to continue to increase, just as it has for the past decades. This can be seen in the average low temperatures for April and October in southwest Michigan (Figure 4.6). It should be noted that the trends are near identical for southwest and northwest Michigan, thus the northwest data is not included in the graph. Low temperatures in these critical months (the beginning and end of the growing season, respectively) are going to rise substantially. Average lows in April will rise somewhere between approximately 2.75˚C and 5˚C (Figure 4.6). A similar trend is reported in October, with the rise in average monthly minimum temperature between 2.5 and 5˚C. This rise in temperatures has implications for the length of the growing season. In these months, average higher minimum temperatures are likely to account for a longer growing season.

Lastly, Michigan's monthly precipitation distribution is likely to undergo a change that could be beneficial to the *vinifera* industry. Currently, Michigan gets a small amount of rain in the early months of the growing season and too much rain at the end of the season. However, while Michigan is likely to receive a slight increase in annual precipitation (the increase according model means from NEX-DCP30 is not statistically significant), the distribution of precipitation across each month is likely to change. The changes over time for southwest Michigan are reported in Figure 4.7. In both scenarios, we see more rainfall in the months of April and May, and less rainfall in August and September, which is critical for reducing issues such as fruit rot or other diseases during the critical verasion phenological stage and at harvest. Less precipitation in the end months may also lead to less dilution of Brix suspended sugars in individual berries, as well (Gladstones 1992).

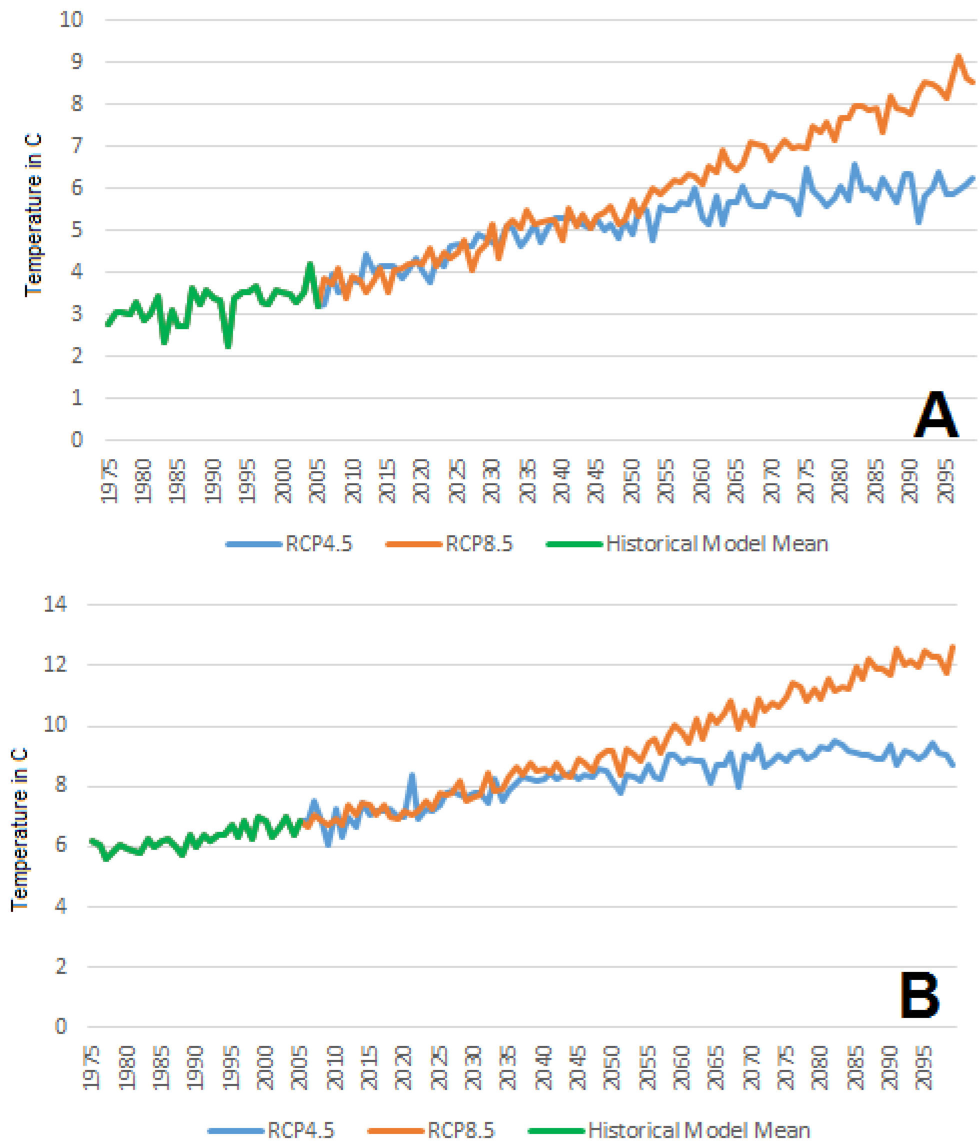

Figure 4.7. Average Monthly Minimum temperature for southwest Michigan in April (Panel A) and October (Panel B).

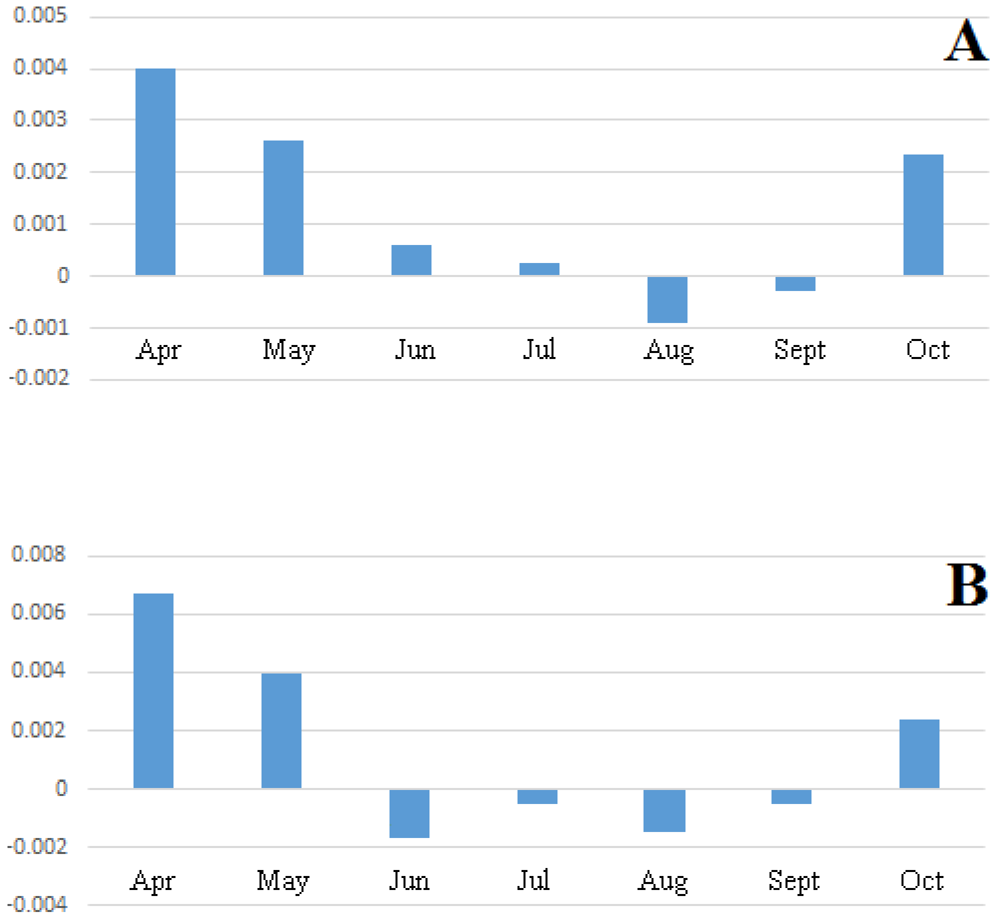

Figure 4.8. Change in monthly precipitation (inches/day x 100) for southwest Michigan from 1950-2009 average to 2010-2099 average for RCP4.5 scenario (Panel A) and RCP8.5 scenario (Panel B) model means.

4. Discussion

4.1 Future Trends

It is clear from the results that the NEX-DCP30 downscaled version of the CMIP5 suite of climate models envisions a different climate for Michigan during the growing season. As Table 4.1 shows, the change has already been occurring over the past few decades, and as Figures 4.2 through 4.7 show, the changes will continue and even accelerate. The direct potential changes to grapes is shown in Figures4.4 and 4.5, with the multi-linear regression for potential yields in to the future. This model was created using yield data from juice grapes (*Vitis labrusca*) and thus is applicable only to this species. This is because *labrusca* vines respond differently to the same climate conditions compared to other grape varieties. However, while all grape varieties respond differently to climate, general trends can be found applying to grapes. Bindi et al (1997), Jones and Davis (2000) and Nemani (2001) are examples of showing what happens to grape varieties under changing climate scenarios. While this model is limited to one variety, the trends should still be interesting from a scientific standpoint; namely the increase in yields as a response to a more favorable climate in Michigan. There is also uncertainty in the climate models used in this study, which makes the exact prediction of climate in a particular year very difficult. However, while the predicted year-to-year yields should not be taken literally, the trends are more valuable for analysis. Thus, it is the trend that is substantial, and in the RCP4.5 and RCP8.5 scenarios we see yields reach new highs as conditions become better for grapes.

The RCP4.5 (Figure 4.3) scenario shows yields eventually leveling off and perhaps even marginally decreasing by the end of the century. This is due to temperatures beginning to drop by a small margin at the end of the 21st Century and because of the slight increase in precipitation and the potential for frost still being existent (although not as strong as it currently is). RCP8.5 (Figure 4.4) shows a trend that continually increases. This is not likely to be a linear relationship, as there is likely to be a point in the climate where grape growth is slowed. However, the trend of increased production is logical, as temperatures in Michigan eventually become analogous to the temperatures currently seen in other viticultural areas such as California. It should also be noted that this model extrapolates “potential yields.” Pests and diseases, management practices and economics were not included in the model. The goal was only to show specifically what a future climate in Michigan could look like and what the response in the vines might be.

Michigan's future climate is likely to accommodate *vinifera* production in a better way than currently exists. This research addressed the three major concerns for Michigan's production (too cool, too short of a season and too much late season rain), and showed that the three issues are likely to lessen in severity to different degrees over time. Michigan, like the rest of the planet, is likely to continue to warm up and thus Michigan's average growing season temperature is likely to increase. Figure 4.5 displays just how much the growing season temperatures could rise, and if those numbers are even near correct, *vinifera* production in Michigan will be vastly different than it currently is in terms of total acreage and varieties grown.

Growing season length and monthly precipitation distributions are also likely to change as well. This will make a warmer Michigan even more accommodating to *vinifera* production. The authors attempted to create a predictive model for season length, but failed to find a statistical model worth sharing. However, the authors feel that using monthly low temperatures for April and October are a logical analog for showing that Michigan's growing season is likely to continue to grow beyond the 28.8 day increase discussed in Schultze et al (2014). A longer season, overall, will get Michigan to the needed 180 days growing season for *vinifera* production. While it is difficult to approximate an exact year for when Michigan will reliably accumulate 180 growing season days, it is reasonable to assume this will occur in the coming decades.

Viticulture in Michigan is limited by precipitation events at the end of the season often evidenced by harvest season cluster-rot, poor ripening and reduced fruit technological maturity. Economically important wine grape varieties possess varying degrees of susceptibility to harvest season cluster rot. However, most of the *Vitis vinifera* cultivar planted in Michigan are particularly susceptible to cluster rot and they are signature varieties for the Michigan grape and wine industry. The changes in rain events projected by this research are beneficial for the grape industry, especially the reduction in total rainfall in the final months of the growing season, reducing the potential of detrimental effects of grape quality at harvest.

4.2 Michigan and the Future

Michigan's presence in a "zone of transition" for grapes is a result of temperatures warming over the past decades. The rate of warming is commensurate with the warming seen in most regions of the northern hemisphere since 1980. Prior to 1970, Michigan's grape producing areas were primarily concentrated on *Vitis labrusca*, a North American variety. However, *Vitis vinifera* production has continued to grow from effectively zero in 1970 to >1,500 acres in 2011, with a near 300% increase in acreage from 2000 to 2011 (USDA-NASS, 2012). This growth in *vinifera* acreage is likely to continue, as conditions get better for accommodating the varieties of grapes that make traditional wines. Michigan's location in a "zone of transition" is an analog to climates that have gained and lost the ability to grow grapes thanks to the Medieval Warm Period and ensuing Little Ice Age. These areas include southern England and the Baltic Sea coastline (Pfister, 1988, Jones, 2005). Jones (2005) discussed the poleward migration of the 12-22˚C isotherm, which is the recommended temperature range for *vinifera* production. Michigan is located within that isotherm and as that area continues to move pole ward, more reliable warm temperatures during the growing season will affect Michigan's potential for different grape varieties.

If Michigan's climate continues to become more promising for *vinifera* production, then it is logical that new varieties should be able to be grown favorably in Michigan. Figure 4.9 shows different *vinifera* varieties with their approximate optimal temperature thresholds derived from Jones (2007) along with the temperatures predicted by the NEX-DCP30 models for the RCP4.5 and RCP8.5 scenarios. This is meant purely as a hypothetical situation based on temperature, but the figure shows that as time goes on in the 21st Century, Michigan is likely to be much more viable for different grape varieties. Not all of the varieties are necessarily feasible for production in Michigan (some require a much drier climate), but the point of Figure 4.9 is to show that over time, this region should be able to take on more *vinifera* varieties than are currently grown. One can see that in both scenarios, Michigan's future temperatures are likely going to be able to accommodate warmer varieties, particularly warmer red winegrapes.

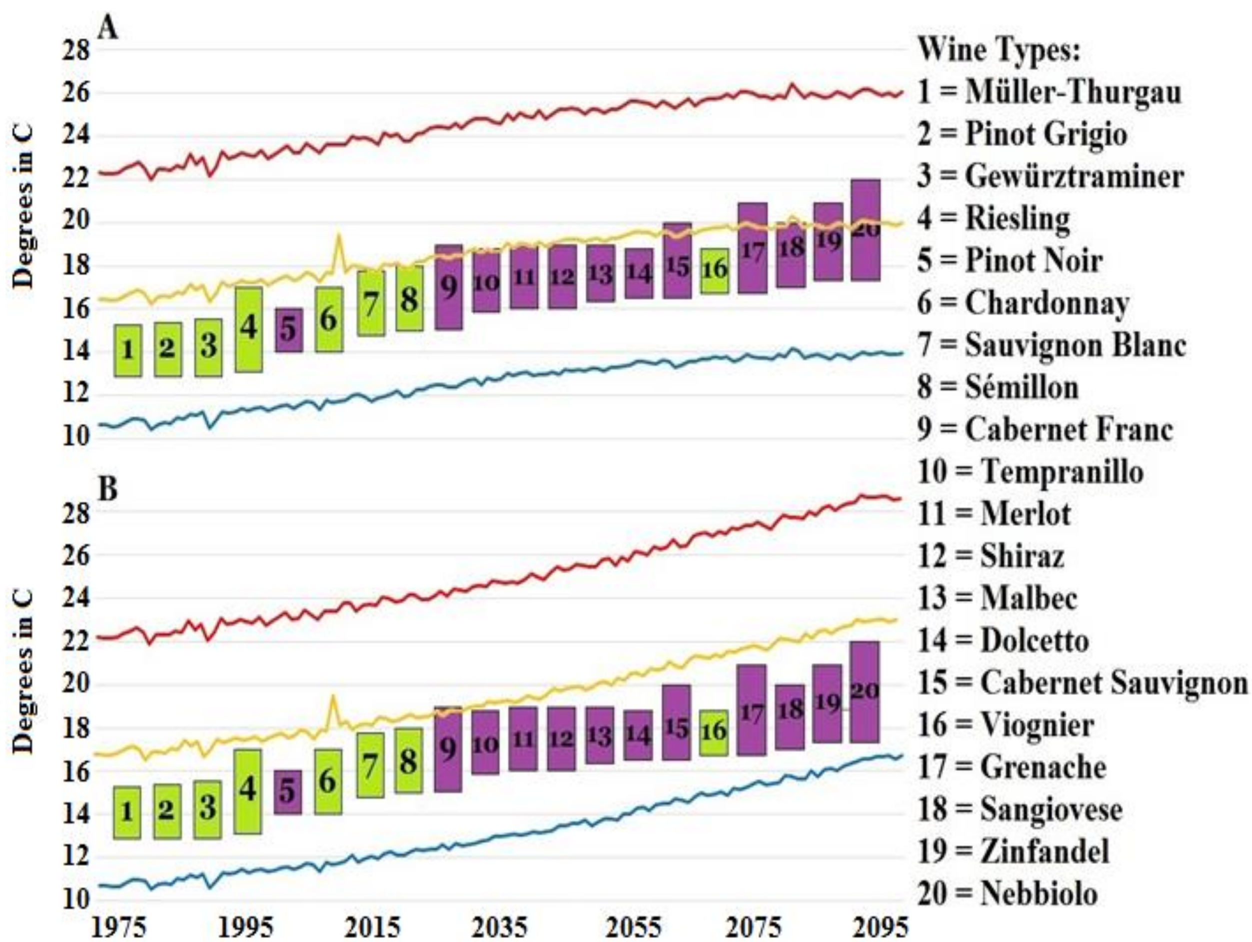

Figure 4.9. Graph of twenty popular *Vitis vinifera* varieties (green = white wine, purple = red wine) with their requisite temperature (Jones, 2007) thresholds along with the RCP4.5 (Panel A) and RCP8.5 (Panel B) temperature maximum (red), average (yellow) and minimums (blue) from 1975 to 2099.

Michigan is not the only place that is in a "zone of transition." Areas at altitude in the western United States and central Europe and areas in southern Russia, northern Germany, southern England and even the Baltic Coast are likely to currently or soon will be in a "zone of transition." However, Michigan has been growing *vinifera* grapes for several decades. This region can be considered a snapshot of what a "zone of transition" looks like. The trials and errors of this region can serve as a model to the other areas that are soon to gain the ability to grow *vinifera* grapes.

5. Conclusion

Michigan's changing climate has made the region more viable for production of *vinifera* grapes in the past few decades. The state has gone from effectively zero percent of acreage planted as *vinifera* grapes to nearly 15% of approximately 15000 acres since 1970. This trend in acreage growth is almost certainly going to continue in the coming decades. The three primary concerns for Michigan's climate are not likely to be problems of the same magnitude that they once were. The growing season will be considerably warmer and longer, and precipitation is likely to fall at more advantageous times, and less at disadvantageous times.

Data availability was of slight concern for this paper. We did not have yield data for the northwest portion of the state, and there is significant production in that region. The yield regression is based solely on *Vitis labrusca* grapes in the southwest part of the state. Different varieties respond uniquely to even slight changes in climate. However, we assume that the *labrusca* data is a viable analog for *vinifera* data, as we are looking for the overall future trend, and not an exact number for yield in an exact year. The authors also conclude that exploring the future trends for Michigan's climate with respect to the three primary concerns shows that Michigan's evolving climate is likely to be generally better for most varieties of grape. It is a near certainty that Michigan will not need to be classified as a “cool” climate for viticulture, and that yields will likely continue to increase as the climate becomes more viable over time and new varieties are introduced to the region.

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CHAPTER 5 – HARVEST.

DISCUSSION AND CONCLUSION

The previous chapters discussed the overall impacts of climate on Michigan's grape industry from three perspectives: past, present and future. The second chapter, published in the American Journal of Enology and Viticulture (AJEV) discussed the historical impacts of climate change on southwest Michigan's grapes and also looked spatially at the distribution of GDD and potential frost during the study time. The third chapter looked at the industry from a current-issues perspective and was focused on the importance of the early part of the growing season and how it relates to the end season crop yields. The fourth chapter explored potential future climate change and how it will likely impact Michigan's grape industry in a likely positive manner; where the three major concerns that limited *Vitis vinifera* production in the past (average season temperature, length of growing season and monthly precipitation distribution) were virtually eliminated. These three previous chapters, when combined, give a picture of the spatial-temporal pattern of grape production in Michigan and its response to changes in climate.

1. Summary of important findings

In the second chapter, the most significant findings were related to the season length and long term trends in GDD accumulation in southwest Michigan. Since 1971, it was found that the growing season in southwest Michigan, calculated as the average date of budbreak and average date of the first fall frost increased by 28.8 days. This increase of nearly a month in growing season length has made the region far more accommodating to grape growers, particularly those focused on growing high quality *Vitis vinifera* grape varietals. Not only does the increase signify a longer amount of time where it could be considered "safe" to grow grapes, it also allows growers flexibility in when to harvest the grapes. Generally, in agriculture it better to harvest when you *want* to and not when you *need* to. Also of particular note, the chapter found that while GDD increases have been approximately 3.1 GDD/year (base 10˚C) since 1980, frost occurrence has not significantly changed over time. This means that while the region may be accumulating more heat and becoming warmer, frost occurrence in the early season is still a significant concern. Combined with the knowledge that the date of budburst is occurring earlier on average, this has increased risk for growers. This realization was the basis for the creation of the third chapter.

The third chapter explored current issues with the Michigan grape industry. As previously mentioned, one primary concern was the increase in risk for growers in the early season. An earlier date of budburst has exposed growers to more risk, as the chance of a hard frost after budburst has increased over time. The study also looked at the importance of the early season. Summers in southwest Michigan's *Dfa* Köppen climate classification have temperatures that are warm enough to sustain both *Vitis labrusca* and *Vitis vinifera* production. However, early season frost occurrence was found to have a direct impact on end season yields. It was also found that the amount of GDD accumulated in the early season (budburst to May 20th, the frost free date for the region) was a successful indicator of whether the region would be in GDD deficit or surplus by the end of the season in 33 of 41 years (>80%). This puts a heavy emphasis on the importance of having a "good" early season that is relatively frost free, yet not too warm such that budburst occurs too early. Finally, the third chapter created a simple budburst calculation model. This was done to replace the outdated and inadequate "5-Days Approximation" developed by Mullins (1992) and used in Jones (2000). The "5-Days Approximation" worked in only 2 out of 41 years in southwest Michigan, and severely missed the day of budburst by an average of more than two weeks and in one case was one month too early. As such, we developed a simple budburst model based on GDD accumulation in March and made an estimate on 1 Apr, which is nearly four weeks before the long term annual average for budburst, on 27 Apr.

The fourth chapter discussed future potential implications of climate change on Michigan's grape industry. The future climate data was obtained from the CMIP5 suite of climate models that were downscaled to 800 meter resolution in the NEX-DCP30 project, run by the NASA Earth Exchange. This downscaled data (downscaled using the Bias Correction-Spatial Disaggregation method of downscaling used by Wood (2003)) provided monthly data for Berrien and Leelanau counties in southwest and northwest Michigan for the following variables: Tmax, Tmin and Precipitation. These data were downloaded from 32 different models for the RCP4.5 and RCP8.5 scenarios of greenhouse gas emissions worldwide. They were also averaged, giving 33 model outcomes in two scenarios out to the year 2099. The chapter first discussed Michigan's main problems with *Vitis vinifera* production prior to its introduction in the 1960s. Considering the climatic conditions and current technology and methodology, a climate scientist or viticulturalist in the 1960s would not have been out of place to say that *vinifera* production anywhere in Michigan was a very risky venture due to the main problems of the region. These problems were that the average season temperature was too low, the season length was too short and that monthly precipitation averages were not conducive for *vinifera* production.

However, this chapter explored those issues and found that growing season temperatures will be increasing somewhere between 1.5 and 2.5˚C (RCP4.5) or 2.5 and 4˚C in the coming decades, that season length will continue to get longer (expanding on the idea from chapter 2) and that monthly precipitation rates in August and September are likely to decrease, which will reduce the percentage of the crop affected by fruit rot and other diseases and pests brought on by late season rains. Beyond that, a multi-linear regression model built on present climate variables and yields was built to predict future yields. This was done for *Vitis Labrusca* grapes, and found that yields (in t/ha) will increase greatly over the next Century. Lastly, this chapter compared future potential temperatures in the RCP4.5 and RCP8.5 greenhouse gas emission scenarios and compared those temperatures with the recommended range of temperatures for growth of a number of *vinifera* varieties of grapes ranging from cooler types (Riesling, Cab Franc) to much warmer types (Cab Sauvignon, Grenache). In terms of seasonal temperatures, Michigan is likely to have a climate warm enough to sustain a very wide variety of *vinifera* grapes in the coming decades.

2. Implications of Findings

First and foremost, the findings within this dissertation should have large implications in the climate-agricultural community. There are countless papers on the connection between climate change and agriculture, and very few of them have a positive outcome for society. This is not to say that this study was done to find a "silver lining" for climate change or to find a contrarian's view that climate change "isn't all bad." A major reason for this study was to point out, as clearly as could be done, that climate change has had real, tangible effects in the very recent past on agriculture and thus should be taken very seriously in the future. Many studies explore the future of potential climate change, but in doing so, inadvertently treat climate change as an abstract idea. The general feeling left to a layperson may be that "some event will happen at some time" but those events are far beyond the horizon of the near future and thus are diminished in importance.

A statement declaring that water availability in India will decline in the 2050s is an alarming statement, but, in concept, can seem distant and contained. Reworded, a sentence stating that hundreds of millions of people will be at risk of lacking water resources in India by the middle of the 21st Century sounds more specific, but still abstract because the decade of the 2050s is over 30 years away. Beyond that, in most climate change studies, "potential" and "likely" are the operative words because ultimately, the computer models are still just speculation (albeit very educated and highly calibrated speculation). The IPCC AR5 report states how the terms “likely” and “extremely likely” should be used. This is an important exercise in the scientific community, but when relaying such information to the public, it is highly ineffective. Even to a college educated layperson who can locate India on a map and knows that India has one of the highest populations on Earth, the fact that water availability in the sub-continent will “likely” decline by the 2050s sounds almost like a neutral statement. This is one of the reasons why this dissertation was done; to show what had already happened because the recent past and present are less likely to be treated as a nebulous span of time.

To put it bluntly, one of the world’s most sensitive, quality-dependent specialty crops has gone from non-existent in the 1960s to exponential growth in the 2000s. It only took a slightly warmer climate (barely half a degree Celsius on average warmer) and forty years for growers in northwest Michigan to go from the relative security of growing tart cherries to barely being able to pull their trees up fast enough to make room for the vines. With that in mind, the logical extension must be: what else will climate change do elsewhere?

We are now reliably growing Cabernet Franc in areas that had apples and cherries 20 years ago, and oak/pine forests 200 years ago. But what can be said of climate change in other regions in the world? Large scale change to climate has led to massive national upheavals (China in the 17^{th} Century) or even completely wiped civilizations off the map (Anasazi in the Medieval Warm Period). It is true that those examples were of cultures long ago, when people lacked the technology and organization to overcome such problems, but one must ask about the third world in the 21^{st} Century. The world watched as famine ravaged East Africa in the 1980s, which on top of governmental mismanagement was caused by the loss of the second rainy season due to climate change (Meze-Hausken 2004). Is this a one-time occurrence, or could this happen again elsewhere? Could the third world, at large, be at risk because they lack the infrastructure, science, governmental or societal wherewithal to change farming practices used for the past decades and centuries?

These are questions far more important than whether Michigan will be able to sustain an award winning crop of Riesling in the 2040s, but are also not completely unrelated. We are now growing wine grapes in a climate that otherwise could not merely 50 years ago, which by definition puts us on the periphery of growing this one crop. However, grapes are not a staple crop. What about staple crops found on the periphery that are also in third world countries? That is a billion life question, and one that needs to be answered.

3. Limitations, constraints, headaches…

One of the primary limitations to this study was the availability of data. The data obtained from Michigan State University's Enviroweather stations, the National Climatic Data Center's network of stations and the crop statistical data from the National Grape Co-op made this study possible. However, as is usually the case with climate and agriculture studies, this study could have used more data. One example was in chapter 2, in the review process with the American Journal of Enology and Viticulture. Our third reviewer, to be left unnamed, is likely a big person in the field who we cited numerous times in all of the previous chapters. His comments were truly insightful and made the paper immeasurably better. His biggest concern pertained to the spatial coverage of the stations in southwest Michigan and whether there were enough stations to be able perform the spatial interpolation we used to identify the trend in GDDs in the region. We agreed entirely with his or her premise: 26 stations is not a lot for covering such a large area. As we said in our comments responding to the reviewers: "We would have used 100 stations if we could…"

However, that was not the case. As it turned out we had a very acceptable root mean square error for the stations and thus we were able to use the dataset. That said, the Enviroweather stations, the NCDC stations and the National Grape Co-op dataset were invaluable to the process.

Another constraint was the length of time of the study. We were excited to have such a long dataset to look at the length of the growing season and daily weather observations in the area. 1950 was the starting point for weather and we could have gone further back. But with the date of first frost going back to 1961 and the date of budburst going back to 1971, we thought that 1950 was a good place to start. However, starting the time of study in these years does lead to the problem of the 1970s anomaly in world temperatures having an effect on our data. This was noted early on, and the solution was to also run the same analysis on GDD and frost starting in the year 1980. This erased the 1970s anomaly which may artificially change long term trends, but doing so came at a cost. It also cut our length of study nearly in half. This led to a discussion on whether we should focus on one or both time frames. Ultimately, we decided on both and that was published in the AJEV. A similar concern occurred in the fourth chapter, pertaining to the date of when to end the study. The CMIP5 downscaled data went to 2099, but it was repeatedly pointed out that predictions that far out the future were speculation at best, especially considering the spin-up time for the model started only in 1950 (going until 2012). However, this problem was considered to be a minor one as it was determined that looking at the future trend (increase vs. decrease) is more important and reliable than saying specifically in exactly seventy years what the yield would be for southwest Michigan *Vitis labrusca* grapes.

Another major limitation was the problem of a lack of spatiality with the National Grape Co-op. While it was crucial to have such in-depth statistics about yearly grape crops, it was a disappointment to only have values that were averaged over an area. Having individual, geolocated data for each of the 25 plots that the Co-op uses from Michigan would have allowed for a much more in-depth exploration of how weather and grapevines interact. Instead, we used the averages over space (located in and around Lawton, MI). We could have looked at the spatiality of budburst over time and its response to different weather conditions, or we could have looked how harvest time led to differences in quality (like Brix). However, this problem was not enough to deter any further study and we are thankful to the National Grape Co-op for their instrumental help.

4. Potential improvements

Of all the potential improvements for this study, the most significant would be a better dataset in terms of spatial or temporal coverage. As previously mentioned, using 26 stations in southwest Michigan was less than ideal and we would have used more if we could have. There are certainly more than 26 stations in the study area (NCDC reports approximately 70 stations), but most of those are either CoCoRaHS stations (a network requiring secondary confirmation) or GHCN (Global Historical Climate Network) stations which either had a dataset that was not close to continuous, or had only run for a few years several decades ago. Our aim was to use stations that had been running for several decades or in the case of the MSU Enviroweather stations, sites with reliable and high temporal accuracy. More stations would have given us more confidence in our accuracy of interpolating the spatial pattern of GDD and frost. Beyond that, more stations could have allowed for a better examination of microclimates. We also had a recommendation from the aforementioned Reviewer 3 from Chapter 2 (published in AJEV) who suggested the use of PRISM temperature data as a substitute for the 26 stations. This was heavily considered, but ultimately decided against due to some issues with PRISM's accuracy in western Michigan (Andresen et al. 2015).

During the process of writing this dissertation there were a number of ideas that were considered, but never included in the study. One of the ideas was to add a forecasting component to the budburst model introduced in Chapter 3. This was not just a mere idea floated during a committee meeting. This concept was turned in a proposal submitted to MSU's Project GREEEN worth more than $80,000 for 2 years of funding. The Forecasting Recurring sub-zerO Spring Temperatures for AGricultural Application (FROSTAGA) system planned to predict the date of budbreak starting on 1 Mar using mid-range daily forecast data from the National Center for Environmental Prediction (NCEP)'s Climate Forecast System (CFS) forecast model (Saha et al, 2006). This methodology was calibrated by using the budburst model using forecasted high and low temperatures to give GDD accumulation over time. This system was updated every 5 days to give a new prediction for the date of budburst from 1 Mar to 27 Apr from 1982 to 2009. The system was accurate to approximately ±2 days on 1 Apr for 27 years studied. Unfortunately, the GREEEN proposal was not funded and the project was put on hold in order to focus on the main objectives of the dissertation.

However, of all of the potential improvements that could have made this dissertation better, the most significant for the field of viticulture and climate would almost certainly have to be a long term high resolution microclimate study. This is an absolute must for the entire field of viticulture. Climate is the main variable that changes over time in the concept of *terroir*. It is imperative that scientists better understand the direct impacts of year-to-year climate variability on individual vines. In order to do so, scientists must embark on a study of unprecedented scale, performing a long term, multi-decadal study across a region. Such a study may require meteorological gauges with the vines and across a vineyard, measuring weather variables consistently over the course of the growing season in a number of different scenarios: vines of similar varietal in similar situations with respect to aspect, slope, spacing and pruning technique (among other variables). This must be done at different vineyards in the same region, and it must be ideally done over the course of approximately thirty years, but even ten years would be acceptable. Weather data logging must continue in to the winter months, as it will also be of high importance to understand winter dormancy better. A study such as this would be a massive undertaking and would have a cost in the millions of dollars. Funding would likely have to come from public and private sources. However, such a study is the next logical step in better understanding the relationship between grapevines and their response to atmospheric conditions.

5. Future Research

A future direction for this research could be combining the fields of water conservation, viticultural methods and climate change. The term "Precision Agriculture" is currently a popular term because it looks to combine the relatively new concept of big data with the relatively old world of farming. The term precision agriculture could be reworded as the modernization of farming. This is an apt statement because many farming techniques are still rooted in the traditions of older generations. One would only need to look at the growth of companies like Climate Corp. and FarmLogs to see that there is a clamoring in the field of agriculture for an effort to bring science and digitalization to what has been decades of "gut feelings" and occasional resistance to change. These companies are new and have barely begun to scratch the surface of what they can do, which could be as simple as delivering real-time weather data to helping build decision-based computer systems to give growers input on how to manage their fields. One hopes are that they will grow responsibly to balance science with the cold economics of running a private enterprise while at the same time not getting too high-minded about what they do, or how they do it.

If “Precision Agriculture” is a relatively new field, then “Precision Viticulture” is barely in its infancy. From personal experience seeing a talk given by E&J Gallo’s Senior Vice-President for Research, Nick Dokoozlian, I have seen where the field is in terms of advancement. To put it bluntly, it has not gone very far. It appears as though GIS is starting to be incorporated in mapping the years’ worth of grape yields across certain vineyards, which shows a wealth of spatial information about each vineyard. The 45 minute talk given by Dr. Dokoozlian was enough to keep me thinking for days on what could possibly be done to create a field that could be generally called “Precision Viticulture.” Considering that E&J Gallo (one of the largest producers and distributors of wine in the world) has field-level yield data but is less than equipped to analyze it and unable to link it to meteorological data, it must follow that “Precision Viticulture” could use an overall aim. It is with that thought that I introduce my concept of “Precision Viticulture” using the current extreme drought situation in California (2014-15) as a simplified potential area of study.

The current drought in California (winter 2013-current present) has been exceptionally damaging to the state’s specialty crop industry. California is the United States’ top producer of specialty crops in terms of variety and volume. Many of these crops are grown in and around the Central Valley, where agriculture consumes the majority of all water through irrigation and groundwater pumping. In most normal years, California gets most of its precipitation in the winter months, where it falls as rain in the low lying areas and snow in the mountain ranges. Summer is very dry in comparison. This winter “wet” season typically is enough to sustain the water needs through the filling of reservoirs or the slow release of the snow pack in the mountains. This water will go to a number of specialty crops ranging from almonds to asparagus to grapes. Different crops have different water requirements, so the process of delivering water to the different areas of production can be expensive. However, specialty crops can make great sums of money per acre, particularly in comparison to a staple crop. Thus, the cost of water in a normal year is not enough to deter a grower from planting hundreds or thousands of acres of their particular crop. In a drought year, there can be water availability issues, but these problems can be subsumed into the cost of production. A price hike of 5% in avocados is not enough to bring down an entire industry.

However, in the winter of 2013-14, the drought that occurred was historic in scale. A large, very powerful and very persistent high pressure system formed over the eastern Pacific Ocean in December 2013. A high pressure forming in that region at that time is not extraordinary, but it was a combination of the strength and persistence of the high pressure and associated ridge of high temperatures that was exceptional. This ridge redirected the jet stream into a highly unusual amplitude, sending warm temperatures as far northward as Alaska. The inverse occurred over the eastern half of North America, where the jet stream drifted further south than normal and colder than average temperatures moved in. This trough, created as a response to the ridge upstream, was also extraordinary in its strength and persistence. With the jet stream in this configuration for more than a month and a half, and rarely diverging from it, exceptionally hot and dry conditions came to the whole of California. Lakes, reservoirs and rivers all fell to historically low levels. To make matters worse, the snow pack in the mountains also fell to record lows, meaning the source for water in the spring and summer months was non-existent. This was a “wet” season without any precipitation. California’s highly water-dependent specialty crop industry was about to come in to a painful decision.

An ordinary drought year, from time to time, could be taken in stride by California’s specialty crop industry. However, this historic drought was anything but ordinary. In such an extreme drought, the only possible response is to uproot hundreds and thousands of acres of crops. Almond trees, a very water-dependent plant, were pulled by the thousands on a daily basis.

Avocados, rice, berries and even flowers were all severely affected by the drought thanks to the severe drop in water availability. Water became a resource that was too expensive to utilize to keep a crop alive. However, grapes were at an interesting crossroad.

Grapevines, naturally, are drought resistant. This is from the *Vitis* genus of plants' origins in the Caucasus Mountains and initial large scale plantings in the Middle East and North Africa followed by thousands of years of selective breeding. As such, it was not as necessary to pull scores of acres of vines. Instead, production was limited. In grapes, a crop highly dependent of quality, a grower can simply reduce yields by X percent. This, in turn, will reduce the water demand for a vineyard. In the 2014 growing year, yields were lower than the previous growing seasons, but quality was not sacrificed as much as it was in other specialty crops, and there were very few instances of vines being pulled on the same order of almond trees.

It is with that in mind where "Precision Viticulture" could fit in. Using GIS data, specifically geo-referenced yield data throughout a vineyard, it could be possible to find areas that are more sensitive to drought (or other inclement weather). These areas will have a large variance in yield in years of drought. This may be due to the soil, the aspect/slope of the area, or something larger scale like that the fetch effect affecting yields on the periphery of yield producing plot of land. Finding these areas will be important, in addition to finding the areas that appear to be more drought resistant in Precision Viticulture. This is because the areas that are less drought resistant are the areas that will be "targeted" more with the resources that a grower has on hand. This could be water, manpower, time or using a different viticultural technique to augment an area's ability to cope with drought. If this were successful, this could be applied to any vineyard where drought may be a concern. Growers could reduce their demand for water and resources, yet still be able to produce similar yields from a normal year. If a number of growers do this, this could potentially save billions of gallons of water that could otherwise be diverted to other specialty crops which in turn saves billions of dollars and keeps those crops alive in to the years after the drought breaks. This means that the region will not lose money in the short term (from a drought) due to a drop in quality or yield and it won't lose its market share in the long term because will not have to pull scores of acres of their crop, which will likely be regrown in another region of country or world.

6. Conclusion (…Am I done yet?)

The goal of this paper was to give a classic Geographic perspective on Michigan's grape industry and how it has responded to climate change. The "Geographic perspective" is a reference to what I have learned to be the true definition of Geography: "The study of spatial and temporal patterns across the Earth at different scales." I believe that this study was successful in doing just that. All four of Pattison's "Four Traditions of Geography" (Pattison 1964) were covered: Regional Studies, Spatial Studies, Man-Land Interaction and Earth Science. It painted a picture of the past, present and future of Michigan's grape industry responding to climate change. It placed Michigan's unique situation on the proverbial map and made comparisons with other places to look for regional differences and similarities to give a global perspective. It explored current issues and how those issues may be overcome. It used previous trends and information to draw conclusions about the future. But having a concluding paragraph assumes that this study is over, or that "the book" on climate change and Michigan's grape industry has now been written. That is not the case. The book has only just begun. I plan to continue exploring the topic of climate change and viticulture in Michigan and elsewhere. Only the simple saying "Onward" feels appropriate at this moment to conclude a study that has taken 3 years of my life. Onward to the next pages, which are currently blank and waiting to be written. Onward to the next topic, whatever it may be.

Onward.

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REFERENCES

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