

# Wine Grape Suitability and Quality in a Changing Climate

An Assessment of Adams County, Pennsylvania (1950 – 2099)

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Practical Exam

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# Introduction

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Wine is perhaps the most universally recognized beverage, with a history that dates back to 8,000 BC. Though many of the viticultural practices have remained the same, the earth's climate has not. It is an intricate and complex relationship between climate and wine, but one that is necessary to understand in order to produce high quality wines. Viticulturists and enologists all over the world have started to see a shift in viable grape production zones, as anthropogenic climate change has become significant. Climate change and shifts in climatic regions pose huge threats to the wine industry, as regions that were once well suited to grow grapes, or certain varieties, may no longer be as well suited. Understanding the importance between site selection and varietal matching is probably the single most important element to viticulture. The wine industry in Pennsylvania is exponentially growing, but knowing and understanding the impacts that climate change could have on the industry are vital components in vineyard planning and the future of the Pennsylvania wine industry. This research examines historical climate variability in Adams County, Pennsylvania as well as the potential for future climate change, based on several greenhouse gas emissions scenarios and how the changes may affect the viability of wine production in Adams County.

## Purpose

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The purpose of this research is to use a provided data set containing average monthly temperatures and precipitation totals in order to assess the potential impact of future climate change on the quality of wine grapes grown in Adams County, Pennsylvania.

In order to provide a comprehensive analysis, the following components will be included:

- Outline parameters imperative to producing quality grapes
- Identify the ideal phenology timeline and milestones
- Identify other quality and suitability measurements
- Provide monthly climate values, particularly for the growing season (April 1-October 31)
- Using the observed data (1950-1999), assess how well the models work to simulate temperature and precipitation
- Using the models, identify what the future climate could be in Adams County
- Relate the future climate to the possible effects on grape growth, quality and viability
- Determine varietal suitability based on the potential future climate
- Consider limitations of the analysis and how they impact the results

## Literature Review

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Terroir is the French word that embodies both the physical environment (climate, soil, slope), and the viticultural practices that will produce a specific wine style (Jones 2004, Cahill et al 2008). While there are many aspects of terroir that can affect the quality or viability of grapes, few can compare to the influence of climate (temperature and hydrologic). Climate has long been a driving force behind agriculture. It has shaped current agro-ecological zones, and helped to determine a geographic location's suitability based on yield and quality (Schultz and Jones 2010). Wine grapes in particular, require such specific conditions that a vintage's tasting notes are reflective of that year's climate. The paired relationship between climate and wine means that grape cultivation can be indicative of the impacts of future climate change.

Understanding the implications of climatic change is becoming more important as the levels of greenhouse gases continue to rise (Schultz and Jones 2010).

## Quality Wine – Sugar, Acidity and pH

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In order to produce a quality premium wine, sugars, acids and tannins should be properly balanced within the grapes. Sugars directly relate to the amount of alcohol that is produced during fermentation. Acids relate to the taste and tartness, and tannins relate to the astringency of the wine. The different types of acids present in grapes/wine also play an important part in the development of wine through microbial processes and attaining a balanced acid level may be one of the most integral parts of producing a quality premium wine (Beelman & Gallander 1979).

The ideal sugar levels (measured in Brix) should be achieved just prior to the full maturation of a wine grape. As the wine grape proceeds through the maturation process, the acid levels often lag behind the development of sugars. If the sugars develop too quickly, then the acids may not reach their ideal levels, producing a flat or “flabby” wine. In addition, grapes that contain too high of a sugar content, may produce a wine with a much higher alcohol content, which in turn derails the fermentation process (Jones 2004, Beelman & Gallander 1979).

Tartaric and malic acid are the primary acid components in grapes and thus wine. The amounts of each acid vary by varietal, but can be influenced heavily by environmental changes such as weather, viticultural practices and vintner’s winemaking philosophies. Both tartaric and malic acids are non-volatile, meaning that they do not boil off when heated (CalWineries 2010). As a grape grows, both tartaric and malic acid are produced. However, the balance between malic and tartaric acid shifts in favor of more tartaric acid as a grape matures. The presence of a high concentration of malic acid signifies an unripened grape (Skelton 2007 pg62). Both types

of acids are lost during respiration. In a warmer climate where more respiration occurs, more acidity is lost. However, the warmer the climate, generally the higher the sugar content is in the grapes. Thus, warmer climates mean lower acidity but higher sugar levels, while cooler climates mean higher acidity but lower sugar levels (Pandell 1999).

Total acidity (sometimes referred to as Titratable Acidity) is the measure of all organic and inorganic acids within a wine. However, generally oenologists refer to the total acidity as the measure of tartaric acid present in the wine. This is done to simplify both the subject and the measurement. Total acidity ranges from 0.4% to 1.0% and is usually reported as grams of tartaric acid per 100 mL of wine. Wines with a total acidity of 1.0% would be far too tart for consumption by most people, while a total acidity of 0.4% is considered to be flat or “flabby”. The general range for total acidity is from 0.6% to 0.8%, and under ideal conditions, can be achieved (Pandell 1999, CalWineries 2010). pH is closely related to total acidity. The pH of a grape/wine measures the active acidity, or the fixed acidity. There are many buffer acids that are contained within a grape that do not contribute the actual acidity, but rather are important in maintaining a constant pH level. pH levels are measured logarithmically, meaning a pH level of 3 is 10 times more acidic than a pH level of 4. It is important to remember that the lower the pH number, the higher the acidity, while the higher the pH number, the lower the acidity. Both total acidity and pH measure acid levels within a grape, but measure different acids as well as presenting it in different ways (Pandell 1999, CalWineries 2010). Climate is intricately involved in the physiological development of sugars and acids within a wine grape, but the complexity of the relationship reaches far beyond the scope of this research.

## The Climate of Wine

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The majority of the world's leading wine producing regions are found in the mid-latitudes. In the Northern Hemisphere, the wine niche correlates to the latitudinal regions between 30°N and 50°N (Schultz and Jones 2010). The climate of a wine region ultimately determines the style of wine produced, but year to year variability can also have a more immediate impact. Warmer years tend to produce wines with higher sugars, but less acidity and tannins, while a cooler year will tend to produce a more acidic wine, but may lack the necessary sugars or balance (Jones 2004, Jones et al 2005, Van Leeuwen & Seguin 2006). A year with excess precipitation may produce diluted grapes, or less robust, while an extremely dry year may actually cause a minimal crop harvest (Pennsylvania Wine Grape Growers Network, Penn State Cooperative Extension 2012).

### Temperature

More importantly than the latitude, are the growing season isotherms. The growing season for the Northern Hemisphere is observed as April 1 to October 31, with average temperatures ranging from 12°C and 24°C (Schultz and Jones 2010). In order for grapevine phenology to begin, the average temperature must steadily exceed 10°C, with April 1 generally being the benchmark. The phenology of grape development can be categorized into several stages. Table 1 contains the phenology timeline for grapevines in the Northern Hemisphere, and can serve as standard against which to measure grape quality.

Table 1. Grapevine Phenology characteristics and timeline. Data adapted from Keller (2010), Jones (2005), Nemani et al. (2001), Halliday (1993).

Grapevine Phenology		
Stage	Characteristics	Timeline

<b>Bud Break</b>	New growth, leaves, flower buds	Mid-March – First week of April
<b>Florasion</b>	Flower growth	Early June
<b>Veraison /Maturation</b>	Grape color change, sugar accumulation, growth, synthesis of tannins, ripening	End of July – Early August
<b>Harvest</b>	Grapes harvested and crushed to make wine.	Harvest: Late September – Mid-October

The amount of time between each phenological stage varies with each varietal, and is dependent on the climate and vineyard location. However, the timing of the stages has been related to not only yield, but also quality. The earlier a stage is reached within the growing season, the better and higher quality that vintage year’s yield generally is (Jones 2004).

Temperature is used to derive several other metrics with which to measure grape quality, which are further explained in the Methods section.

### **Precipitation**

The amount of precipitation that a vineyard receives is important to the suitability of the site to be able to produce a quality grape. Most importantly, it is vital to the health and success of a grapevine, that the soils do not become water logged, as this not only promotes root rot, but also causes physiological differences in grape development. The temporal distribution of the total amount of precipitation is the biggest factor of the precipitation component (PSU Site Assessment 2012). Ideally, the time frame after veraison sets would have limited amounts of precipitation, as excess amounts can cause major quality issues, including disease, fruit rot and excess vine vigor (PSU Site Assessment 2012). Increased precipitation can cause grape berries to swell and split, which would compromise the quality. In addition, precipitation that occurs just prior to harvest can affect Brix (the unit used to measure sugar content) by diluting the sugar content and causing the Brix to drop, which would then result in the production of less



alcohol during fermentation (PSU Site Assessment 2012). Viticulturists perpetuate the theory that excess precipitation (particularly in September/October) is harmful by supporting the notion that water deficits may actually increase the quality of the grapes. Vines that experience water stress have been found to actually produce fewer and smaller grapes, but with higher phenolics, thus higher quality (Van Leeuwen & Seguin 2006). Extreme water deficit is harmful to the development of the fruit, so precipitation amounts do need to be monitored in order to determine if irrigation is necessary.

## **Pennsylvania Grape Production**

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Pennsylvania's wine culture has been shaped by several historical events, Prohibition most notoriously. William Penn was responsible for planting the first set of grapevines in Pennsylvania in 1684, which led to the nation's first commercially successful vineyard, located along the banks of the Schuylkill River near Philadelphia. Prohibition in the early 20<sup>th</sup> century, all but destroyed the wine industry within the state. Though Prohibition was repealed in 1933, it was not until Pennsylvania passed the Farm Winery Act of 1968 that grape growing and the wine industry really began to make a recovery (Pennsylvania Wine Grape Growers Network, Penn State Cooperative Extension 2012). Currently, Pennsylvania ranks 7<sup>th</sup> in the country in wine grape production, with over 14,000 acres of grapes being planted. However, only about 2,800 of those acres contain wine grapes. In the last 30 years, the number of bonded wineries has increased from 23 to over 140, with wine production nearing the 1 million gallon per year mark, as of 2011 (Pennsylvania Wine Grape Growers Network, Penn State Cooperative Extension 2012, Pennsylvania Wine and Wineries 2012). The fastest growing economic grape growing belt in Pennsylvania stretches from Adams County to Philadelphia, and north into the

Lehigh Valley. The rolling foothills of the Appalachian Mountains, moderate winters and warm summers makes South Central Pennsylvania and Adams County, in particular, an suitable location for vineyard placement (Pennsylvania Wine Grape Growers Network, Penn State Cooperative Extension 2012).

### **Pennsylvania's Climate**

Pennsylvania's climate is varied throughout the state, due in part to topography and physiographic regions. Pennsylvania is characterized as being predominantly affected by continental climate, meaning that high pressure systems that move from the Mid-West and through Canada, and low pressure systems that push up from the south bring most of the weather patterns within the state. According to the Northeast Regional Climate Center, average annual temperatures in Pennsylvania range from 6°C to 13°C (2010), with average annual precipitation amounts ranging from 35 to 50 inches (2010). The topographical and physiographic variations are important components that help to determine how weather patterns affect the state, causing Pennsylvania's varied climate (Penn State Site Assessment 2012). Across the south central and south eastern region of the state, the climate tends to be warmer and wetter, with a plethora of south-facing slopes, making this region excellent for European grape varieties (*vinifera*) and hybrids (most commonly French-American) (Pennsylvania Wine Grape Growers Network, Penn State Cooperative Extension 2012).

### **Study Area – Adams County, Pennsylvania**

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Adams County, located along the Mason Dixon line in south-central Pennsylvania, is known for its excellent soil, moderate climate and gently rolling hills, making it one of the most

agriculturally desirable counties in the state. The average annual temperature ranges from 10°C to 12°C, with average annual precipitation amounts ranging from 42 to 45 inches (Northeast Regional Climate Center 2010).

The Pennsylvania Vineyard Site Assessment System (PVSAS) is a geospatial technology system that integrates qualitative land analyses and expert knowledge in order to determine land suitability for vineyard placement within Pennsylvania. Data included in the assessment are terrain, climate, soil and biological environment characteristics (Pennsylvania Wine Grape Growers Network, Penn State Cooperative Extension 2012, Penn State Site Assessment 2012). The PVSAS was developed by the College of Agricultural Sciences, Department of Crop and Soil Sciences Cooperative Extension, Penn State University, as a means to streamline and qualify vineyard management decisions for Pennsylvania grape growers. According to the PVSAS, Adams County's final suitability is mapped as ranging from 5 to 10, with 90% of the county mapped between 7 and 9 (Figure 1). Suitability is ranked on a 3 to 10 scale, with 3 being "poor".

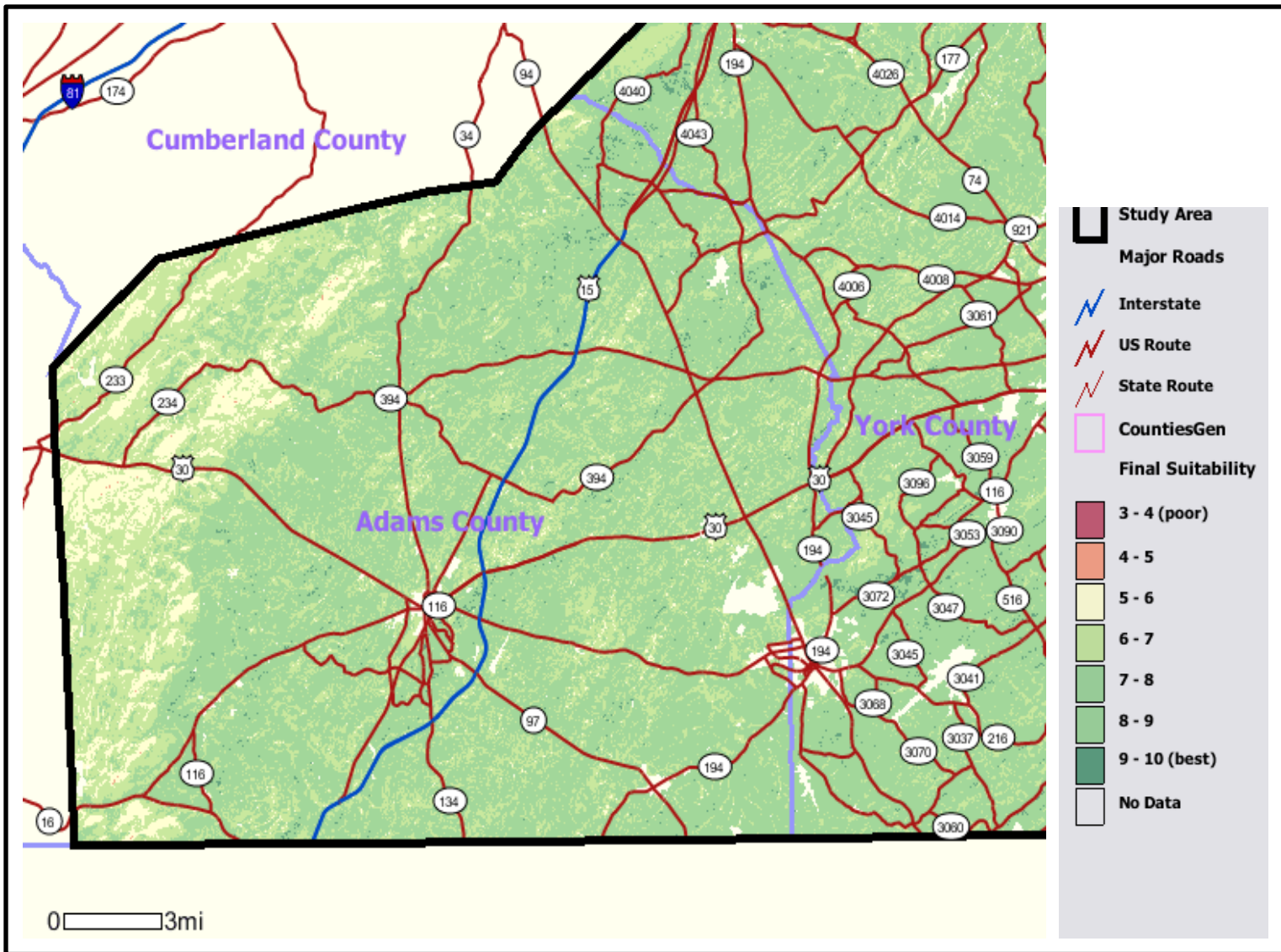


Figure 1. Adams County Vineyard Site Assessment (Pennsylvania Wine Grape Growers Network, Penn State Cooperative Extension 2012, Penn State Site Assessment 2012)

Adams County has three commercially operated vineyards. These vineyards are part of the Pennsylvania AVA and are members of the Mason-Dixon wine trail (Pennsylvania Wine & Wineries 2012). Because of Adams County’s agricultural significance in the state, it is especially important to understand the implications of climate change, as this could have significant impacts on the future of crop viability.

## Grape Varietals in Pennsylvania

Pennsylvania’s climate is more suitable for certain varietals than others. According to the Pennsylvania Wine Grape Grower Network and Penn State Cooperative Extension (2012), there are approximately 70 varietals currently cultivated within the state. However, only about a third of those have found commercial success. Table 2 contains the varietals that are recommended for cultivation within Pennsylvania, as primary and secondary recommendations. Suitability and success are relative terms that can vary based on vineyard site selection, viticultural practices and consumer demand. The varietals that are found in the “Secondary” column may not have the best suitability based on the average Pennsylvania climate, but with the right vineyard site and terroir, it is possible to cultivate these varietals. The varietals highlighted in purple are currently being cultivated in Adams County (Pennsylvania Wine Grape Growers Network, Penn State Cooperative Extension 2012, Penn State Site Assessment 2012, UC Davis National Grape Registry 2012).

Table 2. Grapes currently grown in Adams County, PA (Pennsylvania Wine Grape Growers Network, Penn State Cooperative Extension 2012, Penn State Site Assessment 2012, UC Davis National Grape Registry 2012)

Primary Recommended Grapes	Secondary Recommended Grapes
Cabernet Franc	Cabernet Sauvignon
Catawba	Chancellor
Cayuga	Gewurztraminer
Chambourcin	Merlot
Chardonel	Pinot Noir
Chardonnay	Riesling
Concord	Seyval blanc
Limberger	Sauvignon Blanc
Mourvedre	Vignoles
Petit Verdot	
Pinot Gris/Grigio	
Traminette	
Vidal Blanc	
Viognier	

## Grape Growing in a Changing (Warming) Climate

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Climate models show that the earth's mean surface temperature has increased by 0.6°C-1.2°C over the last 50 years, and precipitation has increased by 5% to 10%, mostly in the form of high precipitation events (Jones 2006, Abler, Shortle & Fisher 2004). Climate models also show that warming will continue for the next century (Lobell et al. 2006).

In California, the climatic warming has brought an average of 20 less frost-days versus 50 years ago. With warmer reported winter and spring temperatures, the growing season is starting 18-24 days sooner than previously observed (Nemani et al. 2001). The earlier the phenology occurs, generally the higher the wine grape quality. Fewer frost occurrences, the advanced growing season, and longer growing seasons have led to not only higher grape yields, but also higher premium wine grape quality over the last 50 years (Jones 2005). However, grape cultivation is most successful within a certain climatic niche and a warming trend could mean trouble for the industry. Experts say that a threshold will be reached, and the warming trend will begin to have adverse effects, not only on production, but the question of quality or quantity will be raised. Generally vineyards have varieties planted that are best suited to the climate that was in place when the vineyard was established, though it is possible to cultivate varieties suited for climates other than what is present (Jones 2004).

Adams County has found success in producing wines from colder-weather suited varieties, such as Chambourcin and Vidal Blanc. Generally, higher grape yields result in a lower quality of grape, and subsequently wine. There are many reasons behind this, but the concept has been empirically validated, as presently, vintners are seeing a cooperative relationship between yield and quality. This may mean that current temperatures are at the ideal level for

producing large, quality yields of wine grapes within Adams County. However, globally, many viticultural regions are either at or nearing their optimum climate thresholds for the varieties grown within that region (Jones 2004). A warming trend may push some varieties into a still-reasonable climate, but others will be forced to move pole-ward, causing major implications for vineyards (White 2006). What if the variety(s) that a vineyard in Adams County has found success in producing quality grapes, suddenly becomes compromised by climatic changes? What if the variety(s) they have found success in, is their signature grape and wine? In an industry in which your reputation is based solely on the quality of your crop, which is in turn so dependent on capricious variables, it is absolutely imperative that the possibilities for change and the potential implications are understood so as to be able to best adapt.

## Data and Methods

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The data used in this research is a compilation of observed data and modeled data from a grid cell centered over Gettysburg, Pennsylvania. The data are based on global climate projections from the World Climate Research Program's Coupled Model Intercomparison Project: phase 3 (WCRP and CMIP3). This data set contains 112 projections, which were utilized in the Intergovernmental Panel on Climate Change Fourth Assessment Report. The data were bias corrected and spatially downscaled in order to more accurately model climate change on a finer, regional scale. The bias correction was used in order to have the models more accurately coincide with historical observations, which in this case is 1950-1999. Spatial downscaling for the data was set to a  $1/8^\circ$  latitude-longitude spatial resolution ( $\sim 12\text{km} \times \sim 12\text{km} = \sim 144\text{km}^2$ ).

The model projections were based on three greenhouse gas emissions scenarios, SRESA2, SRESA1B, SRESB1 (Table 3), and run using different input values, producing a total of 112 values per month for 1950-2099. The variables contained in the data set were:

- Mean Monthly Temperature (Tavg) °C
- Monthly Precipitation Totals (mm/day)

Table 3. Greenhouse gas emissions scenarios as defined by the Intergovernmental Panel on Climate Change (2000).

<b>SRES A2</b>	Higher emissions path modeled in the BCSD climate data set. Characterized by technological change, fragmented economic growth, and higher population growth
<b>SRES A1B</b>	Middle emissions path modeled in the BCSD climate data set. Characterized by technological change with a more balanced energy source portfolio (reliance on fossil vs. non-fossil fuels is balanced)
<b>SRES B1</b>	Lower emissions path modeled in the BCSD climate data set. Characterized by an emphasis on local solutions to economic, social and environmental sustainability and protection, with a lower population increase than the A2 scenario

Using these emissions scenarios, a “best” and “worst” case summary was able to be synthesized in order to assess the viability and suitability of grape cultivation in Adams County, Pennsylvania.

## Methods

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### Model Accuracy

The accuracy of the projections was determined using the observed data from 1950-1999 as a means of comparison. Each projection value was calculated in terms of its root mean square error (RMSE) from the corresponding observed data value. In other words, the amount that a projection deviated from the observed value was calculated. A lower RMSE corresponded to higher accuracy. Each modeled projection RMSE value was then averaged over the 1950-1999 time period in order to determine which models had the lowest average RMSE value. The models with the highest RMSE value were not discounted from the analysis of climate change in



Adams County. Just as the observed data contained high climatic variability, the modeled projections should account for this possibility as well. In fact, in analyzing the models accuracy, it was found that several modeling groups were part of the most accurate and least accurate groupings of projections. The National Center for Atmospheric Research (USA) as well as the Canadian Center for Climate Modeling, both produced RMSE values that were among the lowest, as well as the highest. Input values are varied and because of the number of runs per emissions scenario, it is not surprising that the same modeling group could produce a wide range of resulting projection values (Bias Corrected and Downscaled WCRP CMIP3 Climate and Hydrology Projections 2012). The RMSE calculations were done for both the temperature and precipitation data.

## **Tools for Assessing Grape Suitability and Quality**

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Because the data used in this research are monthly averages, there are some limitations in terms of the types of suitability and quality guidelines that can be used to measure the effects of climate change on grape production. However, the following systems have been utilized, developed or modified in order to best qualify and quantify the assessment:

- Growing Degree Days
- Heat Summation Values
- Annual Average Temperature
- Growing Season Average Temperature
- Growing Season Average Precipitation
- Annual Precipitation Amounts
- Decadal Comparisons of Temperature and Precipitation
- Temporal Distribution of Precipitation
- Grapevine Climate/Maturity Groupings

\*Projected values were grouped based on emissions scenario (A2, A1B, B1), and all methods were performed on each of the three groupings.

## Growing Degree Days (GDDs)

Perhaps the most useful and accurate source of grape to site suitability, is the use of Growing Degree Days (GDDs) and Winkler's heat summation index to delineate five climatic regions which can adequately ripen different cultivars (Jones 2005, Schultz and Jones 2010).

The most accurate calculation of GDDs utilizes the following equation:

$$\text{GDD} = \text{sum of } ((T_{\min} + T_{\max})/2) - 10^{\circ}\text{C}$$

However, because of the limitations in data that were available, a different mathematical calculation was used to derive GDDs for Adams County, PA. Gregory Jones, PhD., of Southern Oregon University, is considered one of the world's leading experts on climate change and viticulture. In a 2005 journal article titled *Climate Change in the Western United States Grape Growing Regions*, Jones summarizes the calculation of GDDs in the Northern Hemisphere as the following equation:

$$\text{GDD} = (\text{Monthly Tavg} - 10^{\circ}\text{C})(\text{Number of Days in the Month})$$

This is the equation that was used in order to derive the GDDs for each of the emissions scenarios, as well as the data used to compare against the established climatic regions. A base of 10°C is used because that is the temperature at which phenology can begin. Growing Degree Days directly correspond to the temperature data. The total number of days within the growing season (April 1 to October 31) is 214. Therefore, an increase/decrease of 1° equates to a change of 214 GDDs. This concept was used in analyzing the climate change.

## Heat Summation Values and Climate Region

Amerine and Winkler (1944), developed a set of suitability guidelines based on temperature and GDDs, which are still used in the industry today. Table 4 is the outline of the heat summation index which provides guidance to growers in terms of grape varietal suitability.

Climatic zones are derived using GDDs based on the temperatures during the growing season.

This table was used to analyze the suitability of grape varieties to the current and future climate in Adams County, as discussed on the Results section.

Table 4: Growing Degree Days (GDD'S) by region (Amerine and Winkler 1944, Halliday 1993). Temperature ranges also defined per region.

Climatic Zone	Temperature and GDDs	Temperature Ranges
Region I	<1390 GDDs °C (<2500 °F)	16.5°C
Region II	1390-1670 GDDs °C (2501-3000 °F)	16.5°C – 17.8°C
Region III	1671-1940 GDDs °C (3001-3500 °F)	17.8°C – 19.07°C
Region IV	1941-2200 GDDs °C (3501-4000 °F)	19.07°C – 20.28°C
Region V	>2200 GDDs °C (>4000 °F)	>20.28°C

### Annual Average Temperature and Growing Season Average Temperature

The original data given contained monthly values for each year from 1950 to 2099 (1950 to 1999 for observed data). Average annual temperatures were derived by means of averaging each month's modeled projections. This gave twelve resulting values per year. Each of these values were averaged in order to get one value per year, 1950-2099.

In order to determine GDDs, the temperatures for the months of April to October were derived using the same method as finding the annual average temperature, excluding twelve month average. The growing season average temperatures were analyzed on a per month, per year basis (GDDs), as well as an annual average growing season temperature.

Observed data values for 1950-1999 formed the basis for which each of the three emissions scenarios data were compared against. The 1950-1999 averages for each of the three scenarios were the same as the observed values, despite the yearly variability. Therefore,

baseline values were determined using the 1950-1999 observed data. Yearly and decadal changes were compared across scenarios, using the 1950-1999 values as the baseline climate.

### **Annual Average Precipitation and Temporal Distribution of Precipitation**

The original data obtained gave precipitation values in mm/day, as a means for being able to compare months with different number of days. However, because the comparison of precipitation amounts was only done for equal months (i.e. April to April, May to May, etc.), values were calculated in order to derive precipitation amounts given in inches/month. This is a more common unit of measurement that is used in site evaluation and suitability within viticulture. Just as temperature values were averaged on a yearly and growing season basis, precipitation values were analyzed in the same manner. However, not only were annual and growing season amounts derived, but so were precipitation amounts for the months of August to October, since precipitation amounts during this period are especially influential to the quality of the grapes.

Observed data values for 1950-1999 formed the basis for which each of the three emissions scenarios data were compared against. The 1950-1999 averages for each of the three scenarios were the same as the observed values, despite the yearly variability. Therefore, baseline values were determined using the 1950-1999 observed data. Yearly and decadal changes were compared across scenarios, using the 1950-1999 values as the baseline climate.

### **Grapevine Climate/Maturity Groupings**

Using data compiled from the Pennsylvania Wine Grape Growers Network, Penn State Cooperative Extension, the Penn State Site Assessment, the University of California Davis National Grape Registry, Jones (2006), Van Leeuwen et al. (2008), and the data resulting from

the aforementioned methods, the growing conditions for grapes currently cultivated in Adams County were able to be analyzed, which provided the most true and accurate measurement of the impacts of climate change in Adams County. The methods employed to measure suitability included phenology milestone comparison, heat summation index comparison, average growing season temperature comparison and GDDs comparison. A more detailed discussion follows in the next section.

## Results and Discussion

Figure 2 contains the data for the average annual temperature from 1950-2099 for each of the three emission scenarios. Though there was yearly variability between each of the modeled

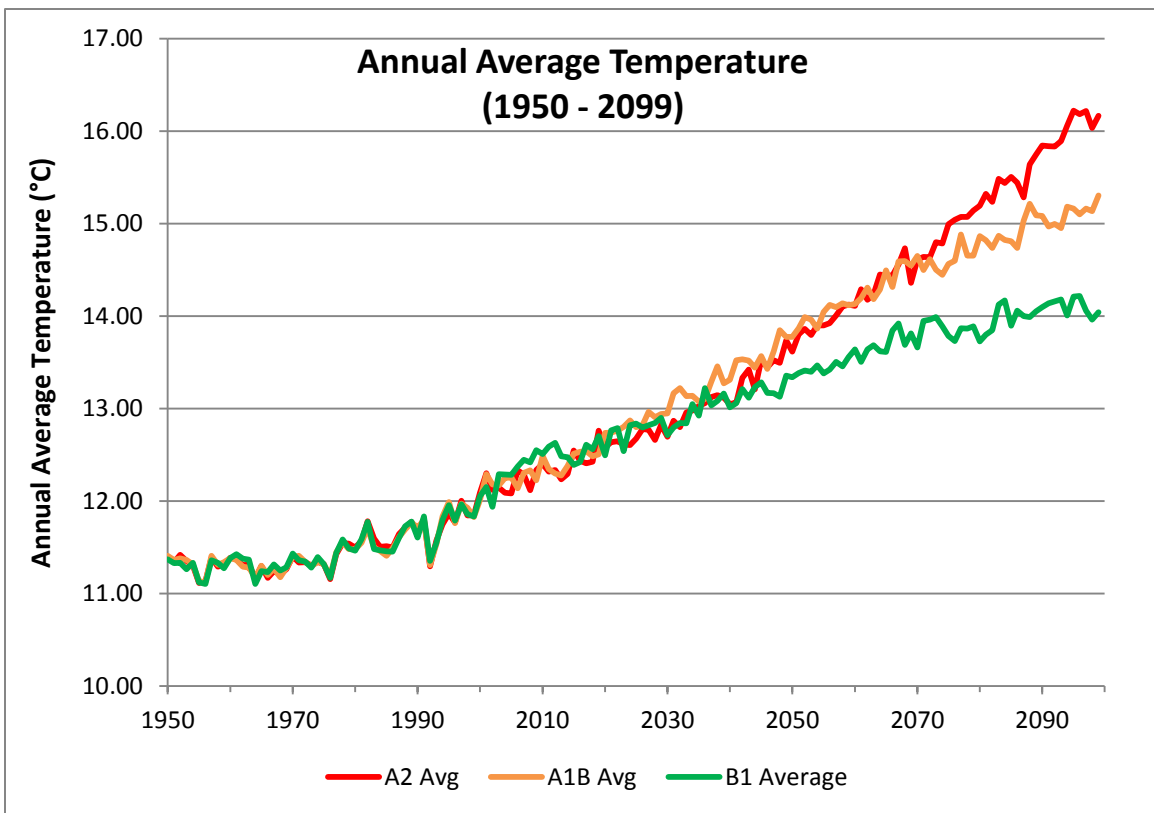


Figure 2: Annual Average Temperature for the three emissions scenarios (1950-2099).

projections, the overall average for each scenario was equal to what was derived as the baseline climate value (11.46°C). Also, the average RMSE value calculated per model was between 1.7 and 1.8, thus making the averaged variability over the 50 year period less significant. Figures 3 and 4 contain the departure from baseline climate values (Annual Temperature = 11.46°C, Growing Season Temperature = 18.07°C) for the 2000-2099 time

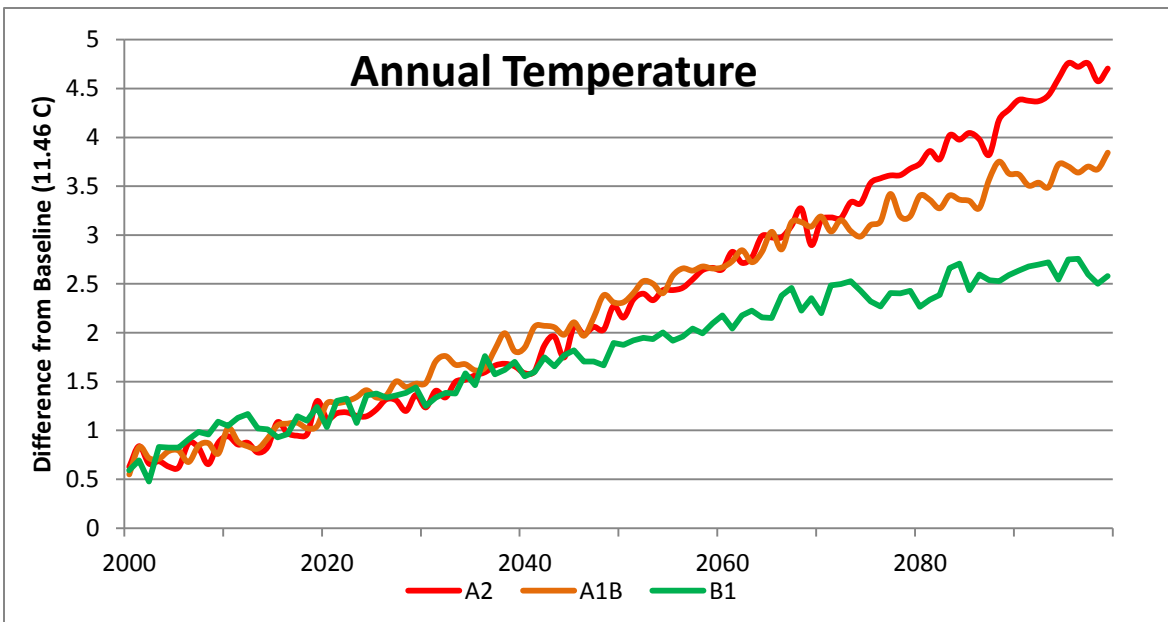


Figure 3: Departure from the Baseline Annual Average Temperature for the three emissions scenarios (2000-2099).

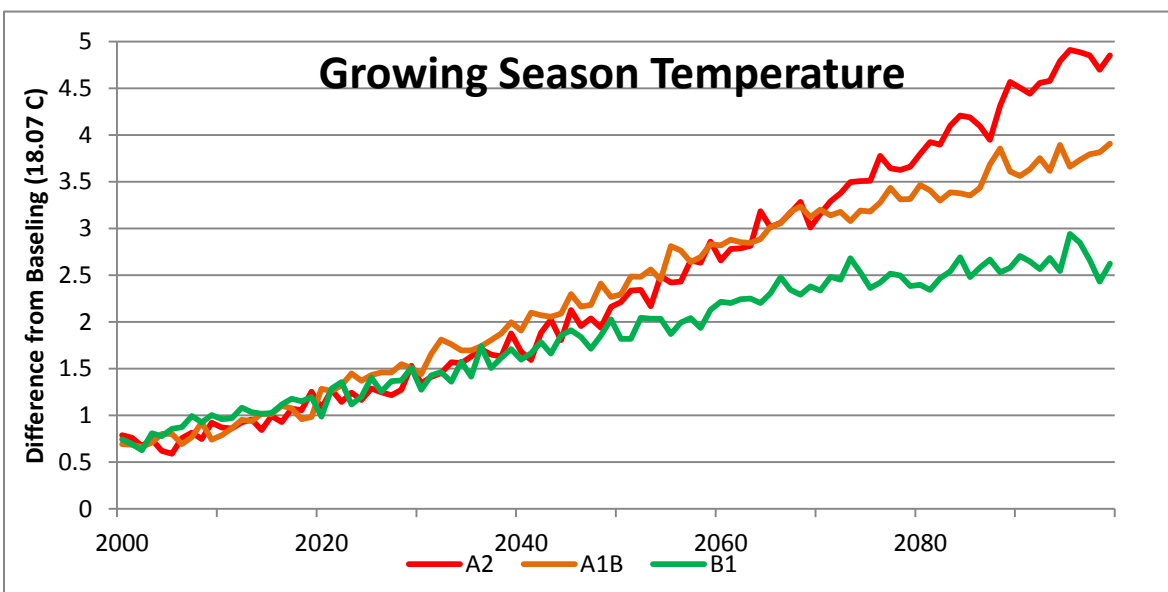


Figure 4: Departure from the Baseline Growing Season Average Temperature for the three emissions scenarios (2000-2099).

period. While Figure 2 depicts the overall temperature trend, Figures 3 and 4 depict the amount of change compared to the baseline climate. The Annual Average Temperature could increase by as much as 4.7°C by 2099, with the Growing Season Average Temperature increasing by as much 4.9°C. An increase of 4.9°C during the growing season would equate to the GDDs increasing by 1048. That is a dramatic increase, and one that could prove detrimental to the current wine industry of Adams County. With the current Growing Season Average Temperature of 18.07°C, Adams County is suited in middle of the Region III climate zone (Table 4), allowing varieties in Regions I, II and III to be cultivated.

Figure 5 is a summary of GDDs and the decadal changes driven by the increase in growing season temperatures. The length of the bar for each scenario contained within each time frame is reflective of the range of GDDs within that decade. This means, time steps where the length of the bar is longer has a larger range of growing season temperature/GDDs, and thus more potential for climatic variability. In addition, the amount of range within the decade can be used to determine whether Adams County is suitable for the climate zone in which the GDDs correspond, particularly if a GDD value is nearing a climate zone threshold. The light gray region corresponds to Region III, medium gray to Region IV, and dark gray to Region V, which is typically reserved for table and raisin grape production, and not premium wine grape production. It should be noted that values begin at 1670 GDDs (Region III). Between 1950 and 1970, there were four years which had growing season temperatures that resulted in GDDs less than 1670. However, the lowest GDD value within that 20 year range, was 1642 GDD, corresponding to an average temperature of 17.67°C. This is a difference of only 0.13°C

throughout an entire growing season. Therefore, these lower end GDDs values were not included within the decadal GDDs categorization.

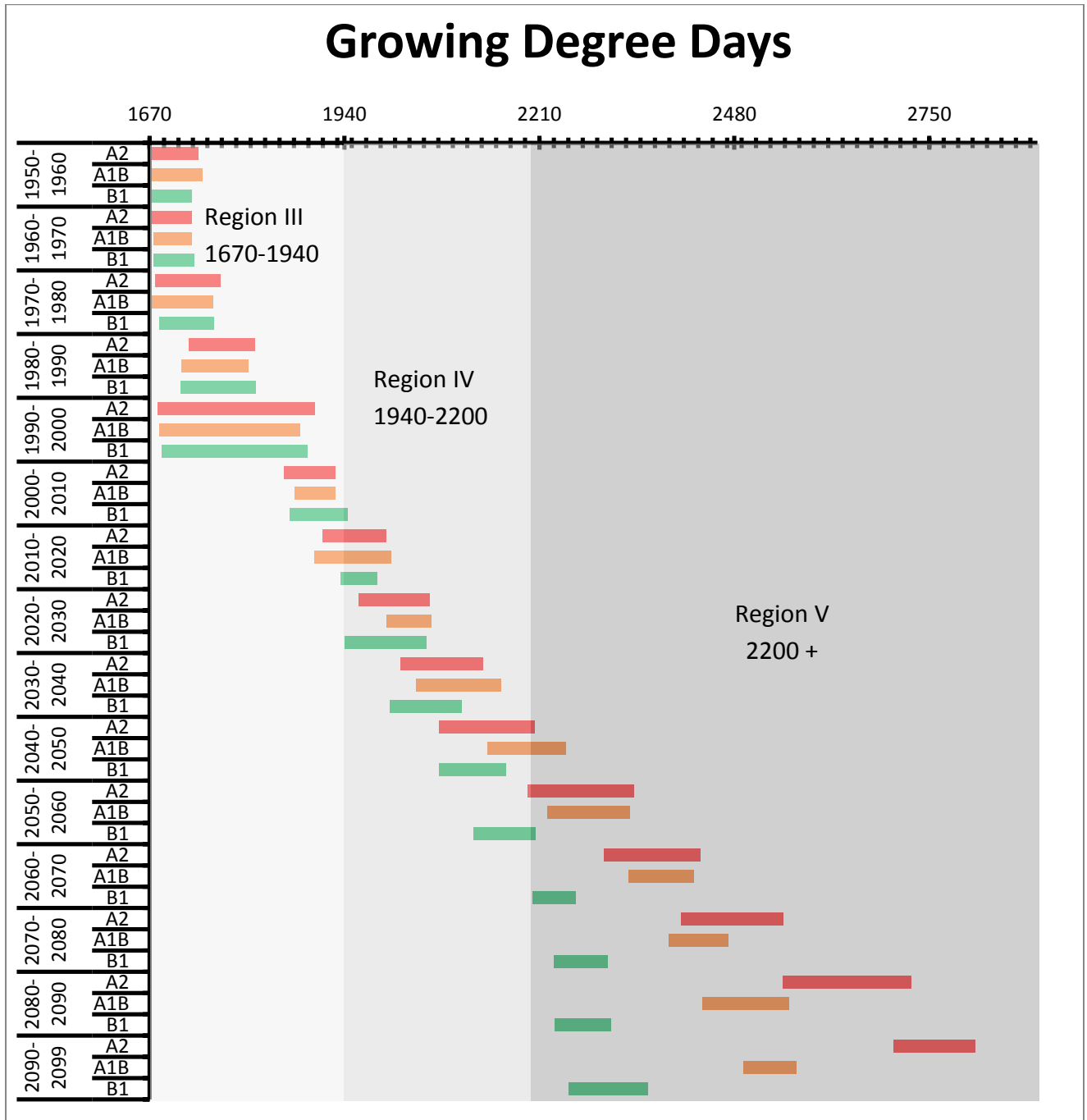


Figure 5: Growing Degree Days as expressed decadal and values based on the derived average growing season temperatures. The length of the bar corresponds to the range of GDDs per decade. Therefore, it is also indicative of the range of average growing season temperatures contained in each decade. (1950-2099).



As stated previously, GDDs could increase to as many as 2754, with an increase of 4.9°C. However, the lowest emissions scenario (B1), projects the growing season temperature to increase by 2.7°C by 2099, equating to 2304 GDDs. Though this is still well outside of the acceptable and suitable range for growing the current varieties, and average annual temperature between 13°C and 14°C and a growing season average temperature between 19°C and 21°C *could* potentially still be suitable for some warm climate grape varieties. Jones (2006) determined “Grapevine Climate/Maturity Groupings” for some of the most widely cultivated varieties, using climate data from several different wine producing regions (Figure 6). This

### Grapevine Climate/Maturity Groupings

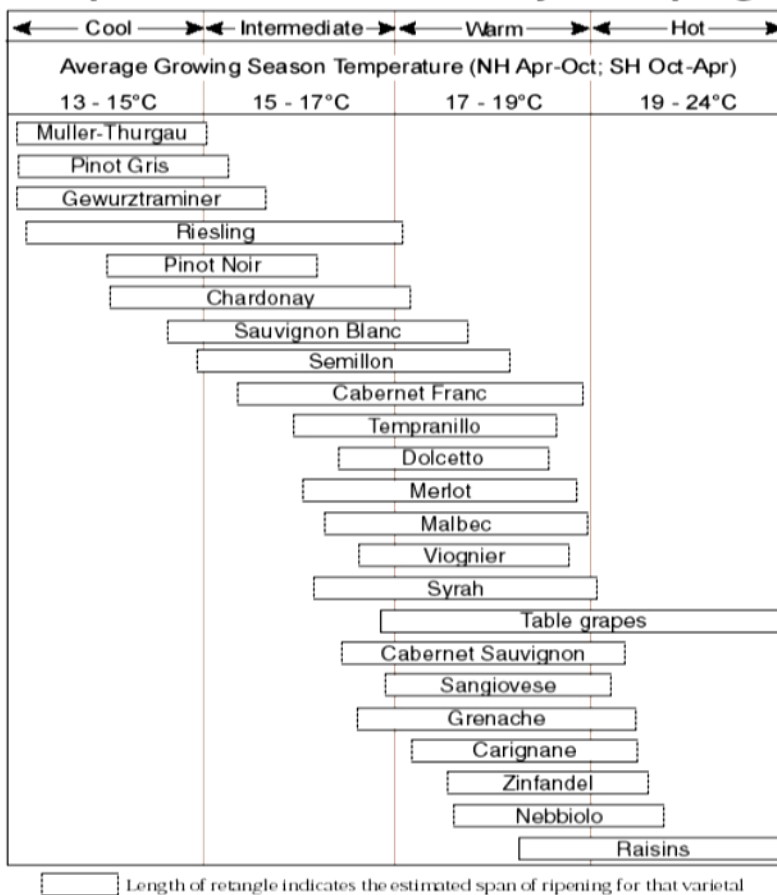


Figure 6. Climate maturity groupings based on average growing season temperature (Jones 2006)

delineation provides a platform upon which varietal suitability can be measured for a particular area. In addition, classifying the cultivated varieties by climatic region (Table 5) and then into the number of GDDs needed to reach phenology milestones (Table 6), allows for a more comprehensive and qualified suitability analysis.

Table 5. Grapes currently grown in Adams County, PA (Pennsylvania Wine Grape Growers Network, Penn State Cooperative Extension 2012, Penn State Site Assessment 2012, UC Davis National Grape Registry 2012)

Varietal	Climatic Zone
Cabernet Franc	II
Cabernet Sauvignon	II
Cayuga	I
Chambourcin	II
Chardonnay	I
Merlot	II
Pinot Gris/Grigio	I
Pinot Noir	I
Riesling	I
Sauvignon Blanc	III
Traminette	I
Vidal Blanc	II
Vignoles	II
Viognier	II

Table 6. Phenology Milestones on a per varietal basis for varietals successfully grown in Adams County

GDDs Necessary to Reach Phenology Milestones*				
	Bud Break	Florasion	Verasion	Maturity/Harvest
Cabernet Franc	40 - 50	350	1172	1540
Cabernet Sauvignon	80 - 90	385	1181	1520
Chardonnay	45 - 55	350	1068	1267
Merlot	55 - 65	383	1128	1474
Mourvedre	65 - 75	409	1128	1940
Pinot Gris/Grigio	45 - 55	333	965	1270
Pinot Noir	55 - 65	334	1014	1251
Riesling	50 - 60	349	1173	1380
Sauvignon Blanc	55 - 65	371	1070	1680

\*These values are a permutation of values from Van Leeuwen et al. 2008, Winkler's heat summation, Penn State Cooperative Extension, and the PSVAS

Unfortunately, Table 6 does not contain data for every varietal cultivated in Adams County.

There is a lack of evidence for some of these varietals in terms of specific maturation characteristics. Chambourcin, Vidal Blanc and Traminette in particular, have had a lot of success in Adams County, but lack the necessary data in order to organize suitability guidelines for these varietals (John Halbrecht, Personal Communication 2012).

By examining Figure 6, in conjunction with the projected temperature increase, it becomes apparent that there is a definite possibility that Adams County could become unsuitable for producing quality wine grapes by 2099. Each of the three emissions scenarios project the growing season temperature to exceed 19°C between 2030 and 2040. Once this temperature threshold is surpassed, it will become much more difficult to produce high quality wines. Figure 6 contains several varietals which can be grown in warmer climates, such as Zinfandel. In addition, Cabernet Sauvignon, which is currently grown in Adams County, has a growing season temperature suitability that will tolerate temperatures between 19°C and 20°C. However, as the temperature begins to exceed 20°C, the suitability will change and the potential for quality grape production decreases.

While much of the focus is on temperature and the variables that are driven by temperature, it is still important to note how precipitation is projected to change. Figure 7 depicts the average annual precipitation amounts for 1950-2099. However, much like the temperature values, this depiction is not the best form of analysis for change detection. While it shows the overall trends, it is hard to quantify the amount of change between 2000-2099. Figures 8, 9, and 10 are all analyses of precipitation amounts in terms of the amount of change from the baseline climate precipitation value (Annual Average Precipitation = 41.24 in/year, Growing Season Average Precipitation = 25.18 in/GS, August-October (post veraison) = 10.33 in/time). The precipitation values have a lot of variability between years, versus the temperature values which had an overall positive increase. However, the fact that there is a lack of a clear precipitation increase pattern can mean positive things for the overall suitability of grape varietals. Because rain events are especially detrimental to the quality of grapes

during the months of August, September and October, it could be viewed as a positive effect of climate change that the amount of amount of change between 2000 and 2099 is confined to

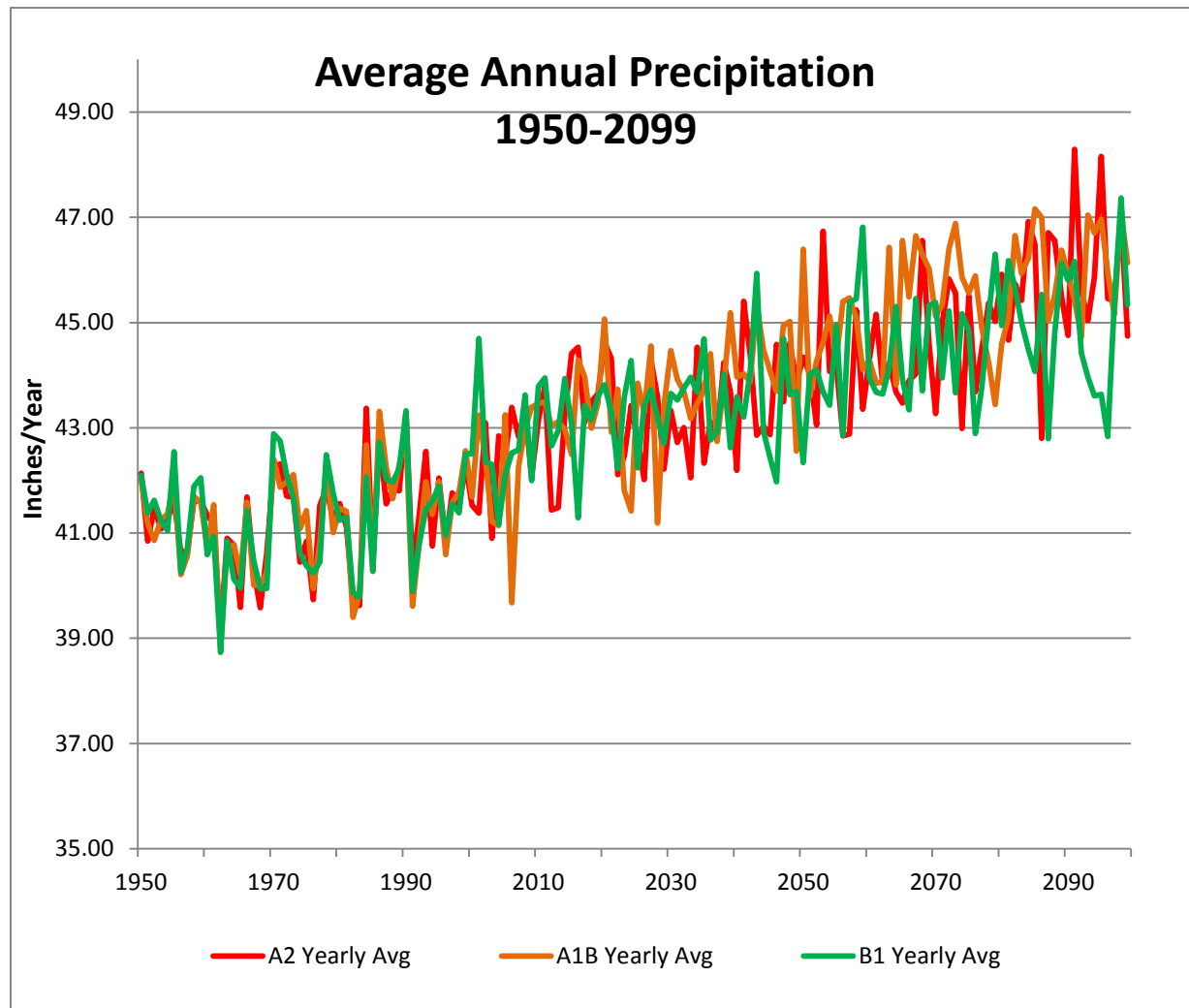


Table 7. Average annual precipitation values for each of the three emissions scenarios 1950-2099.

yearly variations, rather than an overall trend. In fact, rain fall amounts have an overall trending towards decreasing by 2099 during the post-verification months. As rainfall just prior to harvest can have negative effects on the quality of grapes (fruit rot, berry split, lower Brix), this could be a positive effect of climate change. It should be noted though, that while excess precipitation is not preferable, drought conditions are more likely to occur with an increase of temperature. Water deficits can cause vine stress and decrease grape quality if too much stress

is endured.

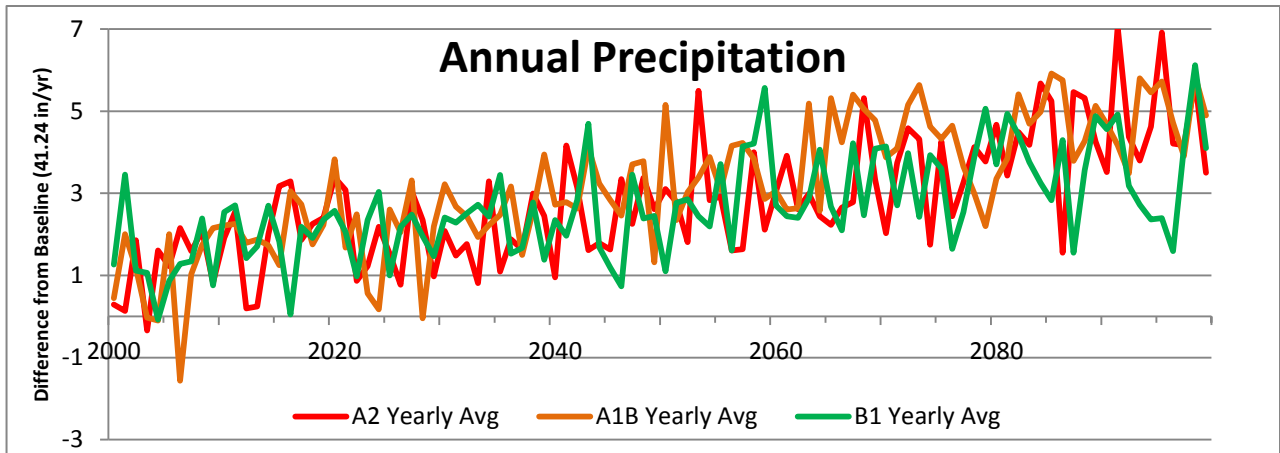


Figure 8: Departure from the Baseline Annual Average Precipitation for the three emissions scenarios (2000-2099).

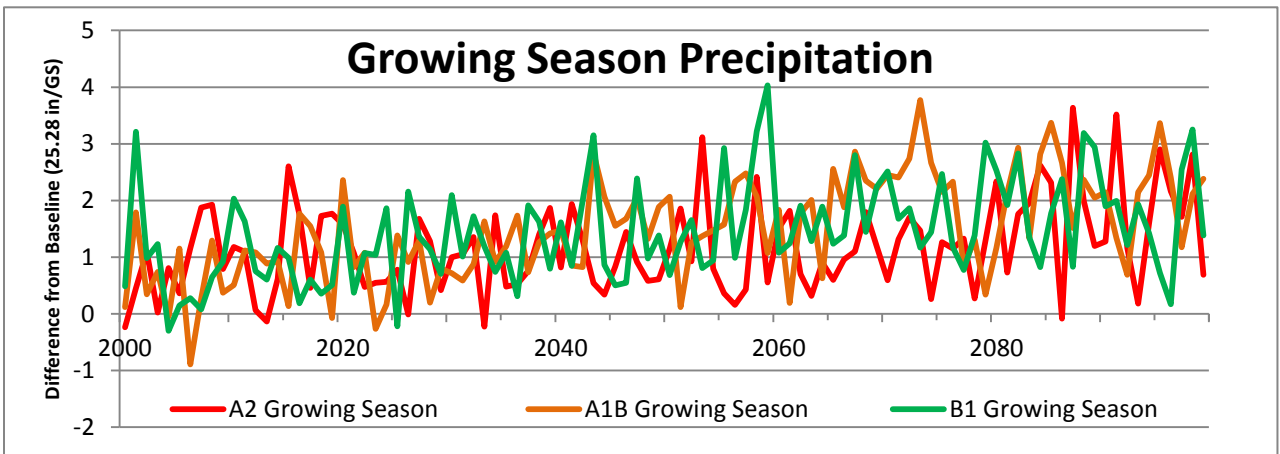


Figure 9: Departure from the Baseline Growing Season Average Precipitation for the three emissions scenarios (2000-2099).

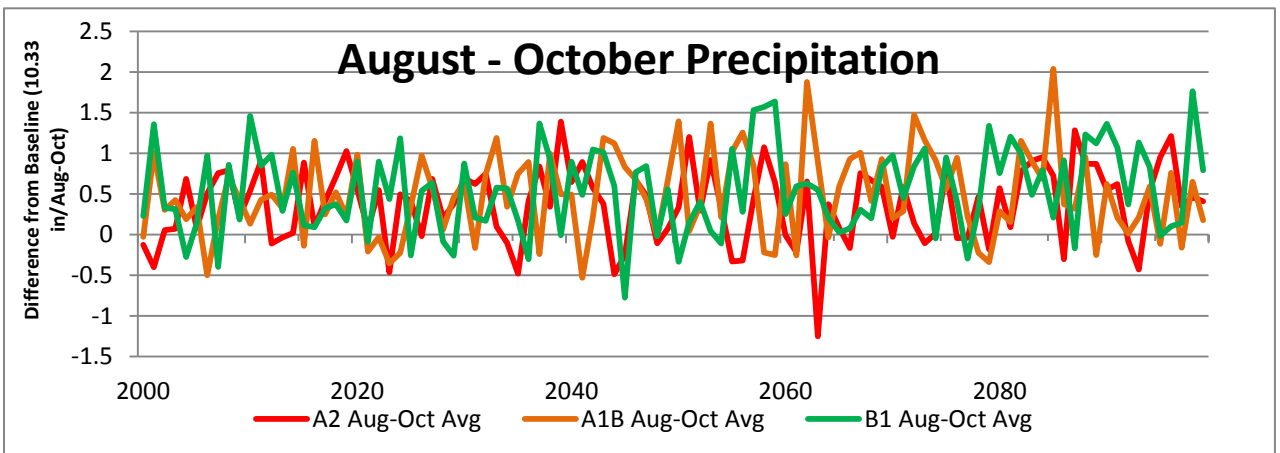


Figure 10: Departure from the Baseline Growing Season Post Maturations Average Precipitation for the three emissions scenarios (2000-2099).

A summary of each of the climate emissions scenarios is provided in Table 7.

Table 7: A summary of temperature and precipitation increases and the suitability guidelines that they can produce. Changes are depicted on a decadal basis in order to best show short term variability.

	Annual Temp (11.46°C)*			Growing Season Temp (18.07°C)*			GDDs (1730)*		
	A2	A1B	B1	A2	A1B	B1	A2	A1B	B1
2000-2010	0.89	0.91	1.03	0.90	0.91	1.02	194	194	219
2010-2020	1.19	1.32	1.25	1.22	1.33	1.26	261	285	270
2020-2030	1.53	1.74	1.52	1.59	1.77	1.53	340	379	328
2030-2040	2.03	2.19	1.78	2.04	2.25	1.82	436	482	390
2040-2050	2.62	2.66	2.07	2.64	2.73	2.10	565	584	450
2050-2060	3.17	3.02	2.32	3.24	3.11	2.38	694	666	509
2060-2070	3.78	3.32	2.48	3.90	3.39	2.52	840	725	540
2070-2080	4.32	3.56	2.61	4.47	3.63	2.62	972	777	561
2080-2090	4.65	3.68	2.64	4.80	3.77	2.68	1052	808	573
2090-2099	4.57	3.64	2.65	4.71	3.74	2.66	1032	800	570
<b>TOTAL</b>	<b>4.57 – 2.65°C Increase</b>			<b>4.71 – 2.66°C Growing Season Increase</b>			<b>1032 – 570 GDDs Increase →Region V</b>		
	Annual Precip (41.24"/yr)*			Growing Season Precip (25.18"/GS)*			Aug-Oct Precip (10.33"/Aug-Oct)*		
	A2	A1B	B1	A2	A1B	B1	A2	A1B	B1
2000-2010	1.74	1.66	1.63	1.15	0.74	0.73	0.45	0.38	0.48
2010-2020	1.95	2.07	1.85	1.01	0.90	1.01	0.40	0.33	0.37
2020-2030	2.00	2.48	2.30	1.05	1.14	1.37	0.49	0.48	0.49
2030-2040	2.64	3.06	2.28	1.15	1.50	1.39	0.41	0.61	0.42
2040-2050	2.72	3.49	2.87	1.07	1.65	1.71	0.26	0.66	0.50
2050-2060	3.18	4.01	3.09	1.08	1.96	1.70	0.15	0.62	0.48
2060-2070	4.05	4.35	3.53	1.58	2.11	1.88	0.45	0.59	0.71
2070-2080	4.57	4.82	3.48	1.86	2.18	1.81	0.05	-0.02	0.19
2080-2090	4.63	5.09	3.24	1.72	2.29	1.63	-0.68	-0.81	-0.52
2090-2099	4.71	4.77	3.50	1.80	2.02	1.65	-0.42	-0.54	-0.15
<b>TOTAL</b>	<b>4.71 – 3.50 in/year Increase</b>			<b>2.02 – 1.65 in/Growing Season Increase</b>			<b>0.42 – 0.13 in/Aug-Oct Decrease</b>		

Each of the decadal values are measured as an increase from the baseline climate data that was derived from the observations (1950-1999). Differences were depicted on a decadal time scale. This is important to examine because it is much easier to analyze change on a 10 year basis, versus the 100 years that the data is calculated for. In addition, grape varieties tend to have a 25-30 year viability. Therefore, using a smaller time scale to analyze change could significantly impact vineyard planning. The average annual temperature could increase 2.65°C to 4.57°C by 2099. In a shorter time frame, the annual average temperature in Adams County could increase by approximately 2°C over the next 20 years, with growing season temperatures potentially increasing 1.53°C to 1.77°C by 2030. Though the temporal distribution of precipitation could change favorably with an increase in temperature, there are other potential concerns that need to be considered. The increase in temperature and decrease in precipitation during the final months of maturation, could potentially lead to quality issues, as vines may potentially undergo water deficit stress and phenology could slow or even stop. With the wine industry increasing within Pennsylvania, and particularly Adams County, these types of changes could drastically change the suitability of the currently cultivated grapevines, and cause a lower quality wine grape to be produced. Instead of the potential for yearly climatic variations which may produce a lower quality grape, the types of changes projected could cause lower quality grapes to be produced on a more regular basis.

## **Considerations and Limitation**

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Though temperature and precipitation are extremely important to the quality of wine grapes, the other factors that terroir entails are also important. One particular aspect of terroir that

was not explored as part of this research is slope. The slope of a vineyard has a lot of influence on the temperature trends and soil drainage. A steeper slope at a higher elevation may be able to compensate for an increase in temperature, but creating airflow congenial to producing quality grapes. The geology, soils, solar radiation, relative humidity, wind, soil moisture and overall viticultural practices are also very influential in the cultivation of wine grapes. It is a combination of all of these variables that make it possible to produce a quality wine grape. Though these parameters were not the focus of this research, they should still be considered important factors when assessing a vineyard for varietal suitability and quality.

Limitations of this data set did not allow for high precision in calculating some of the measurable indices, such as GDDs. Ideally, GDDs should be calculated from daily minimum and maximum values to account for daily variations within each month. The projection values used to derive the monthly average temperatures (the basis for all temperature related calculations) did contain some variability, and may potentially have helped to account for the lack of daily values. Other limitations and considerations include the lack of Adams County based research in order to provide a guideline for quality grape production. There have been many studies in some of the larger wine producing regions of the world, such as Napa Valley, Bordeaux, France, Italy and Australia, but there has been very little research conducted within the Mid-Atlantic region. In a personal communication conversation with Mark Chien, Viticulture Educator for the Pennsylvania Wine Grape Growers Network, Penn State Cooperative Extension, it was reiterated that there is a lack of research pertaining to climate and wine within Pennsylvania. Many of the sources and that do exist, can at best, be adapted to what is present within Pennsylvania's climate. With the increase of wine production and grape growing in



Pennsylvania, it is hoped that more research and studies can be facilities by vineyards within the Keystone State.

## Conclusion

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An increase in temperature is inevitable, according to the climate projections. What these increases mean in terms of wine grape quality can not necessarily be exactly measured, since there are so many other parameters entailed in producing a quality grape, but there are several affects that can be determined. An increase in temperature means that phenology cycles begin earlier, allowing sugars and tannins to fully develop prior to harvest. At the present time, vintners are seeing a cooperative relationship between yield and quality. While this may initially produce some very high quality wines and higher yields, there is a threshold at which a faster maturation sacrifices the quality of grape/wine produced. Often, grapes that are produced from higher grape yields result in a lower quality. While warmer climates, earlier bloom dates, and larger crushes equate to more wine produced, the quality of the grapes are sacrificed. The rapid plant growth creates an unbalanced ripening and maturation stage. The ideal climate allows the sugars to accumulate steadily, regulates acidity levels, and produces a flavor palate that is congenial with that varietal. This produces the highest quality wine.

However, in a too-warm climate, the grapevine phenology will occur rapidly and with flaws. As the grapes ripen faster, the harvest dates are moved to warmer months, leading to potential grape rot or grape shrivel. The sugar levels mature too quickly, while the flavors lag behind. As the vintner waits to harvest the grapes until the flavor is fully developed, they sacrifice the acidity, resulting in a “flabby” wine (high alcohol content as a result of high sugar levels with

very little returned acidity). Determining what these climate thresholds are becomes extremely important to the integrity of the wine industry (Jones 2004). Understanding how the relationship between temperature and grapevine phenology is the basis to all future vineyard planning and suitability determination. With additional research based in Pennsylvania, Adams County specifically, there is great potential for a better understanding of the impacts of climate change on the wine industry in Adams County.

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