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North Carolina has a broad range of physical environments that produce wine from a breadth of grape species/varietals. Its wine industry has grown rapidly for over a decade and the nature of its climates, soils, and topography are varied and unique in the wine world, yet North Carolina remains relatively unknown outside of the Southeastern portion of the United States. In this study, North Carolina’s vineyards and their specific site characteristics were considered both on the basis of their *terroir* and the extent to which they followed extension agency advice on site selection. One characteristic risk of growing grapes in the Southeastern U.S. is a plant illness known as Pierce's Disease, which is deadly to the vines of *Vitis vinifera* parentage. This research used a novel method to reveal the dividing line between *V. vinifera* and Pierce’s Disease resistant grape variety suitability zones across the Southeast. The quantification of the physical elements of terroir and test of the effectiveness of vineyard site selection has revealed the character of North Carolina’s wine regions and commercial vineyards. In addition, the modeling of the Southeastern U.S. Pierce's Disease zone provided clarification on where Pierce’s Disease resistant winegrapes might present new wine industry options for vineyards across the Southeastern U.S.

KEYWORDS: Wine, North Carolina; Southeastern U.S.; Terroir; GIS; Applied Geography; Viticulture; Site Selection; Site Suitability

THE GEOGRAPHY OF WINE IN NORTH CAROLINA: TERROIR, SITE SELECTION EFFICACY, AND IMPLICATIONS FOR PIERCE'S DISEASE RESISTANT GRAPE VARIETIES IN THE SOUTHEASTERN U.S.

by

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Approved by

Rick Bunch
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APPROVAL PAGE

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TABLE OF CONTENTS

Page

LIST OF TABLES vii

LIST OF FIGURES viii

CHAPTER

I. INTRODUCTION AND BACKGROUND 1

- Introduction 1
- Geography > Agriculture > Wine 3
- Wine Regions 8
- Terroir 10
- A Geographic Framework for Terroir and the Wine Region 13
- Wine Region Formation 15
- GIS in the Service of Viticulture: A Literature Review 19
  - Terroir Analysis and/or Site Selection 21
  - Capability/Suitability Analysis 21
  - Scale and Data Sources 22
- North Carolina Terroir 24
- North Carolina Vineyard Site Selection 25
- Pierce’s Disease 27
- Dissertation Objectives 29

II. GEOGRAPHY OF WINE IN NORTH CAROLINA: GEOSPATIAL CONCEPTS APPLIED TO PHYSICAL TERROIR 31

- Abstract 31
- Introduction 32
- Literature Review 33
- Materials and Methods 36
- Results and Discussion 38
- Conclusions 39

III. VITICULTURAL SITE SELECTION: TESTING THE EFFECTIVENESS OF NORTH CAROLINA'S COMMERCIAL VINEYARDS 41

Abstract 41
Introduction 42
Literature Review 46
    Climate 48
    Topography 54
    Soil 58
Methods 59
Results 63
    Climate Results 63
    Topographic Results 68
    Soil Results 71
    Vineyard Results 74
Conclusions 76
    Suggestions for Improving NCWGG 78

IV. NEW PIERCE'S DISEASE RESISTANT GRAPE VARIETIES: THE IMPLICATIONS FOR THE SOUTHEASTERN U.S. WINE INDUSTRY 79

Abstract 79
Introduction 80
Literature Review 83
Materials and Methods 92
Results 96
Conclusions and Discussion 106

V. DISSERTATION THEME CONCLUSIONS 109

BIBLIOGRAPHY 116

APPENDIX A. MEAN TERROIR ANALYSIS RESULTS BY APPELLATION AND VINEYARD, (CHAPTER II) 128

APPENDIX B. VINEYARD SITE SELECTION ASSESSMENT, FAILING CELLS (CHAPTER III) 133

APPENDIX C. LIST OF ACRONYMS 138

LIST OF TABLES

Page

Table 1. Growing Degree-Days, 1981 to 2014, Classified into Updated Winkler Regions (Anderson et al. 2012; Jones et al. 2010) 50

Table 2. July Mean Temperature, 1981 to 2014, Classified by Smart and Dry (1980), with the Addition of Two Hotter Classes Using the Same Class Intervals..51

Table 3. Frost Free Period, 1981 to 2014, 10-Day Interval Classes (After 170 Days), with Ordinal Terms 51

Table 4. Weiss Topographic Position Index, Slope Position Using 2016 National Elevation Dataset...56

Table 5. Recent Late Spring Frosts Occurring After Warm Periods (Preceding 21-Day Running Mean > 60°F) after April 7th, Recorded at the GSO Airport in Greensboro, NC 58

Table 6. Results (out of 57,747 Cells within Vineyards); Counts and Percentages of Cells Failing by Factor (not used for final model in gray).........................75

Table 7. Number of Failing Cells within Vineyards by Count of Failing Factors............75

Table 8. Equations and Class Breaks for Common Viticultural Climate Indexes, Including: Mean Growing Season Temperature, Growing Degree-Days, Huglin Index, and Biologically Effective Degree-Days; This is a Modification of Jones et al. 2010 and Anderson et al 2012.........................95

Table 9. Southeastern U.S. Area Falling in the Pierce's Disease Risk Zone which is Climate Suitable for Viticulture, by State...105

LIST OF FIGURES

Page

Figure 1. Corn for Grain, Harvested Acres, USDA Agricultural Census 2012, Map Generated by the USDA-NASS (2014a) 5

Figure 2. Soybeans for Beans, Harvested Acres, USDA Agricultural Census 2012, Map Generated by the USDA-NASS (2014b) 6

Figure 3. Tame Blueberries, Harvested Acres, USDA Agricultural Census 2012, Map Generated by the USDA-NASS (2014c) 6

Figure 4. Total Acres of All Peaches, USDA Agricultural Census 2012, Map Generated by the USDA-NASS (2014d) 7

Figure 5. Total Acres of Grapes, Harvested Acres, USDA Agricultural Census 2012, Map Generated by the USDA-NASS (2014e). 7

Figure 6. Conceptual Geographic Model of Terroir and the Wine Region 14

Figure 7. NC AVAs, Selected Counties, and Vineyards, January 2016, Map Generated by John W. Nowlin 33

Figure 8. Modeling Process 37

Figure 9. North Carolina Physiographic Regions and American Viticultural Areas as of December 2016, Map Generated by John W. Nowlin 44

Figure 10. Current Worldwide Distribution of the Updated Humid Sub-Tropical Köppen Climate Zone, 1923 to 1993, (Peel et al. 2007), Map Generated by John W. Nowlin 49

Figure 11. Pierce's Disease Risk Zones for the Southeastern U.S. Based on Annual Number of Days Below -9.4°C, 1972-1997, 25-year Mean, Map from Sutton et al. (2005) 53

Figure 12. Pierce's Disease Risk Zones for the Southeastern U.S. Based on Annual Number of Days Below -12.2°C, 1972-1997, 25-year Mean, Map from Sutton et al. (2005) 54

Figure 13. Cold Air Drainage, image from NCWGG (Poling and Spayd 2015) 55

Figure 14. Mean Growing Degree-Days in North Carolina (1981 to 2014) (Amerine and Winkler 1944), Map Generated by John W. Nowlin 64

Figure 15. Mean July Temperature in North Carolina (1981 to 2014), author's Adaptation of Smart and Dry (1980), Map Generated by John W. Nowlin 65

Figure 16. Mean Frost Free Period in North Carolina (1981 to 2014), Map Generated by John W. Nowlin 66

Figure 17. Mean Number of Extreme Cold Risk Days per Decade Below -22.2°C in North Carolina (1981 to 2014) (Wolf and Boyer 2003), Map Generated by John W. Nowlin 67

Figure 18. Mean Combined Pierce's Disease Risk Zones in North Carolina (1981 to 2014), authors' adaptation of Sutton (2005), Map Generated by John W. Nowlin 68

Figure 19. Topographic Position Index, for Cold Air Drainage, Examples of Large Vineyards from The Mountains, Upper Piedmont, and Coastal Plain, Author's adaptation of Weiss (2001), Map Generated by John W. Nowlin 69

Figure 20. Slope, Examples of Large Vineyards from The Mountains, Upper Piedmont, and Coastal Plain of North Carolina, Map Generated by John W. Nowlin 70

Figure 21. Aspect Classified by Primary Effect, Examples of Large Vineyards from The Mountains, Upper Piedmont, and Coastal Plain of North Carolina, Map Generated by John W. Nowlin 71

Figure 22. Soil Depth in North Carolina from gSSURGO (current in Dec 2016), Map Generated by John W. Nowlin 72

Figure 23. Soil Drainage Class in North Carolina from gSSURGO (current in Dec 2016), Map Generated by John W. Nowlin 73

Figure 24. Soil Texture > 50% Silt in North Carolina from gSSURGO (current in Dec 2016), Map Generated by John W. Nowlin 74

Figure 25. Failing Cells in Example Large Vineyards from The Mountains, Upper Piedmont, and Coastal Plain, Map Generated by John W. Nowlin. 76

Figure 26. Electron Micrograph of *Xylella fastidiosa*, images by Doug Cook................80

Figure 27. Pierce's Disease Symptoms, Green Islands on Stems and Drying Leaves, images by John Hartman...82

Figure 28. Vectors of Pierce's Disease: A. Glassy Winged Sharpshooter, image by Reyes Garcia III; B. Broad-headed Sharpshooter, image by Ryan Kaldari; C. Versute Sharpshooter, image by Ryan Kaldari...............85

Figure 29. Map of United States Showing Probable Occurrence of Pierce's Disease, Map from UC Berkeley *X. fastidiosa* website, referenced by Anas et al. (2008)..86

Figure 30. Pierce's Disease in Texas, 1974 Map (left), and 1990's Map (right), Maps from Kamas ed. (2010)...87

Figure 31. Pierce's Disease Risk Zones for the Southeastern U.S. Based on Annual Number of Days Below -9.4°C, 1972-1997, 25-year Mean, Map from Sutton et al (2005)..88

Figure 32. Pierce's Disease Risk Zones for the Southeastern U.S. Based on Annual Number of Days below -12.2°C, 1972-1997, 25-year Mean, Map from Sutton et al (2005)..89

Figure 33. Pierce's Disease in California, Red Globe Vineyard in August, by Jennifer Hashim, California Dept. of Food and Agriculture.......................91

Figure 34. Combined Sutton Pierce's Disease Risk for Southeastern U.S. (Based on Daily PRISM Maximum and Minimum Temperature, 1981 to 2014), Map Generated by John W. Nowlin 97

Figure 35. Annual Precipitation (in mm) for Southeastern U.S. (Based on Monthly PRISM Precipitation, 1981 to 2014), Map Generated by John W. Nowlin 98

Figure 36. Frost Free Period for the Southeastern U.S. (Based on Daily PRISM Minimum Temperature, 1981 to 2014), Map Generated by John W. Nowlin 99

Figure 37. Mean Growing Season Temperature for Southeastern U.S. (Based on Daily PRISM Maximum and Minimum Temperature, 1981 to 2014), Map Generated by John W. Nowlin...100

Figure 38. Growing Degree-Days for Southeastern U.S. (Based on Daily PRISM Maximum and Minimum Temperature, 1981 to 2014), Map Generated by John W. Nowlin 102

Figure 39. Huglin Index for Southeastern U.S. (Based on Daily PRISM Maximum and Minimum Temperature, 1981 to 2014), Map Generated by John W. Nowlin 103

Figure 40. Biologically Effective Degree Days for Southeastern U.S. (Based on Daily PRISM Maximum and Minimum Temperature, 1981 to 2014), Map Generated by John W. Nowlin..........104

Figure 41. Potential Pierce's Disease Risk and *V. vinifera* + *V. arizonica* Hybrid Suitability Zone for Southeastern U.S. (Based on Daily PRISM Maximum and Minimum Temperature, 1981 to 2014), Map Generated by John W. Nowlin..........106

CHAPTER I

INTRODUCTION AND BACKGROUND

Introduction

Wine represents a complex and interconnected set of ideas which transcend any one specialization within the academy. The web of meaning extends to the agriculture of wine, the making of wine, the economics of wine, its consumption, and the culture surrounding the recreational pursuit of wine enthusiasm. All of these activities embody the meaning of wine. Geographers have long studied wine, and before them, there were thinkers who examined the spatial distributions of humans and wine. Wine, it seems, was born alongside civilization about eight thousand years ago (McGovern et al, 1997; McGovern 2007). Wine is historic and geographic.

The European wine grape, known scientifically as *Vitis vinifera*, has been cultivated by humans for more than 8000 years (McGovern et al. 1997; McGovern 2007). Grape growing—viticulture—likely began in the Caucasus Mountains somewhere close to modern day Georgia. Its archeological trail places it alongside the development of the societies of western civilization. The groups associated with early viticulture include the Sumerian, Egyptian, Assyrian, Hittite, Minoan, Mycenaean, Phoenician, Hebrew, Babylonian, and Persian cultures. As this vast region fell to the successive powers, the Roman wine culture was transformed locally in centers of horticultural pursuit (McGovern 2007).

Sustenance, pleasure, and hygiene were not the only reasons for making wine in medieval Europe; wine filled many purposes. Wine was required for the Christian religious ritual of communion as outlined in Mark 14:22-24, Luke 22:20, and 1 Corinthians 11:27-29, verses from books of the Christian Bible. This is likely why monks of this period are credited with the development of many modern practices of viticulture (Blij 1983). While it is likely monks shared varietals with their brothers from adjoining regions, they most likely would have also been crossing varieties found growing wild in their local areas (Unwin 1991). It was in vineyards next to monasteries and abbeys where the work of creating new cultivars happened. Wild Roman cultivars, having been released to the devices of nature, likely interbred with each other, with wild varieties, and with vines being cultivated. This set of historical occurrences began a pattern of modifications to the gene pool which likely resulted in unique varieties that persist today. These varieties were resistant to local disease and compatible with local climate, providing a persistent source crop. In short, these varieties of grapes became particularly well suited to their respective physical environments (Blij 1983). As would be the practice of most agriculturalists, local winemakers isolated grape varieties that were particularly high yielding and well suited to making wine. These successful cultivars were likely traded and incorporated into areas where they prospered. In this way, the history of the European winegrape well illustrates the tangled web of relationships between man, place, and grape.

This dissertation introduces the nested topics of geography, agriculture, and wine, emphasizing the geographic notions of terroir and the wine region, upon which a geographic framework is constructed. After a review of the literature on wine region formation there will be an emphasis on reviewing GIS based inquiries into topics of site selection and terroir analysis. This is followed by a thorough introduction of the primary objectives of the three central chapters, which have been formatted as three distinct publications. These three core chapters answer two questions involving viticulture in the state of North Carolina and one question more broadly related to viticulture in the Southeastern U.S. These three primary questions are as follows. What is the terroir of North Carolina and its subregions? Does the location of the commercial vineyards in North Carolina reflect the advice supplied by the state's cooperative extension documentation? And finally, what are the spatio-viticultural implications across the Southeastern U.S. for the newly developed Pierce's Disease resistant winegrapes being produced by The University of California – Davis?

Geography > Agriculture > Wine

In Pattison's "Four Traditions of Geography," (1964, 1990), the author categorizes the discipline into four distinct but related traditions, bound by a common theme. These four geographic traditions are termed Area Studies, Earth Science, Man-Land, and Spatial. A unifying theme which binds the first three traditions is Pattison's description of the fourth. This final theme is focuses on the exploration of spatial patterns and relationships. There is an emphasis in the Spatial tradition on the development of tools and theoretical frameworks for studying spatial relationships, and of using spatial analysis to address geographic problems. Nelson and Nelson (2014) succinctly summarize Pattison's categorization and proceed to give practical exercises illustrating how spatial science has developed and can be used to do the work of the Area Studies, Earth Science, and Man-Land traditions.

One early example of the use of spatial analysis in the service of economic geography occurred in nineteenth century Europe. A historic figure, influential German economist Johann Heinrich von Thünen (1783-1850) was an important contributor to ideas which might now seem at home in the field of agricultural geography. Thünen was a geographic thinker and farmer who theorized an order to the economic-spatial arrangements between agriculture and cities. In Thünen's model, high market value crops are located in the first ring outside of populated areas (Thünen 1966). Thünen was considering general theoretical principles of farm-to-market transport efficiency and the relationship between land rent and distance from the city center. In so doing, he was also considering the economic geography of agriculture.

Today, however, modern transportation and food distribution technologies have changed the rent paradigm and allow farmers to choose the location for their endeavors with somewhat more freedom than in 19th century Europe. Geographic analysis of agriculture has expanded beyond the distance/value rent ratio. In contemporary times, Geographic Information Science (GIScience) provides the theoretical and methodological support to study the agricultural environment. This is done by analyzing markets for agricultural products and/or modeling the suitability of the environment (soil, terrain, and climate) for a given crop. Agricultural spatial analysis is as relevant today as it was in the 19th century. If Thünen was studying agricultural site selection in relation to the use of space today, he would likely be modeling with the tools of GIScience.

Good examples of how GIScience works in the service of agricultural geography can be found across the spectrum of crops. While some, such as grains and legumes have broad ranges of suitability, horticultural crops such as tree fruit, or bush fruit have more physical restrictions. A clear visual demonstration of these differences can be seen in Figures 1 through 5. As a niche agricultural crop, grapes in general and winegrapes in particular have demanded considerable historic interest. Grapes are a labor and resource intensive crop with a high potential value. While commercial cultivation of grapes is restricted to mid-latitude climates, vineyards are found in a myriad of environments and there are multiple approaches to their management.

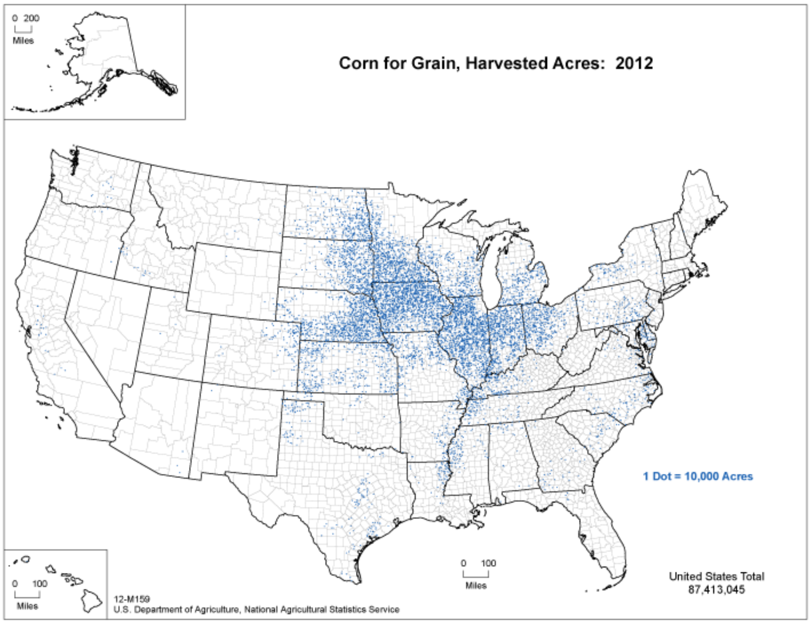

Figure 1. Corn for Grain, Harvested Acres, USDA Agricultural Census 2012, Map Generated by the USDA-NASS (2014a).

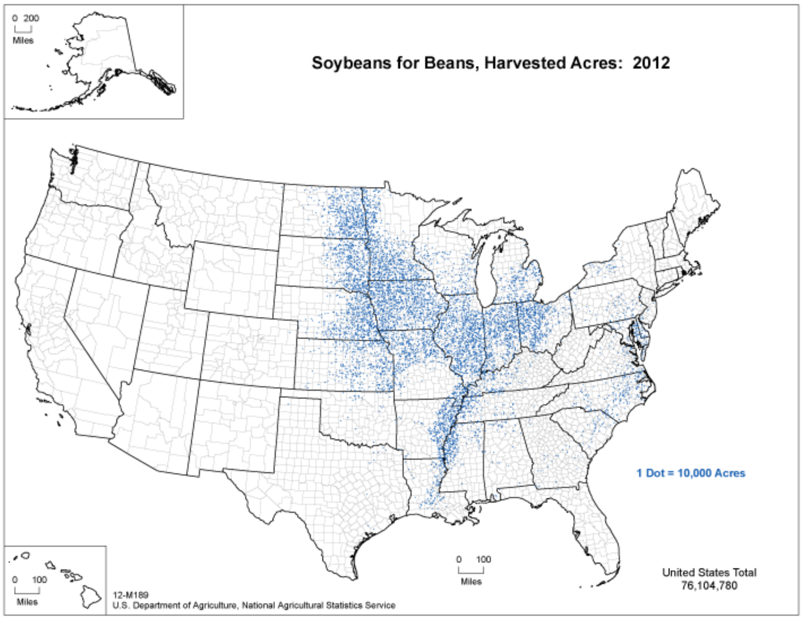

Figure 2. Soybeans for Beans, Harvested Acres, USDA Agricultural Census 2012, Map Generated by the USDA-NASS (2014b)

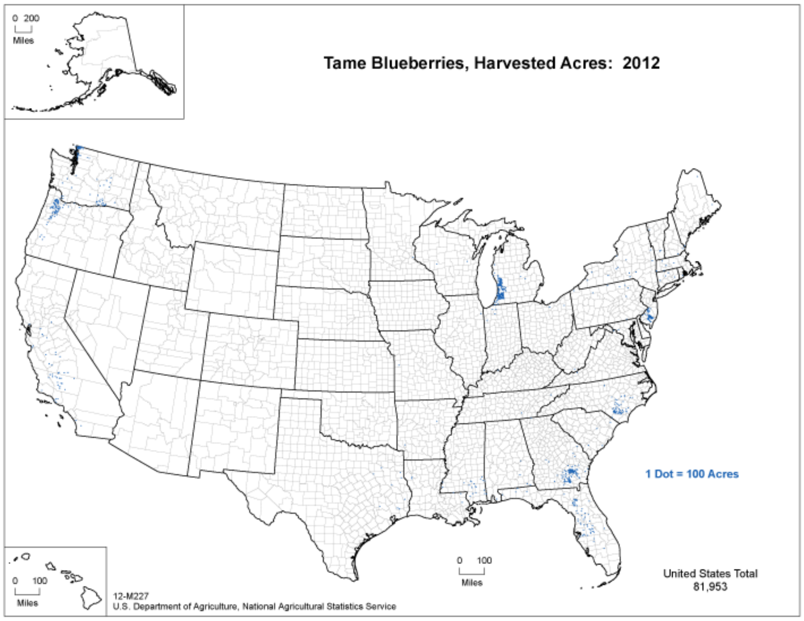

Figure 3. Tame Blueberries, Harvested Acres, USDA Agricultural Census 2012, Map Generated by the USDA-NASS (2014c)

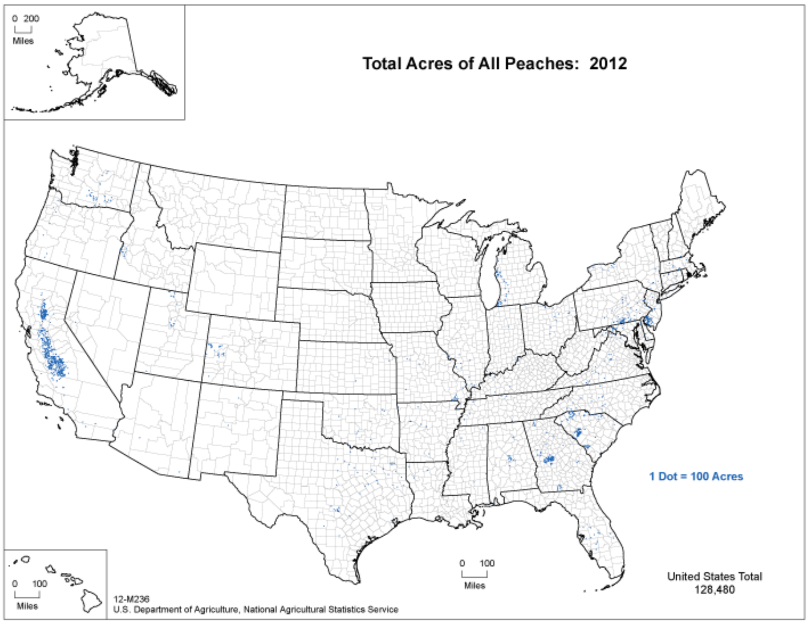

Figure 4. Total Acres of All Peaches, USDA Agricultural Census 2012, Map Generated by the USDA-NASS (2014d)

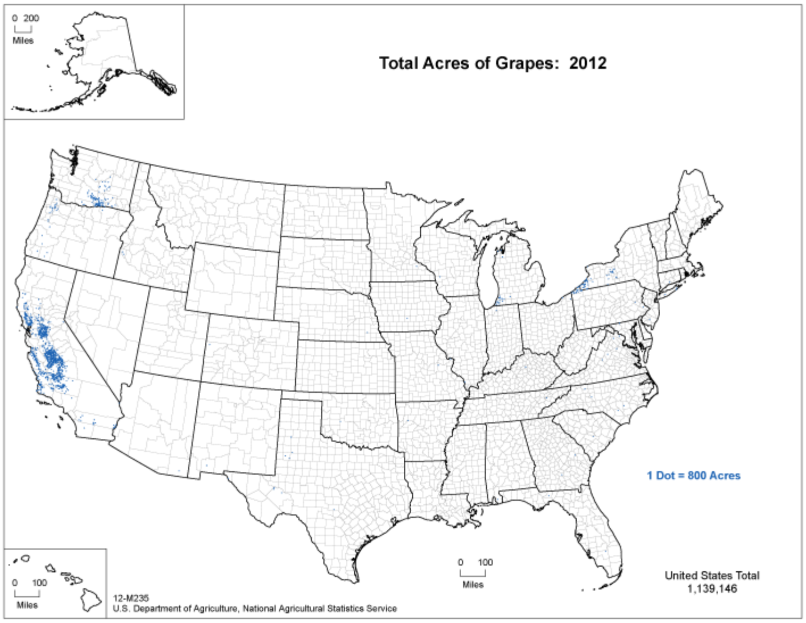

Figure 5. Total Acres of Grapes, Harvested Acres, USDA Agricultural Census 2012, Map Generated by the USDA-NASS (2014e)

Wine Regions

Wine Regions are more than the areas where grapes are grown; they become the moniker, the meaning behind the price of a bottle, the place-value. Wine is a high value agricultural product, while there are wines which are priced at every level of the market. The quality and profitability of wine businesses is directly related to sensory perceptions and the link between quality and value. Many of these ideas of value and quality are inherently tied to location; therefore, where a wine comes from often directly affects its price (Carew and Florkowski 2010). The market forces which vary the price of a bottle and how this connects to regionality are of interest to the economic geographer (Dougherty 2011; Blij 1982; Dickenson and Salt 1982).

The concept of wine regions and the cultural (e.g. Trubek 2009) and physical (e.g. Fanet 2004) differences from region to region are represented by much literature. Chief among these are two large compendia, wine atlases by Domine (2004) and Johnson and Robinson (2007). These two atlases are more than a collection of maps, as they contain lengthy passages on grape varieties, and descriptions of world renowned wine regions, regional practices and the world's most celebrated wines. This literature often emphasizes the history and hierarchy of regions, and tends to contrast Old World and New World themes (Moran 1993). There is also the geography of tourism and wine as attraction (Getz and Brown 2006; Byrd et al. 2012).

In the EU, *Regulation No 1151/2012 of the European Parliament and of the Council on Quality Schemes for Agricultural Products and Foodstuffs,* Protected Geographical Indication (PGI) and the higher certification, Protected Designation of

Origin (PDO) are described. These are systems of controlling the use of place names on agricultural products such as appellations on wine labels (EU 1151 2012). Different countries have different terms for their systems of appellation classification. In France, this system is known as the *Appellation d'Origine Contrôlée* (AOC), meaning controlled designation of origin. The AOC system was formalized in the 1930's but is meant to preserve the traditional systems of practice in place for centuries. This system was a formal codification of a historic regional system of local common vini-viti-cultural practice, and it is further modified by local governing bodies which preside over each wine region and control the local practices.

As summarized by Meloni and Swinnen (2012) and Johnson and Robinson (2007), most other countries with similar systems pattern after the French AOC system. The Italian system has three scales of appellation known as *Denominazione di Origine /Controllata /e Garantita* (DO/DOC/DOCG) in order of increasing status and reputation. Each requires a higher degree of effort, and a greater level of controls, bringing a higher prestige. Spain and Portugal have similar systems to the Italian system, all modeled after the French AOC system. Outside of Europe, in Australia and New Zealand, the system is termed Geographical Indication (GI), and in the U.S. the formal wine region is termed the American Viticultural Area (AVA).

The European systems are uniquely hierarchical, with wine regions sub-divided into sub-regions which carry separate appellation designations and sometimes regionally specified quality designations based on historic reputation. Not only are the regions bordered, but many regional viticultural and oenological practices therein are controlled and specified by the law. The Champagne Wine Region is located in the historic Champagne Province of France. The Comité Champagne, which is the regional regulatory commission with authority over wine practices, lists the following areas of restrictions for the region in relation to terroir and appellation. The main rules of the AOC are (2017):

- Strict delimitation
- Approved grape varieties: Chardonnay, Pinot Noir, Pinot Meunier, Pinot Blanc, Pinot Gris, Arbane, Petit Meslier
- Method of pruning: Royat, Chablis, Guyot, Vallée de la Marne
- Maximum permitted yields per hectare
- Maximum permitted press yield
- Minimum potential alcohol content of newly harvested grapes
- Secondary fermentation in the bottle, and minimum periods of maturation on lees: 15 months for non-vintage Champagne and three years for vintage Champagne

Champagne, a prototypical European wine region, can be contrasted with the American AVA, which has none of these cultural restrictions. In the U.S. an AVA is only the region, only the area within a boundary, only physical, and only political, not cultural (CFR 2017). While the creation of an AVA is tied to local regional meaning, and the boundaries are required to define an area with a unique wine growing environment, the consistency with which these guidelines have been followed is questionable (CFR 2017; Nowlin 2015; Nowlin and Bunch 2016a; Nowlin and Bunch 2016b).

Terroir

Chief among the esoteric viticultural terms is terroir. Terroir is a French term with no English equivalent. In the simplest of terms, terroir can be defined as the regional character of a wine. Somewhat more thorough would be a definition of terroir as a notion relating the regional character of a wine to physical characteristics, viticultural methods, and oenological practices of the area it was grown and produced in (Vaudour 2002; Jones et al. 2004; Van Leeuwen and Seguin 2006; Sommers 2008). Summarized in the French phrase *goût de terroir*, the taste of place or the taste of soil, the term captures the idea that both people and the Earth are tied together (Blij 1983; Van Leeuwen and Seguin 2006; Trubek 2009).

Vaudour's (2002) literature review on the theoretical discussion of the concept of terroir is an excellent summary of the research which defines terroir. This article includes considerations of the sub-fields of wine research that use the term. The fact that there is no English equivalent for the term terroir is not a shortcoming of the English language, because there are no German or Spanish equivalents, either. Vaudour asserts that it likely arises from the *terratorium* of the Provençal language of the Gauls who borrowed it from the Latin term *territorium*, meaning "land around or within the boundaries of a town, or a territory." The Oxford English Dictionary defines the Latin term *terra* as meaning "land or territory" and literally "earth" [meaning soil], and *orium* "…denoting a place for a particular function." It follows, then, that the combination of the meanings of earth, and about a place or a territory, seems like a reasonable description of what terroir means in its contemporary context. Currently, the term terroir has been assigned a broad set of meanings that revolve around the typical character that a wine from a certain place acquires, because of that place; one could also see this character as the wine's nature. Geographers might call this its placeness (Warf ed. 2006) or regionality. Terroir relates to notions of quality and typicality, and is presented by Vaudour as belonging to several spheres of meaning, including “nutriment,” “space,” “slogan,” and “conscience.”

Of these four spheres of meanings, nutriment is the label Vaudour borrows for the plant-growing terroir, otherwise known as viticulture, or the agronomic properties of an environment. Space is the general term used to describe the politico-historical/territorial location of wine producing locations. Terroir as conscience, presented by Vaudour, is a notion of ethnographic and cultural sensibility acquired in the minds of people about a place; it can be better understood as the mythic identity of a location. As for slogan, terroir is the realm of marketing concerned with the labeling of a product, the marking of a wine with designations of origin, the protecting of the identity of a place, albeit solely for the economic protection of its business interests. Vaudour answers the question, which of these four types of terroir could be deemed scientific? In answering this question, she casts away what she calls the “mythical/mystical.” And in the end, the paper is left to consider two types of terroir—the geographic differentiation of: products and raw materials or environmental potentialities. In her terms this is the, “plant-growth and territory-based factors,” (p121) these could be described scientifically as wine region formation and suitability analysis.

Both soil and climate are important components of terroir (Van Leeuwen et al. 2004). Topography has an impact because of its effect on climate above ground and soil below ground. Soil and climate, along with topography, present themselves as continuous phenomena and are important above and below the surface of the earth. The unique combination of topographical, pedological (soil), and climatic factors (topo-pedo-climate) can create distinctively different physical terroirs. The difference between the Rhine Valley in Germany and the slopes around Santiago, Chile is significant, but both produce acclaimed wines, and both contain regionally distinct local terroirs. Topography, pedology, and climate all influence each other; to understand the physical elements describing the terroir of a place is to understand all environmental elements existing together—in concert—in situ.

A Geographic Framework for Terroir and the Wine Region

This dissertation operationalizes a geographic conceptual framework for terroir which situates the wine region within the same space as the concept of terroir. The concept of a wine region in this sense is not scale dependent. It can be seen at all scales, from the large area with multiple sub-regions, often termed the wine region, to the sub-region termed the appellation and even to the vineyard or vineyard block. Across regional scales there are regional terroir characteristics which persist, although with decreasing area there can be more specificity applied to definitions of local terroir. This scale pattern is reminiscent of Waldo Tobler's maxim (1970), "everything is related to everything else, but near things are more related than distant things," which has become known as the First Law of Geography. Within this framework, like a wine region, terroir can be described at a variety of scales.

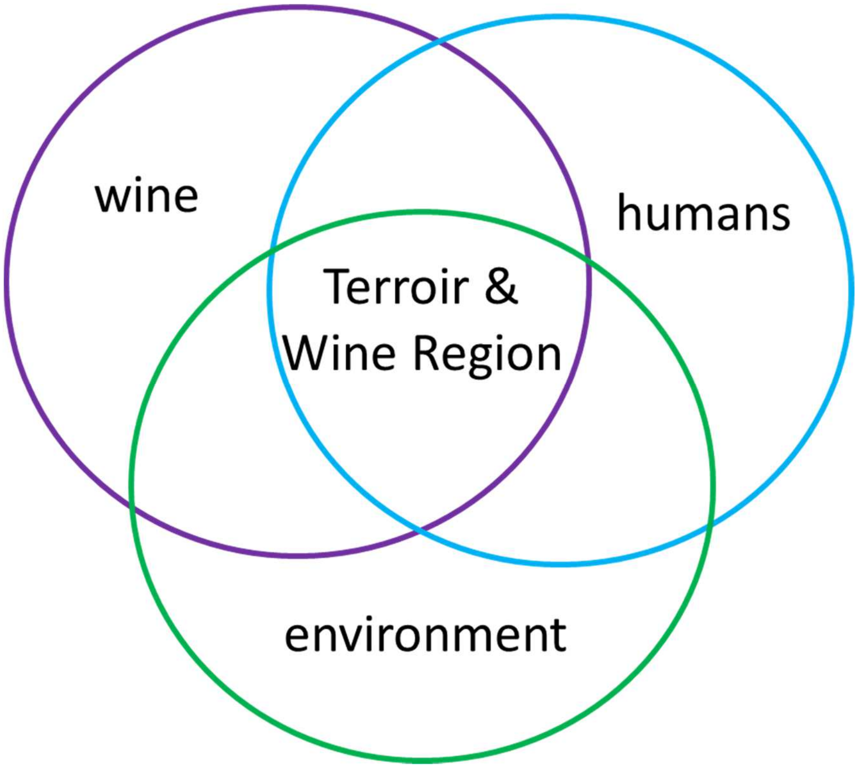

Figure 6. Conceptual Geographic Model of Terroir and the Wine Region

The overlapping circles of the Venn diagram (Figure 6) represent the human-environment interactions which result in wine. Occurring in the center of this diagram are the regional practices of grape growers and wine makers as well as the regional identity ascribed to the product—wine—and living in the minds of the wine marketer and the wine consumer. Recall Vaudour's (2002) characterization of these aspects of terroir as "mythical/mystical." The place of terroir is the place inhabited by the viticulturist, oenologist, and cellar operator. In these places grapes are grown, transformed into wine, aged, packaged and then distributed. These places are collectively bound together, both terroir and the wine region are views of each other from different perspectives. From the geographic perspective, terroir is a component of aerial categorization. Simultaneously, terroir is both aerial and oenological. Its oenological identity is the sensorial component related to its geography.

Wine Region Formation

Wine regions are the spaces which encapsulate and typify the human and environmental interconnections that impart local character onto wine. Terroir itself is used to signify this uniqueness. In this way terroir becomes a regional attribute, used to differentiate one region from another … maybe also used to place regions in a hierarchy by their wine quality. There are a variety of ways to characterize the qualities of a wine region. One way to contrast regions is by the grape varieties grown there. Another is through the set of local cultural practices used in both agriculture and oenology, and how these vary across space. Wines from two different places can be compared and contrasted on the basis of their unique hedonic—sensorial—properties, their terroir.

Terroir is often spoken of as the primary organizing element of an appellation. Moran's (1993) consideration of the appellation as a territory and the political implications of such boundary making reveal that political geography of wine is rich with opportunity for critique. Atkin and Johnson (2010) build on the way in which appellations are used and exchanged as representing designations of quality by representing bounded areas of terroir. This would be a reasonable connection, if purely physical criteria were used to build regions. However, there are myriad problems with how appellations are created, justified, and reified, suggesting that they are not useful as proxies for terroir. The notion that a thorough process of discovery which included a justification backed strongly by objective application of purely physical environmental criteria is not borne out by the evidence. When the stated justification for an appellation boundary is on the basis of a unique physicality, yet the boundary reflects something more or less than the environment, then the justification is weak.

Wine regions can be socially constructed and maintained through reification ... justified through subjection via the wine literati. Hierarchical aesthetic conceptualizations of wine are often created and maintained by celebrity judges with limited subjective ideas about what is good. Their opinions, based in tradition and modified by personal preference, are delivered in esoteric terms—inaccessible except to the few—wine aficionados. The identity of a region and the relative perception of quality associated with its wines is related to the price of those wines, in this way expert opinion and economic valuation are connected.

New wine regions are also socially constructed internally and politically, using environmental parameters. New Zealand has a host of wine regions on the rise in the world wine market. Part of their success relates to a concerted effort at revaluing their wine districts. This involves understanding where their best wines are produced and then developing a marketing plan. A good illustrative example of a region which codified the environmental-economic relationship and then constructed an identity to market their wine is the Gimblett Gravels terroir in New Zealand (Overton and Heitger 2008). The economic development of a wine industry through the construction of the narrative around an environment-quality-value relationship is typical of new wine regions. Notions of quality materials and practices support the wine valuation in Old World regions by virtue of long histories, but in order to compete, New World wine regions attempt to develop an identity in a short timeframe.

There have been critiques on the legitimacy of wine regions as geographic delimitations of terroir. These critiques investigate the political nature of regional formation and boundary making processes. One example which problematizes the use of environmental parameters arose in the Coonawarra region of Australia (Banks and Sharpe 2006). This region has been in wine production since the 19th century and the local growers formed the regional description using a strict biophysical rubric related to a peculiar regional soil type. Some surrounding land owners who grew grapes fell outside of the proposed zone of geographic indication (GI). These surrounding vineyards petitioned that they too grew high quality grapes, even if not on the "Terra Rosa" soil which the Coonawarra is known for. Seeing the economic benefit of being included, they wanted to participate in the GI. The government capitulated after receiving 33 complaints from those growers immediately outside the boundary. The result was a severely adjusted GI boundary, which resulted in the inclusion of many acres of low quality land. This added area did not conform to the initial physical definition for high quality grape growing, yet it was included in the Coonawarra GI because of political pressure.

Other critiques originate from within France where legal designation of wine regions began through the construction of the AOC system. There is a geographic delimitation in the AOC system which specifies the boundary. Wines may only carry the name of the region on the label when they originate within that boundary, however, the AOC system has more restrictions beyond simple vineyard location. The AOC system imposes extensive sets of rules which are particular to the appellation in question. Some examples of these rules are limits on what varieties can be grown, permitted sugar and alcohol content, yield, and sometimes locally relevant techniques of training vines, making wine, or limits on more esoteric practices (Farmer 2014). Farmer relates the regional structures for wine in Bordeaux to those of cheese in Westcountry Farmhouse Cheddar Protected Denomination of Origin (PDO) in the United Kingdom. Farmer says, “At a basic level, AOC status is based on linking together a location, a history of practice, and a reputation around wine. This is legally represented through the usages *locaux, loyaux, et constants* (local, loyal, and constants) test, which highlights that linkage between product and place, and it is by proving each of these individual elements that the right to an AOC is established.” Therefore, the AOC system is an interwoven network of cultural meaning, physical/historical circumstance and particular place. So, the winemakers of the French AOC system can critique other GI systems of new wine regions as not having the historical component. The argument would be that if a region does not relate to a local history or practice, these purely natural boundaries don’t carry the same weight as an AOC. A counter-argument would be that the Old-World wine regions have spent more than a thousand years figuring out what practices and environments might be well mated to wine. New-World wine regions, on the other hand, can look to Europe and build upon that knowledge to produce similar outcomes in a shorter time period.

As a device of wine marketing, product packaging is an important space. On a bottle of wine, the packaging is most typically made up of the bottle, the cork, and the label. While it might not initially be apparent to the wine consumer, it is not by accident that the origin of wine is prominently displayed on the label. These words of origin are valuable and legally protected. To participate in a wine region or appellation, which has a designation of origin, is an economic practice. As such, the historical and political ways in which a territory came to be and has been maintained are ardently defended through the economic protections granted to its members. Chief among these protections is the sole ability to use the territorial name for marketing.

A good example of an EU GI which strenuously defends the use of their PGI and PDO on labels is AOC Champagne. They have successfully defended their name from being used widely on products outside of Europe. Developing countries, however, have a more difficult time protecting their place-name value in Europe (Ilbert and Petit 2009). While the EU is quick to protect their intellectual property, such as the use of its PGI and PDO certified products, they have been criticized for not recognizing and protecting the rights of non-EU products inside of Europe. Arguments about this double standard which favors European GIs over non-EU GIs have come before the World Trade Organization, which has issued guidance to the EU to correct this behavior (Wyk 2006; Bramley and Kirsten 2007; Ilbert and Petit 2009; Bramley and Bienabe 2012).

GIS in the Service of Viticulture: A Literature Review

As a geographer researching terroir and the wine region as described above, this dissertation is situated at the human-environmental nexus and utilizes the theories, materials, methods, and practices of GIScience to solve geographic problems. More than simply tools and techniques, GIScience is underpinned by scientific theory and operates as a comprehensive mode of inquiry which stands apart as its own sub-discipline of the greater discipline of Geography (Goodchild 1992). In the case of the research presented here, as a mode of inquiry, GIScience has been tasked with answering specific questions, and has produced knowledge. This knowledge is both idiographic in its applicability to the Southeastern U.S., and North Carolina's wine regions, appellations, and vineyards, and nomothetic through the generation of new methodologies to advance viticultural site suitability and terroir analysis.

Within the sub-field of geography known as GIScience there are two overlapping and active areas of research related to viticulture. This effort has two primary foci, mapping the physical elements of terroir, and performing capability/suitability analysis, these concepts are introduced at length in the following paragraphs. GIScientists are using geophysical and agricultural parameters to characterize viticultural areas and quantify terroir (Bowen et al. 2005; Bonfante et al. 2011; Hellman et al. 2011). By analyzing the physical character of a wine growing area using empirically generated datasets wine regions can be compared with objectivity. Multi-factor spatial analysis has been used not only to describe a region, but also to model site suitability (Foss et al. 2010; Irimia and Patriche 2011; Irimia and Patriche 2010; Jones et al. 2006; Jones et al. 2004). The interacting effects of latitude, regional climate, soil, and topography makes viticultural site selection computationally complex, and the body of research relating to developing models for risk assessment is growing. The interdisciplinary nature of such research involves the incorporation of expert knowledge and often takes the form of a mixed-methods approach.

Terroir Analysis and/or Site Selection

Examples of terroir analysis include Takow et al. (2009) and Hellman et al. (2011) who both described the appellations of West Texas. Jones et al. (2004) quantified the suitable area of the Umpqua Valley AVA in Oregon and divided it into climate zones. Jones et al. (2006) modeled the Rogue Valley AVA's in Oregon, and Jones and Duff (2011) produced a detailed report for the winegrowers of the Snake River Valley in Idaho and Oregon both quantifying terroir and modeling site suitability. Bowen et al. (2005) studied the Similkameen and Okanagan Valleys in British Columbia in Canada and Reynolds et al. (2007) analyzed vineyards in Ontario, Canada. In Europe, Bonfante et al. (2011) quantifies the terroir of Valle Telesina, Italy. In new Eastern European wine regions researchers such as Szymanowski et al. (2007) in Lower Silesia Poland modeled site suitability Irimia and Patriche (2010; 2011) performed research in both the Averesti and Husi wine regions of Romania, and Shaposhnikova (2010) studied an unspecified Eastern Ukrainian Valley. On the other side of the world from there, Imre and Mauk studied New Zealand Terroir (2009). GIScience brings a large set of methods and practices to both terroir analysis and viticultural site suitability analysis.

Capability/Suitability Analysis

The organizing units of this literature are the scales, parameters, weights, and model methodology used to model viticultural potential. Relevant parameters associating geography with viticulture are organized by Earth's spheres: the lithosphere, atmosphere, pedosphere, and anthroposphere. Surfaces of topography, soil, climate, and land-use can be classified by either capability and/or suitability. Capability in the context of viticulture is a pass/fail test of whether a vineyard can be planted in an area, or most basically it is a prediction of risk for survivability, ripening potential, and harvest likelihood. Suitability, however, is a notion which further classifies viable sites, often ordinally, by grading their capacity for some viticultural goal such as high productivity, high quality, or low risk. These concepts are connected in that the most basic statement of suitability is a statement of capability.

Scale and Data Sources

In the literature, the region being considered is most often the appellation, or a set of closely related appellations in a wine region. These occur at various scales. With regard to aerial size of the appellation and the resolution of the terroir units being modeled, the concept of scale is central (Vaudour and Shaw 2005). The largest appellation considered in this literature review was the Texas High Plains AVA which was 3,585,048 ha; the smallest was the Dric sub-region within the Husi Romania wine region at 264.42 ha respectively. These two examples, which vary by four orders of magnitude in size, illustrate the vast range in scale extent represented by appellations. When deciding how to represent terroir unit surfaces across appellations the resolution becomes important. Raster based surfaces are organized into cells, and the size of these cells must be appropriate for the size of the region being depicted. Surfaces of topography, soil, and climate are available in various resolution.

The topographic parameters in previous studies were typically derived from DEMs with resolutions of 10 (Hellman et al. 2011; Jones et al. 2004; Jones et al. 2006), 20 (Bonfante et al. 2011), 50 (Foss et al. 2010), 90 (downscaled to 10; Irimia and Patriche

2009, Irimia and Patriche 2011) or 100 meters (Bowen et al. 2005). With today's computing processing power, future studies will more than likely use higher resolution surfaces (raster) such as 10m for small areas.

The most common source of soil parameters for terroir analysis and site suitability research have been obtained from soil surveys. Government agencies often provide soil surveys as vector data but more recently raster surfaces have been produced and offered as an alternative. The rasterized soil data resolutions found in the literature were 10, 30, 60, 90 or 100 meters (Jones et al. 2004; Jones et al, 2006), 1:50,000 (Bonfante et al. 2011), 250m (Foss et al. 2010) and 1000m. In the U.S., these datasets are stored either as vector data models in SSURGO and STASGO datasets supplied by the USDA-NRCS. Alternatively, they are converted to raster as needed, or directly supplied as a raster in the newer gSSURGO datasets. SSURGO and gSSURGO are best designed to be used at the 1:24,000 scale and at 10 meters in resolution respectively. STATSGO is meant to be used at scales above 1:250,000 in native form, or as a 100m raster surface if rasterized. These three datasets are available across the contiguous U.S. They are compendiums of historic county scale soil surveys which are sporadically performed, sometimes only once in history, or every few decades. Beyond the data referenced in these studies, many of the viticulturally related soil parameters are presented in detail by White (2003, 2009).

The resolution of climate surfaces were among the lowest of all surfaces used in the reviewed viticultural modeling studies. For example, Foss et al. (2010) used 5 km, Jones et al. (2004; 2006) used ~2km via PRISM, and Hellmen et al. (2011) used 1000m via Daymet. There was one example of a locally produced, extremely high resolution of

20 meters (Bonafe 2011), which was downscaled to the resolution of the DEM used in their study. This is almost unbelievably high for a climate surface. Monthly data and 30-year climate normal data are available at 800m and daily data are available at 4km for the continental U.S. as a download from the PRISM Climate Group website. In addition, a 400m dataset based on a downscale of PRSIM was made available for a fee from Climate Source, Inc. (CSI).

Only two reviewed articles considered land-use zoning areas (Jones et al. 2004; Nowlin and Bunch 2016a), although presumably legal restrictions on land use are common across the country. It appears the inclusion of land use zones was related to the hyper-restrictive zoning regime in the study area, which rendered a large percentage of the AVA incapable for agriculture (Jones et al. 2004).

North Carolina Terroir

North Carolina holds several notable distinctions in the world of wine. The economic impact of the wine industry in North Carolina was estimated at $1.97 billion in 2016 (Frank, Rimerman + Co. LLP 2017). Before Prohibition, North Carolina was producing more wine than any other U.S. state (Mills and Termey 2007). It is also home to the Mother Vine, the oldest known grapevine in the Western Hemisphere (Helsley 2010; Kickler 2012; North Carolina Wine History 2015), and the Biltmore Winery, which is the most visited winery in the Western Hemisphere. Duplin Winery is the largest Muscadine winery in the world (Helsley 2010; Duplin 2015) and the largest winery of any type in the South. Overall, the state ranks as one of the nation’s top five destinations for wine tourism (Byrd et al. 2012). North Carolina’s wine industry is young, originating in the mid-1970s. In the last four decades, the state has grown into the twelfth largest producer of wine in the nation (TTB 2017). As of September 26, 2017, North Carolina is home to 186 wineries, a significant increase from the 21 wineries that were present in 2000 (Winslow 2014, 2016; Fuller 2017).

Beyond the statistics, there are many aspects of North Carolina's wine industry that have not been fully explored. The state's terroir has not been effectively described, and the potential for locating additional vineyards through suitability analysis has not been determined. Even the state's most dense wine growing areas lack a detailed physical description. North Carolina has five American Viticultural Areas (AVAs) (CFR 2017), but little research has been conducted quantifying their spatial characteristics. Wineries, tasting rooms, vineyards, and AVAs need an authoritative source from which to draw narratives relating to the unique combinations of soil, climate, and topography from where their grapes originate. Apart from an outsider's need for descriptive information about the region, the members of the region themselves would benefit greatly from the objective collection and dissemination of this information. The state's wine industry is growing fast. Unfortunately, its terroir is unknown, being entirely absent from the literature. Where does North Carolina fit in the world of wine? The lack of a definition of terroir for North Carolina's formal wine regions and vineyards represents a gap in the literature.

North Carolina Vineyard Site Selection

North Carolina has a broad range of environments which are suitable for growing a wide variety of grapes. These settings vary from montane vineyards planted at elevations above 4000 ft. to coastal vineyards planted less than ten meters above sea level. The climates in the state vary from being as cool as the wine growing regions in Germany and Northern France, to as hot as wine growing regions of Italy's Piedmont, Southwest France and Northern Spain. The broad set of growing conditions allows North Carolina to produce every commercial species of grape grown in North America, including: The Summer Grape (*Vitis aestivalis*), The Fox Grape, (*Vitis labruscana*), Muscadines (*Muscadinia rotundafolia* or *Vitis rotundafolia*), The European Winegrape (*Vitis vinifera*), and hybrids between these species. Of these, the most widely planted in North Carolina are European winegrapes, Muscadines, and hybrid grapes. Cabernet Franc, Cabernet Sauvignon, Chardonnay, Malbec, Merlot, Mourvèdre, Petit Manseng, Pinot Gris, Sangiovese, and Viognier are some of the European winegrapes grown in North Carolina. Popular hybrid grapes include Chambourcin, Seyval Blanc, and Traminette. Common Muscadines include Carlos, Nobel, and Scuppernong. Norton, also known as Cynthiana, is a Summer Grape hybrid grown in the state, and Catawba, Concord, and Niagara, Fox Grape varieties, are also grown (Nowlin 2013).

North Carolina's Cooperative Extension Service has developed the North Carolina Winegrape Grower's Guide (NCWGG) for advising growers (Poling 2007; Poling and Spayd 2015). The purpose of Chapter 4 in the NCWGG is to provide counsel on site selection for potential grape growers. While it does not specify the nature of the most suitable site for each commercial species, there are well illustrated instructions, broadly applicable across most commercial grape species. The most poignant advice focuses on how to avoid the worst sites. Not much is known about the relationship between the state's published guidance and the site selection choices made by its wine growers. This lack of published research on the adoption of extension advice for vineyard site selection represents a gap in the literature.

Pierce's Disease

Pierce's Disease is the primary limiting factor for growing *V. vinifera* grapes, not only in North Carolina, but also throughout the Southeastern region of the U.S. (The Southeast). Over the past four decades, North Carolina has witnessed climate change in the form of warmer winter minimum temperatures (Nowlin 2012; Nowlin 2013). The reduction in winter cooling is evident along the temperature threshold used to predict PD risk, resulting in a reduction in microclimates where European winegrapes would otherwise be suitable. The impact of PD on viticulture has been studied not only in California, but also in North Carolina (Sutton 2005; Myers et al 2007) Virginia (Wallingford et al 2007), and Texas (Kamas ed. 2010). Since PD is native to The Southeast, the threat it poses there is relatively limited in that it is confined to the area along the PD risk boundary. This boundary, which can move due to climate change, has a moderate economic impact due to relatively low volume of wine production in this region. This contrasts with California, which produces more than 84% of the nation's wine (TTB 2017). In California, PD is an existential threat (Pierce's Disease News and Research 2015). The treats posed by PD are also receiving attention from European wine regions (Mårtensson 2007). California has funded research into PD for several decades, pursuing solutions to this disease.

One of the outcomes has been the creation of PD resistant wine grape varieties (Purcell 1974; Feil and Purcell 2001; Hoddle 2004). They have been hybridized with a native grape species, *Vitis arizonica*, to pass on its resistance to PD, and backcrossed to European grapes. These new cultivars are genetically of between 87.5% and 98% European parentage. This allows these new varieties to be both PD resistant while also having desirable wine making properties (Tourney 2009, 2013). These PD resistant hybrid varieties are being produced by a grape breeding program at the University of California at Davis (Riaz et al. 2008; Riaz et al. 2009; Hu et al. 2012; Reiger 2014; Alston et al. 2015). Some of them have also been trialed in Texas and Alabama (Franson 2011; Coneva 2016). The cloning rights to these varieties are expected to be licensed to nurseries for distribution to markets in the very near future (Tourney 2013; Jeffries 2016).

The creation of a new set of PD resistant cultivars will not only be useful for California, but should open up a large area in the Southeast U.S. to viticulture. The implications for such a new crop could have large economic potentials for the region. What is unknown is the zone where PD is the only major limitation to viticulture presently. The extension guidance revealing the area which is at risk for the disease is not clear. Mapping of PD has occurred in the past (Anas 2008), but the best available maps in the Southeast were generated from ad hoc interpolation methods that utilized a limited number of climate measurements (Sutton 2005), or counts of incidents by counties (Kamas ed. 2010). The currently available PD risk maps are too low in resolution to be useful for the site selection along the current boundary between PD risk areas across the Southeast. Also, the spatial methods used to create the past maps are either unpublished

(Anas et al. 2008), or are not in keeping with current technological advancements in climate science and GIScience (Sutton 2005, Kamas ed. 2010). This lack of authoritative risk guidance maps along the PD risk boundary in the Southeast represents a gap in the literature.

Dissertation Objectives

The three objectives of this dissertation all relate to the theme of geospatial modeling and viticulture. This research is performed at multiple scales, beginning with the vineyards, counties, and formal wine regions of North Carolina and expanding to the greater region of the Southeastern U.S. In this dissertation, I address three gaps in the literature summarized above in the literature review and answered in the following three chapters which stand alone as separate publications. The first article (Chapter II) details and quantifies the zones of terroir in North Carolina. This article addresses the gap formed by the lack of description and quantification of terroir of North Carolina's formal wine regions, and vineyards in the literature. The second article (Chapter III) investigates the effectiveness of site selection advice provided by state cooperative extension documentation by testing the adoption rate of this advice in vineyard site location. This article addresses the gap formed by the lack of published research demonstrating the adoption of state cooperative extension advice for the selection of vineyard sites across North Carolina. The final article (Chapter IV) analyzes the implications for Southeastern viticulture to the release of PD resistant grapes from UC Davis, by modeling the zone of potential suitability for these new varieties. This addresses the gap formed by the lack of authoritative risk guidance maps along the PD risk boundary in the Southeast. These three chapters are followed by a summary of the conclusions and contributions produced in the three standalone chapters (Chapter V), which also includes a forecast of the current work and plans for future research.

It should be noted that this dissertation is structured in a format where the goal is to produce three independent publishable articles. The length and format of some of these articles vary due format requirements of the publication outlets. Therefore, each chapter has its own abstract, literature review, and conclusions. These conclusions are summarized in the concluding chapter. The format has created several temporal inconsistencies. For instance, the second chapter was published in July of 2016 and the third chapter is currently under review for publication as of August 2017. These two articles contain maps and references to information from different time frames. For instance, some information was updated in the third chapter, from the period of the second chapter. One example is that a new formal wine region was approved in November of 2016, so references to this region are absent in the second chapter. Also, there are updated counts of wineries in Chapter I, which are from September of 2017, while Chapter II cited a count from January 2016. Another example is some repetition, in the case of the same images being used in Chapter II and Chapter III relating to Turner Sutton's (2005) Pierce's Disease maps. Also, note that all acronyms are referenced in Appendix C. and are defined anew in each of the three independent articles, while the bibliographies from each of the three independent articles were combined into a single list of referenced for the entire dissertation.

CHAPTER II

GEOGRAPHY OF WINE IN NORTH CAROLINA: GEOSPATIAL CONCEPTS APPLIED TO PHYSICAL TERROIR

This chapter was published:

Nowlin, J, and R Bunch. "Geography of Wine in North Carolina: Geospatial Concepts Applied to Physical Terroir." In Proceedings of the XI International Terroir Congress 2016, web 482-87 (print 464-469). Linville College, McMinnville OR: Southern Oregon University, 2016. http://en.calameo.com/read/004433976949ab8885344

Abstract

North Carolina has a broad range of physical environments that produce wine from a breadth of grape species/varieties. While its wine industry has grown rapidly for over a decade, North Carolina remains relatively unknown to the world of wine. The development of a statewide system of terroir is one way to introduce the state to the wine world. This paper will present the regionally relevant factors of terroir derived from the use of Geographic Information Systems (GIS). The goal is to capture the basis for creating a regional terroir unit for North Carolina. The resulting factors will be presented at various scales that range from the state level to its counties, appellations–American Viticultural Areas (AVAs), and commercial vineyards. The definition and description of the elements of the new system are presented along with the geographic methods used to delineate the state's AVAs and vineyards.

Keywords: Terroir, North Carolina, Viticulture, AVA, Vineyard

Introduction

The term terroir is French. It is derived from the root word for soil, yet the word does not mean soil alone. In the context of wine, terroir is the regional character of a wine originating at a particular place, and being produced by the actions of its people who are working with the place's grapevines to process their grapes in a local way. Summarized in the French phrase *goût de terroir*, the taste of place, the term captures the idea that both people and the Earth are tied together (Blij 1983; Van Leeuwen and Seguin 2006).

Many regions of the world have highly defined terroirs. Examples include the appellations within Bordeaux, Burgundy, Piedmonte, and along the Rhine and Mosel Rivers. Many areas of the New World have a short history of wine growing. In North America, the terroirs of California, Oregon, Washington, British Columbia, Ontario, and New York have been described, while regions like Idaho and Texas are just beginning to be documented. North Carolina has four official appellations, and more than 160 wineries/vineyards, yet North Carolina's terroirs are unknown to the world of wine, and it remains undocumented as a wine region in the Literature (Figure 7). The aim of this research is to determine primary zones for classifying North Carolina terroir, and to record the environmental elements of terroir by the states formal wine regions and vineyards.

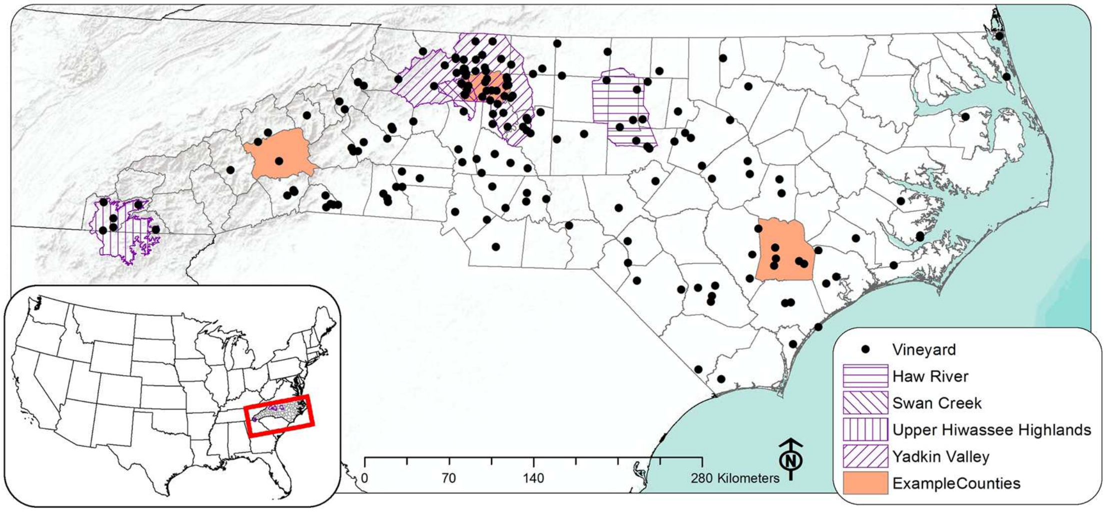

Figure 7. NC AVAs, Selected Counties, and Vineyards, January 2016,
Map Generated by John W. Nowlin

Literature Review

The process of defining terroirs involves multiple physical factors associated with topography, soil/geology, and climate, as well as local cultural practices. The factors interact in complex ways to produce a variety of unique assemblies (Vaudour 2002). Local variations in the physical environment can produce significantly different situations within a single grape growing region. The goal of a system of terroir is to capture the relevant variation. The granular unit of a system of terroir is termed the terroir unit. Once the physical terroirs of a wine growing region are spatially quantified into terroir units, the appellations and vineyards can be contrasted to illuminate differences in terroir. Terroir helps support the decisions made by the wine-grower/wine-maker when acquiring land/grapes, but it also has cultural, economic, and hedonic meaning. An objectively defined terroir unit provides a unit of measure with regard to wine character trials, from which local quality standards can be produced. In this way, terroir can provide a narrative to differentiate between wines in the market place. The narrative acts as a stamp of origin and provides value on which consumer/place preference can be constructed.

Terroir unit models are similar to capability/suitability models (Jones et al. 2004). The difference being that terroir models are primarily descriptive rather than predictive. Any assumptions of value assigned to a terroir are secondary to the function terroir serves to describe the physicality/cultural modality of a wine's origin. There is active discussion surrounding the theoretical granular units of terroir (Carbonneau et al. 2010), including the Natural Terroir Unit (NTU), the Terroir Basic Unit (TBU), and the Viticultural Terroir Unit (VTU). In all cases, the terroir units seek to define a homogeneity of physicality and/or mode of viticultural practice within a given area. The development of surfaces revealing the environmental character and the consideration of interrelationships between the surfaces and a place comes before the construction of terroir.

There are several climate-based indices used to compare wine growing regions. These indices include: frost free period (FFP), growing degree-day (GDD) (Amerine and Winkler 1944), Huglin Index (HI) (Huglin 1978), biologically effective degree day (BEDD) (Gladstones 1992), and growing season temperature (GST) (Jones et al. 2006). There are also some regionally important climate variables in North Carolina separating the state into distinct zones of grape species suitability. These include three low temperature thresholds. The mean annual number of decadal days below –22.2°C is a threshold for extreme cold resulting in vine damage for *V. vinifera*. Areas with three or more days per decade exceeding this threshold are unsuitable for *V. vinifera* (Wolf and Boyer 2003). PD is an existential threat to *V. vinifera*, usually killing the vine within three years. Two thresholds, annual days below –12.2°C and –9.4°C, relate to the overwintering of PD vectors such as the glassy-winged sharpshooter (*Homalodisca vitripennis* aka *Homalodisca coagulate*). Ordinal risk zones are delineated by the mean annual number of days below these thresholds (Sutton 2005).

The following climate-viticultural indices are intended to capture the ripening potential of a given area. The FFP is a measure of the average number of days between the last incidence of 0°C in Spring and the first incidence of 0°C in Fall. The GST is the mean temperature of the growing season. The GDD is a measure of heat accumulation over the growing period above 10°C. The HI sums the difference of the mean and maximum daily temperatures, and the BEDD modifies the GDD to limit temperature accumulation above 19°C. Common characteristics among these indices (in the Northern Hemisphere) are the use the date ranges from 1 April to 31 October, with the exception of the HI which uses 1 April to 30 September. Both the HI and BEDD use a coefficient to adjust for latitude/day-length (K), which increases with latitude. Hall and Jones (2010) reformulated K so that the same adjustment could be used in both HI and BEDD, modifying the effect to begin at 33.3 Degrees Latitude. BEDD has one more refinement, in that there is a Diurnal Temperature Range (DTR) adjustment; BEDD is adjusted up if the DTR is above 13°C, and down if the DTR is below 10°C.

While climate has a primary influence on terroir, soil has historically been a central feature. In the U.S., the USDA/NRCS Soil Series summarizes the variety of soil characteristics occurring in place. The Soil Series is locally described and documented at the county scale. The attributes derived from these surveys are aggregated into the

SSURGO database. Historically these soil attribute tables are joined to vector geometry to produce soil maps, but another option is the recently available gridded SSURGO (gSSURGO), which provides a raster based alternative for soil mapping. Communicating soil character at a high level of detail is difficult in short form since there are numerous soil characteristics. The Soil Series summarizes this complexity, but retains precision and multi-dimensionality. Since Soil Series may not be easy to compare from place to place, instead describing a soil by texture (e.g., percent of sand, silt, and clay) might be sufficient for developing general descriptions of terroir.

Materials and Methods

There are three sets of study areas in this project: 1) commercial vineyards, 2) AVAs, and 3) three North Carolina counties of viticultural importance. [These counties were chosen because they are the contemporary hearths of North Carolina viticulture in the Coastal Plain, the Piedmont, and the Mountains.] Delineation of the AVAs and vineyards as input for a GIS was performed manually, using legal statutes and definitions (27 C.F.R § Part 9), along with NAIP + ESRI World Imagery. Soil surfaces were derived using gSSURGO. Elevation was provided by a NED DEM 10M. Climate Values Maximum, Minimum, and Mean Temperature and Precipitation (TMin, TMax, TMean, and PPT) were taken from PRISM 1981-2014 monthly and daily (4km) surfaces. Surfaces referenced in regional extension documentation (Wolf and Boyer 2003; Wolf 2008), and GIS based site suitability studies were used to guide the inclusion of terroir factors useful for regional formation. In order to measure PDR, a modification was performed using Turner Sutton's temperature thresholds. The sum of the days below -

12.2°C plus the days below -9.4°C are reported as PDR. The values of four or less represent high risk while nine or more are low risk.

The factors were produced as raster surfaces, clipped by the study areas, and reported as annual means or, in the case of soil and physiographic province, as the dominant condition. The following factors were considered using the equations derived by previous researchers: 1) USDA/NRCS Soil Series and texture (for vineyards only), 2) area, 3) absolute elevation, 4) physiographic province, 5) mean annual number of days below mean decadal incidence of –22.2°C, 6) PDR, 7) frost free period (FFP), 8) growing degree-day (GDD), 9) growing season temperature (GST), 10) Huglin Index (HI), and 11) biologically effective degree day (BEDD). See Figure 8 for a visual abstract of the Methods. The algorithm chosen for quantifying terroir in this model was to separate the state into PDR zones, and then further separate those zones by Physiographic Region. Note that GDD, GST, HI, and BEDD climate indices were classified using the methods presented by Jones et al. (2010).

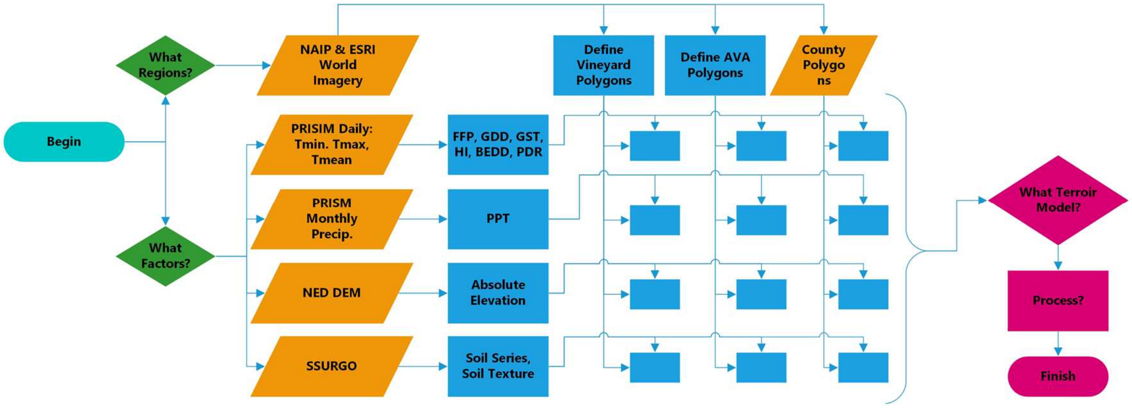

Figure 8. Modeling Process

Results and Discussion

The Appalachian Mountains and the Atlantic Ocean form the defining western and eastern boundaries of the state. With the prevailing northeast-southwest train of the mountains, there is a general increase in elevation from east and south to north and west. This separates the state into three primary physiographic provinces; from east to west these include the Coastal Plain, Piedmont and Mountains. Results are reported for three counties. Duplin County is the home of Duplin Winery the largest Muscadine winery in the world. Yadkin County is the center of the densest grouping of vineyards in the state. Buncombe County is the home of Biltmore Winery the most visited winery in the U.S. Also included are the state's four AVAs: Yadkin Valley, Haw River, Swan Creek and Upper Hiwassee Highlands. These are followed by a comprehensive group of North Carolina's commercial vineyards (Appendix A). North Carolina's vineyards and AVA's are primarily situated in the Northwest Piedmont, but there is a relatively even distribution from the Northern Mountains and Foothills, across the Piedmont, onto the Southeastern Coastal Plain. The results also show a pocket of vineyards in the far Western Mountains.

The state's vineyards vary in elevation from 2.2m to 1234.7m above sea level, and are generally wetter than most wine regions with annual precipitation between 992mm and 1728mm. Precipitation for NC's AVAs is also steadier throughout the year and October has typically been the driest month. The most important feature is the wide variety of climates represented by the state's commercial vineyards, with FFP from 166 to 268 days, GDD ranging from 1045 to 2660, GST ranging from 14.6 to 22.4, HI from

1504 to 3019, and BEGG ranging from 500 to 1998. There is also broad soil character heterogeneity, with sandier soils typical of the Coastal Plain, clay rich soils in the Piedmont, and loamy mixes of extreme variability in the Mountains.

Conclusions

[This research has determined that] North Carolina vineyards are situated at a variety of elevations, on a large variety of soils, in a humid and, with a few exceptions, mostly warm-to-hot wine growing region. The incorporation of regional extension guidance has helped to define the soft boundary that delineates the centers of *V. vinifera*/Hybrid suitability from Muscadine suitability. The group of vineyards in and around the Yadkin Valley AVA and the Swan Creek AVA form the core of a system of terroir for the *V. vinifera* and hybrid grape regions of the state, while those in the Lower Piedmont and Coastal Plain guide terroir descriptions for the M. rotundafolia growing areas. The area of intermediate PD risk along the Interstate 85 corridor including the Haw River AVA represents a challenge for developing a meaningful terroir system that adheres to species delineated zones.

The creation of the general terroir zones is complete, but the act of choosing the particular thresholds between the relevant environmental parameters will form the core of the next step in this research. Multi-factor terroir units have been put to use in the literature. In order to create a cogent system of terroir quantification for North Carolina with its areas specializing in Muscadines, juxtaposed to those growing *V. vinifera*, something new will be needed. In lieu of politicizing the formation of the terroir system and forcing it to follow political boundaries, an approach that allows the system to be guided by the physical situation will be given high priority in this research.

The goals of the terroir system are to definitively describe the differences among viticultural environments in the state by using factors that meaningfully capture variations among vineyard sites. The use of the standardized system of classifying the climate indices into ordinal rankings such as cool, warm, and hot will undoubtedly play a role, as will factors of soil, or geology. Future work will also include topographical factors such as elevation, aspect and relative topographic position.

CHAPTER III

VITICULTURAL SITE SELECTION: TESTING THE EFFECTIVENESS OF NORTH CAROLINA’S COMMERCIAL VINEYARDS

This chapter is being reviewed for publication as of Aug 17, 2017

Nowlin, J, R Bunch, and G V Jones. "Viticultural Site Selection: Testing the Effectiveness of North Carolina’s Commercial Vineyards." Journal of Applied Geography. submitted for publication 06 Aug 2017

Abstract

Growing grapes to make wine is financially risky. The most important factor in the success of a vineyard is site selection. Careful consideration of all relevant environmental characteristics so that the selected variety of grape can be grown successfully will benefit grape growers. Climate, topography and soil are the primary environmental suitability factors for growing grapes. This research addresses a question which is fundamentally geographic; how well have North Carolina Winegrowers performed at vineyard site selection? Did they plant vineyards in the appropriate climates, in the appropriate topographic situations, and on appropriate soils to be agriculturally viable long term? A physical site suitability model was constructed using the advice provided by the North Carolina Winegrape Growers Guide (NCWGG) to address these questions. The site selection guidance in the NCWGG was used to construct the physical site suitability model. Using a Geographic Information System (GIS), the sites of North Carolina’s publicly listed commercial vineyards were geolocated as point features. Using points along with aerial imagery (ESRI Satellite Image compilation, and NAIP Living Atlas Surface accessed between 2013 and 2016), vineyards were located and digitized as polygon features. North Carolina's vineyard site selection choices were examined by taking the output surfaces from the physical site selection model and clipping them using the vineyard boundary polygons. The results show that 82.68% of the area falling within North Carolina vineyards passed the physical site selection requirements listed in CES.

Keywords: GIS; vineyard; site selection; viticulture; site suitability; capability model; geospatial model

Introduction

There are many economic risks associated with agriculture in general and viticulture in particular, especially when it comes to grape production in North Carolina. The primary risks to viticulture in North Carolina are fundamentally climatological. First, there is a long warm humid growing season which promotes fungal diseases especially in varieties of *V. vinifera* and many French-American hybrids (Wolf et al. 2011). Second, in portions of the state, the winter minimums are sometimes cold enough to kill vine wood of *V. vinifera* (Pool et al. 1992; Wolf and Boyer 2003). Third, North Carolina experiences the risk of tropical cyclone events originating from both the Atlantic and the Gulf of Mexico and these high precipitation events during harvest can ruin an otherwise healthy crop. Fourth, the winters in some parts of the state are so mild that PD vectors can survive over winter; PD is caused by a xylem clogging bacterium which is often fatal for *V. vinifera* and many French-American hybrids. Finally, the state experiences late spring frosts which, in some of the coldest years, have been severe enough to damage vines. Even in the typical spring, frosts have limited the profitability of growing varieties which emerge early and are low in yield on secondary buds and non-yielding on tertiary buds such as Chardonnay.

North Carolina is a state located in the Southeastern U.S. which is bordered to the east by the Atlantic Ocean and to the West by the Appalachian Mountains. In the most basic sense, North Carolina can be understood as having three physiographic regions, ordered from east to west. These regions are commonly referred to as the Coastal Plain, the Piedmont, and the Mountains (Figure 9). Based on a survey completed in December 2016, it is apparent that vineyards are distributed across the state, with the densest cluster being located in the Yadkin River Valley (Nowlin and Bunch 2016b). The state has five official American Viticultural Areas (AVAs) and two of them are shared with other states. These areas include The Yadkin Valley AVA (CFR Title 27 § Part 9.174 2002), The Swan Creek AVA (CFR Title 27 § Part 9.211 2008), The Haw River Valley AVA (CFR Title 27 § Part 9.214 2009), the Upper Hiwassee Highlands AVA which is shared with Georgia (CFR Title 27 § Part 9.234 2014), and the Appalachian High Country AVA (CFR Title 27 § Part 9.260 2016), which is shared with Tennessee and Virginia (Nowlin and Bunch 2016b).

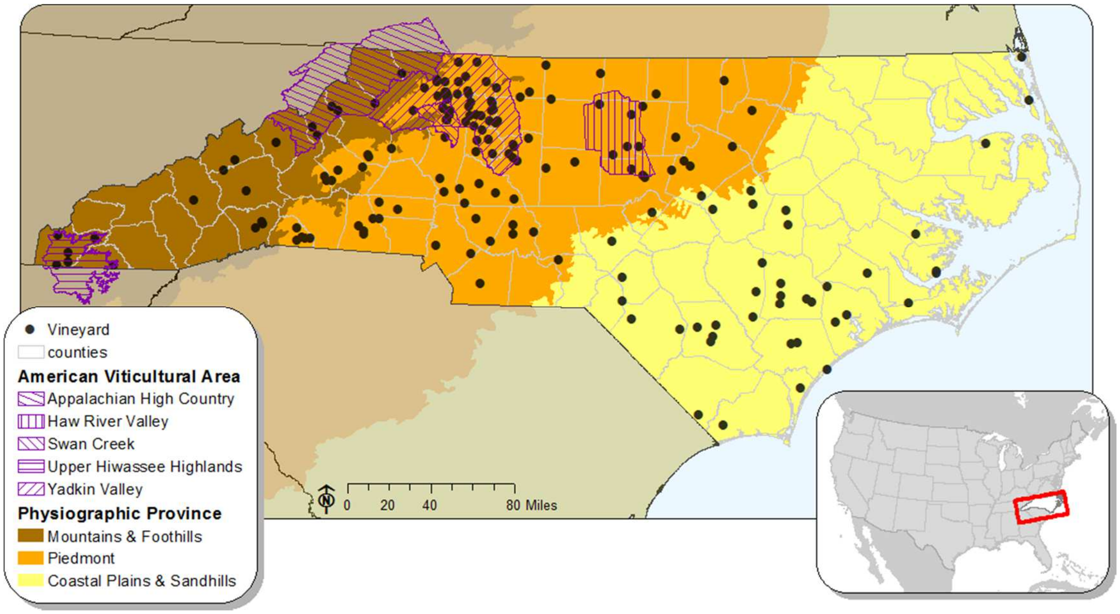

Figure 9. North Carolina Physiographic Regions and American Viticultural Areas as of December 2016, Map Generated by John W. Nowlin

A 1994 estimate for the cost of establishment of a typical four hectares (10 acre) Chardonnay vineyard on a good site in Virginia was $13,950 per hectare ($5,645 per acre) in the first year, rising to $24,260 per hectare ($9,818 per acre) in the 3rd year (Wolf et al. 1995). This is before considering a profit of $5,683 per hectare ($2,300 per acre) of harvested grapes in the third year. The same estimate showed that, including the cost of establishment, recovery of the initial investment took between seven and ten years, after which, the vineyard had a net annual return of $3,961 per hectare ($1,603 per acre). A similar 2005 estimation for establishing a four-hectare (10 acre) Chardonnay vineyard on a good site in North Carolina reported typical costs of $31,816 per hectare ($12,876 per acre) after three years (Poling 2007). In 2016, the installation cost for a typical vineyard was estimated at $49,421 per hectare ($20,000 per acre; Hobson Jr., F.W., owner of Rag Apple Lassie Vineyards). The estimate did not account for the costs associated with land preparation, mowing, herbicides, pesticides, fungicides, soil nutrient adjustment, or labor in the first three years. None of the estimates account for the cost of purchasing the land or performing a host of often needed land preparations, such as: forest removal, fumigation, multi-year cover establishment to modify soil pathogens, or deep ripping before vineyard installation (Nowlin 2013).

The above topics and others form a long list of risks presented to viticulture by North Carolina's environment. The results of some of these risks are financially devastating—even so onerous as to result in the total loss of all vines in the vineyard. These risks highlight the financial commitment associated with establishing a vineyard in this region. On top of that, the vineyard is typically approaching full production at the 5th year mark, meaning that it takes time to recoup the initial investment, and while vines are expected to last about 30 years, they can be severely limited in their average production capacity by the aforementioned risks. Vineyard site selection is the most important factor when attempting to minimize these and other environmental risks (Wolf and Boyer 2003; Poling and Spayd 2015).

The North Carolina Cooperative Extension Service (CES) is tasked with providing agricultural guidance to farmers. The state has invested in viticultural specialists and research with the goal of providing advice to the viticultural industry. The primary document is produced by the CES to supply advice to winegrowers in the NCWGG (Poling 2007; Poling and Spayd 2015). The document is a modified version of an earlier and broader regional document known as the Mid-Atlantic Grape Growers

Guide (Wolf and Poling 1995). Virginia's CES has also produced some widely referenced regional publications that provide specific advice about site selection (Wolf and Boyer 2003). Currently, the most comprehensive guide tailored to the region is the Wine Grape Production Guide for Eastern North America (Wolf 2008). In North Carolina, these documents form the basis of government guidance to the wine industry on vineyard establishment and operation. For the purposes of this research the primary document under consideration within the NCWGG is Chapter 4: Site Selection (Poling and Spayd 2015).

The aim of this study is to determine if North Carolina vineyards have followed the advice given by the CES. The questions asked in pursuit of this objective are related to the geography of the wine industry, namely the location of the vineyards. Have North Carolina's vineyards been established within areas which conform to the government advice on site selection? If not, at what rate do they fail to conform? What is the most likely way vineyard location fails to conform to this advice? At what rates to vineyard sites fail to conform to multiple factors of advice? The source document used as the standard of CES advice is Chapter 4: Site Selection of the NCWGG. Modeling the CES advice with a geospatial model is an effective means of answering these questions.

Literature Review

In North Carolina, no research has compared the selection of vineyard sites to advice given by the state's extension documentation. Local cooperative agents and state viticulturists may have a general sense as to why sites are chosen, but there have been no published investigations quantifying the adoption rate of vineyard site selection advice.

Sara Spayd, the past president of the American Society of Enologists and Viticulturists and the recently retired North Carolina State Viticulturist (2016), has stated that many locations she has run across were chosen on the basis of non-environmental factors. She explained that it is often the case that someone decided to plant grapes on land already owned, often a long-held family farm, rather than seeking the most suitable land (personal communication 2015). One problem associated with this behavior is that a poor site location can compromise the entire vineyard operation, leading to the failure of the business and the loss of the long-held family farm. For many North Carolinian grape growers, the investment to establish the vineyard might come from savings that could have otherwise been used in retirement.

Some vineyard operators in North Carolina have made good site selection choices. Nowlin (2013) and Nowlin and Bunch (2016a), for example, outlined a GIS based site suitability model for Rockingham County, North Carolina that classified land on a spectrum of suitability for *V. vinifera*. The resolution of this model was at 10-meter resolution, which was fine enough for 40 pixels to fit within a one-acre vineyard. The model included four physical realms (with factors): Topography (Absolute Elevation, Relative Elevation, Slope and Aspect), Soil (Texture, pH, Depth, Available Water Capacity, and Drainage), Land Cover (classified as forested, cleared, or failing), and Climate (Absolute Annual Minimum Temperature, Mean Annual Precipitation, PD risk, and Spring Frost Risk). The factors were classified and weighted using the advice of regional (Virginia and North Carolina) extension documentation and then summed to reveal viticultural site suitability. The results displayed unsuitable areas that accounted for approximately 37% of the county's area and classified the remaining area on a spectrum of suitability. Rockingham County had five vineyards that were found to be located in good areas as predicted by the site suitability model. None of these vineyards were planted on unsuitable land, which suggests that these vineyards were established in accordance with acceptable standards. This evidence is enough to say something about five vineyards in one county, but the other hundred-and-fifty plus commercial vineyards in the state have not been studied as a group in a similar manner. It is expected that there will be some vineyards and portions of vineyards which made site selection choices which are contrary to the advice given in the literature; but, where are they and what percentage of vineyard area does this represent?

Based on the CES advice, the factors of climate, soil, and topography can be used in modeling site capability for grape production. The available data for each of these realms tends to vary in resolution with climate surfaces being lower in resolution than soil, and with soil surfaces being less precise than elevation. While they are all interconnected, they are distinct surfaces, and need to be understood separately. Background on these factors, including specific metrics will be discussed independently.

Climate

North Carolina is an example of a wine region in a humid sub-tropical climate (aka Cfa). This is not typical when compared to most of the world's wine regions which are found in Mediterranean or marine west coast climates (Köppen 1936; Peel et al 2007). North Carolina shares more climatological resemblance to wine regions of Uruguay and Brazil than typical wine growing in Spain or Italy. Significant portions of the United States, Argentina, Uruguay, Brazil, China, and Australia share the humid sub-tropical climate zone, with smaller portions being present in Eastern Mexico, Peru, the southeast coast of South Africa, on the Island of Madagascar, within a set of areas north of the Mediterranean, around the Black Sea, in the Caucasus Mountains, on the Island of Taiwan, and the southern half of Japan (Figure 10). A few well-known wine regions in this zone include Southeastern Australia's Hunter Valley, the vineyards of Brazil's southern state of Rio Grande So Sul and Southern Uruguay's Canelones Department, just north of the capital city of Montevideo.

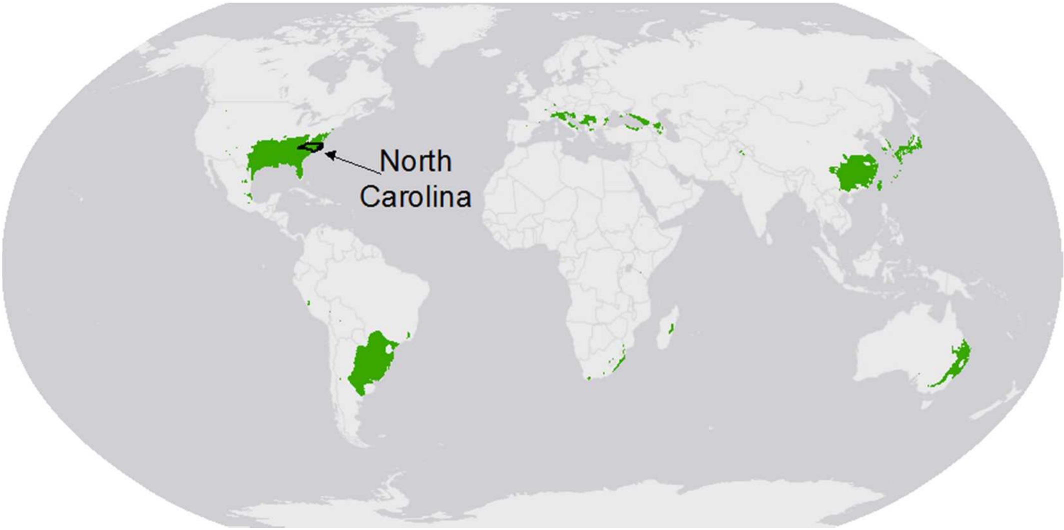

Figure 10. Current Worldwide Distribution of the Updated Humid Sub-Tropical Köppen Climate Zone, 1923 to 1993, (Peel et al. 2007), Map Generated by John W. Nowlin

While the Köppen climate characterization places North Carolina broadly within worldwide climate types, the climate measures assessed in this research relate to temperatures or heat accumulation in the growing season, extreme cold, length of the growing season, and PDR. Each of these measures are very important limiting factors for winegrape production in the region. Heat accumulation and mean temperature indices referenced were growing degree-days (GDD) and Mean July temperature (MJT) (Mean January Temperature in the Southern Hemisphere). GDD is a reflection of growing season heat accumulated above 0°C (50°F) from the beginning of April to the end of October. This metric has been widely reported in the literature and was famously classified into ordinal classes (Amerine and Winkler 1944) known as Winkler Regions for California. This was further updated by Jones et al. (2010) and Anderson et al. (2012) to account for other regions worldwide, for lower and upper limits not originally specified, and a division of Region I into two classes (Table 1).

Table 1. Growing Degree-Days, 1981 to 2014, Classified into Updated Winkler Regions (Anderson et al. 2012; Jones et al. 2010)

Growing Degree-Days (10°C base)	Winkler Regions
< 850	Too Cold
851 to 1111	Region Ia
1112 to 1389	Region Ib
1390 to 1667	Region II
1668 to 1944	Region III
1945 to 2222	Region IV
2223 to 2700	Region V
> 2701	Too Hot

MJT is a measure of the warmth of the growing season (Table 2) with values that are too cool not allowing the fruit to ripen optimally and extreme heat causing the vine to shut off respiration and photosynthesis, ultimately consuming the sugars in the grape instead of allowing them to accumulate (Smart and Dry 1980).

Table 2. July Mean Temperature, 1981 to 2014, Classified by Smart and Dry (1980), with the Addition of Two Hotter Classes Using the Same Class Intervals

July Mean Temperature (°C)	Class
<= 17	Cold
17 to 19	Cool
19 to 21	Warm
21 to 23	Hot
23 to 25	Very Hot
25 to 27	Exceptionally Hot
>= 27	Too Hot for *V. Vinifera*

In Virginia, Wolf and Boyer (2003) assessed extreme cold risk using the decadal incidence of vine wood damaging cold events; they defined the risk in terms of the count of days per decade that are ≤ -22.2°C (-8°F). Three or more days per decade was considered high risk. A conservative measure for the growing season length used in Virginia (Wolf and Boyer 2003) is the frost-free period. The NCWGG states that the growing season should be at least 165 days, and muscadines require 200 days. Using these two facts, a classification of growing season length should resemble the one presented in Table 3.

Table 3. Frost Free Period, 1981 to 2014, 10-Day Interval Classes (After 170 Days), with Ordinal Terms

Frost-Free Period (days)	Class
< 165	Very Short
166 - 170	Short
171 - 180	Intermediate
181 - 190	Sufficient for Most *V. vinifera* Varieties
191 - 200	Long
201 - 210	Very Long; Sufficient for Most Muscadine Varieties
> 211	Extremely Long

PD is a plant disease cause by *Xylella fastidiosa*, a bacterium which clogs the xylem of the grapevine, producing water stress. The disease is usually fatal to *V. vinifera* and most French American hybrid grapes. The disease is known to be spread by insects like the Glassy Winged Sharpshooter and there are many host plants found across North Carolina. One California based study found many plants which act as hosts for PD, from Oleander to Bermuda Grass to wild grapes which are also common in North Carolina (Rodrigo 2012). Since most bunch grapes are not PD resistant, the CES guidance suggests avoiding areas which are prone to the disease. The problem areas have been shown to follow a geographic pattern that closely follows two sets of temperature thresholds. Areas of very high, high, medium, and low risk are shown to be separated by the number of days where winter minimum temperatures occur for 3, 4, or 5 days ≤ -9.4°C (15°F) and also 1, 2, or 3 days ≤ -12.2°C (10°F). These two sets of temperature thresholds either predict the likelihood for the overwintering of the disease vectors or possibly the killing of the bacterium itself. Turner Sutton published several PD maps based on these two thresholds (Sutton 2005; Figure 11 and Figure 12).

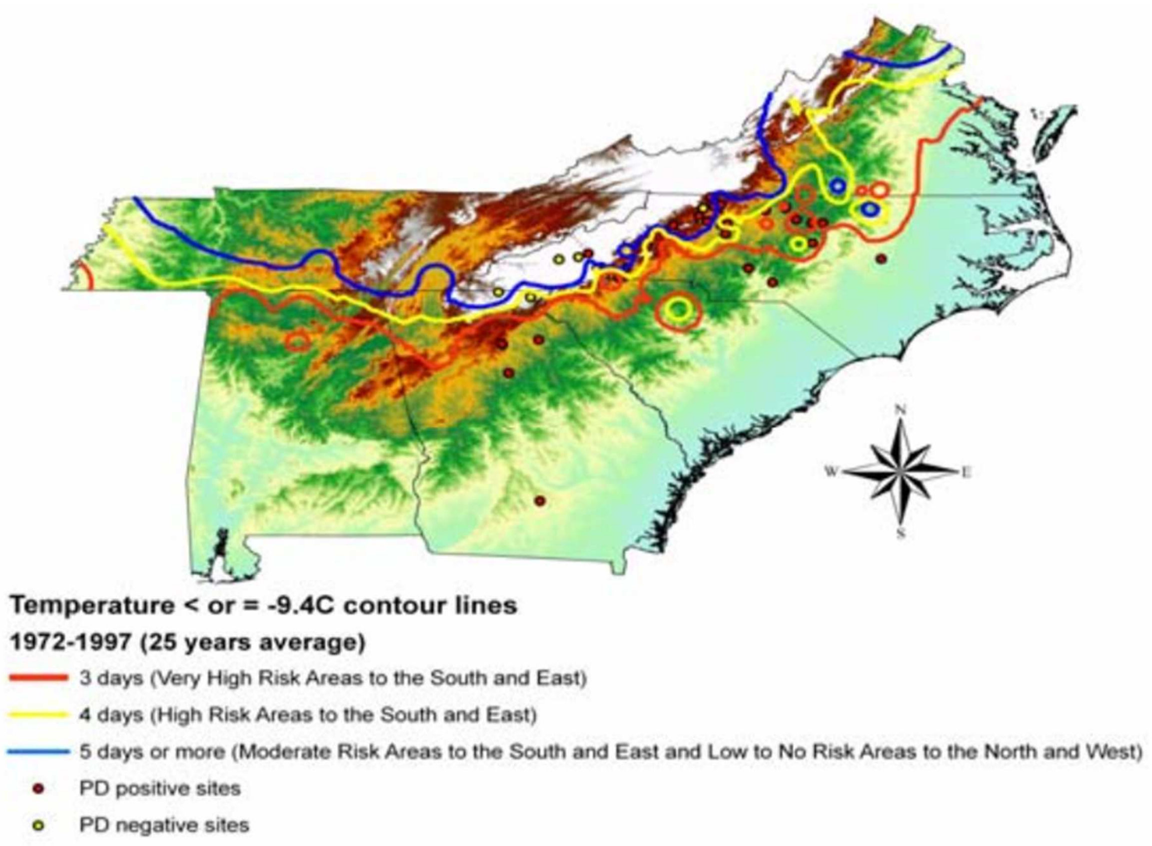

Figure 11. Pierce's Disease Risk Zones for the Southeastern U.S. Based on Annual Number of Days Below -9.4°C, 1972-1997, 25-year Mean, Map from Sutton et al. (2005)

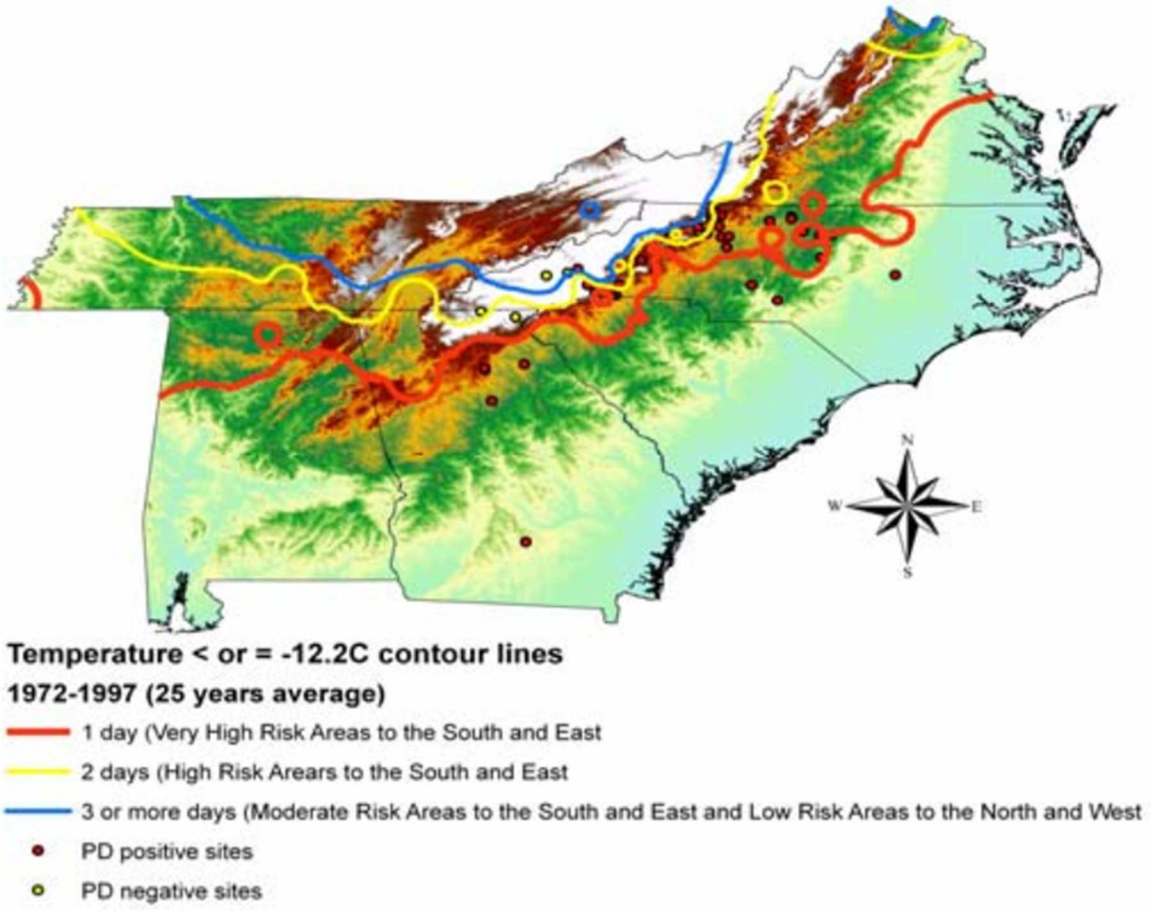

Figure 12. Pierce's Disease Risk Zones for the Southeastern U.S. Based on Annual Number of Days Below -12.2°C, 1972-1997, 25-year Mean, Map from Sutton et al. (2005)

Topography

Topography is important because of its effect on local climate. The topographic factors cited in the CES documentation include measures of absolute and relative elevation, slope and aspect. Absolute elevation is important because of the nature of the atmospheric lapse rate. The rate generally means that with an increase in elevation there is a decrease in temperature, averaging 6.5°C per 1000 meters. Extremely high elevation sites are not suitable because of their short growing seasons, extreme cold, and high advective frost risk. North Carolina has a broad range of elevations, beginning at sea level and rising to the highest point in the U.S. east of the Mississippi River, which is 2037 meters (6684 ft.) on Mt. Mitchell. Absolute elevations ≥ 610 meters (2,000 ft.) are cited as being high risk in the NCWGG, due to the very cold conditions (Poling 2007; Poling and Spayd 2015). In calm, clear conditions, radiative frosts cause severe risks, especially in the spring after bud break. To reduce the impact on vineyards, being located above the valley floor at a site with prominent relative elevation is a way to ensure that cold air can drain away from the vineyard. Like water, air is a fluid albeit much less dense and much deeper at the earth's surface. Cold air typically drains downhill on cool, calm nights. There can be pools of cold air behind structures, or even rows of vegetation like trees, bushes, and/or fence rows, this cold air drainage roughly follows the drainage network of the landscape (Poling and Spayd 2015; Figure 13).

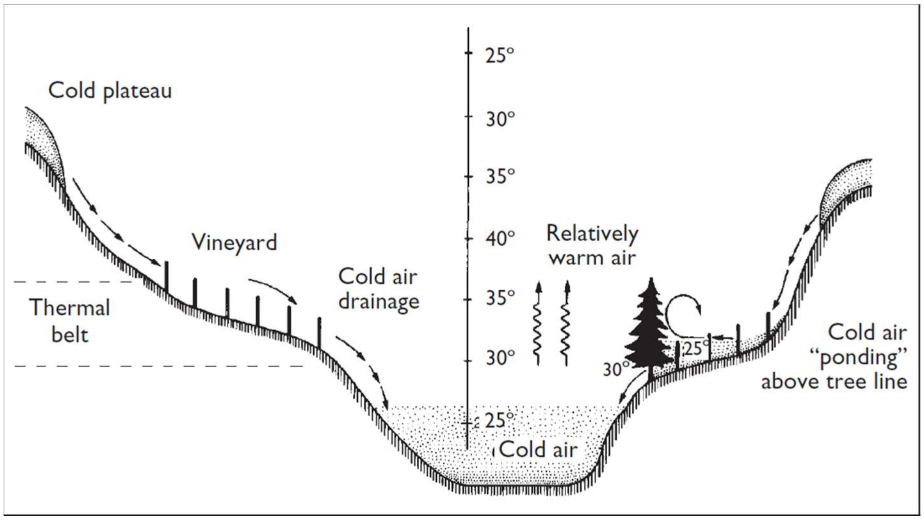

Figure 13. Cold Air Drainage, image from NCWGG (Poling and Spayd 2015)

There are a few spatial concepts which can be used to understand the relationship between a vineyard location and its potential for cold air drainage. These concepts include relative elevation, topographic prominence, and topographic position. The relationship between the elevation of a place compared to the elevations of the surrounding area can be seen as the relative elevation. A ratio of these elevations is a metric describing the local topographic prominence. The major complicating factor influencing the interpretation of topographic prominence is the notion of scale. If the vineyard is on a small hill within a large valley the topographic prominence will be high locally. If you look only at the scale of the valley floor, however, it will be low if you extend the horizontal scale to include the ridges defining the valley. While the physics of cold air drainage may be understood in a closed simple system, the complexity of terrain across a broad area such as a state makes the choice of a common scale even more problematic. Andrew D. Weiss (2001) of the Nature Conservancy, developed a method of classifying slope position focally by utilizing a series of three annuli at three distances and taking the mean focal Z score of topographic position, then classifying the Z score surface into slope position (Table 4).

Table 4. Weiss Topographic Position Index, Slope Position
Using 2016 National Elevation Dataset

Slope Position	Z score
Ridge	> + 1 STDEV
Upper Slope Position	> 0.5 STDEV ≤ 1 STDEV
Middle or Flat Slope Position	≥ -0.5 STDEV, ≤ 0.5 STDEV
Lower Slope Position	≤ -1.0 STDEV, < 0.5 STDEV
Valleys	< -1.0 STDEV

Slope, a measure of the inclination of the land, is an important practical consideration especially when taking into account that a tractor can easily turn over or slip on steep slopes. Another consideration of slope relates to sustainability. Soil erosion, for example, becomes a problem in regions where rainfall rates and slope are high. The NCWGG suggests that vineyard sites not exceed the 15% gradient threshold. Aspect, the cardinal-ordinal direction of the slope (East, West, North, South—Northeast, Southeast, Southwest, and Northwest), is often expressed in degrees from North (clockwise). Aspect is important to the local climate of the vineyard because it relates to the orientation of the slope in relation to the seasonal/diurnal relationship to the sun's rays. In this way, aspect can impact the insolation potential of the vine. For example, in the Northern Hemisphere, a facet of land might be oriented to the South, where it would have warmer days because of the more direct angle of sunlight and the greater insolation incident along each unit area. If oriented to the East, it would receive the first sunlight in the morning which might burn off the dew early, a good way to lower fungal disease pressure. If oriented North, the area would stay cooler in the spring longer, delaying bud break, which could be useful in a Chardonnay vineyard since Chardonnay is one of the first varieties to break bud in the spring. Delaying this developmental milestone can lower the risk that a killing frost will damage the green shoots, which has happened in several recent years (Table 5), especially in parts of the Upper Piedmont north and west of Greensboro.

Table 5. Recent Late Spring Frosts Occurring After Warm Periods (Preceding 21-Day Running Mean > 60°F) after April 7th, Recorded at the GSO Airport in Greensboro, NC

Date	Warm Period: Average Temperature °C (°F)	Daily Low Temperature °C (°F)
4/20/1988	21.1 (70)	-1.1 (30)
4/12/1989	16.8 (62.4)	-1.7 (29)
4/8/1990	16.6 (61.9)	-2.2 (28)
4/12/1990	17.1 (62.7)	-1.1 (30)
4/10/1997	19.5 (67.2)	-1.1 (30)
4/7/2002	17.3 (63.2)	-1.1 (30)
4/18/2001	20.6 (69.1)	0 (32)
4/19/2001	20.6 (69)	-0.6 (31)
4/7/2007	21.7 (71)	-1.1 (30)
4/8/2007	22.2 (71.9)	-3.8 (25)
4/16/2014	20.7 (69.3)	-1.1 (30)
4/10/2016	18.8 (65.8)	-1.7 (29)

Soil

Soil is an important set of factors in vineyard suitability. It provides the basic plant nutrients, access to water, and is the anchoring medium for the roots. The three soil factors which are emphasized in the CES documentation are soil drainage class, soil depth, and fertility. There is no substitute for on-site soil samples and inspection via soil pits and testing of infiltration rates, however, formal USDA-NRCS maintained soil surveys provide a suitable alternative for broad generalizations over large areas. With the high average annual precipitation rates across North Carolina often 1000 to 1300 mm (39.4 to 51.2 inches) annually, soil drainage is important both for vine health and to reduce plant available water so as not to encourage over-vigor, which can be a problem in the region. Soils should be at least “Moderately Well Drained” and at least 76.2 cm (30 in) deep. Fertility also contributes to over-vigor, with highly fertile soils tending to produce vines that put most of their energy into vegetative growth, not fruit production. This is a problem because these vines need continual hedging, exhibit reduced airflow due to excessive shoot growth, and have reduced light infiltration due to an overabundance of leaves. This results in higher risk for fungal diseases and an over-emphasis on making leaves, and with less sunlight on the fruit it reduces the proper balance of flavor and volatile compounds important for desirable fruit and wine aromas.

Methods

A GIS based physical capability model was constructed using the site selection guidance from Chapter 4 of the NCWGG (Poling and Spayd 2015). Capability in this sense refers to a bivariate pass/fail test. A gridded raster surface was formed for each factor. The data sources for these factors were organized into three groups: climate, soil, and topography. New methods were created where no methodology could be gleaned from existing viticulture sources. This is especially relevant to surfaces of relative topographic position and PDR.

The data source for climate layers was the PRISM Climate Group daily data (2016; Daly et al. 2000; Daly et al. 2008; Daly et al. 2012) from between 1981 – 2014 at 4km resolution. Daily minimum, maximum, and mean temperature surfaces were produced for a time period spanning over 33 years (33 years x 365 days x 3 metrics = 36,135 maps). Portions of the year are used from this set to compile: growing degree-day, mean July temperature, frost-free period, extreme cold risk, and PDR, and to classify those layers by capability (pass/fail) as follows:

GDD – Growing degree-days were calculated by summing all daily mean temperatures over 10°C (50°F) between 1 Apr and 31 Oct, and failing those below Winkler Region Ia, which is less than 851 GDD or those above Winkler Region V which is greater than 2700 GDD.

MJT – Mean July temperatures were failed if the mean was <= 17°C or >=27° C. The NCWGG only specifically cites three classes for MJT, including: <21°C (warm), 21°C to 23°C (hot), and > 23°C (very hot) while Smart and Dry (1980), also included <17°C (cold) and 17°C to 19°C (cool). Because the Smart and Dry index was developed for Australia and North Carolina is more humid, and therefore averages higher diurnal mean temperatures, we have included two more classes at the top of the MJT scale termed 25°C to 27°C (extremely hot) and >=27°C (muscadines only). The extra classes in this modified Smart and Dry MJT index reveal the distribution of warm temperatures more precisely in the eastern portion of the state.

FFP – The growing season length was calculated using the mean Frost-Free Period, which is the average span of days between the last vernal frost and the first autumnal frost. Those regions with less than 165 days FFP were failed.

ECR – Extreme cold risk was considered by counting the mean number of days per decade with an incidence of ≤ -22.2°C (-8°F), and failing those with ≥ 3 days. There appears to be little risk for absolute winter low temperatures outside of the mountains.

PDR – The risk presented by PD was considered by summing the annual count of days at or below Turner Sutton's two PDR thresholds. These include the mean annual incidence of days ≤ -9.4°C (15°F) with those ≤ -12.2°C (10°F). Once those two layers were summed, there is a single pattern that can summarize and help visualize the general risk. Those areas with ≤ four days were considered failing.

The data source for topography was the most recent available National Elevation Dataset (NED) 10m raster digital elevation models (DEM) accessible from the Natural Resources Conservation Service - Geospatial Data Gateway as of May 1st, 2016. These were used to compile the Topographic Position Index, Slope, and Aspect, along with classifying those layers by capability (pass/fail) as follows:

TPI – Topographic Position Index was used to classify cold air drainage risk zones, such that the mean Z score across the combined TPI annulus ranges below Z scores representing -1 standard deviations were failed. In accordance with Weiss's (2001) "Slope Position" methodology, this represents the failure of areas with low relative elevation, also known as low topographic prominence. Three annuli of the following radii were used: close = 50 to 200 meters, medium = 500 to 650 meters, and far = 1850 to 2000 meters. These ranges were based on a survey of regional landforms using the DEM and measuring from ridge to ridge across drainages at different local scales.

Slope – Slopes above 15% were failed due to the risk of soil loss from erosion and danger of operating heavy machinery without the danger of slipping or toppling over.

Aspect – Aspects between due South (180°) and due West (270°) were failed due to the potential to break bud too early in the spring and/or lead to winter injury due to lack of cold hardening because of warmth in the winter.

The data source for soil was the USDA – NRCS gSSURGO. This dataset is at 10-meter resolution. Maps were compiled for depth to restrictive layer, drainage class, and percent silt. These three soil factor layers were the classified by capability (pass/fail) as follows:

Depth – Soil depths < 76.2 cm (30 in) were failed.

Drainage – Soil Drainage Classes that were not at least "Moderately Well Drained" were failed.

Percent Silt – Since silt is a good measure in North Carolina for fertility it was used as a proxy, soils with > 50% silt were failed.

A raster to vector function was used to create a set of points for each 10m cell centroid from the DEM falling within the vineyard boundaries of every commercial vineyard that could be located on aerial imagery, within North Carolina. This resulted in 58,124 cells falling within 160 vineyards. These points were used to sample all capability factor surfaces. The results are aggregated by vineyard in Appendix B. This method easily organized the results by cell, vineyard, and factor and made it possible to compare what factors failed in combinations with other factors.

While all failing cells are reported on all of the factors listed, in the end it was determined that the PDR and Aspect failures would not be used in the final capability model. The PDR failing zone will not be used because there are PD resistant grape varieties that can be grown in the PDR failing area. The aspect will not be used, because there was no suitable way given in the NCWGG to assess the degree of aspect effect. This makes its failure somewhat ambiguous, while it is cited and reported due to its presence in the NCWGG, it is not clear from that document at what slope the aspect begins to matter. Also, because there will be varieties which can prosper on the aspects in the failing range, this surface was ultimately deemed to be unnecessarily restrictive.

Results

The research produced a geospatial database, maps for each surface, and a final capability map that categorizes the entire state into pass/fail areas. The data and map will be useful for site selection of future vineyard operations by bridging the gap between extension guidance and practice. Using the surfaces produced by this model along with the boundaries of publicly listed commercial vineyards in the state, North Carolina's vineyard site selection choices have been assessed for suitability. In addition, the model produced visual representation(s) of CES advice. This layer is useful as a quick reference for those seeking to establish vineyards and the parties which advise them such as the state level extension agencies, county extension agents, and members of the North Carolina Winegrowers Association.

Climate Results

The results for GDD (Figure 14) revealed that a large portion of the state falls within Winkler Region V, including all of the Haw River AVA and a small portion of the southeast corner of the Yadkin Valley AVA. The majority of the Yadkin Valley and all of the Swan Creek AVA falls in Winkler Region IV. As for the mountain region AVAs, the Upper Hiwassee Highlands AVA is primarily Region III and IV, while the Appalachian High Country AVA falls within modified Winkler Regions Ia, Ib, and II. This means that North Carolina has AVAs spanning much of the total GDD index range.

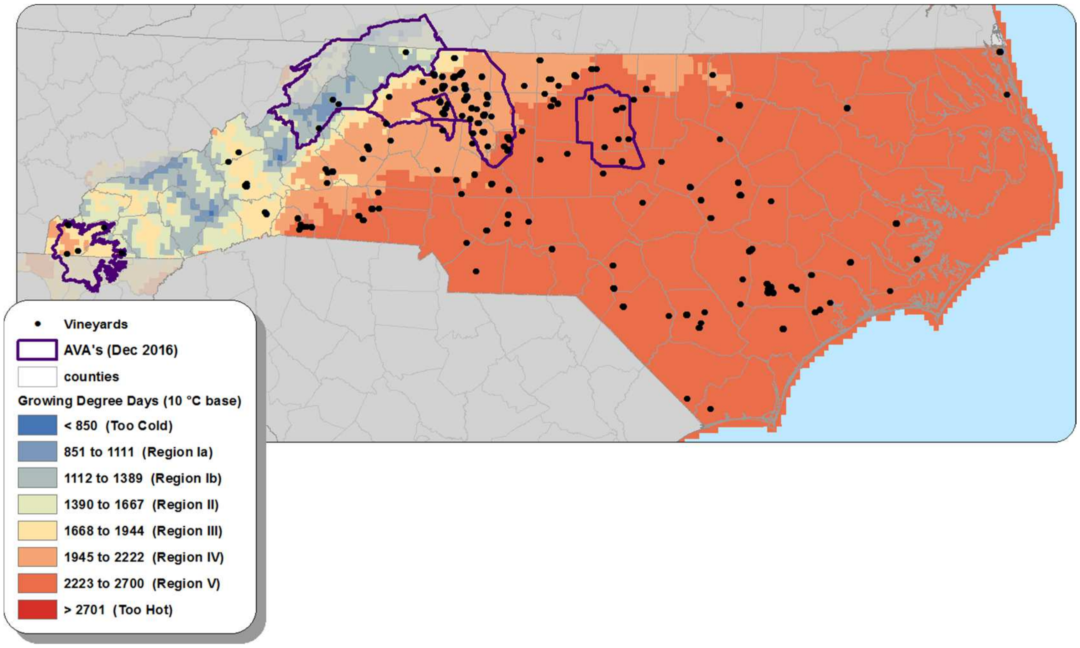

Figure 14. Mean Growing Degree-Days in North Carolina (1981 to 2014) (Amerine and Winkler 1944), Map Generated by John W. Nowlin

As for the MJT results, the pattern is very similar to that of GDD with a clear northwest to southeast pattern of increasing temperatures (Figure 15). The impact of humidity on MJT becomes apparent. North Carolina's relatively high humidity climate results in warmer night temperatures which increases the mean diurnal temperatures far higher than in growing regions with a dry warm season growing climate and higher diurnal temperature range. The January climates in much of Australia's wine regions are a case in point, and where the MJT index was created.

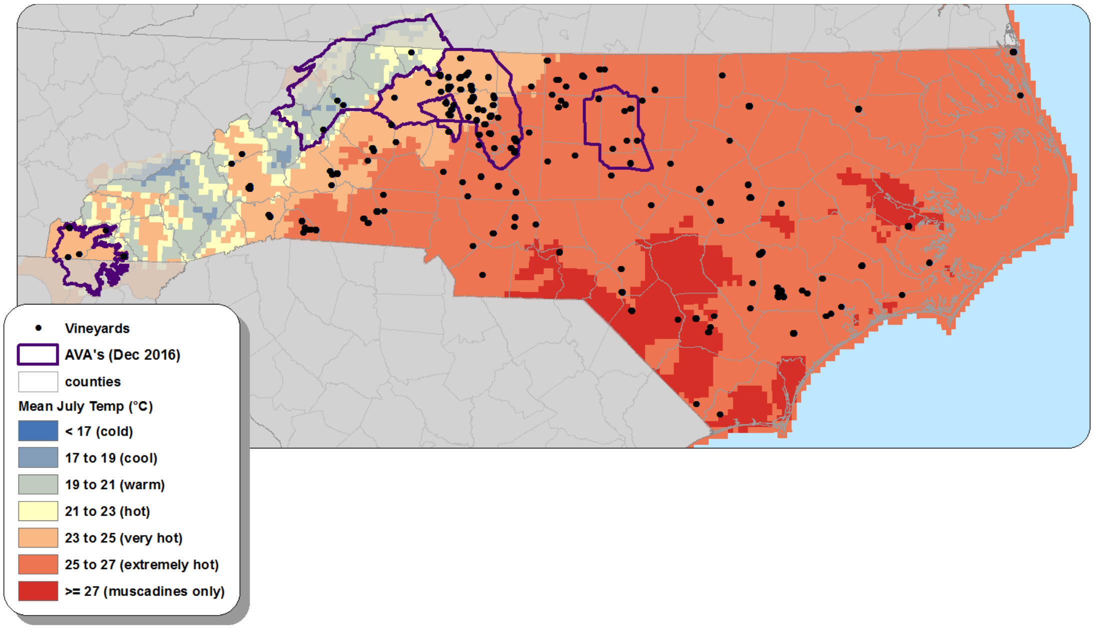

Figure 15. Mean July Temperature in North Carolina (1981 to 2014),
author's Adaptation of Smart and Dry (1980),
Map Generated by John W. Nowlin

The pattern of annual continuous frost-free days shows that there is a general northwest to southeast gradient, varying from below 165 days in the highest portions of the Appalachian Mountains to a nearly year-round growing season on the coastal barrier islands of the Outer Banks (Figure 16). The only AVA with an FFP which severely limits grape varietal is the Appalachian High Country.

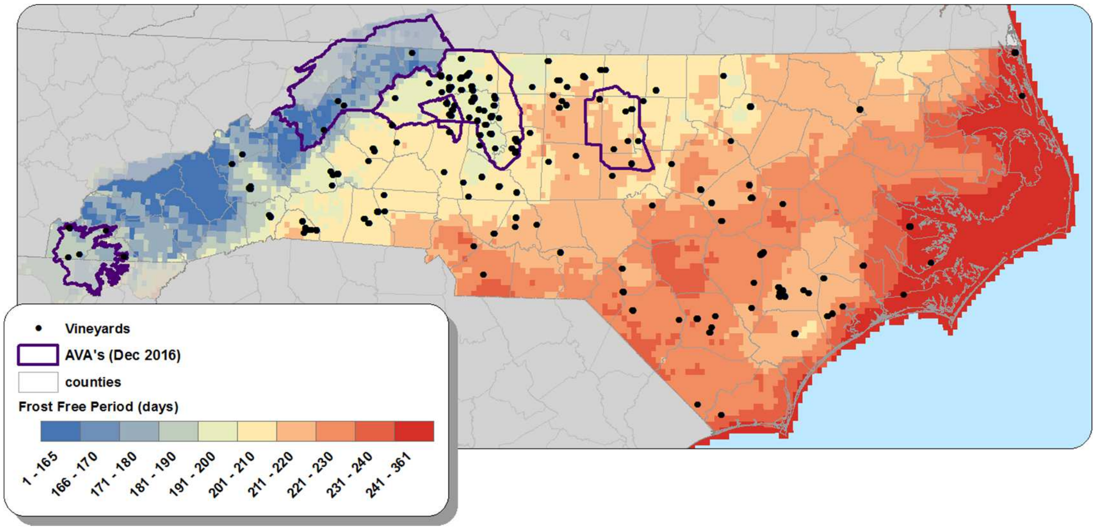

Figure 16. Mean Frost Free Period in North Carolina (1981 to 2014),
Map Generated by John W. Nowlin

The results of the mean number of ECR days is notable, with very few areas of the state experiencing significant multi-decadal risk. The Appalachian High Country AVA appears to have an area which might not be suitable for *V. vinifera* grape varieties due to the incidence of extreme cold which could kill a substantial portion of such vines (Figure 17).

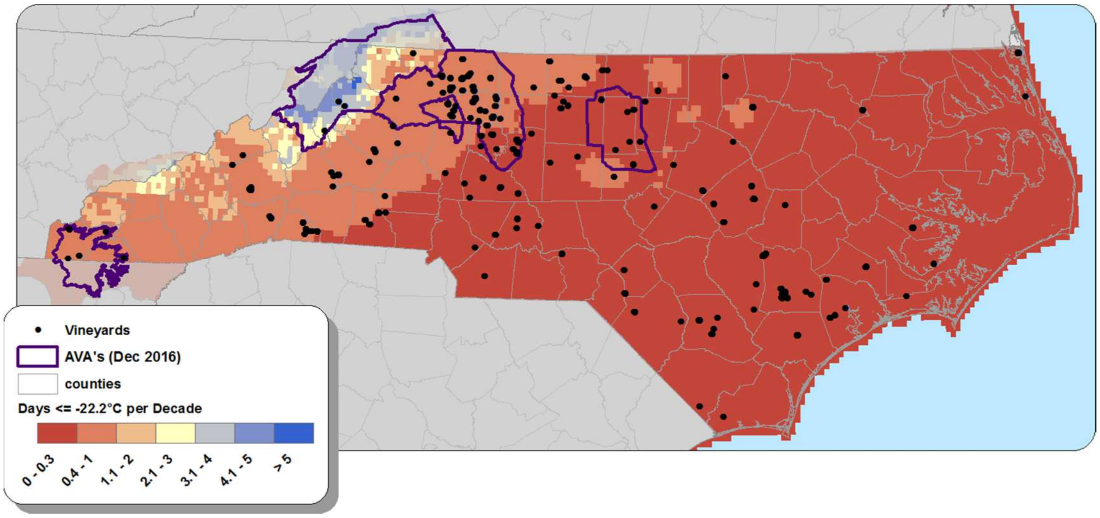

Figure 17. Mean Number of Extreme Cold Risk Days per Decade Below -22.2°C in North Carolina (1981 to 2014) (Wolf and Boyer 2003), Map Generated by John W. Nowlin

The PDR results reveal a familiar pattern with the northwest to southeast climate gradient. There is a major portion of the vineyards in Central North Carolina which are likely to experience PD. The overwhelming majority of the Haw River AVA is at a high risk for PD. This is notable, considering an internet search of the vineyards here reveals *V. vinifera* vines are planted in the AVA (Figure 18).

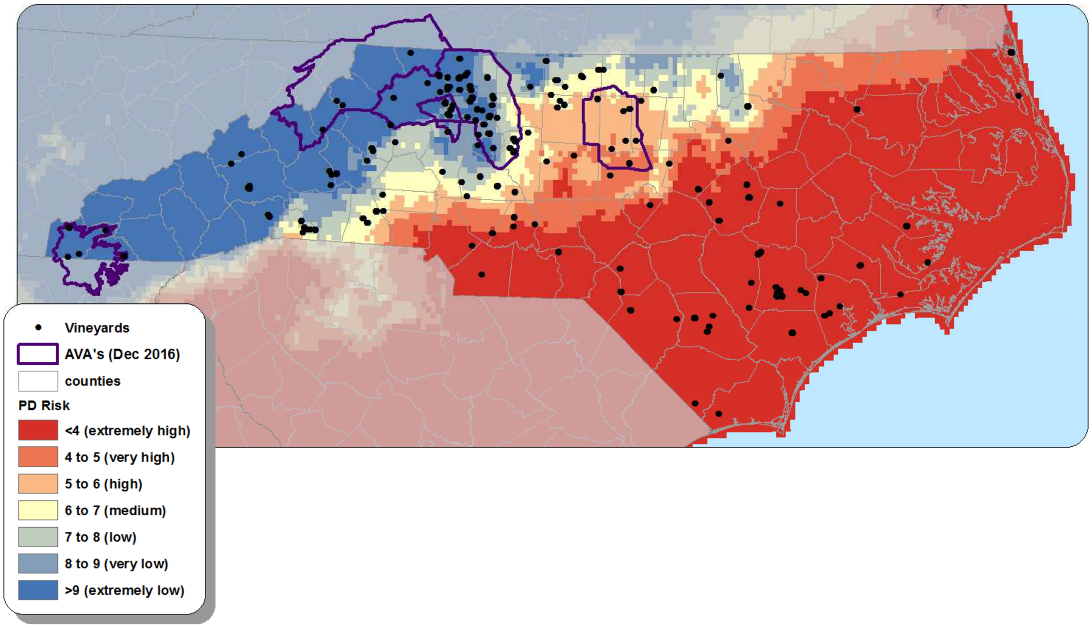

Figure 18. Mean Combined Pierce's Disease Risk Zones in North Carolina (1981 to 2014), authors' adaptation of Sutton (2005), Map Generated by John W. Nowlin

Topographic Results

The map based topographic figures presenting the surface outputs from the methods section are presented at the scale of five large vineyards from across the three physiographic provinces of the state (Figures 19, 20, and 21). In the top left of each figure is Biltmore Vineyards, in the mountains. In the top middle are two adjacent vineyards, Piccione Vineyards and Raffaldini Vineyards in the Northern Upper Piedmont. In the top right vineyard is Childress Vineyards in the Central Piedmont. In the bottom left are the vineyards of Cottle Farms on the Coastal Plain. And finally, in the bottom right is Shelton Vineyards in the Northern Upper Piedmont, the largest commercial vineyard in the state. These figures are all at the same scale, and are used in subsequent sections of the paper for the final results. As a scale reference, the top left vineyard is ~ 1575 meters in extent across its longest axis.

The TPI results show that the large vineyards have portions of their boundaries falling in relatively low areas based on the scales used in this study. The core of these vineyards appears to be off the valley bottom (Figure 19).

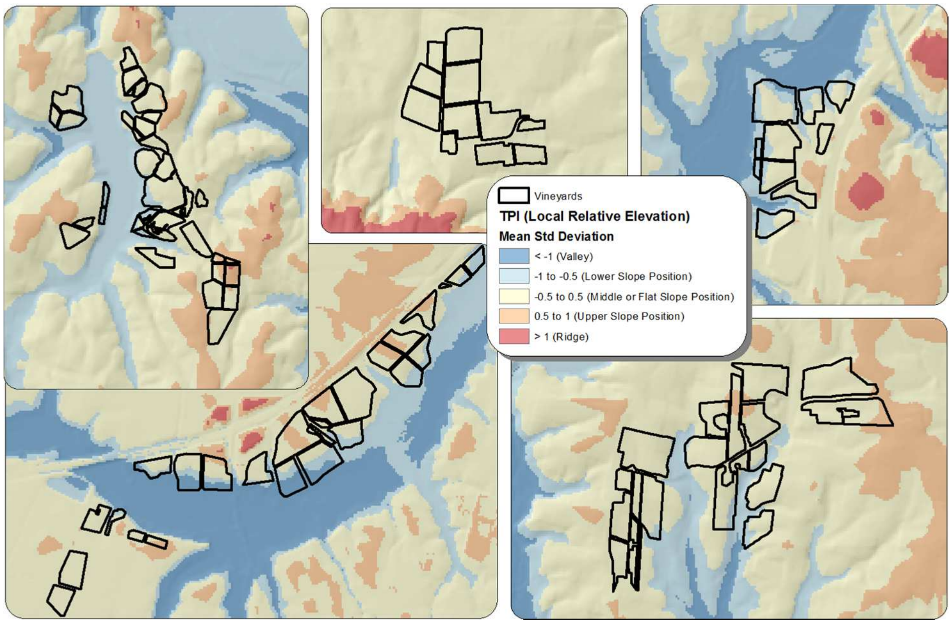

Figure 19. Topographic Position Index, for Cold Air Drainage, Examples of Large Vineyards from The Mountains, Upper Piedmont, and Coastal Plain, Author's adaptation of Weiss (2001), Map Generated by John W. Nowlin

The pattern of slope resulting from the high relief area of the Western Mountains becomes evident when analyzing the Biltmore Vineyards map. There are slopes in this vineyard which surpass the 15% threshold which likely means that special equipment and/or more manual operations are necessary to maintain the vineyard (Figure 20).

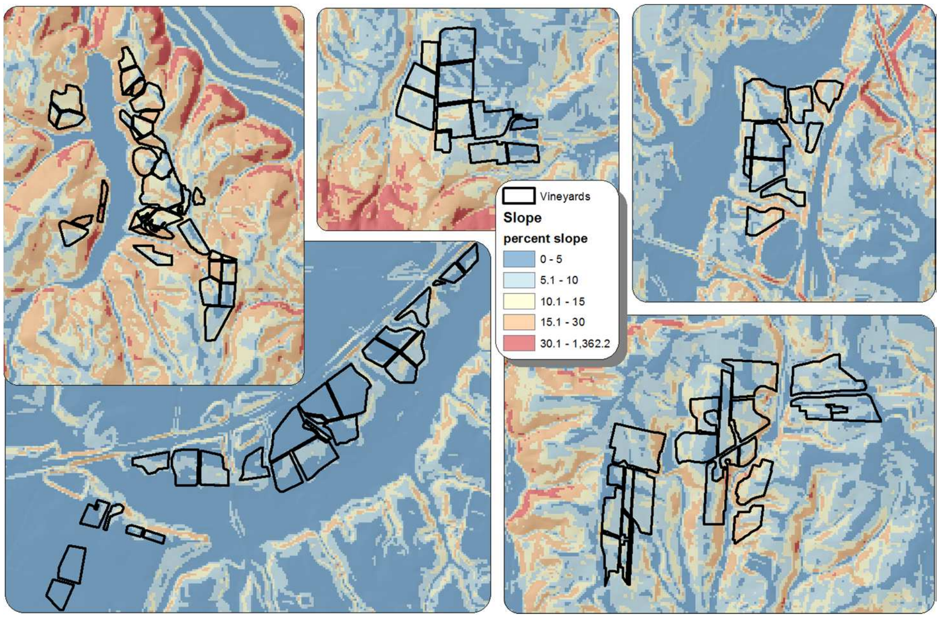

Figure 20. Slope, Examples of Large Vineyards from The Mountains, Upper Piedmont, and Coastal Plain of North Carolina, Map Generated by John W. Nowlin

There is very little discernable pattern to Aspect across the example vineyards. This surface could be helpful in selecting study sites for future research which aims to quantify the impact of the slope/aspect relationship on the relevance of aspect to site suitability. (Figure 21).

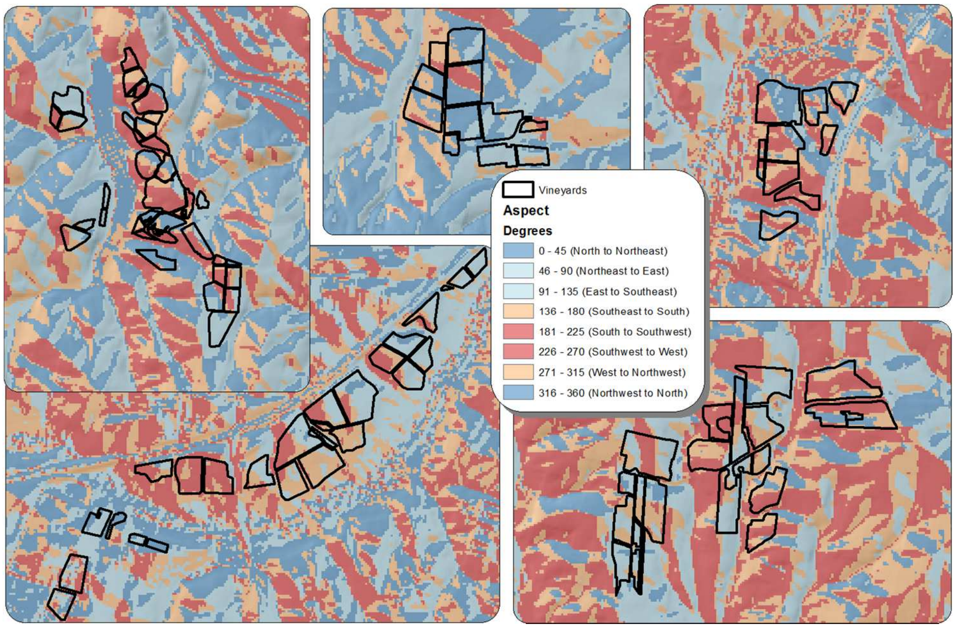

Figure 21. Aspect Classified by Primary Effect, Examples of Large Vineyards from The Mountains, Upper Piedmont, and Coastal Plain of North Carolina, Map Generated by John W. Nowlin

Soils Results

North Carolina’s soils are generally deeper than 101cm (Figure 22), especially on the Coastal Plain, and to a similar degree in the Piedmont, while in the Southern Piedmont south of the Uwharrie Mountains in the Carolina Slate Belt there are large areas with restricted root zones.

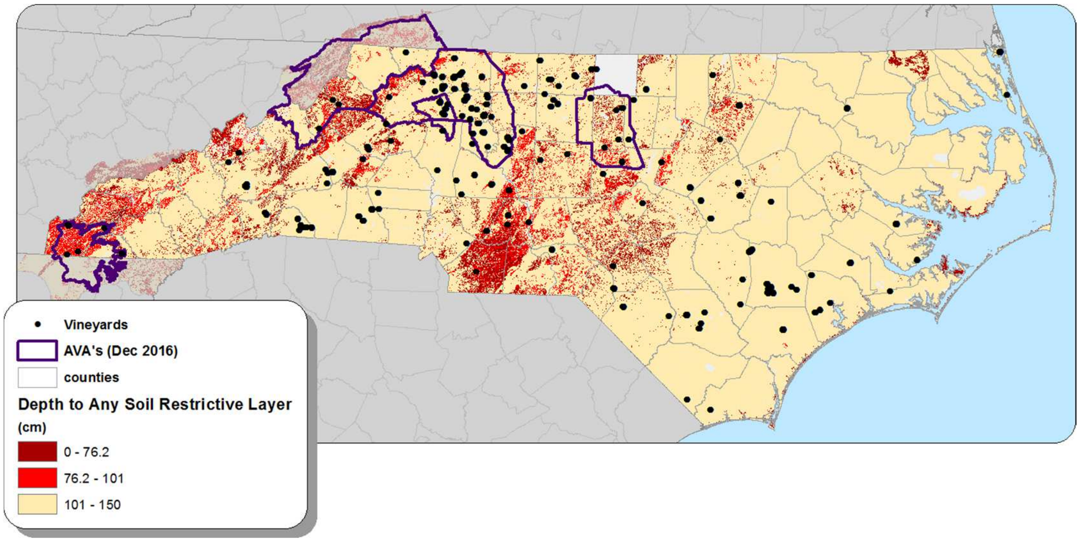

Figure 22. Soil Depth in North Carolina from gSSURGO (current in Dec 2016), Map Generated by John W. Nowlin

This is also the case in the Appalachian Mountains, especially along the highest elevations and immediately west of the Appalachian Escarpment where there are areas of shallow soil. Soils in the lower Coastal Plain approaching the Atlantic Ocean tend to suffer from poor drainage (Figure 23).

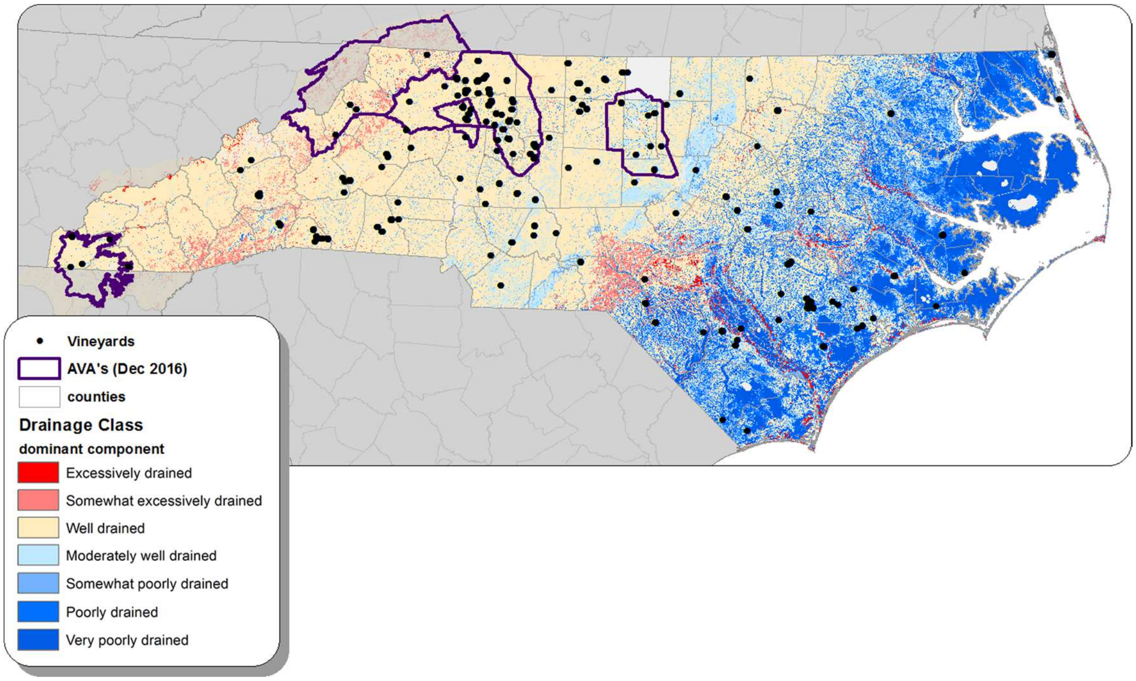

Figure 23. Soil Drainage Class in North Carolina from gSSURGO (current in Dec 2016), Map Generated by John W. Nowlin

This zone is too water logged to be optimal for viticulture, while soils in the Piedmont and the Mountains are moderately drained to well drained. For the most part, other than soils forming from slate or along low alluvial flood plains, North Carolina's soils are moderately low in silt (Figure 24). This textual makeup suggests that they are moderately fertile. One contiguous zone of high silt soils extends northeast from the border of South Carolina immediately west of the Coastal Plain. This is the southern portion of the Carolina Slate Belt.

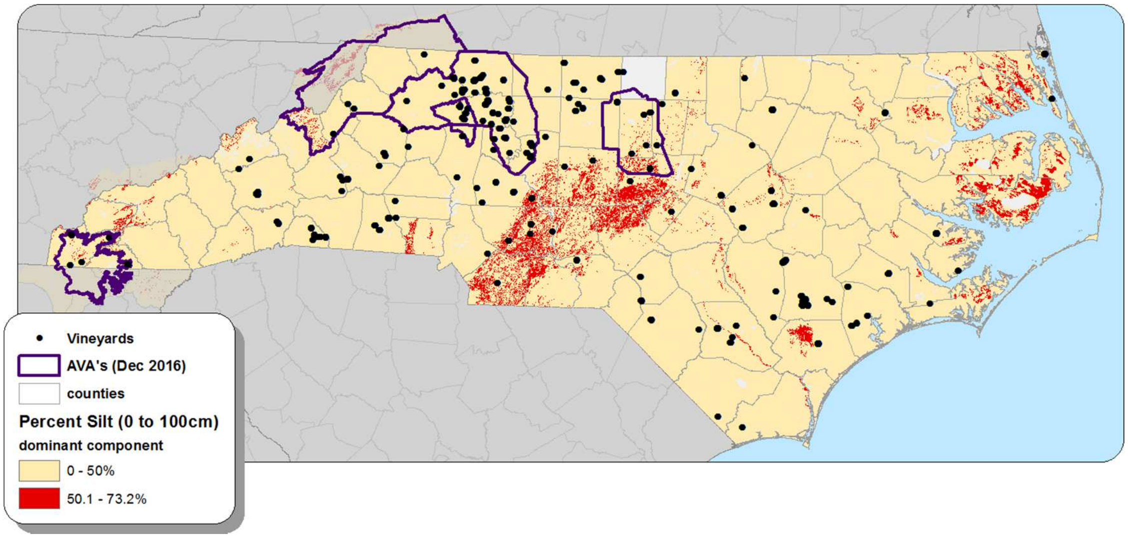

Figure 24. Soil Texture > 50% Silt in North Carolina from gSSURGO (current in Dec 2016), Map Generated by John W. Nowlin

Vineyard Results

Because North Carolina is a relatively new area for viticulture research, it was expected that the vineyard site selection failure rate would be high, maybe even above 33%. The resulting rate is much better than expected. 82.68% of the area falling within North Carolina vineyards passed the tests across all factors in the final model. This represents a failure rate of 16.78% (9,691/57,747) in the final model. It should be noted that these results are based on areas of commercial vineyards that were derived from best available aerial imagery, and that they are disregarding PDR and Aspect failures. It should also be noted that the Virginia extension documentation places more stringent restrictions on site suitability. It is therefore expected that if a model was constructed solely on Virginia's advice the failure rate in North Carolina would likely be higher.

The summary results for cells that failed are reported as raw counts of failing cells and percentages of overall failing area by factor (Table 6).

Table 6. Results (out of 57,747 Cells within Vineyards); Counts and Percentages of Cells Failing by Factor (not used for final model in gray).

Climate Factor	GDD	MJT	FFP	ECR	PDR
# Failing Cells	0	1955	0	153	19999
% Failing	0.00%	3.39%	0.00%	0.26%	34.63%

Topography Factor	TPI	Slope	Aspect
# Failing Cells	441	3608	17485
% Failing	0.76%	6.24%	30.28%

Soil Factor	Depth	Drainage	% Silt
# Failing Cells	616	2900	998
% Failing	1.07%	5.02%	1.73%

The number of failing factors by failing cells are reported by the number of cells which fail by one, two, or three factors (Table 7). Since 90.94% (8,813/9,691) of failing cells failed by only one factor, it is likely that there is a single flaw being highlighted by most failing cells using this model. See Appendix 1 for a list of failing cells aggregated by vineyard.

Table 7. Number of Failing Cells within Vineyards by Count of Failing Factors

Number of failing cells	Number of failing factors
8813	failed by 1 factor
776	failed by 2 factors
102	failed by 3 factors
0	failed by >3 factors

The pattern of failure across large vineyards from across the state and representing the three physiographic provinces of the state can be seen in Figure 25. These cells fail by at least one of the pass/fail tests across all tested layers.

Figure 25. Failing Cells in Example Large Vineyards from The Mountains, Upper Piedmont, and Coastal Plain, Map Generated by John W. Nowlin

Conclusions

The aim of this study was to determine if North Carolina vineyards had followed the advice given by the CES. A GIS based capability model was constructed from the NCWGG, and the vineyard boundaries were created using aerial imagery. Then the vineyards were tested for their fit with the model. The results reveal that, for the most part, North Carolina's vineyard operators are following the guidelines set in the CES more than 82% of the time. Furthermore, only 1.5% of the points failed by more than one factor, a very low rate. Some of the advice given in the CES were rather conservative, for instance, the 15% slope is more restrictive than elsewhere in the literature and the MJT levels experiences in NC are not a problem for *Muscadina rotundafolia*. Removing these restrictions, or clarifying them by species would likely reduce the overall failure rate by more than 33% to a range more like 11%. The output from the modeling also offers a reasonably high resolution look at exactly where the guidelines have not been adopted. There appears to be an edge effect in the TPI results maps of the example vineyards (Figure 25). The effect appears to show that the failing cells tend to be distributed along the edges of vineyards. This could be because the available area for planting was overplanted, or because the Z-score based classification algorithm was too restrictive. This pattern is not substantiated by any formal analysis in this research, however, it does represent a possible future area of research resulting from this study. This would involve surveying growers to see if there is a relationship between the model predictions and frost damage patterns on nights with marginal damaging Spring frost events.

It is notable that two of the surfaces produced for this research utilized novel geospatial applications for viticultural site selection methodology. First is an application of Andrew D. Weiss' topographic position/landform analysis for slope position as a means considering relative elevation represented by the TPI factor in the model. The TPI sub-model must be fit to local conditions, however, it is suitable for a broad range of models and could be incorporated into many future projects. The second novel application is the simplified means of visualizing Turner Sutton's two algorithms for predicting PD—which was represented by PDR in the model. The PDR Surface is most useful for modeling in the Southeastern U.S. and represents an excellent opportunity for future research to test its assertions.

Over a long enough timescale, vineyard location is likely a self-organizing phenomenon where past vineyards that were not on suitable land, failed. This would mean that economics and the landscape are walking hand-in-hand given enough time. In lieu of waiting such a great length of time to learn how to best select sites for vineyards in North Carolina this research presented an efficient means of summarizing basic vineyard site suitability.

Suggestions for Improving NCWGG

There are two suggested improvements in the NCWG. There is some ambiguity about the use of the term bunch grapes. Many grape species are grown in North Carolina, including *V. vinifera, Muscadinia rotundafolia, V. labruscana, V. aestivalis* and hybrids of these species with each other and with other non-commercial species. The advice given in North Carolina CES documentation, however, is almost always presented with a bias toward *V. vinifera/hybrid* production because of the use of the term bunch grapes. It might be prudent to produce different sets of site selection criteria based on the requirements of these different species. Secondly, the NCWGG currently refers to topographic aspect as a factor in site selection, however, the importance of aspect as a site suitability consideration is highly dependent on slope. In general, the higher the slope the more the impact from aspect. This is also dependent on latitude.

CHAPTER IV

NEW PIERCE'S DISEASE RESISTANT GRAPE VARIETIES: THE IMPLICATIONS FOR THE SOUTHEASTERN U.S. WINE INDUSTRY

Abstract

In the Southeastern U.S., Pierce's Disease (PD) is the single most geographically limiting factor for growing *Vitis vinifera*, French-American hybrids, and *Vitis labruscana* grapes. The PD bacterium, *Xylella fastidiosa*, clogs the xylem of the plant, reducing the ability for water to flow upward to the leaves above the infected tissue and typically proves fatal within three years. Commonly cited vectors of PD include the Glassy Wing Sharpshooter, *Homalodisca vitripennis*, but also include many related leafhoppers that thrive in areas with mild winters. The University of California-Davis is developing PD resistant grape varieties from *V. vinifera* and *Vitis arizonica*. These new varieties have been tested in Alabama. With multiple backcrosses to *V. vinifera*, this process has resulted in interspecific hybrid varieties which contain the PD resistance of *V. arizonica* and the oenological qualities of *V. vinifera*. Reports indicate that these varieties are approaching release, bringing major implications for viticulture in the Southeastern U.S. Using the advice of regional agricultural extension documentation, a GIS based suitability model was constructed. The study area was defined using a PD prediction

index which is the sum of annual days at or below two temperature thresholds, -12.2°C and -9.4°C. This index was classified into four risk zones (low, moderate, high, and extremely high risk) that were quantified by the expected viability for growing the new PD resistant hybrids. These zones reveal many areas in the Southeastern U.S. that are potentially suitable for making wines resembling those of Europe, albeit with the need for grapes which are Pierce's Disease resistant.

Keywords: Pierce's Disease, Viticulture, GIS, Modeling, Climate

Introduction

In areas of the Southeastern U.S. (Virginia, North Carolina, South Carolina, Georgia, Florida, Alabama, Mississippi, Louisiana, Texas, Arkansas, Tennessee) which experience PD, growing *V. vinifera* and French/American Hybrid grapes is severely limited (Anas et al. 2008; Kamas et al. 2007; Myers et al. 2007; Sutton 2005). The PD bacterium *Xylella fastidiosa* (Figure 26), clogs the xylem of the plant, reducing the ability for water to flow upward to the leaves above the infected tissue (PiercesDisease.org 2015).

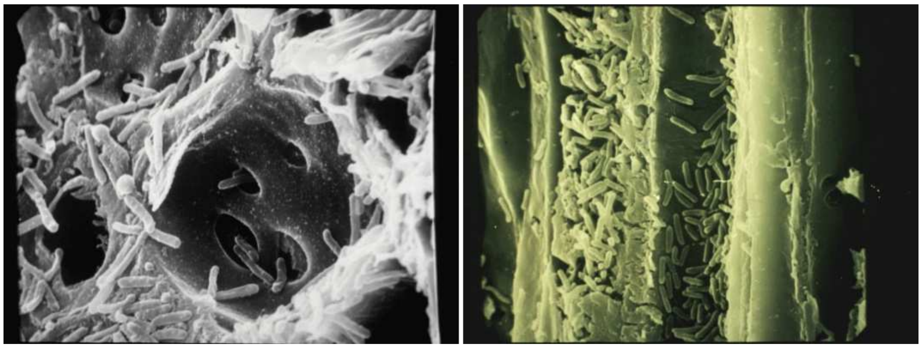

Figure 26. Electron Micrograph of *Xylella fastidiosa,* images by Doug Cook

PD presents as water stress with marginal chlorosis and necrosis which is yellowing and drying of the leaves (Anas et al. 2008; Hartman 2009; Sun et al. 2013) (Figure 27). Other presentations of the disease include matchstick like petioles with no leaves, and green islands on stems (Figure 27). PD typically proves fatal within three years (Thorne 2006). The disease is passed by vectors, such as sharpshooters, related leafhoppers, and spittle bugs, all of which have mouthparts that are used to scrape and chew and/or pierce the green tissues of the plant (Anas et al. 2008; Myers et al. 2007; UCIPM 2007). Many plants have either hosted the vectors of PD or have been found with cultures of the disease. A few examples include: Big Leaf Maple, American Elder, Box Elder, Bermuda Grass, Scotch broom, Yellow Nutsedge, Purple Nutsedge, Hairy Crabgrass, Wild Strawberry, English Ivy, Barley, Sweet Marjoram, Virginia Creeper, Evening Primrose, Timothy, Sycamore, Bluegrass, Rosemary, Lilac, Red Clover, White Clover, Cocklebur, and most wild grapes (Rodrigo 2012). These plants are widespread, and while the strains of PD growing on them might not be the same as the grape variant, their prevalence in the environment suggests that PD is likely established across the entire Southeast region.

Figure 27. Pierce's Disease Symptoms, Green Islands on Stems and Drying Leaves, images by John Hartman

There are some cultural practices which have shown to be helpful in controlling the disease. Since the disease is usually deposited at the growing tips, it is likely the plants can be trimmed away during the winter dormant season through normal winter dormant pruning procedures (Wallingford et al. 2007). Another measure is the removal of any host plants, especially wild grapevines. While the best cover crops are unknown, mowed grasses which have a winter growing season are likely good choices, as is the establishment of at least a 150-foot buffer around the vineyard (Kamas 2015). Relying on these sorts of practices might slow the spread of the disease and effectively reduce losses, but the measures are not sustainable long-term. Many of the vectors are good fliers so they can travel from afar where the vineyard operator has little control (Tipping and Mizell 2004). Insecticides are another possible solution, but the downside is the risk of killing beneficial species such as bees, predatory wasps, and spiders. Unfortunately, the only long-term environmentally sustainable approach is to refrain from planting susceptible grape varieties in areas that are high risk for PD. This severely limits the set of varieties which can be grown in many areas of the Southeast. Currently varieties which show at least some degree of tolerance to PD in marginally risky areas are Chambourcin, Norton, and Villard Blanc. Varieties which have shown good success in high PD risk areas include: Black Spanish, Blanc du Bois, and *Muscadinia rotundafolia* (aka *Vitis rotundafolia*) (Kamas ed. 2010; Dunst 2013). Based on the proximity of the PD affected area to dense wine growing regions in North Carolina, it is presumed that much of the land which presents a high risk for PD is otherwise suitable for growing grapes (Nowlin and Bunch 2016c). This research aims to model PD risk in the Southeastern U.S. at a higher resolution than previous efforts and to determine the likely suitability for wine production where PD risk limits growth of *V. vinifera*.

Literature Review

PD has been shown to be reduced and sometimes eliminated from a vineyard by extreme cold (Dunst 2013; Feil and Purcell 2001; Meyer and Kirkpatrick 2008; Purcell 1980). While the mechanism for this phenomenon is unknown, the expectation is that the bacterium itself is dependent on optimal temperatures to be successful. This is also supported by the research into where PD results in vine losses, and the pattern of low minimum temperatures predicting for the presence of the disease (Sutton 2005). It is notable that the Southeastern U.S. experiences colder temperatures than the wine growing regions of California, so while the disease is native in the Southeast, its eventual northern extent in California is not understood.

In California, the primary vector of PD appears to be the Glassy Winged Sharpshooter, *Homalodisca vitripennis* (UC IPM 2017). This vector is present in the Southeastern U.S. but is not necessarily the primary vector of PD in North Carolina. In North Carolina a survey of leaf hoppers as PD vectors identified *Oncometopia orbona*—the Broad-headed Sharpshooter and *Graphocephala versuta*—the Versute Sharpshooter as the likely primary vectors of the disease, see Figure 21. In a North Carolina study, the blue green leaf hopper was also commonly collected and tested positive for PD, however it was determined that this species is not a risk for transmitting the disease to grapes (Myers et al. 2007).

Figure 28. Vectors of Pierce's Disease:
A. Glassy Winged Sharpshooter, image by Reyes Garcia III;
B. Broad-headed Sharpshooter, image by Ryan Kaldari;
C. Versute Sharpshooter, image by Ryan Kaldari

There have been a few examples of maps produced as part of PD research. A map cited in Anas, et al (2008) was attributed it to the University of California at Berkeley, however the URL referencing the source was no longer active (Figure 29). This map appears to be hand drawn because the zones signifying risk appear to be watercolor. The date of origin of this map is unknown, but there was an outbreak of PD in the wine region around Temecula California in the 1880's, Central Valley in 1930's and 1940's and the late 1990's again in Temecula (Daughtery 2014).

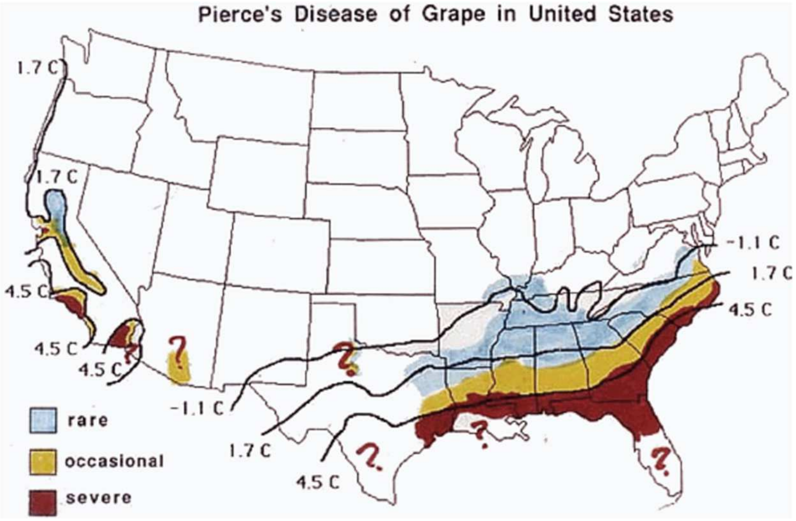

Figure 29. Map of United States Showing Probable Occurrence of Pierce's Disease, Map from UC Berkeley *X. fastidiosa* website, referenced by Anas et al. (2008)

Two other sets of PD maps, originate from research in the Southeastern U.S., one with a study area of Texas (Kamas ed. 2010; Figure 30) and the other of the Mid-Atlantic and Southeastern Regions (Sutton 2005). These maps reveal that about two thirds of North Carolina has a high susceptibility to the disease (Anas et al. 2008; Sutton 2005) and was produced from a limited number of NCDC stations using an ad hoc undescribed interpolation method.

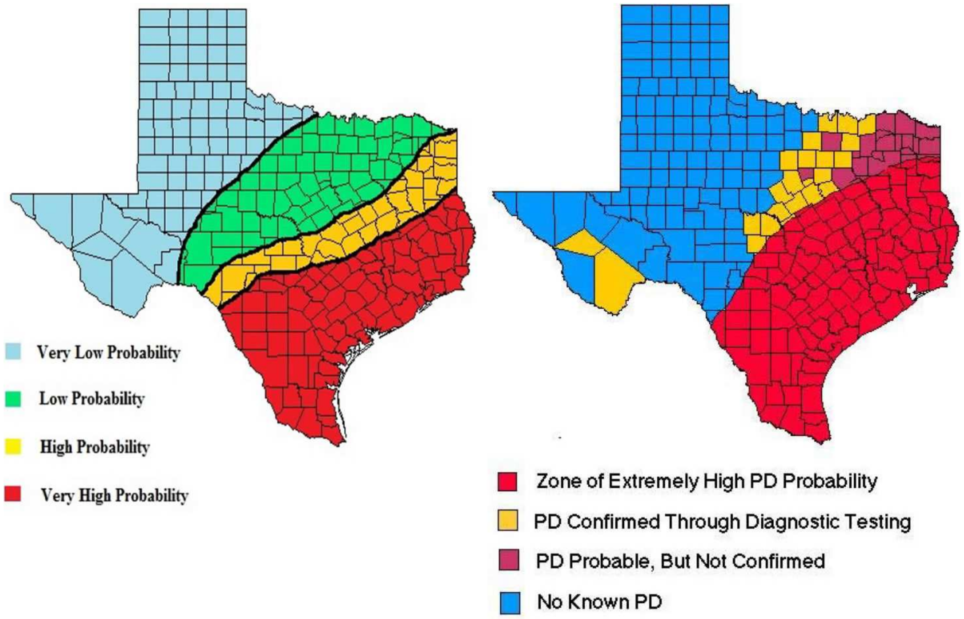

Figure 30. Pierce's Disease in Texas, 1974 Map (left), and 1990's Map (right), Maps from Kamas ed. (2010)

Sutton and company, tested vineyards for PD, and a good correlation was found with certain winter temperature thresholds that predicted the presence of the disease. The number of days per winter at two thresholds, -12.2°C and -9.4°C, was found to be useful for predicting disease. Three days below -12.2°C and five days below -9.4°C were predictive of low PD risk. There was an increase in risk with two days below -12.2°C and five days below -9.4°C, and the risk dramatically increased with less than one day below -12.2°C or three days below -9.4°C (Figure 31 and Figure 32). The line presented by Sutton's (2005) research roughly followed a path situated between and parallel to the Appalachian Escarpment and Interstate 85. His study area did not extend west of Alabama. Following the Sutton (2005) work, a follow-up study was performed in Virginia by a related group of researchers who also showed the advancement of PD in the state of Virginia (Wallingford et al. 2007). It is expected that the algorithm should be applicable across the Southeast, extending from the Atlantic coast to East Texas, where there is a shift to a drier climate west of about the Dallas-Fort Worth region.

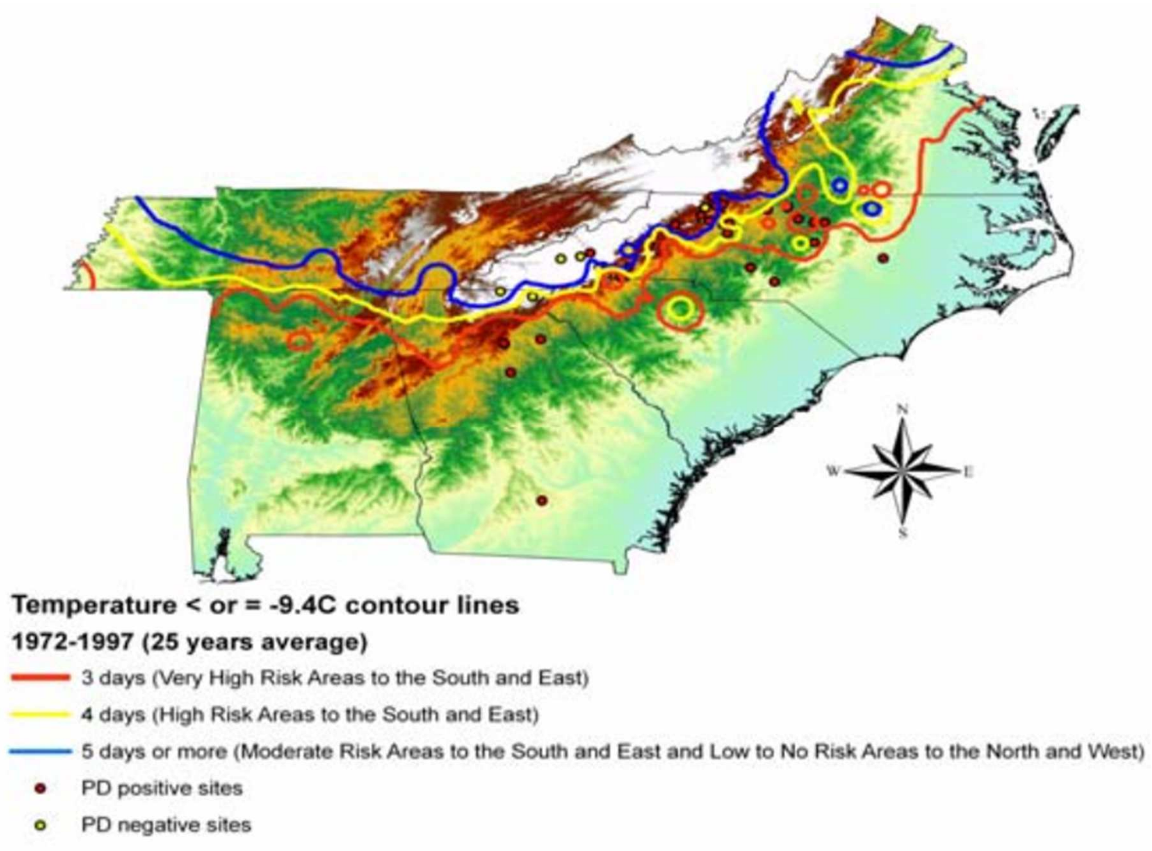

Figure 31. Pierce's Disease Risk Zones for the Southeastern U.S. Based on Annual Number of Days Below -9.4°C, 1972-1997, 25-year Mean, Map from Sutton et al (2005)

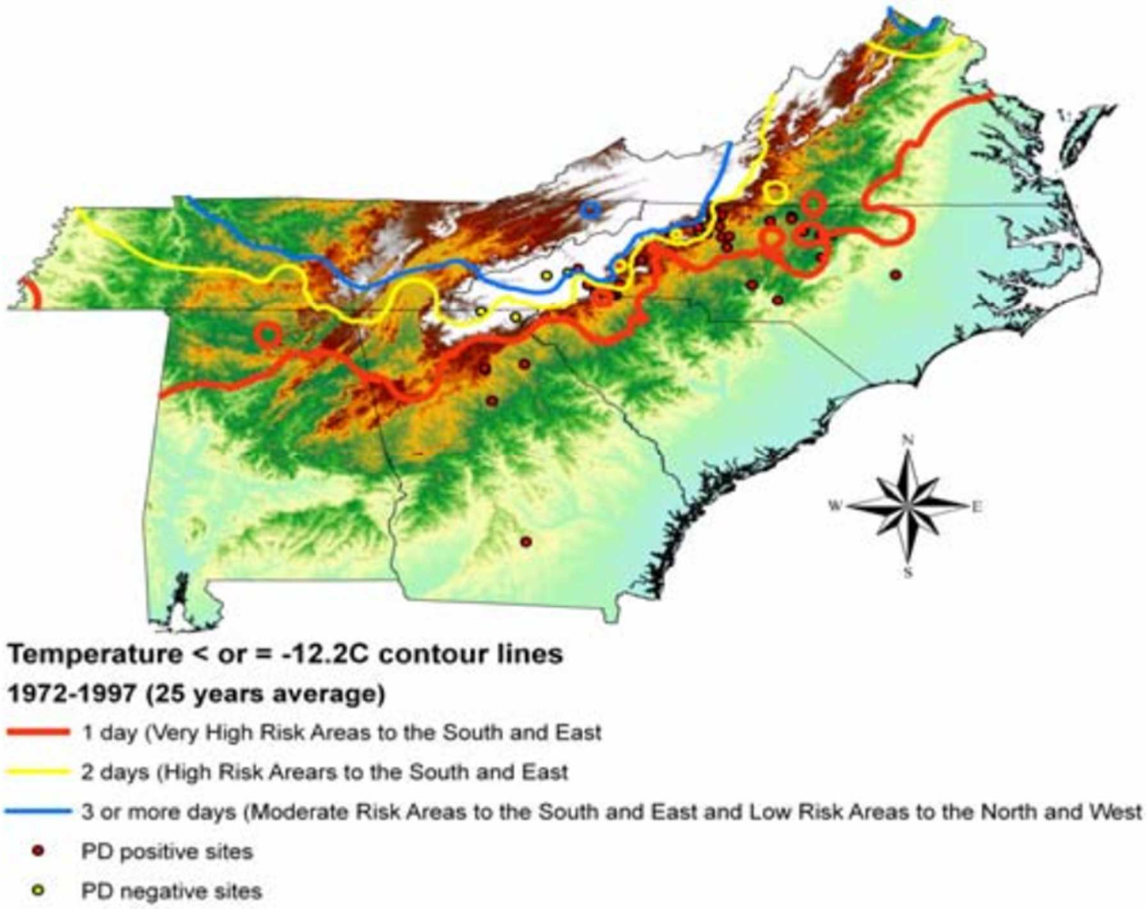

Figure 32. Pierce's Disease Risk Zones for the Southeastern U.S. Based on Annual Number of Days below -12.2°C, 1972-1997, 25-year Mean, Map from Sutton et al (2005)

In an attempt to combine Sutton's two sets of thresholds, Nowlin (2013; 2012) and Nowlin and Bunch (2016b; 2017) used a combined metric of risk between the sets to model the boundary of this PD risk as it fell across Rockingham County, North Carolina. The risk areas predicted by these two thresholds were averaged to present at once a simpler and more comprehensive view of the risk in the study area. At these temperature thresholds, there was less winter cooling in the latter part of the 20th Century. The cooling boundary demarcated by the instance of -12.2°C was absent from most of the county for many years, moving from a period where the majority of the county, not including the southeastern corner, had seen -12.2°C at least one day a winter. Over time, the presence of the -12.2°C threshold moved to the extreme northwestern corner of the county, suggesting that the area to the north and west of Mayodan is the only area in Rockingham County with a low PD risk. One notable finding of this research is that the Haw River AVA, in which there is a large number of *V. vinifera* vines planted, falls on the high-risk side of both of these boundaries. For the period between 1997 and 2005, if the Sutton model is used to consider PD risk, all of the Haw River Valley AVA, except the farthest northwest corner, appear to have a very high risk of PD. The area southeast of Rockingham County is therefore not an optimal place to plant either European winegrapes or their French-American hybrids.

With regard to the Sutton PD indices, the area of low suitability in and around Rockingham County, North Carolina extended into areas which commonly grow grape varieties which are susceptible to PD. This means that it is likely that some of these vineyards will need to be replanted, and the area will have a limited selection of grapes to choose from for replanting, including most Muscadine varieties like Carlos and Nobel, American Hybrids such as Norton, Blanc du Bois, Black Spanish, Villard Blanc, and Herbemont. Other than the Muscadines and Norton, these other varieties are not currently represented by large acreages in North Carolina. The wine produced by the Muscadine grape has a flavor profile which is much different than European variety wines, and Norton vineyards are concentrated in Virginia and Missouri. This means that for many areas of the Southeast which are otherwise suitable for grape production, there are no grapes that have the desirable European flavor profile.

The Southeastern U.S. is not the only area which experiences PD. While present as early as 1885 and named “Anaheim Disease”, PD has produced major losses in Southern California. One especially devastating outbreak occurred in ~1990 in and around Temecula, California (Figure 33). Temecula is south of Los Angeles, outside of the primary wine growing areas of the state, however, PD is advancing northward (TWI 2015).

Figure 33. Pierce’s Disease in California, Red Globe Vineyard in August, by Jennifer Hashim, California Dept. of Food and Agriculture

Because California represents 84.35% of wine production in the U.S. (TTB 2017), this is an existential crisis for America’s wine industry. On account of this risk to its wine industry, intensive research efforts are underway in California focused on how to respond to PD. One of the responses is to breed new varieties. A team lead by Andrew Walker at

The University of California at Davis is developing PD resistant varieties of grapes. These varieties have even been tested in Southern Alabama and Texas, and so far, they are still living. Not only have these varieties been tested for resistance to PD, but wine has been produced from them, and taste tests have verified their wine making potential. Reports indicate that these varieties are approaching release (Coneva 2013; Franson 2011; Hu et al. 2012; Reiger 2014; Tourney 2009, 2013). There are major implications not only within California, but also across the Southeast U.S. for the PD resistant hybrids being bred at UC Davis. Because of PD resistant cultivars, the future holds new opportunities for wine in the Southeastern U.S. While climate change might reduce the amount of suitable land for *V. vinifera* and French/American hybrid varieties, new cultivars open up more suitable land than was lost.

Materials and Methods

There were three raster datasets used in this model, all originate from the same source, the PRISM Climate Group located at Oregon State University in Corvallis, Oregon. The extent covered by these data is the conterminous U.S. and the spatial resolution is 4 km. The PRISM surfaces used were daily minimum temperature, daily maximum temperature, and daily precipitation (January 01, 1981 to December 31st of 2015). This represents 34 years x 365 days x 3 metrics = 37,230 national maps. Much of the work could have been performed with monthly data, but the extreme low temperature counts per decade required daily data, so for consistency all indexes were processed using the daily data.

Guided by the research conducted by Anas et al. (2008), Myers et al. (2007), and Sutton (2005), a simplified PD risk index (PDR) model was constructed. This new PDR index produces a single surface by summing the two Sutton (2005) surfaces. Using the set of daily maps, the average annual number of days with minimum temperatures below -9.4°C (15°F) and -12.2°C (10°F) were counted and these counts were then summed with each other. The effect of this operation emphasizes coldness since days that reached -12.2°C (10°F) have also reached the other threshold, -9.4°C (15°F), states another way, these days were double counted. The resulting surface was classified by summing Sutton's (2005) two sets of risk classes. The resultant classes span from zero which is extremely high risk, to four which is at a moderate risk, to nine which was relatively low risk. An area experiencing between a nine and a zero on this PDR index is considered at risk for PD. This is the area considered by this model which characterizes PD risk conservatively as the likely extent of any notable PD pressure in the Southeastern U.S. The intermediate areas of low, moderate, and high risk are all included in the PD risk zone.

As for the impact that precipitation has on viticultural suitability, for the purposes of this research, areas receiving more than 1500 mm annual PPT were considered too wet for viticulture. This is higher than the number referenced in suitability studies focused on Europe which describes the optimal range between 450mm and 850mm (Coombe and Dry 2005; Foss et al. 2010). This choice is justified in this region both because the long and hot summers have increased capacity to evaporate more water than higher latitude grape growing regions of England, France or Germany, but also because the nature of summertime rainfall in the Southeastern U.S. is of high intensity and short duration thunderstorms, which produce larges pulses of precipitation. Because of the nature of these surges of water, the runoff from these events is often directed quickly to the stream network instead of percolating into the soil or deeper groundwater.

The viticulturally relevant climate indices were guided by the work of Jones and colleagues (2010). The zones falling into failing classes for a set of viticultural suitability indexes were failed in this model. This includes: GST, GDD, HI and BEDD. Stated another way, the PD risk zone was now further restricted to a zone of viticultural suitability as determined by the GST, GDD, HI, and BEDD. The methods used to generate surfaces for these layers are summarized in Table 8. which is a copy of the first table from Jones et al. (2010).

Table 8. Equations and Class Breaks for Common Viticultural Climate Indexes, Including: Mean Growing Season Temperature, Growing Degree-Days, Huglin Index, and Biologically Effective Degree-Days; This is a Modification of Jones et al. 2010 and Anderson et al 2012

Variable	Equation	Months	Class limits[a]
Mean GST	$\dfrac{\sum_{d=1}^{n} \frac{T_{max} + T_{min}}{2}}{n}$	Apr - Oct	Too cool < 13°C Cool = 13–15°C Intermediate = 15–17°C Warm = 17–19°C hot = 19–21°C Very hot = 21–14°C Too hot > 24°C
GDD[b]	$\sum_{d=1}^{n} \max\left[\frac{T_{max} + T_{min}}{2} - 10, 0\right]$	Apr - Oct	Too cool < 850 Region Ia = 850–1111 Region Ib = 1111–1389 Region II = 1389–1667 Region III = 1667–1944 Region IV = 1944–2222 Region V = 2222–2700 Too hot > 2700
HI	$\sum_{d=1}^{n} \max\left[\frac{T_{max} + T_{min}}{2} - 10, 0\right] K^{c}$	Apr - Sep	Too cool < 1200 Very Cool = 1200–1500 Cool = 1500–1800 Temperate = 1800–2100 Warm temperate = 2100–2400 Warm = 2400–2700 Very Warm = 2700–3000 Too hot > 3000
BEDD	$\sum_{d=1}^{n} \min\left[\max\left(\frac{T_{max} + T_{min}}{2} - 10, 0\right) K + \mathrm{DTR}^{d}{}_{adj}, 9^{e}\right]$ where $\mathrm{DTR}_{adj} = \left\{ \begin{matrix} \text{if DTR} > 13, \text{then } 0.25[\text{DTR} - 13] \\ \text{if } 10 < \text{DTR} < 13, \text{then } 0.25[\text{DTR} - 13] \\ \text{if DTR} < 10, \text{then } 0.25[\text{DTR} - 10] \end{matrix} \right\}$	Apr - Oct	< 1000 1000–1200 1200–1400 1400–1600 1600–1800 1800–2000 > 2000

a. The ordinal terms given in the classes were assigned by their creator(s) in different publications and are not synonymous, I.E. GST cool ≠ HI cool

b. The GDD classes (in parenteses) are based on Winkler et al. (1974), and rounded to °C units from °F.

c. K is a latitude coefficient that takes into account the increase in day length with latitude, described in Hughlin (1978) & Jones et al. (2010)

d. DTR = diurnal temparature range, in °C units

e. BEDD has a lower limit of 10°C and an upper limit of 19°C, this results in a maximum difference of 9°C

Using the zone defined by the PD Risk map with greater than low risk of PD, the area was further masked using the failing classes of the above listed climate indexes. This PD Risk Zone was then considered on the basis of the GST climate index and classified according to the standard classes used in Table 8.

Results

The results reveal the zone of PD Risk along with the viticulturally relevant climate indexes: PPT, FFP, GST, GDD, HI, and BEDD. Finally, the output from the model represents the portion of the PD Risk zone which passes by all climate indices graded by GST climate zones. This output is the portion of the southeast which is likely viable for the newly developed PD resistant cultivars being developed by UC Davis.

The PD Risk map (Figure 34) reveals that the PD risk boundary includes Southeastern Virginia, Central and Eastern North Carolina all, but the highest elevations and most northern portions of South Carolina, Georgia, and Mississippi, the Southern two thirds of Arkansas, and the Southeastern corner and extreme Southern portion of Oklahoma. As for Tennessee, the only significant zone of risk is the lowland Delta Area in the Southwest corner of the state. Since the precipitation regime of Texas is so different between East Texas and West Texas, this map can only speak to the portion of Texas which has similar rainfall to the rest of the Southeast. This means that for the purposes of this model, all the area in East Texas can be understood to be at risk for PD.

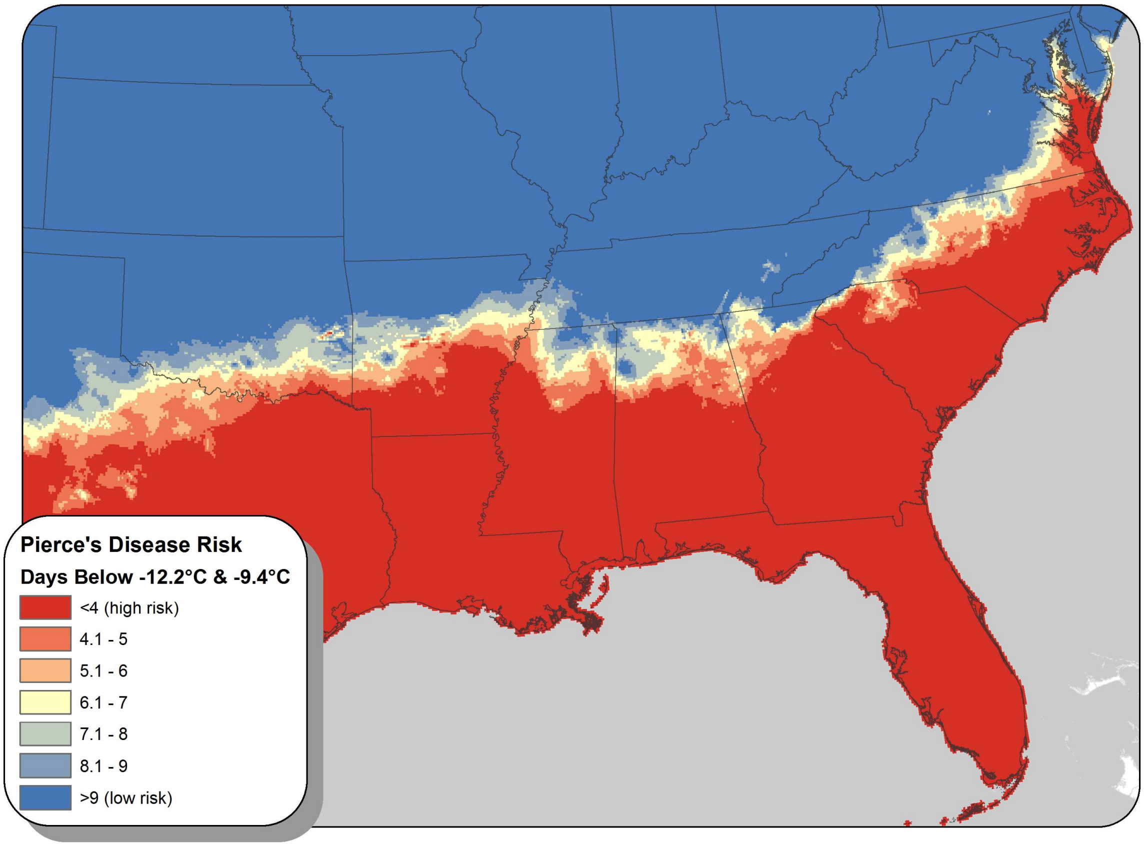

Figure 34. Combined Sutton Pierce's Disease Risk for Southeastern U.S. (Based on Daily PRISM Maximum and Minimum Temperature, 1981 to 2014), Map Generated by John W. Nowlin

The map of PPT (Figure 35) reveals a similar pattern as seen earlier on Figure 10. The Köppen Climate Classification known as "Humid Subtropical" (aka Cfa) defines the region of the Southeastern U.S. The states in the Eastern U.S. which have high PD Risk per the Sutton 2005 model, all reside in this U.S. region. As the map illustrates, while annual precipitation varies across the region, the states of the Southeast are distinguished by higher average annual precipitation than those states to their east and immediate north. The PPT zone which failed due to being more than 1500mm PPT is distributed along the Gulf Coast, and on windward slopes of the Appalachian Mountains. This is in contrast to the Piedmont regions of Georgia, South Carolina, North Carolina, and Virginia which have moderately drier climates. The zone of humid summers speaks to the environmental similarities associated with the Southeast and why this study chose to focus on this precipitation as an important organizing characteristic for this study.

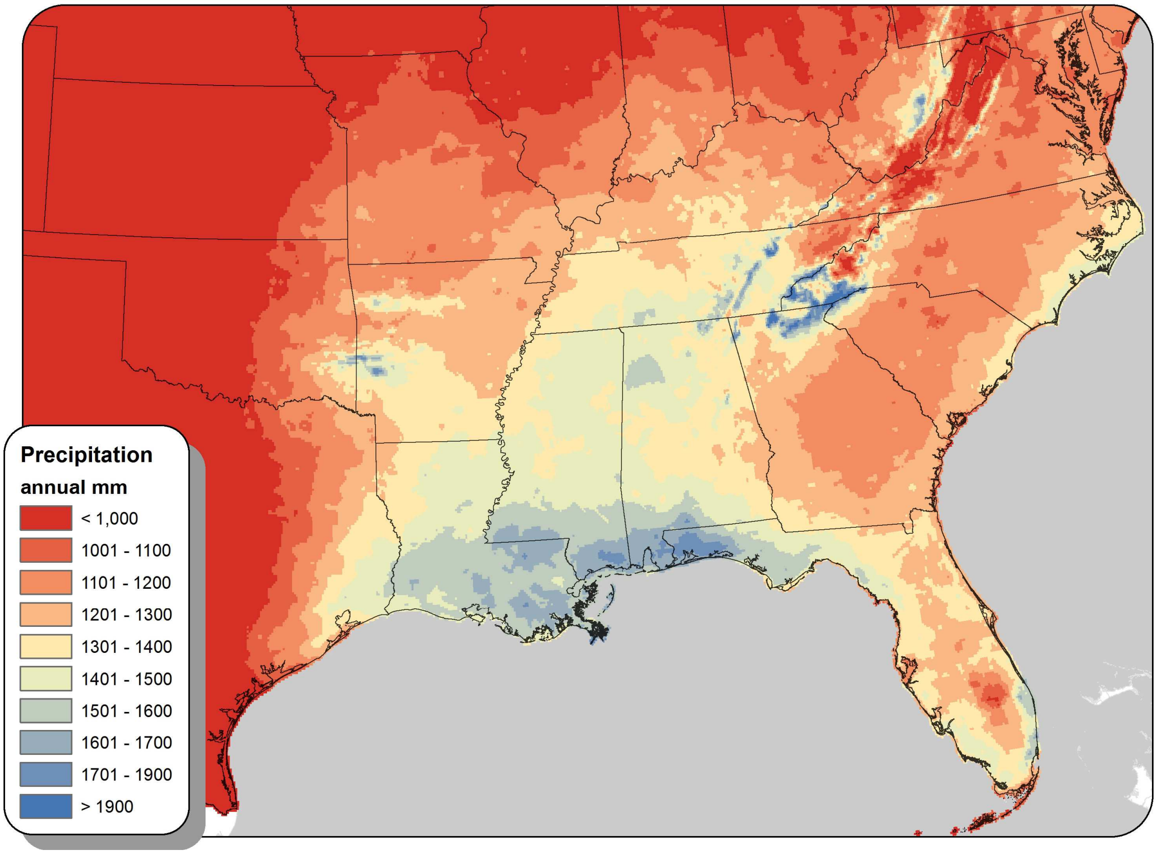

Figure 35. Annual Precipitation (in mm) for Southeastern U.S. (Based on Monthly PRISM Precipitation, 1981 to 2014), Map Generated by John W. Nowlin

The resulting FFP map (Figure 36) illustrates the long growing seasons across the Southeastern U.S. Except for the high elevations of the Appalachian Mountains, the region experiences more than 180 days without frost, and in the majority of the south receives greater than 200 days without frost. The entire Southeast has a long enough season to grow any variety of commercial grapes. Simply stated, growing season length is not one of the viticultural suitability limitations that exists in this region.

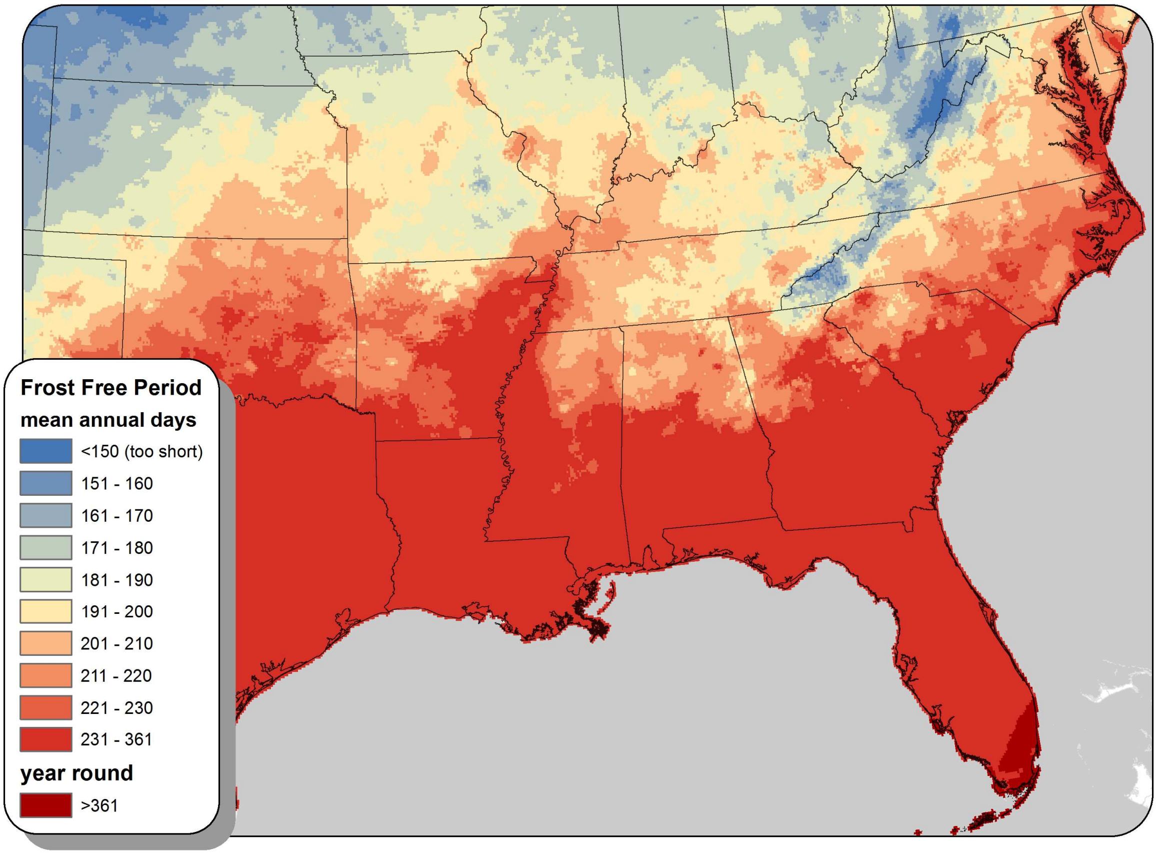

Figure 36. Frost Free Period for the Southeastern U.S. (Based on Daily PRISM Minimum Temperature, 1981 to 2014), Map Generated by John W. Nowlin

The map of GST (Figure 37) reveals that most of the Southeast fits into the hottest suitability class, 21°C to 24°C. There is a relatively large portion of the upland portions of the Southeast which is in the next cooler class as well, 19°C to 21°C. The elevations of the Appalachians span the index all the way to the coldest GST class, but this is a very small portion of the area of Western North Carolina and Virginia as well as most of the state of West Virginia and extreme Western Maryland. There is a zone which is considered unsuitable due to excessively hot summers along the Gulf Coast, including the whole state of Florida, the Southern half of Louisiana, and the Southern two thirds of East Texas. This failing zone has an average GST above 24°C and of the general viticultural climate indexes it is the most permissive, at least in the Southeastern U.S.

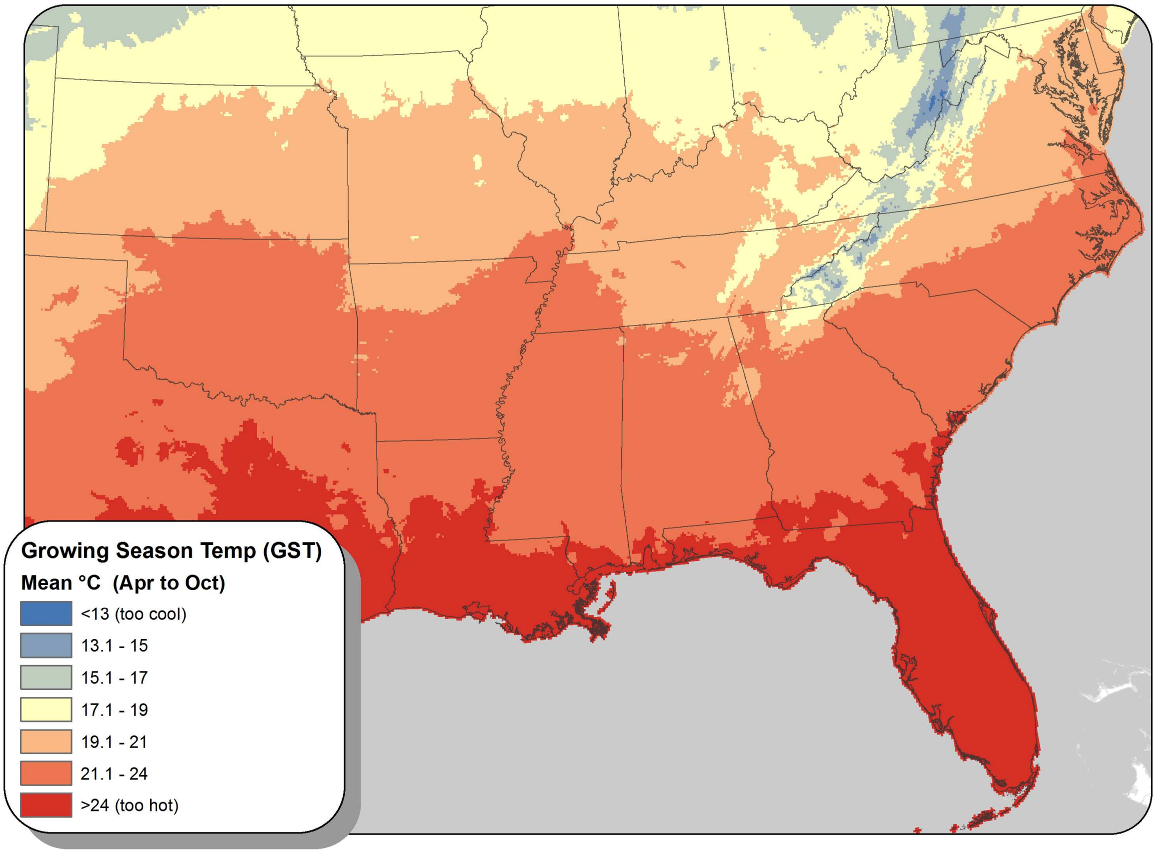

Figure 37. Mean Growing Season Temperature for Southeastern U.S. (Based on Daily PRISM Maximum and Minimum Temperature, 1981 to 2014), Map Generated by John W. Nowlin

The GDD results map (Figure 38) has a similar pattern to the GST map (Figure 37), except all the classes are moved northward. This shift was on average 200 km northward in the eastern portions of the failing area and up to 310 km northward in the central and western portions of the failing area. The failing class on the GDD map is greater than 2,718. On the GDD map this failing class bisects the states of South Carolina, Georgia, and Alabama. All but the Northeastern quarter of Mississippi fails, along with the Southern border region and Southeastern corner of Arkansas. All of Florida, all of Louisiana, and Eastern Texas fail to be suitable due to the GDD index.

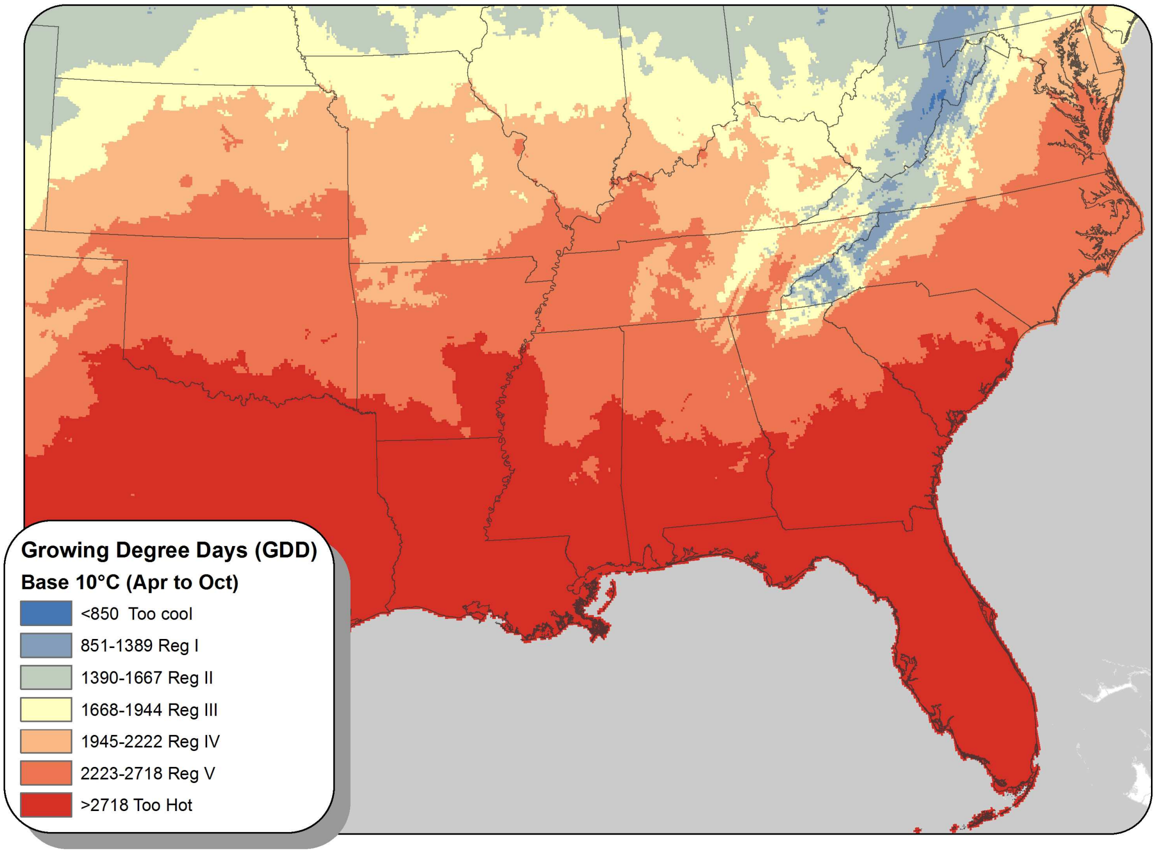

Figure 38. Growing Degree-Days for Southeastern U.S. (Based on Daily PRISM Maximum and Minimum Temperature, 1981 to 2014), Map Generated by John W. Nowlin

The HI results map (Figure 39) has a similar pattern to the GDD map (Figure 38), except that all classes have moved further norward still. This shift northward was less than from the GST to the GDD, in that it averages between 20 km and 120 km. It generally moved farther northward in lower elevation areas than into areas of increasing elevation. This boundary represented the most restrictive failing area across all climate indexes.

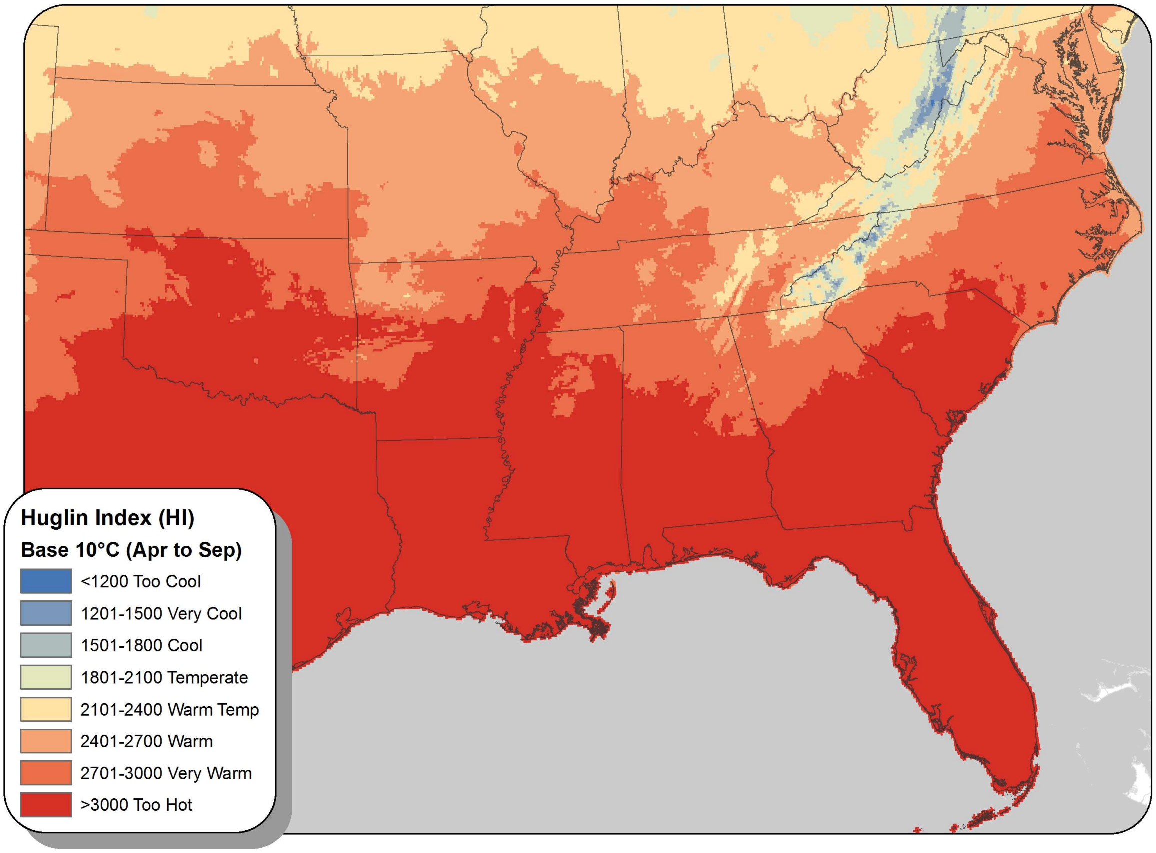

Figure 39. Huglin Index for Southeastern U.S. (Based on Daily PRISM Maximum and Minimum Temperature, 1981 to 2014), Map Generated by John W. Nowlin

Unlike all other climate indexes used in this study, the BEDD map (Figure 40) reveals that no area of the Southeastern U.S. was in the hottest class of BEDD. In fact, most of the southern portions of the region fall two classes above the hottest class at 1800 to 2000 BEDD.

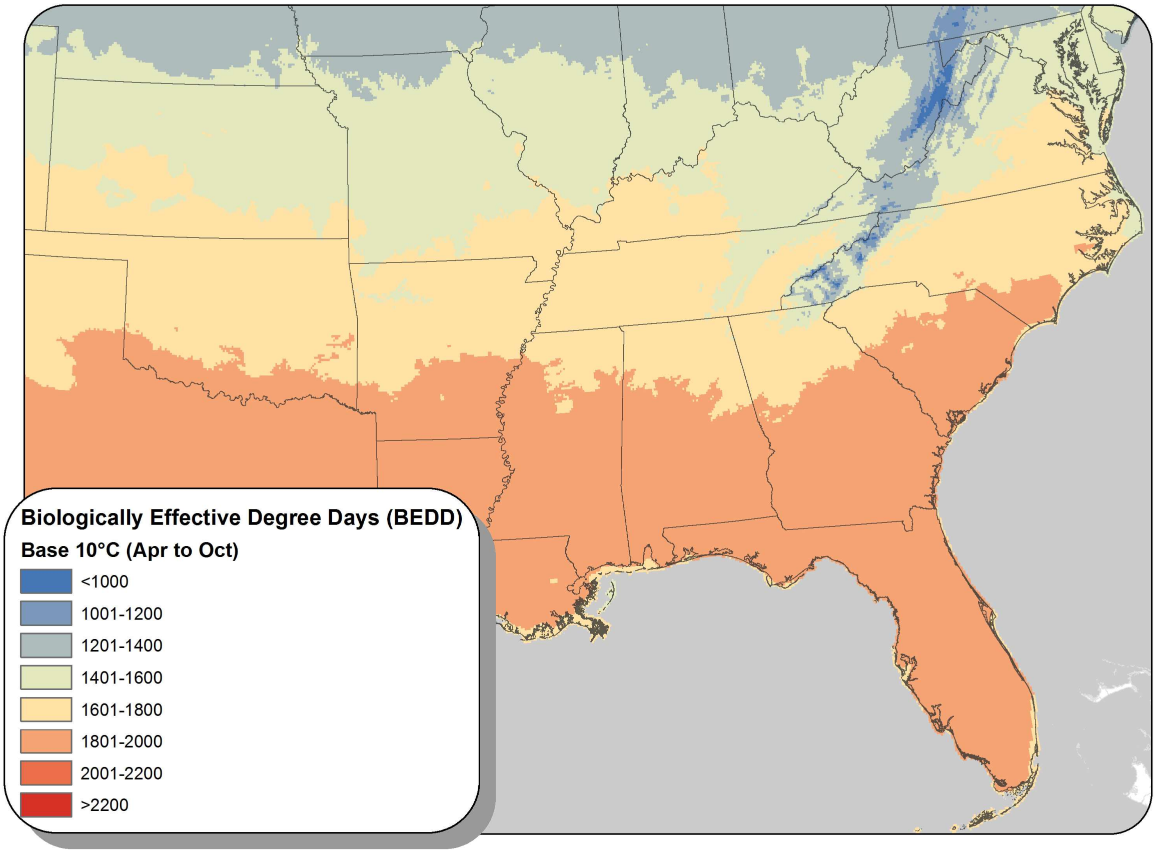

Figure 40. Biologically Effective Degree Days for Southeastern U.S. (Based on Daily PRISM Maximum and Minimum Temperature, 1981 to 2014), Map Generated by John W. Nowlin

The percentage of the remaining land which has the capacity to grow the new PD resistant *V. vinifera* + *V. arizonica* hybrids totaled 269,661 sq. km. The final result map and summary statistics reveal the region of future possible wine growing of the new PD resistant cultivars. These regions were: the northern 2/3 of Arkansas, most of Tennessee except the Delta region around Memphis and the lowland around Chattanooga in the Tennessee River Valley, the extreme northern most portions of Alabama, Georgia, and South Carolina, the North Carolina Piedmont, and all of Virginia except the Tidewater and the DelMarVa Peninsula (Table 9 and Figure 41). This area has been further divided into the GST classes which reveals that there are two climate zones in this region. These could be described as Warm (19°C to 21°C) and Hot (21°C to 24°C). They are humid by all accounts, but given good fungal management should be suitable for growing Pierce’s Disease Resistant grape varieties, such as those being Developed by Andrew Walker and company at UC Davis.

Table 9. Southeastern U.S. Area Falling in the Pierce's Disease Risk Zone which is Climate Suitable for Viticulture, by State

State Name	Sq. km
North Carolina	98,243
Georgia	40,736
Alabama	38,591
Virginia	24,051
South Carolina	21,820
Arkansas	14,630
Mississippi	13,963
Tennessee	8,847
Maryland	4,535
Oklahoma	4,246
total	269,661

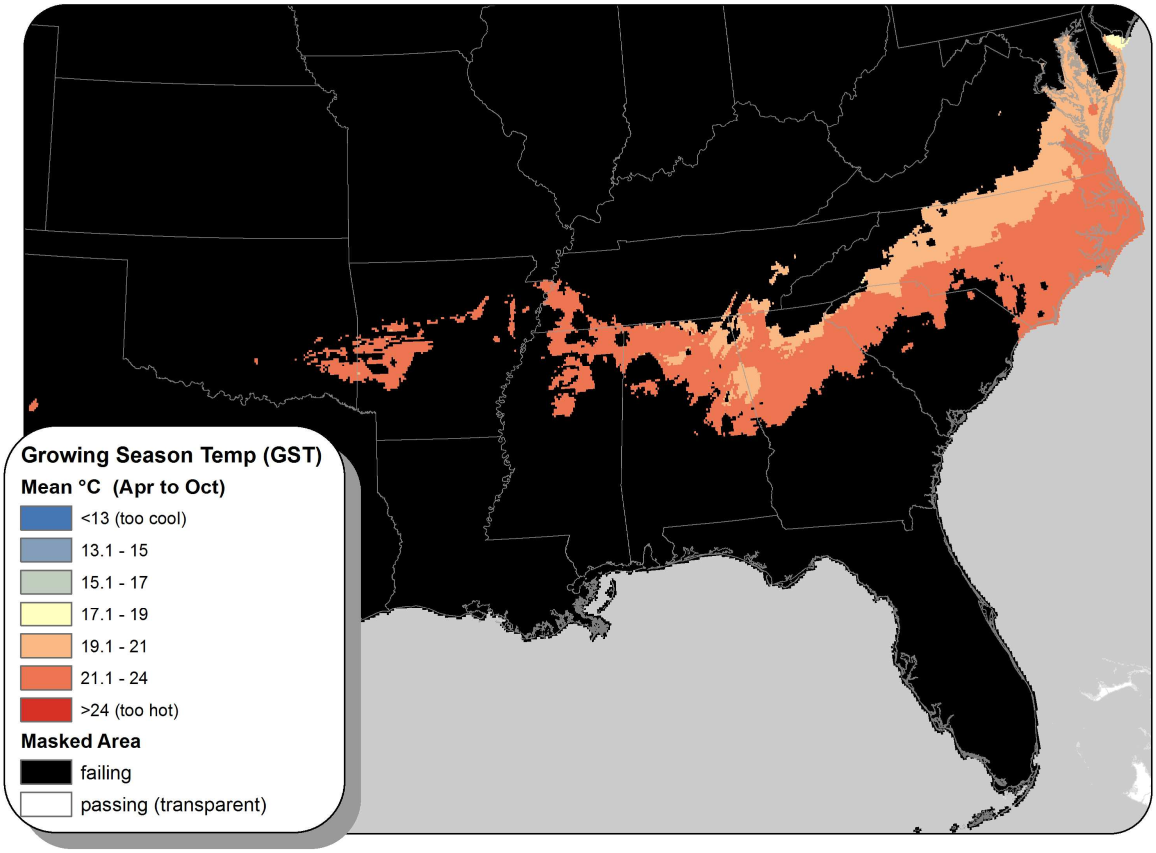

Figure 41. Potential Pierce's Disease Risk and *V. vinifera* + *V. arizonica* Hybrid Suitability Zone for Southeastern U.S. (Based on Daily PRISM Maximum and Minimum Temperature, 1981 to 2014), Map Generated by John W. Nowlin

Conclusions and Discussion

This research aimed to model PD risk in the Southeastern U.S. at a higher resolution than previous efforts and to determine the likely suitability for wine production where PD risk limits growth of *V. vinifera*. This was accomplished through the construction of a geospatial model. Using the advice provided by the regional extension documentation, PD prediction index was constructed, and the PD risk zone was determined. The failing classes of a set of common climate indices related to viticulture were used to further limit the area of the study. The results reveal areas which might be viable for producing wine from the new PD resistant grape varieties soon to be released by U.C. Davis.

As a geographer researching terroir and the wine region described above, this dissertation is situated at the human-environmental nexus and utilizes the theories, methods, and practices of GIScience to solve geographic problems. More than simply techniques or tools, GIScience is a comprehensive mode of inquiry (Goodchild 1992). In the case of the research presented here, this mode of scientific inquiry has been tasked with specific applied research projects and has produced knowledge. This knowledge is both idiographic to North Carolina wine regions, appellations, and vineyards, and nomothetic in its use of GIS tools generating new formulations and ways of using geographic data to advance viticultural site suitability. These new methods had broad applicability not only to wine, but also to other agricultural pursuits were climate, topography, and soil are integral factors in site selection.

The primary contribution of this research was the modification of Turner Sutton's two algorithms for visualizing PD over a larger range than the Sutton (2005) research and the use of PRISM data for these calculations. This higher resolution mapping of the modified Sutton indexes has helped reveal a higher precision representation of the zone of PD risk across the Southeastern U.S. The zones of potential viticultural suitability have been located and exist primarily (in order of volume) in North Carolina, Virginia, Georgia, Alabama, Tennessee, Arkansas, Oklahoma, and South Carolina.

Further testing within the zone outlined by these climate indices with the new cultivars will be needed to determine their performance in situ. This zone should be appropriate for the current set of PD resistant American Hybrids, but Blanc Du Bois may need testing to verify winter hardiness in this entire zone. While there is a greater degree of freedom in locating Muscadine vineyards, in that they are native along the Atlantic and Gulf Coasts (Magee 1997). The areas of suitability presented by the results are also capable of growing Muscadines (NRCS Undated; Miller and Miller 2005).

CHAPTER V

DISSERTATION THEME CONCLUSIONS

Wine is rooted in the wisdom of thousands of years of practice and experimentation. As a topic of study, wine represents many opportunities for research across the discipline of Geography. Its appeal in the academy as a geographic subject relates not only to the origin of grape species and the historic range of wine production, but also to the many factors which describe agricultural suitability, sensorial variety, market valuation, and the concentration of wine production in hyper-specified regions. The spatial distribution of viticulture is related to biogeographic factors, isolating winegrape growing to a relatively small set of latitudes, physiographic regions, and territories inhabiting those spaces. The typology of wine regions, their scale, and surface factors predicting viticultural success are inherently geographic topics. The hedonic properties of a wine, its flavor, texture, and odor, as well as how these sensory characteristics might be promoted and categorized, are related to origin. Origin in this case is connected to both the physical environment and to cultural practice, both of which are unified to place through the concept of terroir. These topics connect to the traditional purists of geographers through area studies, physical geography, human-environment interactions, and spatial analysis. Wine is an inherently geographic subject.

As geographers analyze the distribution of wine regions worldwide, they model and categorize the physical environment, they map and describe appellations within these regions, and they model site selection and suitability for vineyard establishment. The connections between man, place and grape are as important in North Carolina and across the Southeastern U.S. as they are in France and throughout other important viticultural regions. North Carolina provides a rich area of study for research into the geography of wine. Because North Carolina's wine industry is young and quickly growing, there were gaps in the literature. The research presented in this dissertation used these gaps as opportunities to contribute to the literature. The second, third and fourth chapters of this dissertation stand alone as independent publications, each addressing a different gap. The second chapter presented the quantification of the terroir of North Carolina and its counties, AVAs, and commercial vineyards. The third chapter proposed a methodology for testing the effectiveness of vineyard site selection choices. The fourth chapter provided an article which increased the scale extent from North Carolina to the Southeastern U.S. and modeled the possible viable future areas for the PD resistant winegrape varieties currently in development at UC Davis. These three articles were bound together by a common theme: the study of North Carolina viticulture. All three of the articles were related to the geography of wine, and they involved geospatial modeling, and the use of the theories, methods, and practices which underlie the field of GIScience. The vineyards and AVA's of North Carolina have been outlined in detail, and the terroir research results revealed a broad set of terroir zones in the state. The primary dividing line between terroir zones can be defined by two factors. The first is location in relation to risk zone for Pierce's Disease, and the second is physiographic province.

The first article (Chapter II) quantified the terroir of the state's wine regions and vineyards. This article addressed the gap formed by the lack of description and quantification of terroir of North Carolina's formal wine regions, and vineyards in the literature. The research revealed that the state's five AVAs represented considerably different climate zones. The Upper Hiwassee Highlands AVA is shared by Georgia, and the Appalachian High Country AVA, which is the coolest in the state, is shared with Tennessee and Virginia. These two AVAs are the newest in the state and both are in the Mountains. The Yadkin Valley AVA is in the Piedmont and is the densest area of viticulture in the state. The Swan Creek AVA is a subset of the south central portion of the Yadkin Valley AVA. While there is some risk for Pierce's Disease in the southeastern portion of the Yadkin Valley AVA, the climate of the Haw River Valley AVA is likely to experience significant Pierce's Disease pressure. North Carolina's soils contain more sand in the east on the Coastal Plain, have more silt on the alluvial terraces and in the Carolina Slate Belt, and more clay in the Piedmont, with variable loams in the mountains. The elevations of the vineyards range from 2.2m (7.2ft) to 1234.7m (4050ft) above sea level, and the climate variable ranges are as follows: PPT 992mm (39in) to 1728mm (68in), FFP from 166 to 268 days, GDD ranging from 1045 to 2660, GST ranging from 14.6 to 22.4, HI from 1504 to 3019, and BEDD ranging from 500 to 1998. The results for the state's AVAs, the counties representing the three hearths of viticulture in the state, and the set of commercial vineyards are recorded in Appendix A.

The second article (Chapter III) executed a test of North Carolina's vineyards for site selection effectiveness. This article addressed the gap formed by the lack of published research demonstrating the adoption of state cooperative extension advice for the selection of vineyard sites across North Carolina. This research revealed that the great majority of North Carolina's commercial vineyards are located on sites which were supported by the North Carolina Cooperative Extension's NCWGG site suitability guidance. One criticism of the NCWGG is that the treatment of topographic aspect did not relate to slope, although these two measures are intimately tied together. Aspect only becomes meaningful as it begins to impact the insolation pattern, and at low slope this effect is negligible. The maximum topographic slope limit given in the NCWGG is rather conservative at 15%; this is more restrictive than elsewhere in the literature which tends to put the maximum limit at 30%. However, the high rainfall rates in the state might cause erosion, so this was not modified in the model. There are PD resistant bunch grapes growing in the state, and a major portion of the state's viticulture industry is devoted to Muscadines, which are also PD resistant. However, the guidance in the NCWGG did not address the differences in needs between Muscadines and *V. vinifera*. Muscadines are native to the eastern portion of North Carolina, and they are likely capable of tolerating lower drainage rates than *V. vinifera*. These species should be treated separately in the literature to maximize the value to all of North Carolina's wine industry. The largest two failing factors were slope, with 6.24% of vineyard area failing, and soil drainage with 5.02% of vineyards failing. Overall, only 16.78% of the vineyards in the state fail to follow the guidance provided across all factors (except aspect and PD risk which were discarded as failing factors). This research also recorded the percentages of failing factors by vineyard (Appendix B).

The final article (Chapter IV) broadened the scope from North Carolina to include the larger region of the Southeastern U.S. Viticulture in this region is severely limited by PD, yet with the new cultivars out of U.C. Davis that may change. This addressed the gap formed by the lack of authoritative risk guidance maps along the PD risk boundary in the Southeast. Building on the work of Turner Sutton and his students, a higher resolution Pierce's Disease Risk zone was established, and then restricted to an area with climate suitability for *V. vinifera* winegrape production. The results show that across the upper Southeast, the new PD resistant varieties coming out of UC Davis should be suitable across a large potential climate suitability zone with an area of 269,661 km^2 (104,117 miles^2). This new zone crosses the following states: North Carolina, Georgia, Alabama, Virginia, South Carolina, Arkansas, Mississippi, Tennessee, Maryland, and Oklahoma. The resulting map also sub-classified this new suitability zone into two climate zones using the GST index. These are classified as warm and hot by the GST (Jones et al. 2010), suggesting areas which might be suitable for different sets of PD resistant cultivars.

The modeling performed in this dissertation contributes generally to the literature beyond the realm of wine and viticulture. It has implications for environmental modeling of other crops, and human-environment research defined by topographic, soil, and climate based characteristics. Beyond general contributions to environmental modeling there are three primary contributions to the literature offered by this dissertation. First, the terroir of North Carolina's AVAs, the counties representing hearths of viticulture in the state, and its vineyards have been quantified. They can now be compared to other wine growing regions. This should also help local vineyards and wineries build a cogent narrative on the basis of authoritative research, and objective terroir analysis.

The second major contribution relates to the creation of a new means of visualizing PD risk across the Southeast. This was accomplished by summing the mean annual number of days below the two temperature minimum thresholds outlined in Turner Sutton's PD risk analysis by using daily PRISM climate surfaces. The daily PRISM surfaces spanned a 33-year period, and represented a methodology which took into account local topography, lapse rates, and historic temperature from PRISM. The algorithms used to develop PRISM surfaces are superior to a simple local regression from a few climate data points and model this across the region over a 33-year period. The resulting surface illustrates the change in risk along the PD risk boundary in a single map instead of the previous two maps. The 4km resolution effectively summarizes the diffusion of risk along the PD risk boundary in the Southeast.

The final contribution relates to the interpretation of Andrew Weiss' topographic position modeling technique. The creation of a locally calibrated topographic position index surface is perhaps the most broadly applicable to site suitability analysis. This surface reveals relative elevation and takes into account the terrain at three different distance scales. This should not only be useful for viticulturists, but also niche agricultural modeling where pooling cold air is a risk.

This dissertation addressed gaps in the literature, relating geography to wine through GIScience-based modeling of viticultural terroir. This research addressed the gaps in the literature relating to the terroir of North Carolina, Pierce's Disease risk modeling, vineyard site selection considerations related to relative elevation and topographic position. It revealed the zone which, other than PD risk, is otherwise climate suitable for viticulture across the Southeast. This sets the foundation for a career-long academic research program.

I am currently researching climate change using the PD risk boundary in the Southeast. The results of this research will reveal winter warming which has occurred over the last four decades in this region. I am planning to research the spatial patterns associated with cultural practices in viticulture and oenology related to row direction and variety selection. I am also planning to take a census of the relative percentages of grape varieties being grown in the state. Future research plans include development of a multi-criteria terroir analysis model for Southeastern viticulture, the modification of these modeling techniques to other niche agricultural crops and other human-environment problems. Surveying the North Carolina Winegrowers Association members on their PD risk outcomes, and historic frost damage spatial patterns are also topics of interest.

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APPENDIX A

MEAN TERROIR ANALYSIS RESULTS BY APPELLATION AND VINEYARD, (CHAPTER II) *

No.	**Appellation**		**Area (sq. km)**	**elev (m)**	**Phys Prov**	**ECR**	**PDR**	**PPT**	**FFP**	**GDD**	**GST**	**HI**	**BEDD**
1	Yadkin Valley		5788.03	353.2	Pied.	0.28	10.1	1184	198	2037	19.5	2540	1461
2	Haw River		2478.80	187.6	Pied.	0.01	5.4	1145	213	2305	20.8	2785	1586
3	Swan Creek		593.29	294.3	Pied.	0.33	8.5	1166	202	2118	19.9	2596	1464
4	Upper Hiwassee Highlands		1786.96	602.6	Mts.	0.53	14.4	1468	181	1816	18.5	2342	1382
5	Buncombe		1708.71	818.0	Mts.	1.05	17.1	1132	181	1591	17.4	2122	1274
6	Yadkin		874.09	290.4	Pied.	0.33	9.2	1162	199	2078	19.7	2601	1469
7	Duplin		2122.42	28.9	Cst.	0.00	2.3	1281	219	2523	21.8	2938	1718
	Vineyard Name	**Soil Series-Txt-Dominant %**	**Area (ha)**										
8	A Secret Garden Winery	Norfolk loamy sand 71.9%	0.31	39.8	Cst.	0.00	2.3	1190	226	2521	21.8	2946	1714
9	Adagio Vineyards	Fairview sandy clay loam 92.6%	1.65	370.4	Pied.	0.33	10.9	1204	196	2018	19.4	2534	1424
10	Adams Vineyards & Winery	Norfolk loamy sand 95.9%	3.69	103.1	Cst.	0.00	3.8	1179	218	2402	21.2	2855	1620
11	Addison Farms Vineyard	Clifton clay loam 100%	1.29	683.8	Mts.	1.00	16.5	1010	176	1689	17.9	2282	1282
12	Allison Oaks Vineyards	Clifford sandy clay loam 96.9%	1.87	274.4	Pied.	0.33	10.1	1141	197	2083	19.7	2600	1477
13	Autumn Creek Vineyards	Poplar Forest sandy clay loam 95.8%	2.11	291.0	Pied.	0.33	8.5	1172	200	2113	19.9	2638	1482
14	Backroad Farm & Vineyard	Cecil sandy clay loam 100%	0.46	145.3	Pied.	0.00	8.0	1118	202	2215	20.4	2730	1521
15	Baker Buffalo Creek Vineyard & Winery	Pacolet sandy clay loam 70.6%	2.40	272.9	Pied.	0.00	6.7	1192	205	2262	20.6	2746	1554
16	Banner Elk Winery	Porters gravelly loam 54.8%	0.32	1234.7	Mts.	4.33	34.5	1409	169	1045	14.6	1504	500
17	Bannerman Vineyard & Winery	Onslow loamy fine sand 79.4%	5.87	6.0	Cst.	0.00	2.4	1379	215	2570	22.0	2972	1762
18	Beaverdam Vineyards	Thurmont-Dillard complex 53.2%	1.20	540.6	Mts.	0.67	16.2	1728	179	1824	18.5	2404	1373
19	Belle Nicho Winery	Hayesville clay loam 100%	0.12	363.6	Pied.	0.33	10.4	1262	198	2092	19.8	2638	1497
20	Benjamin Vineyards & Winery	Appling coarse sandy loam 76.6%	1.82	155.8	Pied.	0.00	5.4	1134	213	2318	20.8	2797	1576
21	Bennett Vineyards	Lynchburg fine sandy loam 41.7%	10.25	9.2	Cst.	0.00	1.1	1307	248	2660	22.4	2966	1998
22	Biltmore Winewery & Vineyards	Evard-Cowee complex 73.8%	27.84	636.2	Mts.	0.67	13.7	1068	183	1761	18.2	2302	1331
23	Botticelli Vineyards	Goldsboro-Urban land complex 82.0%	2.18	5.1	Cst.	0.00	1.8	1411	228	2581	22.1	2924	1865
24	Brandon Hills Vineyard	Nathalie fine sandy loam 47.3%	1.27	271.6	Pied.	0.33	9.1	1149	199	2095	19.8	2620	1481

25	Burntshirt Vineyards	Bradson gravelly loam 43.3%	7.36	672.5	Mts.	0.67	11.1	1396	195	1810	18.5	2325	1401
26	Calaboose Cellars	Lonon-Northcove-Urban land complex 100%	0.04	557.1	Mts.	0.67	15.3	1619	181	1840	18.6	2174	1397
27	Cape Fear Vineyard & Winery	Wakulla sand 95.9%	1.22	35.9	Cst.	0.00	1.6	1231	225	2613	22.2	3012	1784
28	Carolina Heritage Vineyard & Winery	Fairview sandy clay loam 100%	2.60	295.1	Pied.	0.33	9.6	1182	196	2045	19.6	2610	1464
29	Cauble Creek Vineyard	Lloyd clay loam 97.2%	2.80	242.1	Pied.	0.00	7.3	1079	200	2212	20.3	2700	1561
30	Cellar 4201	Tomlin sandy clay loam 65.9%	1.70	283.4	Pied.	0.33	8.5	1136	200	2124	19.9	2629	1482
31	Charts Hill V	Poindexter-Wynott complex 70.9%	1.61	254.2	Pied.	0.00	6.6	1114	206	2225	20.4	2699	1583
32	Chestnut Trail Vineyard	Pacolet sandy clay loam 100%	0.33	238.9	Pied.	0.00	9.4	1109	194	2193	20.2	2726	1549
33	Childress Vineyards	Pacolet sandy loam 53.1%	17.13	220.5	Pied.	0.00	6.7	1105	204	2279	20.6	2748	1540
34	Cloer Family Vineyards	White Store sandy loam 79.2%	0.50	97.2	Pied.	0.00	5.3	1160	217	2351	21.0	2815	1613
35	Cottle Farms	Norfolk loamy sand 39.4%	39.18	43.6	Cst.	0.00	2.1	1222	222	2523	21.8	2939	1691
36	Crooked Run Vineyards	Autryville loamy sand 100%	6.14	33.4	Cst.	0.00	1.9	1230	222	2559	22.0	2963	1715
37	CrossIn Back Vineyards	Herndon silt loam 100%	0.27	166.3	Pied.	0.00	5.4	1142	210	2311	20.8	2784	1581
38	Cypress Bend Vineyards	Kenansville loamy sand 100%	3.15	64.2	Cst.	0.00	2.4	1164	224	2594	22.1	3019	1752
39	Davesté Vineyards	Lloyd clay loam 53%	1.50	269.8	Pied.	0.33	7.2	1128	204	2175	20.2	2649	1549
40	DD Farms & Vineyard	Cecil sandy clay loam 100%	0.12	218.9	Pied.	0.00	2.9	1137	230	2459	21.5	2854	1837
41	Deerpath Farm	Blanton sand 98.7%	0.76	37.0	Cst.	0.00	1.9	1266	221	2568	22.0	2986	1764
42	Demariano Vineyards	Hayesville clay loam 100%	0.33	394.3	Pied.	0.33	9.7	1285	197	2070	19.7	2555	1452
43	Dennis Vineyards & Winery	Badin channery silt loam 71.6%	2.61	150.2	Pied.	0.00	3.9	1191	211	2407	21.2	2910	1649
44	Divine Llama Vineyards	Tomlin sandy clay loam 50.3%	1.48	294.8	Pied.	0.33	8.5	1139	200	2128	19.9	2629	1482
45	Dobbins Creek Vineyards	Poplar Forest gravelly fine sandy loam 100%	2.18	407.7	Pied.	0.33	8.6	1204	202	2035	19.5	2545	1453
46	Douglas Vineyards	Saw-Pacolet complex 100%	0.20	251.6	Pied.	0.00	5.8	1121	205	2265	20.6	2798	1601
47	Eagle Fork Vineyards	Reddies loam 66.7%	0.39	653.2	Mts.	0.33	15.5	1628	186	1618	17.6	2086	1539
48	Elkin Creek Vineyard	Fairview sandy loam 97.6%	1.66	319.9	Pied.	0.33	10.7	1204	196	2018	19.4	2570	1451
49	Fiddler’s Vineyard	Cecil sandy clay loam 91%	0.58	305.0	Pied.	0.00	6.5	1187	205	2255	20.5	2752	1587
50	Flint Hill Vineyards	Tomlin sandy clay loam 100%	1.81	284.3	Pied.	0.33	8.2	1139	200	2125	19.9	2595	1488
51	Foster Vineyards	Vance sandy loam 63.0%	16.67	113.0	Pied.	0.33	7.1	1146	205	2249	20.5	2779	1561
52	Fussy Gourmet Farms, LLC	Autryville loamy sand 100%	0.04	112.9	Cst.	0.00	3.1	1169	221	2533	21.8	2977	1697
53	Garden Gate Vineyards	Mecklenburg clay loam 72.7%	0.21	244.3	Pied.	0.00	9.3	1120	197	2175	20.2	2693	1507
54	Ginger Creek Vineyards	Fairview sandy clay loam 100%	0.15	365.7	Pied.	0.33	7.7	1217	209	2138	20.0	2571	1593
55	Golden Road Vineyards	Woolwine-Fairview-Westfield complex 99.5%	1.94	378.3	Pied.	0.33	11.9	1227	193	1952	19.1	2515	1407
56	Grandfather Vineyard & Winery	Ashe-Chestnut complex 57.7%	1.22	968.7	Mts.	3.67	29.4	1409	171	1197	15.4	1680	1207
57	Granny Pearls Farm	Appling sandy loam 100%	0.01	112.7	Pied.	0.00	4.3	1156	219	2347	21.0	2783	1595
58	Grapefull Sisters Vineyard	Goldsboro fine sandy loam 64.0%	0.74	14.0	Cst.	0.00	1.3	1307	227	2625	22.3	2983	1750
59	Grassy Creek Vineyard & Winery	Fairview sandy clay loam 100%	7.65	363.4	Pied.	0.33	10.0	1204	196	2018	19.4	2568	1449
60	Green Creek Winery	Cecil sandy clay loam 100%	2.82	311.8	Pied.	0.33	5.8	1331	209	2246	20.5	2777	1597
61	Green River Vineyard	Pacolet-Bethlehem complex 96.5%	1.78	272.8	Pied.	0.33	7.1	1260	206	2259	20.6	2785	1582
62	Gregory Vineyards	Gilead sandy loam 100%	2.53	63.5	Cst.	0.00	3.9	1152	218	2420	21.3	2905	1633
63	Grietje's Garden of Rocky Ridge Farm	Woolwine-Fairview-Westfield complex 96.2%	0.76	289.8	Pied.	0.33	8.8	1155	203	2126	19.9	2631	1469
64	Griffin Evergreens & Vineyard	Dothan loamy sand 67.2%	0.57	132.1	Cst.	0.00	4.3	1154	221	2431	21.4	2867	1682

65	Grove Winery & Vineyards	Enon fine sandy loam 53.0%	2.17	214.0	Pied.	0.00	5.8	1151	210	2284	20.7	2759	1592
66	Hanover Park Vineyard	Clover fine sandy loam 100%	3.21	273.0	Pied.	0.33	8.9	1132	199	2117	19.9	2633	1489
67	Herrera Vineyards	Fairview sandy clay loam 57.6%	4.44	335.8	Pied.	0.33	9.4	1192	194	1985	19.3	2533	1424
68	Hinnant Family Vineyards & Winery	Dorian fine sandy loam 37.0%	24.54	49.5	Cst.	0.00	3.2	1189	220	2448	21.4	2901	1641
69	Huffman Vineyards & Winery	Stallings loamy fine sand 88.2%	0.32	20.9	Cst.	0.00	2.6	1297	215	2487	21.6	2905	1694
70	Hutton Vineyards	Fairview sandy clay loam 100%	13.05	318.6	Pied.	0.33	9.4	1165	197	2037	19.5	2578	1449
71	Iron Gate Vineyards & Winery	Helena coarse sandy loam 53.6%	2.91	191.7	Pied.	0.00	5.8	1149	209	2300	20.7	2800	1545
72	Jewel of the Blue Ridge Vineyard	Walnut-Oteen-Mars hill complex 100%	0.16	640.4	Mts.	1.00	16.5	992	176	1790	18.4	2389	1379
73	JOLO Winery & Vineyards	Woolwine-Fairview-Westfield complex 82.3%	3.36	308.2	Pied.	0.33	7.9	1148	201	2100	19.8	2618	1464
74	Jones von Drehle Vineyards & Winery	Fairview sandy loam 56.3%	11.94	446.1	Pied.	0.33	11.8	1246	193	1863	18.7	2405	1382
75	Junius Lindsay Vineyard	Pacolet sandy loam 100%	3.97	252.3	Pied.	0.00	6.8	1102	204	2242	20.5	2720	1545
76	Lake Road Winery	Lynchburg fine sandy loam 100%	0.02	7.4	Cst.	0.00	0.9	1437	250	2624	22.3	2866	1958
77	Laurel Gray Vineyards & Winery	Nathalie fine sandy loam 52.1%	4.12	336.5	Pied.	0.33	8.7	1186	200	2068	19.7	2549	1446
78	Lazy Elm Vineyard & Winery	Clifford sandy clay loam 100%	2.26	248.8	Pied.	0.00	8.2	1114	197	2172	20.2	2671	1492
79	Linville Falls Winery	Edneytown-Pigeonroost complex 82.2%	0.73	1045.7	Mts.	2.33	28.8	1357	166	1220	15.6	1705	1273
80	Little River Vineyards & Winery	Mayodan sandy clay loam 85.1%	8.04	73.1	Pied.	0.02	3.4	1197	219	2542	21.9	2992	1720
81	Locklear Vineyard & Winery	Norfolk loamy sand 88.4%	1.97	56.6	Cst.	0.00	2.3	1167	227	2601	22.2	3016	1740
82	Lu Mil Vineyard	Norfolk loamy fine sand 46.7%	14.39	35.3	Cst.	0.00	1.5	1175	227	2630	22.3	3012	1771
83	Martin Vineyard & Orchard	Conetoe loamy sand 95.9%	2.24	3.1	Cst.	0.00	0.9	1193	257	2440	21.4	2656	1428
84	Maxwell Creek Vineyard	Autryville loamy fine sand 73.4%	5.63	24.8	Cst.	0.00	2.2	1299	218	2521	21.8	2937	1720
85	McDuffie Family Farm	Norfolk loamy fine sand 57.6%	3.59	33.1	Cst.	0.00	1.4	1220	227	2639	22.3	3013	1780
86	McRitchie Winery & Ciderworks	Fairview sandy clay loam 82.9%	1.06	422.0	Pied.	0.33	11.8	1246	193	1863	18.7	2405	1382
87	Medaloni Cellars	Siloam sandy loam 78.4%	0.39	246.6	Pied.	0.33	9.5	1131	198	2133	20.0	2649	1495
88	MenaRick Vineyard & Winery	Fairview sandy clay loam 84.1%	3.14	371.2	Pied.	0.33	10.5	1200	199	2067	19.7	2540	1423
89	Mill Branch Vineyards	Noboco loamy fine sand 60.9%	1.38	22.3	Cst.	0.00	2.4	1297	215	2504	21.7	2936	1742
90	Misty Creek Vineyards	Oak Level clay loam 31.9%	5.61	245.3	Pied.	0.33	8.8	1119	200	2145	20.0	2654	1490
91	Morgan Ridge Vineyards	Uwharrie silty clay loam 93.5%	2.72	221.1	Pied.	0.00	6.0	1125	204	2314	20.8	2794	1572
92	Mountain Brook Vineyards	Madison sandy clay loam 81.7%	2.77	275.4	Pied.	0.33	7.1	1269	206	2261	20.6	2782	1596
93	Myrick Vineyards, LLC	Norfolk loamy sand 66.1%	1.86	55.3	Cst.	0.00	3.2	1186	224	2439	21.4	2883	1643
94	Native Son Vineyard & Farm	Badin-Tarrus complex 100%	1.21	272.2	Pied.	0.00	5.0	1135	219	2303	20.8	2743	1667
95	Native Vines Winery	Appling sandy loam 87.0%	0.23	245.1	Pied.	0.00	7.1	1086	203	2246	20.5	2750	1524
96	Neuse River Winery	Yonges loamy fine sand 94.1%	1.18	2.2	Cst.	0.00	0.9	1387	256	2631	22.3	2898	1993
97	Nottely River Valley Vineyards	Braddock gravelly loam 91.4%	1.98	514.6	Mts.	0.67	13.3	1396	186	1980	19.3	2496	1434
98	Old Stone Winery	Appling sandy loam 99.7%	3.54	238.4	Pied.	0.00	6.6	1100	203	2253	20.5	2697	1542
99	Overmountain Vineyards	Pacolet-Bethlehem complex 85.5%	2.55	298.3	Pied.	0.33	6.5	1269	206	2261	20.6	2747	1571
100	Owl's Eye Vineyard & Winery	Cecil sandy clay loam 70.1%	4.12	266.6	Pied.	0.33	6.6	1202	204	2272	20.6	2766	1572
101	Parker-Binns Vineyard	Pacolet sandy clay loam 100%	1.53	303.4	Pied.	0.33	7.3	1368	203	2213	20.3	2747	1561
102	Patria Properties	Fairview fine sandy loam 100%	0.49	253.0	Pied.	0.33	8.5	1122	203	2173	20.2	2671	1485
103	Pennini Vineayrds	Rhodhiss sandy loam 82.6%	0.92	188.2	Pied.	0.00	6.6	1145	205	2254	20.5	2732	1518
104	Piccione Vineyards	Fairview sandy clay loam 88.3%	5.99	343.6	Pied.	0.33	9.0	1206	200	2032	19.5	2655	1486

105	Raffaldini Vineyards & Winery	Fairview sandy clay loam 99.1%	16.96	353.2	Pied.	0.33	9.0	1206	200	2032	19.5	2655	1486
106	RagApple Lassie Vineyards	Clifford sandy clay loam 79.4%	10.21	318.7	Pied.	0.33	9.7	1163	197	2041	19.5	2596	1471
107	RayLen Vineyards & Winery	Oak Level clay loam 48.0%	15.35	238.2	Pied.	0.00	8.5	1121	197	2186	20.2	2705	1526
108	Rinaldi Estate Vineyard	Pacolet sandy clay loam 86.9%	2.43	254.7	Pied.	0.00	7.0	1102	203	2224	20.4	2720	1561
109	Roaring River Vineyards	Rhodhiss-Bannertown complex 62.2%	0.78	360.2	Pied.	0.33	11.1	1178	196	2011	19.4	2497	1401
110	Rock of Ages Winery & Vineyard	Enon fine sandy loam 61.5%	10.25	189.7	Pied.	0.00	6.6	1153	206	2258	20.5	2756	1537
111	Rocky River Vineyards	Goldston very channery silt loam 90.7%	2.71	159.8	Pied.	0.00	4.0	1144	218	2452	21.5	2915	1637
112	Round Peak Vineyards	Woolwine-Fairview-Westfield complex 98.1%	5.34	392.2	Pied.	0.33	11.9	1221	193	1907	18.9	2453	1401
113	Saint Paul Mountain Vineyards	Hayesville loam 96.6%	1.18	660.4	Mts.	0.67	11.1	1331	190	1784	18.3	2325	1401
114	Sanctuary Vineyards	Bojac loamy sand 42.1%	1.42	3.5	Cst.	0.00	0.5	1246	268	2440	21.4	2566	1231
115	Sanders Ridge Vineyard & Winery	Clifford fine sandy loam 93.9%	5.69	293.1	Pied.	0.33	9.5	1163	197	2041	19.5	2591	1456
116	Shadow Springs Vineyard	Nathalie fine sandy loam 40.1%	4.25	331.4	Pied.	0.33	8.8	1180	200	2073	19.7	2589	1445
117	Shelton Vineyards	Fairview sandy clay loam 92.9%	46.74	371.8	Pied.	0.33	10.7	1204	194	1955	19.1	2496	1410
118	SilkHope Winery	Georgeville-Badin complex 100%	0.65	198.3	Pied.	0.00	4.7	1162	218	2299	20.7	2780	1606
119	Silver Coast Winery	Foreston loamy fine sand 100%	0.18	15.5	Cst.	0.00	1.4	1346	227	2615	22.2	2948	1854
120	Silver Fork Vineyard & Winery	Fairview sandy clay loam 100%	1.21	371.0	Pied.	0.33	9.8	1246	199	2111	19.9	2649	1499
121	Six Waterpots Vineyard & Winery	Woolwine-Fairview-Urban land complex 100%	0.32	387.9	Pied.	0.33	8.5	1208	204	2118	19.9	2592	1478
122	South Creek Vineyards & Winery	Hayesville-Evard complex 47.2%	0.54	351.9	Pied.	0.33	10.4	1262	198	2092	19.8	2669	1516
123	Stephens Vineyard & Winery	Pantego fine sandy loam 100%	0.07	43.4	Cst.	0.00	1.7	1161	227	2605	22.2	3002	1738
124	Stonefield Cellars Winery	Clifford sandy loam 100%	0.62	288.2	Pied.	0.00	5.8	1124	212	2223	20.4	2669	1733
125	Stony Knoll Vineyards	Clifford sandy clay loam 64.4%	2.02	331.3	Pied.	0.33	9.3	1165	197	2037	19.5	2567	1441
126	Stony Mountain Vineyards	Enon very cobbly loam 100%	1.14	183.4	Pied.	0.00	4.3	1196	212	2495	21.7	2975	1711
127	Sweet Home Carolina Vineyard & Winery	Clifford sandy clay loam 100%	0.12	266.8	Pied.	0.33	10.4	1137	197	2089	19.8	2601	1475
128	The Tipsy Bee	Rains fine sandy loam 91.4%	0.35	20.9	Cst.	0.00	2.5	1306	215	2516	21.8	2930	1730
129	Treehouse Vineyards	Badin-Urban land complex 100%	1.40	178.6	Pied.	0.00	2.5	1164	227	2489	21.6	2886	1709
130	Triple B Vineyard	Cecil sandy clay loam 94.7%	0.77	267.9	Pied.	0.33	6.8	1186	207	2267	20.6	2766	1580
131	Twisted Vine Winery	Fairview sandy clay loam 100%	0.10	387.4	Pied.	0.33	8.9	1217	204	2093	19.8	2610	1486
132	Uwharrie Vineyards	Tarrus channery silt loam 86.8%	5.33	180.4	Pied.	0.00	4.5	1191	209	2360	21.0	2823	1623
133	Valley River Vineyards	Statler loam 72.6%	0.71	505.9	Mts.	0.67	13.6	1392	183	1920	19.0	2321	1321
134	Waldensian Heritage Wines	Meadowfield-Rhodhiss complex 50.0%	0.10	349.9	Pied.	0.33	8.4	1216	204	2147	20.0	2661	1484
135	Warren Farms Vineyard	Goldsboro loamy sand 83.3%	7.13	7.2	Cst.	0.00	1.5	1335	230	2563	22.0	2926	1767
136	Weathervane Winery	Pacolet sandy loam 100%	0.78	247.3	Pied.	0.00	6.8	1102	204	2242	20.5	2735	1546
137	White Rock Vineyard	Helena sandy loam 100%	0.03	224.1	Pied.	0.00	5.7	1161	210	2295	20.7	2789	1573
138	Willis Dixon Vineyard	Norfolk loamy fine sand 100%	1.01	15.1	Cst.	0.00	1.9	1384	227	2553	21.9	2914	1808
139	Windsor Run Cellars	Clifford sandy clay loam 62.4%	2.69	338.5	Pied.	0.33	8.9	1188	200	2068	19.7	2589	1445
140	Wolfe Wines	Orange silt loam 100%	0.20	183.8	Pied.	0.00	5.1	1134	216	2301	20.8	2768	1600
141	WoodMill Winery	Cecil sandy clay loam 71.9%	3.48	318.0	Pied.	0.33	6.9	1194	205	2223	20.4	2711	1555
142	Younts Wine Farm	Clover fine sandy loam 100%	2.17	211.2	Pied.	0.33	8.9	1132	198	2105	19.8	2619	1472
143	Zimmerman Vineyards	Badin-Tarrus complex 100%	1.93	162.3	Pied.	0.00	6.8	1130	205	2308	20.8	2781	1591

* Appendix A represents the results from Chapter II; the parameter data sources listed below were used to generate this data along with the methods described in Nowlin and Bunch 2016a and Nowlin and Bunch 2016b [Chapter II]:

Appellation Boundaries: created by John W. Nowlin from the textual descriptions given in C.F.R. Title 27 § Part 9.174, 9.211, 9.214, 9.234, and 9.260. These boundaries were generated manually by following the text and creating the polygons using the referenced USGS base maps and their features; this was performed in ESRI ArcMap 10.3.1

County Boundaries: generated by John W. Nowlin using data supplied by ArcGIS for Desktop Data and Maps, 2015 (\usa\census\dtl_cnty.gdb)

Vineyard Boundaries: boundaries were created by John W. Nowlin from geolocating public lists of NC commercial vineyards {NCWine.org, northcarolinamuscadinegrapeassociation.org, Nowlin (2013), Nowlin and Bunch 2016a, and Nowlin and Bunch 2016b [Chapter II]}, and creating polygons using aerial imagery from publicly available sources (ArcGIS Online: world imagery and NAIP layers along with Google Maps imagery)

Soil Series-Txt-Dominant %: generated by John W. Nowlin using ESRI ArcMap 10.3.1. & gSSURGO

Area: generated by John W. Nowlin using ESRI ArcMap 10.3.1

[Absolute] Elevation: generated by John W. Nowlin using ESRI ArcMap 10.3.1. and the most recently available NED DEM (10m) in July 2015.

[Physiographic Province] Phys Prov: Mts.= Mountains, Pied. = Piedmont, and Cst. = Coastal Plain; generated by John W. Nowlin using ESRI ArcMap 10.3.1.U.S. EPA Eco Regions Level IV

[Precipitation] PPT: generated by John W. Nowlin using ESRI ArcMap 10.3.1.; derived from PRISIM monthly precipitation between 1981 and 2014

ECR, PDR, FFP, GDD, GST, HI, and BEDD: generated by John W. Nowlin using ESRI ArcMap 10.3.1, & derived from PRISIM maximum & minimum temperature, daily data between 1981 and 2014

APPENDIX B

VINEYARD SITE SELECTION ASSESSMENT, FAILING CELLS (CHAPTER III) *

Vineyard	#Cells	PDR	Aspect	GDD	MJT	FFP	ECR	TPI	Slope	Depth	Drain.	Pct. Silt
A Secret Garden Winery	31	31	9	0	0	0	0	0	0	0	8	0
Adagio Vineyards	165	0	0	0	0	0	0	0	4	0	0	0
Adams Vineyards and Winery	363	363	147	0	0	0	0	0	0	0	13	0
Addison Farms Vineyard	128	0	32	0	0	0	0	0	71	0	0	0
Allison Oaks Vineyards	187	0	105	0	0	0	0	0	0	0	5	0
Autumn Creek Vineyards	206	0	107	0	0	0	0	0	9	0	0	0
Backroad Farm and Vineyard	46	0	0	0	0	0	0	0	0	0	0	0
Baker Buffalo Creek Vineyard & Winery	236	0	200	0	0	0	0	0	0	0	0	0
Banner Elk Winery	32	0	25	0	0	0	32	0	14	0	0	0
Bannerman Vineyard and Winery	577	577	110	0	0	0	0	1	0	0	117	0
Beaverdam Vineyards	120	0	89	0	0	0	0	0	33	0	0	0
Belle Nicho Winery	12	0	12	0	0	0	0	0	0	0	0	0
Belsogno Vineyard @ Fiore Farms	112	0	50	0	0	0	0	0	0	0	0	0
Benjamin Vineyards & Winery	180	0	30	0	0	0	0	0	0	0	0	0
Bennett Vineyards	1005	1005	358	0	0	0	0	1	0	0	554	0
Benny Parsons Rendezvous Ridge	166	0	117	0	0	0	0	0	161	0	0	0
Biltmore Winery and Vineyards	2718	0	998	0	0	0	0	0	737	0	0	0
Botticelli Vineyards	214	214	40	0	0	0	0	0	0	0	0	0
Boulder Vineyard	85	0	4	0	0	0	0	0	0	0	0	0
Brandon Hills Vineyard	125	0	23	0	0	0	0	0	1	0	0	0
Burntshirt Vineyards	723	0	107	0	0	0	0	0	0	0	36	0
Calaboose Cellars	4	0	0	0	0	0	0	0	1	0	0	0
Cape Fear Vineyard and Winery	121	121	0	0	0	0	0	0	0	0	0	0
Carolina Heritage Vineyard & Winery	257	0	63	0	0	0	0	0	112	0	0	0
Cauble Creek Vineyard	275	0	263	0	0	0	0	0	0	0	0	0
Cellar 4201	172	0	58	0	0	0	0	0	16	0	0	0
Cerminaro Vineyard	149	0	73	0	0	0	0	0	50	0	0	0
Charts Hill V	160	0	8	0	0	0	0	0	24	0	0	0
Chateau Laurinda Vineyards	35	0	29	0	0	0	0	0	18	0	0	0
Chestnut Trail Vineyard	34	0	33	0	0	0	0	0	10	0	0	0
Childress Vineyards	1671	0	606	0	0	0	0	56	150	0	55	0
Chinqua Penn	107	0	65	0	0	0	0	0	0	0	0	0
Cloer Family Vineyards	52	0	8	0	0	0	0	0	0	0	2	0
Cottle Farms	3837	3837	962	0	0	0	0	340	0	0	526	0
Crooked Run Vineyards	604	604	0	0	0	0	0	0	0	0	0	0
CrossIn Back Vineyards	26	0	0	0	0	0	0	0	0	0	0	26

Cypress Bend Vineyards	310	310	73	0	0	0	0	0	0	0	0	0
Davesté Vineyards	141	0	19	0	0	0	0	0	1	0	0	0
DD Farms and Vineyard	11	11	11	0	0	0	0	0	0	0	0	0
Deerpath Farm	76	76	30	0	0	0	0	0	0	0	0	0
Demariano Vineyards	33	0	0	0	0	0	0	0	2	0	0	0
Dennis Vineyards & Winery	257	41	10	0	0	0	0	0	0	0	0	191
Divine Llama Vineyards	147	0	73	0	0	0	0	0	0	55	0	0
Dobbins Creek Vineyards	215	0	52	0	0	0	0	0	74	0	0	0
Douglas Vineyards	19	0	6	0	0	0	0	0	0	0	0	0
Eagle Fork Vineyards	36	0	10	0	0	0	0	0	0	0	5	0
Elkin Creek Vineyard	169	0	32	0	0	0	0	0	120	0	0	0
Enoch Winery & Vineyard	178	178	17	0	0	0	0	0	0	0	2	0
Fiddler’s Vineyard	61	0	15	0	0	0	0	0	0	0	0	0
Flint Hill Vineyards	176	0	32	0	0	0	0	0	0	0	0	0
Foster Vineyards	1642	0	673	0	0	0	0	0	17	0	18	0
Fussy Gourmet Farms, LLC	4	4	4	0	0	0	0	0	0	0	0	0
Garden Gate Vineyards	21	0	10	0	0	0	0	0	0	0	0	0
Ginger Creek Vineyards	13	0	5	0	0	0	0	0	0	0	0	0
GlenMarie Vineyards & Winery	47	0	16	0	0	0	0	0	0	4	0	0
Golden Road Vineyards	191	0	53	0	0	0	0	0	59	0	0	0
Grandfather Vineyard & Winery	116	0	0	0	0	0	116	0	112	69	0	0
Grapefull Sisters Vineyard	75	75	8	0	0	0	0	0	0	0	24	0
Grassy Creek Vineyard & Winery	750	0	435	0	0	0	0	0	10	0	0	0
Green Creek Winery	277	0	137	0	0	0	0	0	0	0	0	0
Green River Vineyard	175	0	48	0	0	0	0	0	91	0	0	0
Gregory Vineyards	248	248	25	0	0	0	0	0	0	0	0	0
Grietje's Garden of Rocky Ridge Farm	77	0	0	0	0	0	0	0	0	0	0	0
Griffin Evergreens & Vineyard	55	55	10	0	0	0	0	0	0	0	0	0
Grove Winery & Vineyards	214	0	27	0	0	0	0	0	0	0	0	0
Hanover Park Vineyard	317	0	131	0	0	0	0	0	0	0	0	0
Herrera Vineyards	440	0	160	0	0	0	0	0	14	0	0	0
Hinnant Family Vineyards & Winery	2404	2404	740	0	0	0	0	23	0	65	148	0
Horizon Cellars	102	0	63	0	0	0	0	0	0	0	0	92
Huffman Vineyards Winery ...	34	34	1	0	0	0	0	0	0	0	30	0
Hutton Vineyards	1299	0	446	0	0	0	0	0	2	0	0	0
Iron Gate Vineyards & Winery	281	0	33	0	0	0	0	0	0	0	0	0
Jewel of the Blue Ridge Vineyard	19	0	7	0	0	0	0	0	13	19	0	0
JOLO Winery & Vineyards	329	0	107	0	0	0	0	0	73	0	0	0
Jones Vineyards & Winery	1174	0	854	0	0	0	0	0	204	0	0	0
Jones von Drehle Vineyards & Winery	1	0	1	0	0	0	0	0	0	0	0	0
Junius Lindsay Vineyard	387	0	136	0	0	0	0	0	1	0	0	0
Lake Road Winery	4	4	0	0	0	0	0	0	0	0	3	0
Laurel Gray Vineyards & Winery	406	0	255	0	0	0	0	0	0	0	0	0
Lazy Elm Vineyard and Winery	219	0	20	0	0	0	0	0	0	0	0	0
Linville Falls Winery	71	0	46	0	0	0	0	0	62	0	0	0

Little River Vineyards and Winery	790	782	249	0	0	0	0	0	1	0	0	0
Locklear Vineyard & Winery	191	191	6	0	191	0	0	0	0	0	1	0
Lu Mil Vineyard	1557	1557	533	0	1402	0	0	0	0	0	130	0
Martin Vineyard & Orchard	219	219	88	0	0	0	0	0	0	0	10	0
Maxwell Creek Vineyard	549	549	324	0	0	0	0	0	0	0	53	0
McDuffie Family Farm	350	350	57	0	350	0	0	0	0	0	2	0
McRitchie Winery	98	0	59	0	0	0	0	0	59	0	0	0
Medaloni Cellars	38	0	24	0	0	0	0	0	24	28	0	0
MenaRick Vineyard & Winery	303	0	0	0	0	0	0	0	27	0	0	0
Mill Branch Vineyards	135	135	83	0	0	0	0	0	0	0	0	0
Misty Creek Vineyards	552	0	294	0	0	0	0	0	28	0	0	0
Moonrise Bay Vineyard	392	392	63	0	0	0	0	0	0	0	0	0
Morgan Ridge Vineyards	266	0	0	0	0	0	0	0	1	0	0	0
Mountain Brook Vineyards	277	0	66	0	0	0	0	0	28	0	0	0
Myrick Vineyards, LLC	180	180	13	0	0	0	0	0	0	0	0	63
Native Son Vineyard and Farm	115	0	0	0	0	0	0	0	3	0	0	0
Native Vines Winery	22	0	4	0	0	0	0	0	0	0	0	0
Neuse River Winery	117	117	32	0	0	0	0	0	0	0	110	0
Nottely River Valley Vineyards	193	0	47	0	0	0	0	0	0	0	0	0
Old Stone Winery	352	0	44	0	0	0	0	0	0	0	0	0
Overmountain Vineyards	253	0	96	0	0	0	0	0	45	0	0	0
Owl's Eye Vineyard & Winery	406	0	153	0	0	0	0	0	33	0	0	0
Parker-Binns Vineyard	150	0	87	0	0	0	0	0	14	0	0	0
Patria Properties	48	0	13	0	0	0	0	0	7	0	0	0
Pennini Vineyards	92	0	9	0	0	0	0	0	2	18	0	0
Piccione Vineyards	589	0	57	0	0	0	0	0	7	0	64	0
Plott Hound Vineyard	8	0	8	0	0	0	0	0	0	0	0	0
Raffaldini Vineyards & Winery	1666	0	162	0	0	0	0	0	17	0	0	0
RagApple Lassie Vineyards	1014	0	190	0	0	0	0	0	12	0	0	0
RayLen Vineyards & Winery	1512	0	640	0	0	0	0	0	25	0	0	0
Rinaldi Estate Vineyard	240	0	15	0	0	0	0	0	46	0	0	0
Riverbirch Vineyard	162	0	36	0	0	0	0	0	0	0	0	0
Roaring River Vineyards	76	0	33	0	0	0	0	0	69	0	0	0
Rock of Ages Winery & Vineyard	1011	0	85	0	0	0	0	0	0	0	0	0
Rockhouse Vineyards	314	0	84	0	0	0	0	0	4	0	0	0
Rocky River Vineyards	266	266	111	0	0	0	0	0	6	244	0	266
Round Peak Vineyards	529	0	144	0	0	0	0	0	78	0	0	0
Saint Paul Mountain Vineyards	114	0	66	0	0	0	0	0	0	0	0	0
Sanctuary Vineyards	136	136	11	0	0	0	0	0	0	0	51	0
Sanders Ridge Vineyard & Winery	559	0	301	0	0	0	0	0	10	0	0	0
Shadow Springs Vineyard	417	0	15	0	0	0	0	0	0	0	4	0
Shelton Vineyards	4579	0	1358	0	0	0	0	0	380	0	0	0
SilkHope Winery	58	0	0	0	0	0	0	0	0	0	0	0
Silver Coast Winery	11	11	0	0	0	0	0	0	0	0	0	0
Silver Fork Vineyard & Winery	116	0	3	0	0	0	0	0	63	0	0	0

Six Waterpots Vineyard & Winery	32	0	0	0	0	0	0	0	0	0	0	0
South Creek Vineyards & Winery	50	0	0	0	0	0	0	0	21	0	26	0
Stephens Vineyard & Winery	7	7	2	0	7	0	0	0	0	0	7	0
Stonefield Cellars Winery	61	0	0	0	0	0	0	0	0	0	0	0
Stony Knoll Vineyards	205	0	108	0	0	0	0	0	7	0	0	0
Stony Mountain Vineyards	112	0	0	0	0	0	0	0	110	0	0	0
Storr's Vineyard	109	0	31	0	0	0	0	0	0	109	0	0
Surry County Community College Vineyard & Winery	290	0	151	0	0	0	0	0	0	0	0	0
Sweet Home Carolina Vineyard & Winery	11	0	0	0	0	0	0	0	10	0	0	0
The Tipsy Bee	35	35	1	0	0	0	0	0	0	0	31	0
Treehouse Vineyards	132	132	68	0	0	0	0	0	1	1	0	131
Triple B Vineyard	75	0	41	0	0	0	0	0	0	0	0	0
Twisted Vine Winery	10	0	10	0	0	0	0	0	0	0	0	0
Unknown Maple Hill Vineyard	259	259	65	0	0	0	0	0	0	0	232	0
Unknown Rose Hill Vineyard	2967	2967	843	0	0	0	0	0	0	0	611	0
Unknown Vineyard	229	63	69	0	5	0	5	2	41	4	8	5
Unknown Vineyard close to Lake Brandt	19	0	0	0	0	0	0	0	0	0	0	0
Unknown Vineyard off Pleasant Ridge Rd	26	0	0	0	0	0	0	0	0	0	0	0
Upper Piedmont Research Station	72	0	55	0	0	0	0	0	0	0	0	0
Uwharrie Vineyards	516	0	8	0	0	0	0	0	0	0	0	67
Valley River Vineyards	67	0	1	0	0	0	0	0	0	0	7	0
Ventosa Plantation Vineyard & Winery	659	659	352	0	0	0	0	0	0	0	0	0
Waldensian Heritage Wines	9	0	8	0	0	0	0	0	0	0	0	0
Warren Farms Vineyard	700	700	79	0	0	0	0	0	0	0	7	0
Weathervane Winery	71	0	46	0	0	0	0	0	0	0	0	0
Westbend Vineyards	715	0	181	0	0	0	0	0	40	0	0	0
White Rock Vineyard	3	0	1	0	0	0	0	0	0	0	0	0
Willis Dixon Vineyard	100	100	30	0	0	0	0	0	0	0	0	0
Windsor Run Cellars	265	0	24	0	0	0	0	0	0	0	0	0
Wolfe Wines	20	0	5	0	0	0	0	0	0	0	0	20
WoodMill Winery	346	0	0	0	0	0	0	0	0	0	0	0
Younts Wine Farm	211	0	81	0	0	0	0	0	24	0	0	0
Zimmerman Vineyards	186	0	0	0	0	0	0	18	99	0	0	137
Grand Total	**57747**	**19999**	**17485**	**0**	**1955**	**0**	**153**	**441**	**3608**	**616**	**2900**	**998**

*Appendix B represents the results from Chapter III; the parameter data sources listed below were used to generate this data along with the methods described in Nowlin and Bunch 2016a, Nowlin and Bunch 2016b, and Nowlin and Bunch 2016c [Chapter III]:

Vineyard Name: boundaries were created by the author from geolocating public lists of NC commercial vineyards {NCWine.org, northcarolinamuscadinegrapeassociation.org, Nowlin (2013), Nowlin and Bunch 2016a, and Nowlin and Bunch 2016b [Chapter II]}, and creating polygons using aerial imagery from publicly available sources (ArcGIS Online: world imagery and NAIP layers along with Google Maps imagery)

10m cells falling in each area: generated by John W. Nowlin for each area using ESRI ArcMap 10.4.1

[Topographic] Aspect, TPI, Slope: generated by John W. Nowlin for each area using ESRI ArcMap 10.4.1, & the most recently available NED DEM (10m) in July 2015

[Soil] Depth, Drainage, %Silt: generated by John W. Nowlin for each area using ESRI ArcMap 10.4.1 & gSSURGO (10m)

GDD, PDR, MJT, FFP, ECR: generated by John W. Nowlin for each area using ESRI ArcMap 10.4.1, & derived from PRISIM maximum & minimum temperature (originally 4km sampled at 10m), daily data between 1981 and 2014

APPENDIX C

LIST OF ACRONYMS

(AOC)	Appellation d’Origine Contrôlée
(AVA)	American Viticultural Area
(BEDD)	Biologically Effective Degree Day
(CES)	Cooperative Extension Service
(DEM)	Digital Elevation Model
(DO/DOC/DOCG)	Denominazione di Origine/ Controllata/ e Garantita
(DTR)	Diurnal Temperature Range
(ECR)	Extreme Cold Risk
(FFP)	Frost Free Period
(GDD)	Growing Degree-Days
(GI)	Geographic Indication
(GIS)	Geographic Information Systems
(GIScience)	Geographic Information Science
(gSSURGO)	Gridded SSURGO
(GST)	Growing Season Temperature
(HI)	Huglin Index
(MJT)	Mean July Temperature
(NAIP)	National Agricultural Imagery Program
(NED)	National Elevation Dataset
(NCWGG)	North Carolina Wine Grower’s Guide
(NRCS)	Natural Resources Conservation Service
(PD)	Pierce’s Disease
(PDO)	Protected Denomination of Origin
(PDR)	Pierce’s Disease Risk
(PGI)	Protected Geographical Indication
(PPT)	Precipitation
(SSURGO)	Soil Survey Geographic Database
(STATSGO)	State Soil Geographic Dataset
(TPI)	Topographic Position Index
(TMean)	Mean Daily Mean Temperature
(TMax)	Mean daily Maximum Temperature
(TMin)	Mean daily Minimum Temperature