Summer 10-2-2013

Spatial Analysis of Climate and Winegrape Production in Winegrape Growing Regions of Oregon, United States of America

Willow Devin Campbell
Portland State University

Let us know how access to this document benefits you.

Follow this and additional works at: https://pdxscholar.library.pdx.edu/open_access_etds

Part of the [Viticulture and Oenology Commons](#)

Recommended Citation

Campbell, Willow Devin, "Spatial Analysis of Climate and Winegrape Production in Winegrape Growing Regions of Oregon, United States of America" (2013). *Dissertations and Theses*. Paper 1442.

[10.15760/etd.1441](https://pdxscholar.library.pdx.edu/open_access_etds/10.15760/etd.1441)

This Thesis is brought to you for free and open access. It has been accepted for inclusion in Dissertations and Theses by an authorized administrator of PDXScholar. For more information, please contact pdxscholar@pdx.edu.

Spatial Analysis of Climate and Winegrape Production in Winegrape Growing Regions of
Oregon, United States of America

by

Willow Devin Campbell

A thesis submitted in partial fulfillment of the
requirements for the degree of

Master of Science
in
Geography

Thesis Committee:
Hejun Chang, Advisor
Martha Works
David Banis

Portland State University
2013

© Willow Devin Campbell

Abstract

American Viticultural Areas (AVAs) are susceptible to small variations in climate and microclimates and are found within a narrow latitudinal range of prime climate conditions. These AVAs are geographically determined based on the best soil, climate, precipitation and temperature combinations for specific winegrape regions. As climate change continues to alter the local weather and the greater climate region of the Western United States, winegrape growing regions in Oregon are being affected. In an effort to determine what the pattern of change is, and compare previous studies of climate change using climate indices, a comparative study based in part on prior research was conducted. Using 800 meter resolution Parameter-elevation Regressions on Independent Slopes Model (PRISM) climate datasets, four individual climate indices were analyzed for statistical correlation with the climate data. These climate indices are: growing degree-days (GDD), the average growing season temperatures (GST), Huglin Index (HI) and the biologically effective degree-day (BEDD). Based on currently available data for this research, these climate indices were statistically analyzed during the years 2000 to 2010. A further avenue of research included a statistical analysis of the reported winegrape production, although this data was available only at an aggregated county-level. Results show that all four climate indices exhibit statistical significance, although the inclusion of the winegrape production data exhibited no statistical significance for

many of the analyses, most likely due to subjective and aggregated data, few did result in significance with the climate indices. The research discussed here confirms the accuracy of the four climate indices and suggest that a longer time frame, coupled with less aggregated and subjective winegrape production data could produce interesting results in future research on the results of climate indices in winegrape growing regions.

ACKNOWLEDGMENTS

I would like to give a sincere thanks to my advisor, Dr. Heejun Chang, for his lasting commitment over the progression of my thesis research. His dedication through the course of these years, to my studies, this thesis and me is infinitely valued.

I would like to thank Dr. Gregory Jones for whom, without his dedication and profound knowledge of the subject, this thesis would not have been possible. His enthusiasm and availability, despite broad geographic differences, to offer guidance and support is immeasurable and greatly appreciated.

In addition to Heejun and Greg, I would like to thank the other members of my committee, Dr. Martha Works and David Banis, for their continued support and time they have allotted for this manuscript.

I would like to say a special thank you to my cohort, especially Kate Clark and Cale Richards, for being there during the late nights and the early mornings, to commiserate the downs and celebrate the highs. Cheers to victory laps.

Karin Waller, I owe you a prodigious thank you. Without you to take the time out of your day to guide an overwhelmed, sleep-deprived graduate student, I would have never made it past that first term. Thank you, Karin.

More than anything, I would like to give a heartfelt thank you to my friends and family for all of their overwhelming support and love while pursuing my master's degree. Thank you for seeing in me what, at times, I could not see in myself and for encouraging me to keep going.

I would like to especially thank Eric Crum for his unwavering patience, encouragement and love while completing my thesis. Lots of lost adventure filled weekends and relaxing evenings are on the horizon. Thank you, Eric.

TABLE OF CONTENTS

ACKNOWLEDGMENTS.....	iii
LIST OF TABLES.....	vii
LIST OF FIGURES.....	viii
GLOSSARY.....	x
Chapter One – Introduction.....	1
1.1 Background	1
1.2 Research Objectives.....	3
Chapter Two - Climate and winegrape growing regions.....	5
2.1 Climate and world winegrape growing regions	5
2.2 Climate and Oregon winegrape growing regions	6
2.3 Oregon AVA Characteristics.....	7
2.3.1 Willamette Valley.....	9
2.3.2 Columbia Gorge	10
2.3.3 Columbia Valley	11
2.3.4 Snake River Valley	11
2.3.5 Southern Oregon	12
Chapter Three - Materials and Methods.....	13
3.1 Data	13
3.1.1 Wine production data.....	13
3.1.2 Climate data.....	13
3.2 Climate Indices	15
3.2.1 Growing season temperature	15
3.2.2 Growing degree day.....	18
3.2.3 Huglin index	19

3.2.4 Biologically effective degree day	21
3.3 Data processing	21
3.4 Statistical analysis	25
Chapter Four – Results.....	26
4.1 Correlation of climate indices and wingrape production at the Oregon County Scale	47
4.2 Correlation at the Oregon winegrape growing region scale.....	30
4.2.1 Willamette Valley winegrape growing region	31
4.2.2 Columbia Gorge winegrape growing region	32
4.2.3 Columbia Valley winegrape growing region	34
4.2.4 Snake River Valley winegrape growing region.....	36
4.2.5 Southern Oregon winegrape growing region	37
4.3 Previous reseach comparison	38
Chapter Five - Discussion and conclusions.....	47
REFERENCES.....	55

LIST OF TABLES

Table 1 Oregon Winegrape growing regions elevations and area characteristics.....	8
Table 2: Distribution of American Viticultural Areas per Oregon County.....	19
Table 3: Oregon American Viticultural Area (AVA) 2000-2010 PRISM-calculated quantile statistics for growing season average temperature (GST, °C), growing degree-days (GDD, C° units), Huglin index (HI, C° units), and biologically effective degree-days (BEDD, C° units).....	27
Table 4: Pearson Correlations for Climate Indices and Winegrape Production by Oregon County for 2000 to 2010.....	30
Table 5: Pearson Correlations for Climate Indices and Winegrape Production for the Willamette Valley Winegrape Growing Region in Oregon for 2000 to 2010.....	32
Table 6: Pearson Correlations for Climate Indices and Winegrape Production for the Columbia Gorge Winegrape Growing Region in Oregon for 2000 to 2010.....	33
Table 7: Pearson Correlations for Climate Indices and Winegrape Production for the Columbia Valley Winegrape Growing Region in Oregon for 2000 to 2010.....	35
Table 8: Pearson Correlations for Climate Indices and Winegrape Production for the Snake River Valley Winegrape Growing Region in Oregon for 2000 to 2010.....	36
Table 9: Pearson Correlations for Climate Indices and Winegrape Production for the Southern Oregon Winegrape Growing Region in Oregon for 2000 to 2010.....	38

LIST OF FIGURES

Figure 1:	Wine Producing regions of the World.....	5
Figure 2:	Study Area: Winegrape growing regions of Oregon and Counties.....	7
Figure 3:	American Viticultural Areas and Oregon Counties.....	22
Figure 4:	Scatter plot matrix for climate indices and winegrape production within Oregon County and Winegrape growing boundaries for the years 2000 - 2010	28
Figure 5:	Scatter plot matrix for climate indices and winegrape production for the Willamette Valley winegrape growing region for the years 2000 - 2010	32
Figure 6:	Scatter plot matrix for climate indices and winegrape production for the Columbia Gorge winegrape growing region for the years 2000 - 2010	34
Figure 7:	Scatter plot matrix for climate indices and winegrape production for the Columbia Valley winegrape growing region for the years 2000 - 2010	35
Figure 8:	Scatter plot matrix for climate indices and winegrape production for the Snake River Valley winegrape growing region for the years 2000 - 2010	37
Figure 9:	Scatter plot matrix for climate indices and winegrape production for the Southern Oregon winegrape growing region for the years 2000 – 2010	38
Figure 10:	Average growing season temperatures within Oregon winegrape growing regions for the time frame of 2000-2010.....	39
Figure 11:	Box-whisker plot of average growing season temperature within Oregon by county for the years of 2000 – 2010.....	40
Figure 12:	Box-whisker plot of average growing season temperature in Winegrape Growing Regions of Oregon from the years of 2000 – 2010.....	40
Figure 13:	Average growing degree day within Oregon winegrape growing regions for the time frame of 2000-2010.....	41
Figure 14:	Box-whisker plot of average growing degree day within Oregon by county for the years of 2000 – 2010.....	42

Figure 15: Box-whisker plot of average growing degree day in Winegrape Growing Regions of Oregon from the years of 2000 – 2010.....	42
Figure 16: Huglin index within Oregon winegrape growing regions for the time frame of 2000-2010.....	43
Figure 17: Box-whisker plot of Huglin index within Oregon by county for the years of 2000 – 2010.....	44
Figure 18: Box-whisker plot of Huglin index in Winegrape Growing Regions of Oregon from the years of 2000 – 2010.....	44
Figure 19: Biologically effective degree days within Oregon winegrape growing regions for the time frame of 2000-2010.....	45
Figure 20: Box-whisker plot of biologically effective degree days within Oregon by county for the years of 2000 – 2010.....	46
Figure 21: Box-whisker plot of biologically effective degree days in Winegrape Growing Regions of Oregon from the years of 2000 – 2010.....	46
Figure 22: Number of vineyards by Oregon County for the years of 2000 -2010.....	49

Glossary

AVA

American Viticultural Areas

BEDD

Biologically effective degree-day

DTR

Diurnal temperature range

DTR_{adj}

Diurnal temperature range adjustment

GDD

Growing degree-day

GST

Growing season temperatures

HI

Huglin index

PRISM

Parameter-elevation Regressions on Independent Slopes Model

Tmax

Temperature maximum

Tmin

Temperature minimum

USDA

United States Department of Agriculture

Chapter One – Introduction

1.1 Background

Climate is a dominating factor in practically all fields of agricultural sciences, including viticulture (Coombe 1987, Motha and Baier 2005, Jones and Goodrich 2008, Duchêne 2010). A wine growing region's climate influences whether grapes can be grown, what varieties would achieve their greatest success (Amerine et al. 1980) and overall annual yield (Rankine et al. 1971, Gladstones 1992, Ramos 2008). To fully understand the best combination of these variables that creates the most suitable environment, it is important to take into account the spatial distribution of regional climates and microclimates within winegrape growing regions (Jones et al. 2009).

Factors that contribute to a winegrapes' success and suitable location other than climate (Webb et al. 2008, Jones et al. 2009) include vineyard management (Coombe and Lland 2004, Bisson et al. 2003) and soils (Ramos and Martinez-Casanovas 2009, 2010). Included in these climate variables are simple to intricate calculations, or indices, related to temperature used to measure and compare different winegrape growing regions' climatic characteristics (Winkler et al. 1974, Gladstones 1992, Hall and Jones 2010, Jones et al. 2010). Air temperature indices for winegrape growing regions have been calculated and studied in many different ways over the course of time in various regions (Winkler et al. 1974, Gladstones 1992, Jones et al. 2010). These studies include

modeling both past (Maurer et al. 2009) and future (Bindi et al. 1996, Jones and Storchmann 1998, Costantini et al. 2009) scenarios for multiple variables related to winegrapes and climate. A common variable of interest is the effect climate has on a grapevine's phenology, or stages of a plant's growth (Coombe 1988, Due et al. 1993, Jones and Davis 2000, White et al. 2008), though there are not standardized calculations by which to measure phenological events. One of the major setbacks in conducting this type of research is the lack of and inconsistency of climatic data (Hall and Jones 2010, Jones et al. 2010).

Temperature-based indices are common statistical analyses that can be used to assess the suitability of winegrape growing regions and their long-term aptness for a specific varietal of grape (Winkler et al. 1974, Gladstones 1992, Hall and Jones 2010, Jones et al. 2010). Quantifying spatial variations in temperatures across winegrape growing regions (deBlij 1983, Dickenson 1990, Vaudour 2002, Jones et al. 2005) allows researchers and winegrape growers a unit of measurement to compare with quantifiable indices across different regions (Jones et al. 2010 and Hall and Jones 2010). Even with advancements in spatial climate data and resources, very little research has been conducted for winegrape growing regions in the Western United States (Jones et al. 2010).

1.2 Research objective

The objective of this paper is to investigate the spatial patterns of winegrape production and their relation to commonly used regional winegrape growing regions climate indices. This research is based on the publication “Spatial Analysis of Climate in Winegrape Growing Regions in the Western United States” (Jones et al. 2010). The goal of this research is to describe the temperature regimes of Oregon winegrape growing regions (American Viticultural Areas [AVAs]) and the correlations with winegrape production for an eleven-year timespan between 2000 to 2010 using the same climate indices that have been used for analysis in previous research (Jones et al. 2010, Hall and Jones 2010). In order to achieve this goal, the research objectives are twofold: (1) provide an updated analysis from the previous article for four climate indices; (2) analyze the correlation between winegrape production data and the significance of climate indices as an indicator of overall production of winegrapes in Oregon. First, with this updated analysis, I will investigate what the major observations will be compared to that of the Jones et al. 2010. In addition, I will analyze and discuss if these climate indices are in fact statistically significant predictors of winegrape production in Oregon.

Recently, these four climate indices were used to describe the temperature regimes in the Western United States AVA's (Jones et al. 2010) and Australian winegrape growing regions (geographical indication [GI's]) (Hall and Jones 2010). With these current data, the Oregon winegrape growing conditions may be directly compared

with those previous research studies in the Western United States, Australia, and other regions in which similar research has been conducted.

Chapter 2: Climate and winegrape growing regions

2.1 Climate and world winegrape growing regions

Prime winegrape growing climate falls within certain specific temperature thresholds (Jones and Davis 2000, Jones 2005, Webb et al. 2008), ideal precipitation accumulations (Rodó and Comín 2000), along with frost and wind limitations (MacNeil 2001, Tate 2001). Winegrapes, though able to grow in sub ideal climatic conditions, achieve their greatest success in specific climate environments and thrive between specific latitude boundaries (deBlij 1981) at 30 to 50° north and 30 to 50° south (Figure 1). The majority of all winegrapes worldwide are grown within these narrow bands of ideal climatic conditions.

Figure 1 The world's viticulture regions fall primarily within latitude bounds with average growing season temperatures of 10°C to 20°C (Figure from GeoCurrents.info 2012).

2.2 Climate and Oregon winegrape growing regions

The state of Oregon resides on the west coast of the United States of America between Washington to the north and California to the south, bounded on the west by the Pacific Ocean. The entire state is 254,810 km² (98,381mi²) and approximately 475 km (300 mi) north to south and 636 km (400 mi) east to west (Census, 2013). The topography of Oregon is comprised of a wide variety of geographic features, including fertile valleys, a deep gorge, high deserts, and volcanic mountain ranges. Three of the most important physiographic features affecting climate in Oregon are the Pacific Ocean, the Coastal Range (884 – 1,067 m [2,900 – 3,500 ft.] elevation) and the Cascade Range (3,426 m [11,250 ft.] elevation) (USGS, 2013). The natural movement of air masses from west to east, known as the Westerlies, is modified by the Pacific Ocean and is forced to rise over the Coastal Range, resulting in the abundance of rainfall on the western portion of the state. These air masses are once again forced to rise over the larger Cascade Range, approximately 110 km to the east, and parallel to the Coastal Range. The Coastal Range and Cascade Mountains act as barriers and create rain shadows which keep the majority of the precipitation in the western section of the state. The western regions experience a Marine west coast climate with wet winters and cool, dry summers. The eastern portion of the state is classified as semi-arid (Oregon Climate Service, 2013).

Figure 2 Study Area: Winegrape growing regions of Oregon and Counties

2.3 Oregon AVA Characteristics

Covering 13,876 km², the Willamette Valley AVA is the largest within Oregon.

The smallest AVA is the Ribbon Ridge which spans only 14 km² (Table 1). The Columbia Valley AVA is the largest in the western U.S., and covers an area over 46,000 km² in both Oregon and Washington. However, for the purposes of this research, only the portion located in Oregon (9,587 km² or approximately 21% of the total area) is analyzed. The median AVA area is 3,080 km² within the state of Oregon, which is slightly larger than the Umpqua Valley AVA.

Table 1 Oregon Winegrape growing regions elevations and area characteristics

Winegrape Growing Region and Associated AVAs	Area ^a (Km ²)	Elevation (meters)				Lat/Long ^b
		Median	Max	Min	Range	
Willamette Valley	13,875.9	122	797	6	791	-122.9 / 44.8
Chehalem Mountains	252.8	157	455	39	419	-122.9 / 45.3
Dundee Hills	50.8	122	301	54	247	-123.0 / 45.2
Eola-Amity Hills	158.8	127	314	57	257	-123.1 / 45.0
McMinnville	149.3	152	355	60	295	-123.3 / 45.1
Yamhill-Carlton	235.3	122	362	51	314	-123.2 / 45.3
Columbia River Gorge	496.6	380	849	43	806	-121.4 / 45.6
Columbia Valley	9,587	379	1036	22	1014	-119.5 / 45.6
Walla Walla Valley	406.4	356	784	161	623	-118.4 / 45.9
Southern Oregon	9245.3	406	1987	34	1953	-123.2 / 42.7
Applegate Valley	1,125.8	690	1973	304	1669	-123.2 / 42.2
Red Hills of Douglas County	22.5	286	378	182	196	-123.2 / 43.5
Ribbon Ridge	14.2	110	181	61	120	-123.0 / 45.3
Rogue Valley	4,638.4	576	1987	244	435	-123.1 / 42.3
Umpqua Valley	2805.8	236	718	34	684	-123.4 / 43.4
Snake River Valley	6222.4	865	1398	549	849	-117.3 / 44.1

^a Area rounded to the nearest 0.1 km² (10ha); approximate due to the grid-based estimation procedure.

^b Lat/Long values are the geographic center of the AVA derived from functions using GIS.

Elevations range from at nearly sea level in the Willamette Valley (6 m), to the highest in the Rogue Valley AVA (1,987 m). The lowest median elevation is 110 m in the Ribbon Ridge AVA with the highest median elevation of 865 m in the Snake River Valley AVA. The average elevation of Oregon AVAs is 317.8 m, and the Southern Oregon AVA

displays the greatest range in elevation at 1,953 m. The smallest elevation range is 120 m in the Ribbon Ridge AVA.

2.3.1 Willamette Valley

The Willamette Valley AVA include the following AVAs within its boundary; Chehalem Mountains, Dundee Hills, Eola-Amity Hills, McMinnville and Yamhill-Carlton. The climate in the Willamette Valley (Benton, Clackamas, Lane, Linn, Marion, Multnomah, Polk, Washington, and Yamhill Counties) is relatively free of extended below freezing or high (above 30°C) temperatures during the growing season, making it an ideal agricultural region. The Willamette Valley hosts a large and diverse agriculture industry because of an excellent combination of fertile soils and ideal temperature ranges. This region is situated between the Cascade Mountains to the east and the Coast Range Mountains to the west (Orr et al. 1999). The Columbia River forms the northern border and the Willamette Valley is 209 km (130 mi) long and ranges from 32 - 64 km (20 – 40 mi) wide (USGS 2013). The floor of the Willamette Valley is an alluvial plain, and the Willamette River runs north-northeast to its confluence with the Columbia River. These alluvial fans overlay Tertiary-aged marine sediments, volcanic and Pleistocene silts derived from outbreaks of the ice-dammed glacial Lake Missoula. These latter deposits rise to an elevation of 122 m (400 ft.) above the valley floor (Orr et al. 1999), resulting in diverse and rich soils.

2.3.2 The Columbia Gorge

The Columbia Gorge region (Hood River, Sherman and Wasco Counties) was created when the Columbia River cut a course through the rising Cascade Range during the Pleistocene period. The steep walls and dramatic cuts into the side of the topography were created during the Missoula Floods that drastically down cut the Columbia River bed and stripped away the sides to create a unique topographic setting composed of basalts, remnants of marine sediments and Pleistocene silt, sand and gravel (Orr et al. 1999). Volcanic material outcroppings and features are common throughout the eighty-mile length of the gorge. The climate of the Columbia Gorge is highly variable with a dramatic distinction between the east and west ends displaying greater seasonal temperature variability and less precipitation to the east than that of the western section (Oregon Climate Service 2013). Additionally, this region is influenced considerably by the rain shadow from the Cascades; the winds funnel east and west and across substantial elevation variations from the eastern side to the western side and from the higher ranges on the south (Oregon side) to the slightly more weathered topography to the north (Washington side). All of these variables create a unique location with highly sensitive micro- and macro-climates for winegrape growing.

2.3.3 Columbia Valley

The eastern side of the Columbia Gorge blends directly into the Columbia Valley (Morrow, Umatilla, Gilliam, Wallowa and Wheeler Counties). This large region extends across both Oregon and Washington. The region lies in the deep rain shadow of the Cascade Mountain Range with its enormous volcanic peaks of Mt. Hood (3,426m [11,250 ft.] elevation) and Mt. Adams (3,743m [12,280 ft.] elevation) to the north and west. The other major geologic feature for this region is the Wallowa Mountains (2,400 m [6,165 ft.] elevation) to the east (USGS 2013). The majority of this region's AVAs lie within the State of Washington though a portion resides within the northeastern boundary of the State of Oregon and is home to the Walla Walla AVA [(406 km² and a maximum elevation of 356m) Jones, Southern Oregon University and the Federal Code of Regulations. 2008] within the massive Columbia Valley AVA.

2.3.4 Snake River Valley

The Snake River Basin (Baker, Malheur and Union Counties) in eastern Oregon is home to the Wallowa, the Blue and the Malheur Mountains, as well as Hell's Canyon, which partially resides within the northeastern portion of the state and extends into Idaho. Dominant water features within this region are the Malheur and Owyhee Rivers, and the Snake River defines the boundary between Oregon and Idaho. Located in the rain shadow of the Cascade Mountain Range, this region experiences an arid climate

(approximately 21 cm average annual precipitation [Oregon Climate Service 2013]) with large elevation ranges (849 meter) from low valleys to high mountain peaks, resulting in greater temperature extremes than other regions of Oregon. The climate of this region is drier than that of western Oregon and in some places, is classified as desert, though it still receives a significant amount of snow (3.8 to 7.6 meters) during winter months (Oregon Climate Service 2013).

2.3.5 Southern Oregon

The Southern Oregon region (Douglas, Jackson, and Josephine Counties) is nestled between the Klamath Mountain System (2,296 m [7,533 ft.] elevation) (USGS 2013) and the Coastal Range to the west, the Cascades to the east and the Calapooya Mountains (1,879 m [6,165 ft.] elevation) to the north. The location within these mountain systems creates a minor rain shadow effect with low amounts of precipitation at lower elevations and an abundant amount of precipitation at higher elevations (Oregon Climate Service 2013). The Umpqua and Rogue Rivers and their tributaries create much of the topography of this region. The climate is classified as Mediterranean with generally warm to hot dry days and cool evenings during the summer months (approximately June to September), which receive approximately 25 percent annual precipitation (Oregon Climate Service 2013).

Chapter Three - Materials and Method

3.1 Data

3.1.1 Wine production data

Winegrape production data was obtained from the USDA, National Agricultural Statistics Service from the Oregon vineyard and winery report for each individual year between 2000 and 2010 at a County scale (USDA, National Agricultural Statistics Service. 2011). The purpose of including production data in this study is to determine to what degree climate indices correlate with the winegrape yield by year. For the purposes of this research, the production category from the vineyard and wine report was used to represent the effects of climate on overall winegrape yield, and is considered the best approach to the inclusion of this variable in this type of research (Jones, personal communication, 11 April 2011). The production category is the reported total harvested amount of winegrapes for the entire year by ton per County.

3.1.2 Climate data

The Parameter-elevation Regressions on Independent Slopes Model (PRISM) grids of monthly climate data from 2000 to 2010 were used to calculate the climate indices described below. PRISM is the official climate data set used by the US Department of Agriculture (USDA) (Daly et al. 2008).

PRISM uses a collaborative collection of weather stations from multiple sources, including the U.S. Forest Service Remote Automatic Weather Stations, the National Weather Service Cooperative Network, USDA Snow Telemetry and other local networks. Combined with a DEM grid, PRISM is used to interpolate climatic conditions at locations without weather stations to create a continuous raster dataset of a region (Daly et al. 2008). This combination of data takes into account other variables such as elevation, aspect, location, coastal proximity, orographic effects and vertical differences in atmospheric layers (Daly et al. 2008). PRISM has been peer reviewed and validated in the western United States coastal and mountainous regions, displaying a greater accuracy for regions that exhibit cold air drainage, rain shadows, inversions, and coastal effects which are difficult to accurately account for with just local weather station data (Daly et al. 2008).

The PRISM dataset was used in the context of the current research because of the widespread, region-wide focus of the dataset. The PRISM data output is at a resolution of approximately 800 m grid cells within Oregon. Data used in the current research was specific to the winegrape growing regions within the Oregon boundaries.

3.2 Climate Indices

Climate indices chosen for this research are the same four climate measures used in previous studies by Jones et al. 2010 and Hall and Jones 2010. This research is intended to build upon and update this prior research, with a focus on Oregon. These indices have been selected for the specific nature in which they address winegrape growing styles (Jones et al. 2010) within different regions and their ability to highlight differences between regions on a quantifiable scale. These indices are region-specific and best depict the nature of the winegrape growing climate per region (Jones et al. 2010).

3.2.1 Growing Season Temperature

The growing season in the Northern Hemisphere is from April 1st to October 31st. An average growing season temperature (GST) index was created by taking the average temperature derived from the PRISM data for this seven-month timeframe.

$$\sum_{Apr1}^{Oct31} \frac{(T_{max} + T_{min})/2}{n}$$

Following the same methods from previous research (Jones et al. 2005, Hall and Jones 2010 and Jones et al. 2010), the results were categorized into five groups according to cool, intermediate, warm, hot, and very hot climate-variety maturity types (Table 2).

Table 2 Climate indices derived for the Oregon boundaries using the PRISM 2000-2010 climate normals along with the number and percent of total counties

Variable	Equation
Average growing season temperature (GST, °C)	$\frac{\sum_{Apr1}^{Oct31} (T_{max} + T_{min})/2}{n}$

Months	Class Limits†	Counties (n)	County (%)
Apr - Oct	Too Cool <13°C	0	0
	Cool 13-15°C	3	15
	Intermediate 15-17°C	16	80
	Warm 17-19°C	1	5
	Hot 19-21°C	0	0
	Very Hot 21-24°C	0	0
	Too Hot >24°C	0	0

Variable	Equation
Growing degree-days (GDD, C°) ^a	$\sum_{Apr1}^{Oct31} \max[(T_{max} + T_{min})/2 - 10, 0]$

Months	Class Limits†	Counties (n)	County (%)
Apr-Oct	Too Cool <850	0	0
	(Region I) 850-1389	16	80
	(Region II) 1389-1667	4	20
	(Region III) 1667-1944	0	0
	(Region IV) 1944-2222	0	0
	(Region V) 2222-2700	0	0
	Too Hot >2700	0	0

Variable	Equation
Huglin index (HI, C° units)	$\sum_{Apr1}^{Sep30} \max([([Tmean-10]+[Tmax-10])/2],0)K$
where K is an adjustment for latitude/day length ^b	

Months	Class Limits†	Counties (n)	County (%)
Apr-Sept	Too Cool <1200	0	0
	Very Cool 1200-1500	7	35
	Cool 1500-1800	4	20
	Temperate 1800-2100	8	40
	Warm 2100-2400	1	5
	temperate		
	Warm 2400-2700	0	0
	Very Warm 2700-3000	0	0
	Too Hot >3000	0	0

Variable	Equation
Biologically effective degree-days (BEDD, C° units)	$\sum_{Apr1}^{Oct31} \min[(\max([Tmax+Tmin]/2)-10,0)],9]DTRadj * K$
	where $DTRadj = \begin{cases} 0.25[DTR - 13], [DTR] > 13 \\ 0, 10 < [DTR] < 13 \\ 0.25[DTR - 10], [DTR] < 10 \end{cases}$
where K is an adjustment fo latitude/day length ^b	

Months	Class Limits†	Counties (n)	County (%)
Apr-Oct	Too Cool <1000	1	5
	1000-1200	9	45
	1200-1400	10	50
	1400-1600	0	0
	1600-1800	0	0
	1800-2000	0	0
	2000-2200	0	0
	Too Hot >2000	0	0

*GDD classes (regions) are based on rounded °F limits as defined by Winkler et al. (1974), which produce nonrounded classes in °C units.

^bK is a latitude coefficient that takes into account increasing day lengths starting from 1.0 at 33.3° increasing incrementally poleward and is based on day lengths using Julian day and latitude.

† The GDD classes are based upon limits originally given by Amerine and Winkler (1944) along with lower and upper bounds for Region I and Region V as detailed in the text. Also note that the class names given above are not directly comparable (e.g., GST cool does not necessarily compare to HI cool.)

3.2.2 Growing Degree-Days

Growing degree-days (GDDs) were calculated from the PRISM data for the seven-month growing season. This calculation uses the standard simple degree-day formula, which uses the average temperature above 10°C as its base.

$$\sum_{Apr1}^{Oct31} \max\left[\left(\frac{T_{max}+T_{min}}{2}\right)-10, 0\right]$$

This index uses the accepted hypothesis that grapevines will not grow until the base temperature reaches a sustained 10°C (50°F). For every degree over 10°C, the unit is assigned a degree day and is summed to obtain a total to be categorized into five groups: region I, region II, region III, region IV and region V (Table 2). This methodology was created in California and is often used in western winegrape growing regions, though it is not generally used in other international winegrape growing regions. This process could be easily adapted to other global locations as long as the climate data is available. The original index for GDD used to describe a general winegrape style climate (Amerine and Winkler 1944, Winkler et al. 1974) was created from general wine styles in California and uses five general regions (classes). A lower Winkler Region I limit and an upper Winkler Region V limit were added in previous research (Jones et al. 2010) to provide a lower and an upper class limit, respectively.

3.2.3 Huglin Index

Although the Huglin Index (HI) is similar to GDD, there are additional components that create a different calculation and results.

$$\sum_{Apr1}^{Sep30} \max([(T_{mean}-10)+(T_{max}-10)]/2, 0)K$$

Created by Pierre Huglin for European vineyards, this index gives a higher weight to maximum temperatures and includes a multiplier (coefficient of correction (K)) which accounts for the latitude accumulation of daylight period (Huglin 1978). The Huglin index is based on the growing season as a six-month time period of April 1st until September 30th in contrast with the Northern Hemisphere seven-month growing season (April 1st to October 31st). Although several regions in Europe and elsewhere harvest in October, Huglin considers the heat accumulation to be less important during this month and therefore does not include the month of October in this index (Huglin 1978). This coefficient takes into account the increasing day length, during the growing season, poleward. The original adjustment of latitude (K=1.02 at 40°N to K=1.06 at 50°N) was created as a linear response to the increasing day lengths, and the coefficient of correction increases with higher latitude. Previous research has compared the difference of the seven-month growing season with that of the six-month growing

season and have found that many of the regions are highly correlated ($r > 0.95$) (Jones et al. 2010), making the one-month difference not significant.

3.2.4 Biologically Effective Degree-Day

After making the observation that plant growth responds in a nonlinear manner to temperature, Gladstones (1992) developed the Biologically Effective Degree-Day (BEDD) index.

$$\sum_{Apr1}^{Oct31} \min[(\max[(T_{max}+T_{min})/2-10, 0]), 9] DTR_{adj} * K$$

$$\text{where } DTR_{adj} = \begin{cases} 0.25[DTR - 13], & [DTR] > 13 \\ 0, & 10 < [DTR] < 13 \\ 0.25[DTR - 10], & [DTR] < 10 \end{cases}$$

This method is similar to the aforementioned indices, though it makes additional adjustments to account for variations of vineyard locations that may be influenced by micro or mesoclimates. The temperature range of this index is based on the premise that phenological growth does not occur until 10°C, though there is a maximum threshold of 19°C which is the maximum temperature in which a plant achieves its greatest phenological development (Gladstones 1992). This index also accounts for a latitude adjustment to include the increase in daylight at higher latitudes during the growing season.

Lastly, Gladstone includes a diurnal temperature range adjustment (DTR_{adj}). This adjustment is calculated upward if the diurnal temperature range (DTR) (the difference between the daily minimum and maximum temperature) is greater than 13°C and downward if less than 10°C. Similar to previous indices, a range of April to October growing season daily averages are summed and assigned within the threshold of upper and lower class boundaries. A difference between this class system and others is that there is an associated value with either Too Cool or Too Hot, but there is not necessarily a defined numerical value (Table 2). These classes represent cold regions with low or late maturity potential (low values), and hot regions with high or earlier maturity potential (high values) (Jones et al. 2010).

3.3 Data Processing

PRISM data were downloaded for the growing season for North America from April 1st to October 31st for the years during 2000 to 2010. Data used from PRISM are average minimum and maximum temperatures, as well as, precipitation on a monthly scale at a 30-arc second (800m) resolution. Prior research was at a monthly scale of a 15-arc second (400m), though comparisons show little, if any, variation in results between these two scales (Jones, personal communication, 11 April 2011). Data were extracted for geographic regions using both County and AVA boundaries. For example, instead of using the entire AVA, the data was only taken for the area for which the AVA intersected with the County. Since many of the AVAs overlay with several different

Counties, the AVA is represented several times intersecting with several different Counties (e.g., Willamette_AVA_Polk; Willamette_AVA_Lane, etc.). This allows for per County analysis and accounts for an accurate comparison to County-level production data.

This analysis created a total of 37 different AVA-County combinations within the state of Oregon by using the above described methods. These County data do not represent each entire County, rather only the areas that have designated AVAs within that County.

Figure 3 American Viticultural Areas of Oregon shown with the overlapping Oregon County boundaries representing the 37 different AVA-County combinations and displaying areas of which only were analyzed for AVA coverage within a County

Data were organized by AVA-County combination and then was summarized by averaging the minimum and maximum temperatures for the seven-month growing season (April 1st to October 31st) for each of the eleven years. Since the Huglin Index only requires a six-month timeframe (April 1st to September 30th), the above mentioned was conducted for the six-month period.

For each of these 37 different combinations, a monthly minimum temperature (Tmin) and monthly maximum temperature (Tmax) were calculated for the eleven-year timeframe. In addition, the DTR (Tmax-Tmin) was calculated along with the adjusted DTR (see Table 2 for calculations). These steps were conducted for both the seven-month growing season and the six-month growing season for input for the HI and BEDD.

The K coefficient was calculated by determining the geographic center of the AVA-County polygon with the use of the Polygon-to-Point tool in a geographic information system (ArcGIS version 9.3; ESRI, Redlands, CA) environment to determine the centroid of the polygon. With the use of this tool, the center of each AVA-County combination was calculated, which yields a set of coordinates, the latitude of which was used to calculate the K coefficient with the different values per specified latitude adjustment ($K = 1.02$ at 40°N to $K = 1.06$ at 50°N) (see Table 2 for calculations) for each county. Since this latitude adjustment is only conducted for Oregon, it is limited to these boundaries (42°N to 46°N , respectively), thus producing a small variation in this adjustment (see Table 1 for latitudes), though still necessary for proper calculation of the

index.

In order to normalize the data to account for the partial representation of area being analyzed (i.e., only the section of the County that is a designated winegrape growing region), a weighted analysis was performed. Once the weighted averages were figured, they were multiplied by each of the climate indices and summed to obtain the normalized total for each County. This process was completed for all Counties over the eleven-year span.

To avoid a potential issue with the production data and nested AVA-County boundaries (i.e., the Willamette Valley AVA has several other AVAs within its bounds within a single County) a different approach was taken with this data than that of the climate indices. Since the production data is aggregated by the entire County it is not necessary to disaggregate it any further and it may be taken as reported. It is not possible to know if the winegrapes came from one AVA or another and is not necessary for this analysis. Any potential issue with nesting is negated because, spatially, these data did come from within the bounds of winegrape growing regions which are the regions being analyzed with the climate indices.

Not all of the Oregon Counties are represented in the USDA data by individual name. There is an “All Other Counties” category with a total amount of production representing all the other Counties within Oregon that produce winegrapes. These are Baker, Gilliam, Malheur, Morrow, Multnomah and Sherman Counties all of which have

AVAs within their boundaries. A spatially weighted analysis, based on AVA areas residing within County boundaries, was performed to gain the totals for each of the above mentioned Counties. Each of the Counties only had one AVA which overlapped their borders.

Both climate indices and winegrape production data were aggregated into the five major AVAs within Oregon (Willamette Valley, Columbia Gorge, Columbia Valley, Snake River Valley and Southern Oregon) for localized analysis. The winegrape growing regions were based on designated AVA boundaries. Climate and production data were taken from within these five different aggregated bounds and used for analysis over the eleven-year time period of this study.

3.4 Statistical analysis

To statistically test the above-mentioned observations, Pearson correlation coefficients were run in SPSS (version 17.0) along with a matrix scatterplot for each of the four climate indices and for the production data. This was performed for all the climate indices and production data for all of Oregon as well as for each of the 5 different winegrape growing regions. The sample size (n) for the Oregon analysis is 220 (20 Counties over the 11 year timeframe) and for the individual winegrape growing regions the sample size is 11 (1 region over the 11 year timeframe) and represents the relationship of the median of each of the County values.

Chapter Four – Results

4.1 Correlations of Climate Indices and Winegrape Production at Oregon County scale

Climate index values generally follow a pattern where lower values represent cooler climates and higher values represent warmer climates, or the further south in latitude, the warmer the climate; and the higher the elevation, the cooler the climate. These observations are classified into categories that describe the spatial climate characteristic of a region. Large ranges in elevation results in large ranges in temperature which in turn result in large variations in the indices. Climate index data are summarized by both County and AVA in Table 3 using quartiles.

Table 3 Oregon American Viticultural Area (AVA) 2000-2010 PRISM-calculated quantile statistics for growing season average temperature (GST, °C), growing degree-days (GDD, C° units), Huglin index (HI, C° units), and biologically effective degree-days (BEDD, C° units)

County Name	GST					GDD				
	Min	25%	Median	75%	Max	Min	25%	Median	75%	Max
Baker	14.1	14.6	15.1	15.4	16.0	997.8	1131.3	1140.6	1281.1	1376.0
Benton	14.4	14.6	15.0	15.5	16.0	966.9	1025.0	1071.1	1189.0	1281.1
Clackamas	14.5	14.9	15.3	15.6	16.2	979.1	1073.1	1138.5	1210.9	1331.6
Douglas	15.1	15.5	15.9	16.0	16.5	1111.5	1204.4	1270.8	1298.6	1424.2
Gilliam	15.8	16.7	17.3	17.7	18.7	1269.2	1453.7	1556.9	1660.8	1861.5
HoodRiver	13.4	13.8	14.1	14.6	14.8	792.4	921.8	941.0	1027.4	1095.1
Jackson	14.8	15.4	15.9	16.1	16.3	1112.0	1172.3	1286.1	1334.6	1441.6
Josephine	15.0	15.4	15.9	16.1	16.7	1112.8	1214.9	1265.0	1376.0	1451.5
Lane	14.4	14.8	15.2	15.4	16.1	966.9	1065.7	1134.7	1164.3	1322.2
Linn	14.5	14.7	15.0	15.2	15.9	962.9	1059.0	1090.5	1133.7	1255.6
Malheur	15.5	16.1	16.6	16.9	17.6	1235.4	1379.7	1476.6	1489.1	1681.0
Marion	14.5	14.8	15.2	15.6	16.1	997.6	1060.0	1109.9	1200.6	1320.4
Morrow	15.5	16.3	16.5	16.8	17.7	1200.1	1359.4	1434.5	1468.9	1653.6
Multnomah	14.9	15.4	15.9	16.0	16.8	1052.9	1158.9	1263.6	1280.9	1450.7
Polk	14.2	14.6	15.0	15.4	15.8	927.6	1026.6	1068.0	1170.8	1262.8
Sherman	15.0	15.6	16.0	16.2	17.1	1108.4	1231.9	1297.3	1348.7	1549.2
Umatilla	15.8	16.1	16.6	16.8	17.4	1252.1	1324.6	1411.6	1474.4	1585.9
Wasco	14.9	15.6	15.9	16.1	16.9	1076.2	1212.8	1283.6	1322.5	1493.4
Washington	14.4	14.7	15.2	15.5	16.0	994.9	1032.7	1116.3	1182.4	1290.7
Yamhill	14.6	14.9	15.0	15.7	15.9	996.7	1074.1	1117.8	1217.6	1271.6

	HI					BEDD				
	Min	25%	Median	75%	Max	Min	25%	Median	75%	Max
Baker	1678.6	1883.3	2029.5	2118.0	2241.3	973.1	1094.0	1157.2	1193.1	1236.6
Benton	1333.2	1415.2	1525.8	1608.6	1693.8	1004.2	1088.9	1123.5	1189.1	1282.5
Clackamas	1098.2	1247.5	1394.0	1441.2	1545.7	1000.8	1090.3	1135.4	1184.9	1269.3
Douglas	1518.6	1566.0	1683.6	1751.8	1853.1	1074.6	1198.2	1237.6	1293.4	1348.1
Gilliam	1704.6	1836.6	1909.7	1988.0	2110.8	1133.2	1268.2	1345.1	1403.3	1438.7
HoodRiver	1200.3	1388.3	1441.2	1512.0	1620.9	835.2	953.6	1000.4	1041.1	1091.1
Jackson	1759.4	1805.9	1900.3	1960.8	2008.7	1042.4	1194.8	1247.7	1310.1	1370.4
Josephine	1785.4	1812.7	1873.3	1965.4	2060.4	1035.3	1227.2	1265.9	1315.4	1360.5
Lane	1331.6	1467.5	1577.3	1606.6	1738.2	987.2	1100.9	1145.4	1185.2	1286.7
Linn	1425.4	1437.4	1530.5	1560.0	1725.5	993.5	1049.2	1111.8	1152.6	1278.6
Malheur	1949.6	2138.1	2213.6	2358.2	2434.9	1160.0	1289.1	1315.4	1328.6	1404.0
Marion	1180.2	1305.4	1432.3	1484.2	1571.8	1019.1	1081.3	1125.4	1179.7	1274.1
Morrow	1722.9	1895.8	1922.4	2016.6	2063.1	1103.2	1249.0	1283.5	1308.5	1384.1
Multnomah	1100.2	1237.3	1385.5	1445.3	1540.9	1061.5	1145.0	1203.0	1264.0	1326.5
Polk	1202.4	1352.4	1473.0	1527.2	1651.6	975.7	1074.6	1094.2	1175.0	1274.0
Sherman	1625.9	1746.3	1817.5	1889.0	1968.5	1025.7	1175.3	1210.2	1254.9	1335.2
Umatilla	1710.8	1881.9	1958.8	2027.2	2080.4	1125.2	1240.2	1263.9	1287.7	1357.1
Wasco	1564.7	1709.7	1812.6	1821.9	1950.4	1035.4	1175.9	1222.9	1271.9	1327.8
Washington	1056.1	1156.9	1343.8	1443.1	1529.7	1006.3	1059.9	1097.6	1150.8	1247.5
Yamhill	1141.1	1280.9	1456.6	1481.4	1597.8	1014.9	1097.6	1118.8	1183.7	1260.3

All climate indices and winegrape production calculations are represented by a matrix scatterplot for a holistic comparison. These figures compare the similarity of these variables to that of a linear relationship through representation of proximity of

the circles, or the degree of scatter to one another, in a straight line. For example, Figure 4 shows the GDD and GST are functionally fairly similar through the representation of low scatter and the degree of the straight line, which represents the high correlation ($r=0.983$) between the two variables. Furthermore, the relationship between the HI and BEDD shows a great deal of scatter and much less clustering. Although these results appear to be less functionally similar, the results do display a linear direction form, thus suggesting a noticeable linearity even if not a highly statistically significant value ($r= 0.677$; $p < 0.05$). The correlation between the production data and any of the four climate indices illustrates nearly no pattern, and the scatter is sporadic rather than uniform, thus representing no linear relationship with the other climate indices and are not statistically significant ($r= -0.200$ to -0.352 ; $p > 0.05$).

Figure 4 Scatter plot matrix for climate indices and winegrape production within Oregon County and Winegrape growing boundaries for the years 2000 - 2010 (n = 220)

The highest correlation was between the GDD and GST ($r = .983$; $p < 0.01$) (Table 4), which shows that these two climate indices accurately represent the climate data in comparison to that of previous research. Previous research (Jones et al. 2010 and Hall and Jones 2010) produced similar results ($r = 0.99$) for these two climate indices as well.

HI had the lowest correlation ($0.673 < r < 0.744$) to the three other indices (Table 4). These results differ from those of previous research (Jones et al. 2010 and Hall and Jones 2010) where the BEDD had lowest correlation to the other three indices and is attributed to the addition of the DTR adjustment (Jones et al. 2010). This research displays the lowest correlation to be HI and GST ($r = 0.673$) and the next lowest correlation is to be the HI and the BEDD ($r = 0.677$). Even with the low correlation between the HI and the BEDD, the HI shows the lowest across all three indices whereas the BEDD, with the exception of the correlation with the HI, exhibits relatively high correlations with the other two (GST and GDD) indices, respectively ($r = 0.915$ and 0.925).

With the HI lacking the DTR adjustment as a possible reason for the low correlation results, it may be deduced that these results are due to alternate variables within the equation such as a multiplier or the latitude coefficient. Furthermore, it must be noted that while the median County values exhibit moderate to high correlation, the

climate indices class names and limits may not be directly comparable (e.g., the cool class limit of the GDD will not have the same value as the cool class limit of the HI).

The production data were not significantly correlated with any of the climate indices ($-0.200 < r < -0.352$; $p > 0.05$). These results indicate that there are too many variations with the production data to be directly compared with the climate indices. GST and GDD were expected to have the highest correlation with production data, based on the highly correlated results with this study and previous research. The median County values for the four climate indices displayed varied results from highly correlated ($0.915 < r < 0.983$; $p < 0.01$) to fairly correlated ($0.673 < r < 0.744$; $p < 0.05$). These results indicate the four climate indices can be directly compared and depict similar spatial climate characteristics.

Table 4 Pearson Correlations for Climate Indices and Winegrape Production by Oregon County for 2000 to 2010

Correlations					
		GDD	HI	BEDD	Production
GST	Pearson Correlation	.983**	.673*	.915**	-.209
GDD	Pearson Correlation		.744**	.925**	-.244
HI	Pearson Correlation			.677*	-.352
BEDD	Pearson Correlation				-.200
**. Correlation is significant at the 0.01 level (2-tailed) (n=220).					
* . Correlation is significant at the 0.05 level (2-tailed) (n=220).					

4.2 Correlation at the Oregon Winegrape Growing Region scale

To assess if climate indices and production results would benefit from being separated and analyzed by the five different winegrape growing regions instead of the

entire state, further analysis was performed. Although the above discussed analysis was conducted for winegrape growing regions for the state of Oregon, it may not account accurately for the different winegrape growing regions over the state and their widely varying climate regimes (e.g., Willamette Valley compared to the Snake River Valley). Therefore, to test this observation, additional analyses were conducted to assess these geographic differences and analyze these localized correlations.

4.2.1 Willamette Valley Winegrape Growing Region

All four of the climate indices are significantly related to each other at the 0.01 level (2-tailed) as shown for the Pearson's Correlation Coefficients (Table 5). The GST and GDD resulted in the highest correlation ($r = .980$). Following the pattern of the entire state analysis the BEDD displayed the next highest correlation results with the GDD ($r = 0.925$) and GST ($r = 0.899$). The HI resulted in the lowest correlations with the BEDD ($r = 0.768$). The Production data analyzed for the Willamette Valley resulted in no statistically significant correlations ($-0.100 < r < -0.329$; $p > 0.05$). These results could be because the climate is relatively homogeneous over the study region during the study period.

Table 5 Pearson Correlations for Climate Indices and Winegrape Production for the Willamette Valley Winegrape Growing Region in Oregon for 2000 to 2010

Correlations					
Willamette Valley					
		GDD	HI	BEDD	Production
GST	Pearson Correlation	.980**	.860**	.899**	-.214
GDD	Pearson Correlation		.874**	.925**	-.182
HI	Pearson Correlation			.768**	-.100
BEDD	Pearson Correlation				-.329
**. Correlation is significant at the 0.01 level (2-tailed) (n=11).					

Figure 5 Scatter plot matrix for climate indices and winegrape production for the Willamette Valley winegrape growing region for the years 2000 - 2010 (n=11)

4.2.2 Columbia Gorge Winegrape Growing Region Results

The Columbia Gorge resulted in similar pattern of results to that of the Willamette Valley. The GST and the GDD showed the highest correlations ($r = 0.963$) with the BEDD

displaying the next most significant correlations ($r = 0.881$ and 0.920) and the HI resulting in the weakest of the correlations ($r = 0.789$, 0.833 and 0.870). All of the climate indices correlations were significant at the 0.01 level (Table 6). These climate indices results display similar results to the Oregon results as well as the Willamette Valley results. Production results did not display in any statistically significant correlations ($0.238 < r < -0.268$; $p > 0.05$) staying consistent with the above analyses.

Table 6 Pearson Correlations for Climate Indices and Winegrape Production for the Columbia Gorge Winegrape Growing Region in Oregon for 2000 to 2010

Columbia George					
		GDD	HI	BEDD	Production
GST	Pearson Correlation	.963**	.789**	.881**	-.268
GDD	Pearson Correlation		.870**	.920**	-.179
HI	Pearson Correlation			.833**	.238
BEDD	Pearson Correlation				-.140
**. Correlation is significant at the 0.01 level (2-tailed) (n=11).					

Figure 6 Scatter plot matrix for climate indices and winegrape production for the Columbia Gorge winegrape growing region for the years 2000 - 2010

4.2.3 Columbia Valley Winegrape Growing Region Results

Resulting in similar correlations between the four climate indices levels as above mentioned winegrape growing regions, the Columbia Valley displayed the strongest correlations between the GST, GDD and BEDD ($r = 0.989, 0.934$ and 0.916 ; $p < 0.01$) and the weakest between the HI and all of the other indices ($r = 0.624, 0.644$ and 0.630 ; $p < 0.05$) (Table 7). Unlike other AVAs that do not show any significant correlations between production and climate indices, the Columbia Valley production is significantly associated with three climate indices. These results could be due to more homogenous topography and climate than that of the other study regions. The strongest correlation

is with the GST ($r = -0.749$; $p < 0.01$) followed by the BEDD and the GDD ($r = -0.714$ and -0.701 ; $p < 0.05$). The HI is not significantly correlated to production.

Table 7 Pearson Correlations for Climate Indices and Winegrape Production for the Columbia Valley Winegrape Growing Region in Oregon for 2000 to 2010

Columbia Valley					
		GDD	HI	BEDD	Production
GST	Pearson Correlation	.989**	.624*	.916**	-.749**
GDD	Pearson Correlation		.644*	.934**	-.701*
HI	Pearson Correlation			.630*	-.115
BEDD	Pearson Correlation				-.714*
**. Correlation is significant at the 0.01 level (2-tailed) (n=11).					
*. Correlation is significant at the 0.05 level (2-tailed) (n=11).					

Figure 7 Scatter plot matrix for climate indices and winegrape production for the Columbia Valley winegrape growing region for the years 2000 - 2010

4.2.4 Snake River Valley Winegrape Growing Region Results

All climate indices correlations were significant at the 0.01 level for the Snake River Valley winegrape growing region. The correlation between GST and GDD was the strongest ($r = 0.955$) for this region, where both the BEDD and the HI displayed similar correlation results to other winegrape growing regions where the HI resulted in notable weaker results than that of the BEDD (Table 8). Statistical correlations between production data and the climate indices resulted in various outcomes. The correlation between the production and GST was significance at the 0.05 level ($r = -0.608$) while the remainder of the other climate indices were not significantly correlated to production (-0.244 , -0.448 and -0.532 ; $p > 0.05$).

Table 8 Pearson Correlations for Climate Indices and Winegrape Production for the Snake River Valley Winegrape Growing Region in Oregon for 2000 to 2010

Snake River Valley					
		GDD	HI	BEDD	Production
GST	Pearson Correlation	.955**	.858**	.801**	-.608*
GDD	Pearson Correlation		.858**	.902**	-.448
HI	Pearson Correlation			.820**	-.532
BEDD	Pearson Correlation				-.244
**. Correlation is significant at the 0.01 level (2-tailed) (n=11).					
*. Correlation is significant at the 0.05 level (2-tailed) (n=11).					

Figure 8 Scatter plot matrix for climate indices and winegrape production for the Snake River Valley winegrape growing region for the years 2000 - 2010

4.2.5 Southern Oregon Winegrape Growing Region Results

Results for the climate indices correlation resulted in varying outcomes different from the results of the above mentioned winegrape growing regions. For the Southern Oregon winegrape growing region, the GST and GDD climate indices displayed the strongest correlation ($r = 0.948$; $p < 0.01$). The BEDD is significantly correlated to the GST and GDD at the 0.01 level while it is not significantly related to the HI ($r = 0.490$) (Table 9). Similarly, the correlation between production and any of the four climate indices resulted in no statistical significance ($0.152 < r < -0.079$; $p > 0.05$).

Table 9 Pearson Correlations for Climate Indices and Winegrape Production for the Southern Oregon Winegrape Growing Region for 2000 to 2010

Southern Oregon				
		GDD	HI	BEDD Production
GST	Pearson Correlation	.948**	.706*	.802** .126
GDD	Pearson Correlation		.713*	.804** .152
HI	Pearson Correlation			.490 .026
BEDD	Pearson Correlation			
				-.079
**. Correlation is significant at the 0.01 level (2-tailed) (n=11).				
*. Correlation is significant at the 0.05 level (2-tailed) (n=11).				

Figure 9 Scatter plot matrix for climate indices and winegrape production for the Southern Oregon winegrape growing region for the years 2000 - 2010

4.3 Comparison with Previous Research

Since this research was conducted by County and winegrape growing regions rather than by individual AVA, it is not possible to do a side-by-side comparison between

the current study and Jones et al. 2010 study. Regardless, a general comparison between the two studies is possible to provide a holistic view.

Generally speaking, the GST for this study displays similar results (Figures 10, 11 and 12) to those of the previous study where the majority of the sample falls within the Intermediate class limit. A total of three (15 percent of the sample) Counties were in the Cool class limit (13 – 15 °C), sixteen (80 percent of the sample) Counties were in the Intermediate class limit (15 - 17°C) and one (5 percent of the sample) was in the Warm class limit (17 - 19°C) (Table 2).

Figure 11 Box-whisker plot of average growing season temperature within Oregon by county for the years of 2000 - 2010

Figure 12 Box-whisker plot of average growing season temperature in Winegrape Growing Regions of Oregon from the years of 2000 – 2010

The results for GDD (Figures 13, 14 and 15) are similar to those of the previous study. Of the AVAs, ninety percent reported in the previous study fell into the Region I class limit (cool), where 10 percent fell into the Region II class limit. For the current study, sixteen Counties (80 percent of the sample) (Table 2) were in the Region I class limit (850 – 1389) and four Counties (20 percent of the sample) were in the Region II class limit (1389 – 1667).

Figure 13 Average growing degree days within Oregon winegrape growing regions for the time frame of 2000-2010

Figure 14 Box-whisker plot of average growing degree-days with in Oregon by county for the years of 2000 – 2010

Figure 15 Box-whisker plot of average growing degree-days in Oregon winegrape growing regions for the time frame of 2000 - 2010

The HI displays the greatest variation to that of previous research (Figures 16, 17 Figure 18). With this study, there is a fairly even spread over three of the class limits. The previous research shows no results for the Very Cool class limit and in the majority of the AVA results falling fairly equally between the Cool and Temperate class limits. For this study (Table 2), seven Counties (35 percent of the sample) were in the Very Cool class limit (1200 – 1500), four Counties (20 percent of the sample) were in the Cool class limit (1500 – 1800) and eight Counties (40 percent of the sample) were in the Temperate class limit (1800 – 2100).

Figure 16 Average Huglin index within Oregon winegrape growing regions for the timeframe of 2000 - 2010

Figure 17 Box-whisker plot of the average Huglin index with in Oregon by County for the years of 2000 – 2010

Figure 18 Box-whisker plot of the average Huglin index in Oregon winegrape growing regions for the time frame of 2000 – 2010

Similar to the HI, the BEDD also displays different patterns when compared to previous research (Figures 19, 20 and 21). Previous research shows the majority falling into the Cool (1000 – 1200) and Very Cool (1200 – 1400) class limits with few displaying results for the Temperate (1400 – 1600) class limit. This study results with 95 percent falling in either the Very Cool or Cool class limits and the remaining in the Too Cool (< 1000) class limit (Table 2). Overall, the outcomes between the two studies are very close, though previous research results in slightly higher values than those of the current research.

Figure 19 Average biologically effective degree-day within Oregon winegrape growing regions for the timeframe of 2000 - 2010

Figure 20 Box-whisker plot of the average biologically effective degree-days with in Oregon by county for the years of 2000 – 2010

Figure 21 Average biologically effective degree-day within Oregon AVAs 2000-2010

Chapter Five – Discussion and Conclusions

Summary

The results display similar outcomes as previous research (Jones et al. 2010). Since the data for this study break the AVAs into sections to conform to the County boundaries, the results are not directly comparable with those of previous research. Tobler's Law states that things that are close together are likely to be more related than those that are further apart (Tobler 1970). Although both studies are not directly comparable, there are similarities, and since many of the AVAs are in close proximity to one another, the results of the previous research and those of the current research are in fact similar.

The results show the GDD and GST are similar, though display slight variations and are not as highly correlated as the results from previous research. HI and BEDD are much less alike, though still exhibit statistically significant results. These findings vary from those of the previous research where there were statistically significant correlations between these two indices. Previously, the largest variation was between the BEDD and the other indices. This research showed the largest variation between the HI and the other indices. Production data resulted with little, to no correlation to the four climate indices at the Oregon County scale analysis but some statistically significant correlations with the individual winegrape growing regions, indicating that production data may be inconsistent and have too many variables to be included at the County

level analysis. However, in some wine production regions, winegrape production was negatively associated with interannual variability of some climate indices, suggesting that such winegrape regions could be potentially vulnerable to fluctuating climates. Additionally, the eleven-year time frame for this study may not be a significant amount of time to assess climate variability and conduct an accurate or thorough analysis. The thirty-year time frame of previous research may prove to display greater accuracy.

Caveats

The annual yield of a winegrape and phonological effects ate highly susceptible to alternate variables other than climate, such as anthropological affects, and this study only examined the relationship between climate and production data. Quantifiable production data is available through the annual production totals per county for the state of Oregon. However, the use of such a variable in statistical analysis may not produce solid analysis results. A vineyard's vintner may use a variety of methods to increase or decrease the annual yield, which may include irrigation, pesticides and other pro-growth/anti-loss variables, which has an unquantifiable effect on the overall production. There are numerous anthropogenic factors that effect winegrape production, thus making it difficult to quantify the climate influences on these results. Furthermore, a continued increase of new winegrape producers and wineries every year (Figure 22) affects the amount of harvest over the course of the study period.

Figure 22 Number of vineyards by Oregon County for the years of 2000 -2010

The eleven-year time frame in comparison to that of the standardized thirty-year time frame used in the previous research could prove as a limitation to the current research. Although a ten-plus year time frame is acceptable in statistical analysis, it is not ideal and generally a thirty-year time frame is the statistically preferred length of time. Even though climate data are available for 30 years, winegrape production data were not comprehensively available for the whole period. The eleven-year time frame was the only comprehensive available winegrape growing data for this analysis.

Suggestions for Future Research

Climate change is of increasing concern to local, national, and international interests, and particularly amongst members of the agricultural industry (Metzger and Rounsevell 2011). The effects are displayed in the droughts in the Midwest and unusual early harvests or late frosts throughout the United States that have become very common in recent years. Vintners, wine makers and enthusiasts would like to know what pattern will emerge in a changing climate and how that will affect winegrape growing regions (Holland and Smit 2010). In order to better understand the climates of the best winegrape growing regions, it is important to understand the multitude of variables that affect the climate and the grapevine (Nicholas and Durham 2012). The current research sought to correlate climate indices, for which temperature is a key variable, to winegrape production data.

Climatic variables to consider inputting into this statistical model would be precipitation, the number of frost-free days or solar insolation. These variables were not included in the current research because they lack consistent, available data during the study time period and comprehensively for the study areas. Additionally, they were not included in prior research and modeling used for comparison. These variables represent an avenue of future research that could potentially yield interesting correlations and result in richer and more useful climate indices.

This initial research was intended as an update for the previous research that analyzed an industry-accepted time frame of thirty years. The decision of a ten year time frame update to that of the previous research was discussed and accepted as an acceptable statistical time period for analysis. However, the results, possibly in conjunction with the sample size, displayed statistically less significant results than that of previous research; indicating the time frame as a possible variable for less robust results. Additionally, during the composition of this manuscript, new PRISM data were released for the years (1981 to 2010). Subsequently, the current research are now relatively out-of-date, although since winegrape production data is not comprehensive for the thirty-year time span, the correlations between winegrape growth and production continues to be an area of interest and potentially future work.

There are many numbers of ways to analyze the overall annual production of a winegrape growing region; though there is little quantifiable data to support winegrape quality. One of the original intents in the primary stages of this research was to compare climate indices with overall winegrape quality. During the course of the research, multiple issues with the quality component became apparent, from inconsistent data to subjective sources. The only quantifiable way to analyze wine production is through the statistical results from the Department of Agriculture. In future research, it would behoove winegrape growers and the larger community to create a quantifiable quality

rating system. This creation would allow a standardized system for rating wine quality in a scientific manner.

Additional research may benefit from analyzing anthropogenic responses to a changing climate and winegrape production. Climate indices could be used to analyze which varieties can be planted, if irrigation methods or other climate protection methods were used. A winegrape growing region could be analyzed to study if trends appear in a changing climate and the social and cultural response on inter-annual variability of winegrape production.

Conclusions

Climate indices provide valuable information for comparing the climate characteristics and regional sustainability of winegrape growing region. Prior to recent publications, there were only comparisons using station data, which can over or under represent the actual climate indices of wine growing regions (Webb et al. 2008, Jones et al. 2009, Jones et al. 2010, Hall and Jones 2010). Analyzing the spatial climate characteristics of a winegrape growing region provides researchers, vintners, and wine aficionados with quantifiable information for comparison across regions, both nationally and internationally. This research also provides a resource to update previous research results for the state of Oregon for the time period of 2000 to 2010. This update includes an additional variable of winegrape production data and its relation to climate indices.

The research objectives were met by analyzing the four climate indices in conjunction with winegrape production data over the course of eleven-year time frame within the state of Oregon's winegrape growing regions. The results of this study are very similar to the findings of previous research, though there are slight variations. Throughout winegrape growing regions of Oregon, climate indices values remain in the cooler to intermediate temperature classifications, supporting previous results for the same region. Both the GST and GDD displayed similar results to that of previous research with the majority of the samples falling within lower to mid classifications, with lower sample percent residing on either side of this class limits. The HI showed the greatest variation from that of previous research. Samples fell equally between Cool and Temperate class limits in previous research; where in current research, the samples were distributed over Very Cool (35 percent), Cool (20 percent) and Temperate (40 percent) class limits. The BEDD classifications displayed similar results to those of the HI where previous research results indicated slightly warmer class limits than those of the current research. Previous research results for the BEDD had the majority of samples residing into the Cool and Very Cool class limit where few resulted in Temperate. The current research results indicate that 95 percent of the samples fell in either Very Cool or Cool and the remaining in the Too Cool class limit.

Lastly, production data included a new component to previous research, resulted in little or no statistical significance in relation to the four climate indices for the holistic

state analysis. Alternatively, the localized analysis by individual winegrape growing regions production resulted in some significant correlations to climate indices. These results may be due to a more homogenized climate over the study area for the specific winegrape growing region (e.g., the production results for the Columbia Valley).

These results highlight the need to standardize climate data for these regions worldwide to produce a quantifiable data source for direct comparison between the climates of winegrape growing regions. Future researchers would benefit from inclusion of alternate variables such as frost free days, solar insolation, or storm events. Data analysis processes, such as future climate scenarios, could highlight alternate outcomes and possibilities for winegrape growing regions. Overall, there are a multitude of potential avenues for future research in such a new and under-studied subject. This research and those of similar nature contribute to the holistic view of oenology; though there are infinite options to continue these studies and to continue filling in the missing gaps.

References

- Amerine, M.S., Berg, H.W., Kunkee, R.E., Ough, C.S., Singleton, V.L., and Webb, A.D. 1980. *The Technology of Wine Making*. AVI Publishing, Connecticut.
- Amerine, M.A., and A.J. Winkler. 1994. Composition and quality of musts and wines of California grapes. *Hilgardia*, Vol. 15, pp. 493-675.
- Bindi, M. 1996. Modelling the impact of future climate scenarios on yield and yield variability of grapevine. *Climate Research*, Vol. 7, pp. 213-224.
- Bisson, L.F., A.L. Waterhouse, S.E. Ebeler, M.A. Walker, and J.T. Lapsley. 2003. The present and future of the international wine industry. *Nature*, pp.418, 696-699.
- Braganza, K. 2004. Diurnal temperature range as an index of global climate change during the twentieth century. *Geophysical Research Letters*, Vol. 31, L13217.
- Code of Federal Regulations. 2008. Alcohol, Tobacco Products, and Firearms. Title 27, Parts 1-199, Part 9 – American Viticultural Areas, pp. 101-223. Alcohol and Tobacco Tax and Trade Bureau, Department of the Treasury, U.S. Government, Washington, D.C.
- Coombe, B. G. 1987. Influence of temperature on composition and quality of grapes. *Acta Horti*, Vol. 206, pp. 23-35.
- Coombe, B.G. 1988. Grapevine Phenology, Ch. 7 in *Viticulture* Vol. 1., Australian Industrial Publishers, Adelaide, pp. 139-153.
- Coombe, B.G., and Lland, P. 2004. Grape berry development and wine quality. *Viticulture*, Vol. 1, pp. 210-248.
- Costantini, E.A.C. 2009. Relevance of the Lin's and Host hydrological models to predict grape yield and wine quality. *Hydrology and Earth System Sciences*, Vol. 13, pp. 1635-1648.
- Daly, C., M. Halbleib, J.I. Smith, W.P. Gibson, M.K. Doggett, G.H. Taylor, J. Curtis, and P.A. Pasteris. 2008. Physiographically-sensitive mapping of temperature and precipitation across the conterminous United States. *Int. J. Climatol*, Vol. 28, pp. 2031-2064.
- deBlij, H.J. 1981. *Geography of Viticulture*. Miami Geographical Society, Miami, FL.

deBlij, H.J. 1983. Geography of viticulture: rationale and resource. *J. Geography*, pp. 112-121.

Dickenson, J. 1990. Viticultural geography: An introduction to the literature in English. *Journal of Wine Research*, Vol. 1, pp. 5-21.

Due, G. 1993. Modelling grapevine phenology against weather: considerations based on a large data set. *Agricultural and Forest Meteorology*, Vol. 65, pp. 91-106.

Duchêne, E., H. Frédéric, D. Vincent, S. Christophe, M. Didier. 2010. The challenge of adapting grapevine varieties to climate change. *Climate Research*, Vol. 41. No. 3, pp. 193-204.

Gladstones, J. 1992. Viticulture and Environment. *Winetitles, Adelaide*, pp. 310.

GeoCurrents.info. 2012. The food and wine of Georgia. Retrieved from <http://geocurrents.info/cultural-geography/the-food-and-wine-of-georgia> on March 3rd, 2013.

Hall, A. and G.V. Jones. 2010. Spatial analysis of climate in winegrape growing regions in Australia. *Australian Society of Viticulture and Oenology Inc.* doi: 10.1111/j.1755-0238.2010.00100.x.

Holland, T. and B. Smit. 2010. An Emerging Agenda for Wine Industry Research: Vulnerability to Climate Change. *American Journal of Enology and Viticulture*, Vol. 61. No. 3, pp. 438A-438A.

Huglin, P. 1978. Nouveau Mode d'Évaluation des Possibilités Héliothermiques d'un Milieu Viticole. *C.R. Acad. Agr. France* 64:1117-1126.

Jones, G.V., and K-H Storchmann. 1998. Empirical assessment of Bordeaux wine pricing-determinants, sensitivities, and forecast. *Vitic. Enol. Sci.*, Vol. 53. No. 3, pp. 136-149.

Jones, G.V., and R. Davis. 2000. Climate Influences on Grapevine Phenology, Grape Composition, and Wine Production and Quality for Bordeaux, France. *American Society for Enology and Viticulture*, Vol.51. No. 3, pp.249-261.

Jones, G.V. How Hot is Too Hot? *Wine Business Monthly*, February 2005, pp.1-4.

Jones, G.V., M. White, O. Cooper, K. Storchmann. 2005. Climate Change and Global Wine

Quality. *Climatic Change*. Vol. 73, pp. 319-343.

Jones, G.V., and G. Goodrich. 2008. Influence of climate variability on wine regions in the western USA and on wine quality in the Napa Valley. *Climate Research*, Vol. 35, pp. 241-254.

Jones, G.V., M. Moriondo, B Bois, A. Hall, and A. Duff. 2009. Analysis of the spatial climate structure in viticulture regions worldwide. *Bull. OIV* (944-946):507-518.

Jones, G.V., A. Duff, A. Hall, and J. Myers. 2010. Spatial Analysis of Climate in Winegrape Growing Regions in the Western United States. *American Journal Enology and Viticulture*. Vol. 61:3, pp. 313-326.

MacNeil, K. 2001. *The wine bible*. Workman Publishing, New York, pp. 738-749.

Maurer, C. 2009. BACCHUS temperature reconstruction for the period 16th and 17th centuries from Viennese and Klosterneuburg grape harvest dates. *Journal of Geophysical Research*, Vol. 114, pp.1-13.

Metzger, M. J. and M. D. A. Rounsevell. 2011. A need for planned adaptation to climate change in the wine industry PERSPECTIVE. *Environmental Research Letters*, Vol. 6. No 3.

Motha, R. and W. Baier. 2005. Impacts of present and future climate variability on agriculture in temperate regions: North America. *Climatic Change*, Vol. 70. No.1, pp.137-164.

Nicholas, K. A. and W. H. Durham. 2012. Farm-scale adaptation and vulnerability to environmental stresses: Insights from winegrowing in Northern California. *Global Environmental Change-Human and Policy Dimensions*, Vol. 22 No.2, pp. 483-494.

Oregon Climate Service. 2013. Oregon Climate. Retrieved from <http://www.ocs.orst.edu/climate-of-oregon> on January 4th, 2013.

Oregon Pinot Noir Wine, LLC. 2012. Oregon Pinot Noir. Retrieved from <http://www.oregonpinotnoirwine.com/ava.php> on February 3rd, 2013.

Orr, E., Orr, W.H., and Baldwin, E.M. 1999. *Geology of Oregon*. 5th ed., Kendall/Hunt, Dubuque, Iowa.

Ramos, M.C. 2008. Structure and Trends in Climate Parameters Affecting Winegrape

Production in Northeast Spain. *Climate Research*, Vol. 38. No. 1, pp. 1-15.

Ramos, M.C. and J.A. Martinez-Casanovas. 2009. Impacts of Annual Precipitation Extremes on Soil and Nutrients Losses in Vineyards of NE Spain. *Hydrological Processes*, Vol. 23. No. 23, pp. 224-235.

Ramos, M.C. and J.A. Martinez-Casanovas. 2010. Soil water balance in rainfed vineyards of the Penedès region (Northeastern Spain) affected by rainfall characteristics and land leveling: influence on grape yield. *Plant Soil*, Vol. 333, pp. 375-389.

Rodó, X. and Comín, F.A. 2000. Links between large-scale anomalies, rainfall and wine quality in the Iberian Peninsula during the last three decades. *Global Change Biology*, Vol. 6, pp. 267-273.

Rankine, B.C., Fornacho, J.C.M., Boehm, E.S., and Cellier, K.M. 1971. Influence of grape variety, climate and soil on grape composition and quality of table grapes. *Vitis*. Vol. 10, pp. 33-50.

Tate, A.B. 2001. Global Warming's Impact on Wine. *Journal of Wine Research*, Vol. 12. No. 2, pp. 95-109.

Tobler W. 1970. A computer movie simulating urban growth in the Detroit region. *Economic Geography*, Vol. 46. No.2, pp. 234-240.

United States Department of Agriculture, National Agricultural Statistics Service. 2011. Oregon vineyard and winery report. 2000 - 2010. Retrieved from www.nass.usda.gov/or on April 11th, 2011.

United States Geological Survey. 2013. Science in your backyard: Oregon. Retrieved from <http://www.usgs.gov/state/state.asp?State=OR> on January 4th, 2013.

United States Census Bureau. 2013. Quick Facts. Retrieved from <http://quickfacts.census.gov/qfd/states/41000.html> on January 2nd, 2013.

Vaudour, E. 2002. The quality of grapes and wine in relation to geography: Notions of *terroir* at various scales. *Journal of Wine Research*, Vol. 13, pp. 117-141.

Webb, L.B., P.H. Whetton, W.W.R. Barlow. 2008. Climate change and winegrape quality in Australia. *Climate Research*, Vol. 36, pp. 99-111.

Webb, L.B., P.H. Whetton, W.W.R. Barlow. 2008. Modelling the relationship between

climate, winegrape price and wingrape quality in Australia. *Climate Research*, Vol. 36, pp.89-98.

White, M.A., Diffenbaugh, N.S., Jones, G.V., Pal, J.S., and Giorgi, F. 2006. Extreme Heat Reduces and Shifts United States Premium Wine Production in the 21st Century. *Proceedings of the National Academy of Sciences of the United States of America*. Vol. 103. No. 30, pp. 11217-11222.

Winkler, A.J., J.A. Cook, W.M. Kliewer, and L.A. Lider. 1974. *General Viticulture*. 4th ed. University of California Press, Berkeley, California