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The North Carolina wine industry is growing at a fast pace; many new vineyards are being planted with European varieties. *Vitis vinifera* varieties in general are the most challenging species of grape grown, and the cost of vineyard establishment is high. While many grapes are native to North Carolina, *V. vinifera* are not; they require considerable effort to consistently produce good quality grapes for wine making. The challenges of growing *V. vinifera* in this region are primarily due to the warm, humid climate which encourages the presence of many insect pests as well as a broad host of viral, bacterial, and fungal diseases. When these risks are considered alongside the possibilities of late spring frost and heavy rain from harvest time tropical systems, it is apparent that there is a need for a system which mitigates these risks and helps guide the choices for vineyard location.

The model produced in this research was designed to help guide site selection for *V. vinifera* vineyards in the North Carolina Piedmont. The area of interest for this case study is Rockingham County, North Carolina. The primary goal is to give the prospective grape grower every opportunity for success by choosing the best possible place to establish a vineyard. This is accomplished using a model based on the science of Geographic Information Systems (GIS) along with predictive geophysical parameters. The model consists of four physical sub model composites which represent the

capability/suitability of: climate, land cover, soil, and topography. Using the concepts of map algebra, the four sub model composites are combined to produce the final output that summarizes the physical site suitability of the study area at a spatial resolution of ten meters.

A MESOSCALE GEOPHYSICAL CAPABILITY/SUITABILITY MODEL

FOR *VITIS VINIFERA* VINEYARD SITE SELECTION IN THE

NORTH CAROLINA PIEDMONT TRIAD REGION,

CASE STUDY: ROCKINGHAM COUNTY NC

by

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APPROVAL PAGE

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CHAPTER I

INTRODUCTION

Boom in North Carolina Viticulture

A recent study states that the economic impact of the North Carolina wine industry is $1.28 Billion (Frank, Rimerman + Co. LLP 2011). This same study also indicates that the demand for NC grapes now outpaces supply. In 2005, there were 55 bonded wineries in North Carolina. As of December of 2011, the number of wineries has grown to 106 across 49 of the state's 100 counties. This represents an increase of 93% in less than six years (Owens 2011). The explosive growth of the wine industry and vineyards in North Carolina is expected to continue well into the future. The installation of a vineyard is expensive, time-consuming, and takes considerable effort. There is great benefit for the grape grower to plan accordingly by thoroughly considering all of the site location characteristics so that the variety of grape being grown matches the vineyard's site (Wolf 1995; IAGT 2011; Poling 2007; Sommers 2008; Jones et al. 2004). A 1994 estimate for the cost of establishment of a typical four hectare (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. This is before taking into account a profit of $5,683 per hectare ($2,300 per acre) of harvested grapes in the third year; this 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; Wolf 1995). A similar 2005 estimation for establishing a four hectare (10 acre) Chardonnay vineyard on a good site in North Carolina was that it typically costs $31,816 per hectare ($12,876 per acre) after three years (Poling 2007). In 2008, the installation cost for a typical vineyard was estimated at $29,652 per hectare ($12,000 per acre; Hobson Jr., F.W., owner of Rag Apple Lassie Vineyards). This 2008 estimate did not account for land preparation, mowing, herbicides, pesticides, fungicides, soil nutrient adjustment, or labor in the first three years. If there were no more expenses in the first year other than the cost of installation, and all other costs were similarly increased, the three year cost in 2008 would be about $46,702 per hectare ($18,900 per acre). None of these estimates account for the cost of the land or preparation before vineyard installation.

These estimations illustrate the economic commitment made when establishing a vineyard. This commitment illustrates the importance of choosing a suitable site for the vineyard, not only because of the initial costs, but also because the site choice will impact the annual operating expenses and long term productivity of the vineyard. The proper site can reduce the risk of vine health problems and increase the likelihood of good long term yields, increasing economic sustainability for the vineyard operator.

Thesis Objectives

The objective of this thesis is to produce a mesoscale geophysical site capability/suitability model that will assist those intending to establish a commercial *Vitis vinifera* vineyard in the Piedmont Triad region of North Carolina. The product of the model is a high resolution continuous graded surface county map that is created by using a database and site suitability/capability concepts at a spatial resolution of 10 meters. This media is intended to be useful in either printed or digital form so as to be capable of being incorporated into digital resources, such as web mapping applications.

The intended audience for the proposed model is represented by three groups. The first group consists of those seeking land to purchase for the establishment of a *V. vinifera* vineyard. This would include hypothetical agents of rural gentrification streaming from the cities to inflate rural land prices. The second group consists of current land owners considering the capability/suitability of their land for establishing a *V. vinifera* vineyard; among others, this includes transitioning tobacco farmers. The third group consists of those with a regional focus, such as those advising groups one and two, namely viticultural extension professionals, viticultural consultants, real estate agents, vineyard operators, and/or wineries investigating the creation of an American Viticultural Area (AVA), as well as other researchers interested in viticultural site selection in a region. The processes and data outlined herein may also be incorporated into other similar agroclimatic site capability and/or suitability studies.

Another important goal of this project was to produce a methodology that can be improved as new data and information clarifies the valuations of the model parameters. This model should also compliment other viticultural GIS work in North Carolina. Other than the maps produced directly by this model, with its limited study area, it should be understood that there is great purpose in the idea of a county scale viticultural suitability model. There is also great value in the use of GIS for other agricultural site suitability research. The value extends past local capability/suitability maps toward consideration of the development of practical GIS based tools useful for considering the viticultural and other niche agricultural potential of the greater North Carolina Piedmont Region. Many choices are made in this model about specific parameters of influence and thresholds of suitability which are based on physical law, empirical evidence and logical reasoning, yet it is fully acknowledged that there may be better ways to arrange the parameters and/or thresholds. This is a relatively new region for *Vitis vinifera* and this project should be useful for organizing the set of spatial concepts which should guide the future of viticultural site selection.

CHAPTER II

BACKGROUND

Historical Geography of Viticulture

It is estimated that *V. vinifera*, commonly known as the European wine grape, has been cultivated by humans for more than 6000 years. Viticulture likely began in the Caucasus Mountains somewhere close to modern day Georgia. Through trade and conquest, wine was passed between the early Sumerian, Egyptian, Assyrian, Hittite, Minoan, Mycenaean, Phoenician, Hebrew, Babylonian, and Persian cultures. The Greeks passed viticulture along to the Romans, who cultivated wine grapes across their empire. As this vast region fell to the successive powers, many vineyards were abandoned, yet cultivation continued as did scientific horticultural pursuit (McGovern 2007).

Sustenance, pleasure, and hygiene were not the only reasons for making wine in medieval Europe. 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 (Zondervan 2011), books of the Christian Bible. This is likely why the monks of this period are credited with the development of many modern practices of viticulture (Blij, H. J. de, 1983). While it is likely that the monks shared varieties with their brothers from adjoining regions, they most likely would have also been crossing varieties found growing wild in their local area. The wild Roman cultivars, having been released to the devices of nature, likely interbred with each other, with the wild varieties, and with those vines being cultivated. This pattern of modifications to the gene pool likely resulted in unique varieties that persisted where they were resistant to local disease and compatible with local climate. In short, these varieties of grapes became particularly well suited to their respective physical environments (Blij, H. J. de, 1983). As would be the practice of most agriculturalists, the local wine makers isolated grape varieties that were particularly high yielding and well suited to making wine. These successful grape cultivars likely were traded and incorporated into areas where they prospered. These concepts of historical viticulture of the European wine grape well illustrate the tangled web of the relationships between man, place, and grape.

History of Wine in North Carolina

North Carolina has a long and storied past as a wine and grape producing region. Native Americans consumed grapes long before Europeans visited the state, and from the first accounts of European visitors, it is apparent that the region was home to a diverse variety of native grapes. The oldest cultivated grapevine in North America is on Roanoke Island in the northeastern corner of North Carolina; it is a scuppernong vine known affectionately as the “Mother Vine,” and its origin is a mystery. The first historical evidence dates to 1720, but it could be far older, and some think that it either predates European settlement or was planted by the lost colony of Roanoke Island in the mid 1580’s (Helsley 2010; Kickler 2012).

In her 2010 book titled "A History of North Carolina Wine," Alexia Jones Helsley shares some very early accounts which highlight the history of wine grapes in the region. The earliest account is in 1524; upon a trip to the North Carolina coast, Giovanni da Verrazanno writes to the King of France stating that there are, "many vines growing naturally," and "without all doubt, they would yield excellent wines." Another account comes from 1584 by Arthur Barlow, an explorer along with Phillip Amadas; Barlow describes a land so full of grapes that they grow over the trees on the hills and down the beach to the edge of the ocean waves. John Smith in 1606 also notes the manner that Native Americans grew grapes around their villages and at the forest edge. In January of 1670, Joseph West of Charles Town in the Province of Carolina (today's Charleston, SC) planted an experimental vineyard. In 1671, Joseph Dalton wrote Lord Anthony Ashley asking for grapevines and describing what must be a local muscadine cultivar from which he planned to try and make wine. Influenced by John Lawson, there are records of vineyards in Bath and New Bern before 1737 (Helsley, 2010). It is apparent that the vine of North Carolina's wine history has deep roots.

As European settlers peopled the state, the production of wine grew; in the mid 1800's, "The Old North State" produced more wine than any other state. Most of this early North Carolina wine was muscadine wine, but there was also wine produced from native fox grapes (*V. labrusca*) such as Catawba, Concord, and Niagara. This is not to say that there was no effort to grow the European varieties in North Carolina. There were many early attempts to grow *V. vinifera* varieties, all of which eventually failed due to the susceptibility of European grapes to the many diseases native to North Carolina. *V. vinifera* cannot be grown commercially in this state without modern forms of agriculture which include regular chemical spray routines.

Regardless of the variety, Prohibition had a devastating effect on the Tar Heel wine industry. After almost completely destroying wine production, the major producers moved their operations out of the state, and in 1930, there were only 383 vines growing in commercial vineyards. By 1969, there were no more wineries producing wine in North Carolina, yet many grapes were grown for processing out of state (Helsley, 2010).

Three notable wineries in the history of modern wine production in North Carolina are Duplin Winery, Westbend Vineyards, and Biltmore Estate Winery. In 1972, Jack Kroustalis established Westbend Vineyards and produced the first commercial *V. vinifera* wine grown in North Carolina. By 1986, they had a 70 ton grape harvest. Following in the footsteps of Deerfield Cellars, in 1975, Duplin Winery produced its first wine from muscadine grapes, and in 1976, they sold their first bottle. Duplin is now the largest winery operating in the Southeast and sells more wine made from muscadine grapes than any other winery in the world—1.4 million gallons in 2009. The Biltmore Estate started a vineyard in the early 1970s and grew French hybrids and European varieties. They sold their first bottle in 1979, and as of 2012, the Biltmore Estate Winery has the most annual visitors of any winery in North America (Helsley, 2010). In 2005, there were 55 bonded wineries in North Carolina; today there are 106 spread across 49 of the state's 100 counties. This is an increase of 58% in less than six years (Owens 2011).

Commercial vineyards and wineries are businesses requiring specialized know-how. There has certainly been an effort by the wine industry in North Carolina to develop the educational resources needed for the burgeoning wine trade. Each of the physiographic provinces in the state has schools specializing in Viticulture and Enology. In the mountains, Appalachian State University has developed a Bachelor of Science degree program in Fermentation Sciences within their Enology and Viticulture Program (http://wine.appstate.edu/program). On the Coastal Plain, James Sprunt Community College (http://www.jamessprunt.edu/Viticulture.html) has developed a Viticulture and Enology Technology program offering Certificates and an Associate of Applied Science degree in Viticulture and Enology Technology. In the Piedmont, Surry County Community College has an excellent new facility in its Shelton-Badgett North Carolina Viticulture and Enology Center (http://ncviticulturecenter.com/). This program also offers Associate Degree Programs in Viticulture and Enology as well as offering their facilities for regular meetings of wine professionals, especially at meetings of the regional trade organization known as the North Carolina Wine Growers Association (http://www.ncwinegrowers.com).

The following grape species are currently grown commercially in North Carolina: *Vitis aestivalis*, *Vitis labrusca*, *Muscadinia rotundifolia (formerly Vitis rotundifolia)*, *Vitis vinifera*, and French or American Hybrids between these species. Native American varieties originate from *V. aestivalis*, *V. labrusca*, and *M. rotundifolia.* *V. aestivalis* is known as The Summer Grape, the primary variety is Norton, aka Cynthiana. *V. labrusca* is known as The Fox Grape; common varieties include Catawba, Concord, and Niagara. *M. rotundifolia* is known as the muscadine and is primarily grown on the Coastal Plain and Lower Piedmont; there are many varieties of muscadines, but one of the most popular is scuppernong, the variety of the Mother Vine. *V. vinifera* is the European grape; some of the most common varieties are Cabernet Sauvignon, Chardonnay, and Merlot. French Hybrids are hybrids between French and American species developed in France; common varieties grown in North Carolina include Chambourcin and Seyval Blanc. American Hybrids are hybrids between French and American species developed in North America; common varieties include Chardonel and Traminette.

V. vinifera can generally be considered as the most challenging species of grape grown in North Carolina. Because of the shared *V. vinifera* genes, hybrids of *V. vinifera* have similar challenges, therefore the model being presented here should also be applicable to site selection for both French and American Hybrids. *V. vinifera* sites should be equally suitable for *V. aestivalis* and *V. labrusca* vines, but *V. aestivalis* can be grown on many sites not suitable for *V. vinifera*, particularly in areas troubled with Pierce's Disease to the East and South of the wine growing regions of the Piedmont. *V. labrusca* is more cold tolerant than *V. vinifera* and can be grown in areas with cooler winters. On the other hand, in all but the coolest locales of the state, *M. rotundifolia* would be able to be planted on a *V. vinifera* site chosen with this model, however *V. rotundafolia* is much more at home in the eastern part of North Carolina where *V. vinifera* can't be grown. For these reasons, it is assumed that this model is not useful for the Native American varieties based on *V. rotundafolia*, *V. aestivalis*, or *V. labrusca*, even if it could be used in certain locations in the Piedmont. This is primarily because these varieties tend to be less needy, more cold tolerant, and/or more disease resistant than *V. vinifera.* Basically, this model will be too restrictive to be optimal for typical Native American varieties.

Terroir

Regionality is an important concept when considering the geography of wine. One particularly important term associated with wine and related to regionality is *terroir*. The term *terroir* comes from the French word for "earth" or "soil"; it is a viticultural concept which characterizes the interrelations between winemakers, vineyard operators, vineyard sites, and grapes. Terroir is a viticultural notion which attempts to summarize the set of variables associated with a certain place that, together, impart a local character to its wine. These variables are both cultural and physical (Vaudour 2002; Blij 1983; Van Leeuwen and Seguin 2006; White 2009; Sommers 2008).

The cultural aspects of terroir relate to the practices of the viticulturist in the vineyard and the winemaker in the winery which affect the regional character of a wine. The winemaker and viticulturist make choices together and communicate about timing of the harvest for certain sugar and acid levels; they also schedule pickup, transportation, and delivery of the picked grapes. The viticulturist makes many choices that affect the grape, such as the method of training, which includes vine and row spacing, height and shape of the canopy, location of the fruit on the vine, and the type of plants that grow between the rows. They choose the height of the fruit, the method, timing and volume of fruit thinning, the maintenance of the canopy, canes and cordons, and the amount of light and air circulation experienced by the grapes, as well as the use, volumes, and application intervals of solutions of fertilizer, pesticide and fungicide. The winemaker makes many choices about the timing of the various processes associated with making wine. They crush and de-stem the grapes, adjust and monitor sugar content, acid content, sulfur content, nitrogen content, and the amount of oxygen allowed to be in contact with the aging wine. They choose the yeast variety, control the temperature, punch down the cap, and choose when and how to press the grapes, what to store the aging wine in, and when to bottle. Furthermore, they make decisions about whether or not to perform a host of optional processes such as: cold soak, extended maceration, malolactic fermentation, use of oak, toast of oak, time in oak, whether or not to use enzymes, glycerin, gums or tannins, and in what proportions to blend with other wines. All of these and the many other processes not mentioned that are associated with the running of the vineyard and the making of wine can be categorized as cultural practices (Cox 1999; Johnson and Robinson 2007; Poling 2007; Wolf 1995).

The physical side of terroir is related to the physical variables which change from place to place. These are variables of climate, geology, soil, land cover, and topography. These categories correlate to each other in complex ways and vary across the surface of the earth to produce a variety of unique environments capable of supporting viticulture

(Vaudour 2002). While the purpose with this research is not to model terroir in the holistic sense, because this model does not consider culture, the parameters of the model relate directly to and can be considered as major elements of the physical geography of terroir.

Wine Regions, Appellation, and Scale

Growing grapes for wine can be considered at many geo-spatial scales from the sub-continental scale down to one row in a particular vineyard. The common scales at which wine regions are typically considered are the synoptic scale where wine growing areas are described in terms such as the Mediterranean Basin or Eastern Australia. Another common scale used to describe wine growing regions is the macroscale; these regions may use political boundaries in their names such as France, Chile, or California, or even sub regions within political units such as Italy's Piedmonte or South Africa's Western Cape. The legally defined polygon known as an appellation is another common unit of area related to wine regions. There are a few very large appellations that would fit into the macroscale. One particularly important scale is the mesoscale. Most appellations fall within this scale, and these regions are most typically mentioned on a bottle of wine; some good examples include Saint-Émilion, Barolo, or Napa Valley. At the microscale is where wine regions are limited to a group of vineyards, a single vineyard, or even a few rows of a particular vineyard plot. There are even a few exclusive and very small appellations that fit within this smallest scale such as La

Romanée in the Burgundy region of France which has an area smaller than .85 hectares (< 2.1 acres).

The concept of an appellation originated in France as a notion somewhat related to terroir. France's appellation system, known as Appellation d'Origine Contrôlée (AOC), is the result of a highly detailed set of laws, firmly in place by 1930. The purpose is related both to controlling quality and protecting the economies of established wine growing regions. Appellations are precisely defined wine growing regions, wherein the producers of wine have sole legal rights to the use of the appellation name and other appellation specific terms on the label, as long as they follow the rules for making wine in that area. These rules specify which varieties can be used, the yield of grapes per unit area, the way the vines are trained, pruned, spaced within the row, the distance between rows, dates and conditions of harvest, and length of ageing, among many other rules. A practical example of the function of the AOC would be the case of Champagne, unless a wine originates in the Champagne appellation and conforms to 35 rules of the AOC, including approved varieties, height, spacing and harvest techniques, etc., it may not be labeled "Champagne." Today many countries have similar systems. For instance, in Italy there is an appellation system known as Denominazione di Origine Controllata (DOC). There is a large amount of variance from country to country on how these regions came into being and the level of complexity needed for a wine to receive a designation (Johnson and Robinson 2007; Blij, H. J. de, 1983).

The American system of appellation, known as the American Viticultural Area (AVA) is administered by the Department of Alcohol, Tobacco, Firearms and Explosives, which is set forth in Title 27 of the Code of Federal Regulations (27 C.F.R § Part 9. 1979). While the U.S. had its first European wine grapes planted around 1600 by Spanish monks close to El Paso, Texas, the first legally designated appellation in the U.S. was the Augusta AVA in Augusta, Missouri (27 C.F.R § Part 9. 1979). As of May 24, 2011, there were 197 AVAs in the US. The AVA system is quite simple by European standards and exists to control the use of the AVA name to the growers within the boundaries of the AVA. This differs from the AOC, DOC, and other European systems of appellation in that the AVA is purely geographic and currently has no cultural restrictions. Most wine produced in the U.S. is sold by varietal name, such as Cabernet Sauvignon, Pinot Noir, or Chardonnay, rather than by regional blend such as Bordeaux, Burgundy, or Champagne. Even with a varietal name rather than a blend, however, the AVA is typically listed on higher quality U.S. wines.

One particularly important choice when modeling the physical properties of viticultural site suitability is the extent of the area to be considered. This scale component will direct the choice of resolution, or granular scale, for the model when the model is producing an output such as a map. The common extent of recent viticultural GIS studies is the local wine growing region, which measures between 10 and 100 km (6 and 60 miles) across in the example studies. This area is the mesoscale region mentioned earlier as the most common scale for viticultural appellations. In fact, most of these studies were considering the area within a formal appellation. The common granular scale or resolution of these viticultural GIS studies is 10 m (32.8 feet), which extends into the microscale (Vaudour 2002; Jones, Snead, and Nelson 2004; Jones, Duff, and Myers 2006; Irimia and Patriche 2010; Irimia and Patriche 2011). North Carolina's counties range in area from about 570 to 3885 sq. kilometers (220 to 1500 sq. miles). Its commercial vineyards range from under one to over 80 hectares (under 1 to over 200 acres) (Helsley 2010). Ten meters is a good granular scale for both of these spatial entities—counties and vineyards. This is because 10 meters is small enough to communicate useable information on the scale of the typical vineyard while being large enough to be individually perceptible at the scale of the typical North Carolina County. An important practical benefit of 10 meter data is that many different types of information are available at this scale, and the file sizes for county sized extents of all such data needed for this model would fit onto a 16 gigabyte flash drive.

CHAPTER III

LITERATURE REVIEW

Modeling Site Suitability

Studies in the geography of wine in general and those using GIS in particular are quite consistent in their organization of the important physical realms of consideration. It makes sense that the parameters of comparison and characterization of physical terroir tend to be similar from study to study; this is because vines growing grapes have a set of physical requirements which are fixed and not relative to where they are planted. Consider the example where vine wood is propagated from a single plant and planted in two different wine growing regions. For example, consider if a vine is planted in the Mosel Valley of Germany and the other in the Uco Valley of Argentina. The needs of the plant are the same, yet the places are quite different. It would not make sense to discuss those things which are similar between these two locations, such as the relative percentages of oxygen and nitrogen in the air or the nature of gravity in the two locations. While those phenomena do vary across space, the amount of variation is inconsequential, or at least we are not capable of quantifying how those slight differences matter to vines which grow grapes. It is natural, however, to focus on the environmental differences between these two locations. The wines produced in Germany tend to be different from those produced in Argentina, even if they come from the same mother vine. So the topics found in the literature about using GIS to analyze wine growing regions tends to focus on information that is useful for comparing one place to another. The use of GIS to consider viticultural site selection tends to focus on the extremes of the physical environment which limit the capability of planting a vineyard as well as those characteristics which can differentiate one place from another. Descriptive and predictive GIS models are in good agreement about the general physical characteristics that should be considered as a part of physical terroir. These physical parameters fall into four general realms: topography, soil, climate, and land cover.

GIS studies in viticulture tend to fall into two categories, descriptive or predictive. They are either primarily studies which describe the physical character of a region, or those which evaluate the capability and/or suitability for viticulture (Bowen et al. 2005; Foss et al. 2010; Hellman et al. 2011; Imre and Mauk 2009; Jones, Duff, and Myers 2006; Jones, Snead, and Nelson 2004; Shaw 1999). The descriptive GIS studies tend to focus on the physical attributes of the terroir within the viticultural region (Hellman et al. 2011; Bowen et al. 2005). These studies are typically intended to inform a general readership about what is unique in a particular viticultural region, or what is similar to other regions. These descriptions tend to focus on notable landforms and the statistics of regional viticulture. Descriptive studies may describe sub regions, but they are not specifically instructive about where to place a vineyard. Predictive studies tend to include the same kinds of information as the descriptive studies; however, they go a step further and model the viticultural capability and/or suitability of the region. The models are typically illustrated by thematic maps which are intended to be useful for understanding which areas were good for planting a vineyard or even a certain set of varieties and which areas should be avoided (Foss et al. 2010; Irimia and Patriche 2010; Irimia and Patriche 2011; Jones, Snead, and Nelson 2004; Jones, Duff, and Myers 2006).

Viticultural capability models based on GIS are constructed entirely of pass/fail variables (Foss et al. 2010). A simple example of this would be a map which illustrates land cover with three classes: soil, water, and exposed bedrock. Since a vineyard cannot be planted on water or exposed bedrock, a capability model would be applied to these three classes such that the class of soil would pass and the classes of water and bedrock would fail. There are two members to the domain in this example: passing and failing. The passing member is made of the class of soil, and the failing member is made up of the water and bedrock classes. One set of classes is capable and passes, while the other is incapable and fails. Alone, this type of model is quite primitive compared to suitability modeling.

Suitability models are typically combinations of pass/fail variables and variables with more than two classes of value. A simple suitability model could have three members to its domain, such as good, fair, and poor. A simple example of such a suitability model would be with a parameter such as soil depth. In the example model, as soil gets deeper, it is more suitable for viticulture, therefore deeper soils would get a higher grade of suitability than shallower soils, this could be done in discrete classes, i.e., below 60cm (2 ft) = poor, 60 to 90 cm (2 to3 ft) = fair, and > 90cm (3ft) = good. It is also common to consider capability as one of the classes of suitability. For example, in the above soil depth suitability model, maybe there would be a class of capability such that soils must be at least 30 cm (1ft) deep to pass. Then, their suitability would increase with depth. i.e., below 30cm (1ft) = fail, 30 to 60cm (1 to 2 ft) = poor, 60 to 90 cm (2 to3 ft) = fair, and > 90cm (3ft) = good. In this case, the soil parameters are graded for both capability and suitability. (Irimia and Patriche 2010; Irimia and Patriche 2011; Jones, Duff, and Myers 2006; Jones, Snead, and Nelson 2004).

In most GIS based viticulture models, there are multiple parameters considered and then combined with each other to produce a composite suitability. Take for example the combination of the above two models, land cover and soil depth. The land cover parameter classes of water, bedrock, and soil would be graded pass or fail. Then, the soil depth parameter would be graded as fail, poor, fair, or good. Then the two layers of graded surfaces would be combined with each other to give a composite layer. This composite later would be a more comprehensive view of the viticultural suitability of the area than either of the previous models had produced individually. This multi parameter model can be called a capability/suitability model.

Topographic Suitability

Topographic analysis about advantageous vineyard position along the surface of the earth is a central component of all reviewed literature relating viticulture to GIS. The terrain or surface relief of an area and the relative location of phenomena along this surface are considerations of spatial analysis. Spatial analysis performed using GIS is particularly useful for the situation of vineyard sites along the terrain as well as communicating the nature of the change in suitability over space. The consideration of a change in viticultural suitability with a change in position along the surface of the planet is a significant key to optimizing the climate of the vineyard. The absence of GIScience, spatial analysis, and the use of GIS tools might contribute to decisions such as locating a vineyard in a topographic concavity which could lead to an overabundance of water in the soil. It could also lead to the location of a vineyard in the shadow of a mountain such that the site would receive sunlight in less than optimal amounts at less than advantageous times. These examples illustrate that slight changes in position can result in large changes in the vineyard environment, impacting productivity, health, and ultimately success or failure of the vineyard.

The topographical parameters included in most GIS models for viticultural site suitability are elevation, slope, and aspect (Foss et al. 2010; Irimia and Patriche 2010; Irimia and Patriche 2011; Jones, Snead, and Nelson 2004; Jones, Duff, and Myers 2006). The data used to derive GIS layers for topographic parameters are Digital Elevation Models (DEMs; Boyer 1998, Foss et al. 2010; Irimia and Patriche 2010; Irimia and Patriche 2011; Jones, Snead, and Nelson 2004; Jones, Duff, and Myers 2006). The spatial resolution of modern studies has increased significantly (30 m to 10 m) along with advances in geospatial data collection (Boyer 1998, Foss et al. 2010; Irimia and Patriche

2010; Irimia and Patriche 2011; Jones, Snead, and Nelson 2004; Jones, Duff, and Myers 2006).

Usually, as elevation increases there is a decrease in temperature due to less atmosphere being above each point. This phenomenon is known as adiabatic cooling and is related to a decrease in pressure with altitude. This is well illustrated in mountainous areas where there is often an obvious elevation based boundary such as a tree line or a snow line. The limits of elevation for viticultural suitability are set by temperature. The primary reasons for failing high elevations are short growing seasons, extreme cold temperatures, or frosts occurring during the growing season (Foss et al. 2010; Irimia and Patriche 2010; Irimia and Patriche 2011; Jones, Duff, and Myers 2006; Jones, Snead, and Nelson 2004). Valley bottoms are also limited by temperature because of cold air ponding. Mid-Atlantic regional viticultural extension documentation suggests that in counties where elevations fail to exceed1500 ft, a good rule of thumb is to seek land within the highest 20th percentile elevation (Wolf and Boyer 2003). The extension documentation acknowledges that relative and absolute elevations are important considerations for protection from cold air drainage (Wolf 1995; Poling 2007). No reviewed viticultural GIS literature evaluated relative elevation as a layer; instead they focused solely on absolute elevation, yet the extension documentation mentions relative elevation as well. The importance of relative elevation is due in large part to cold air drainage away from the vineyard.

An article by Jones et al. (2004) evaluates elevation in six graded classes. They found that the most suitable elevation class in the Umpqua Valley of Oregon was 400 to 799 ft., while elevations above 1200 ft were incapable due to freeze hazards. They gave the optimal range a grade of 2, failed elevations above 1200 ft, and classified the remaining elevations into suitability classes with intermediate grades. Table 1 summarizes their model grading for elevation.

Table 1. Grades for elevation range classes (Jones et al. 2004)

Elevation Range ft(m)	Grade
0 - 199 (0 - 650)	0
200 - 399 (50 - 1309)	1
400 - 799 (1310 - 2619)	2
800 - 999 (2620 - 3279)	1
1000 - 1199 (3280 - 3934)	0
> 1200 (3935)	-1

The limits on slope are related to cold air drainage, ease of equipment operation, erosion and soil retention. In areas of low slope, cold air is unable to drain from the surface and can pose a significant frost threat to grape vines. At the other extreme, when slope is too high, it is unsafe to operate agricultural machinery because of tip over hazards. High slope environments also suffer from higher erosion rates, making soil retention problematic. As to the range of capable slope values, Jones et al. suggest that land should fail if flat, defined by slopes below 1%, or on steep slopes which were defined as greater than 30%. They found that the optimal slopes were 5 - 15% (Irimia and Patriche 2010; Irimia and Patriche 2011; Jones, Snead, and Nelson 2004; Jones, Duff, and Myers 2006). Jones et al. (2004) separated slope into six graded classes. The most suitable slopes were assigned a grade of 2. All cells with slopes greater than 30% failed and were assigned -1 (Table 2).

Table 2. Grades for slope range classes (Jones et al. 2004)

Slope Range (%)	Grade
< 1	0
1 - 5	1
5 - 15	2
15 - 20	1
20 - 30	0
> 30	-1

In the reviewed GIS studies, aspect was always considered in terms of four cardinal and four ordinal directions: N, NE, E, SE, S, SW, W, and NW (Foss et al. 2010; Irimia and Patriche 2010; Irimia and Patriche 2011; Jones, Duff, and Myers 2006; Jones, Snead, and Nelson 2004). The studies that weigh aspect give higher weight to southern aspects as more desirable, but it must be noted that these studies were all in cooler climates and higher latitudes than North Carolina. It is not clear from the reviewed GIS literature how to weigh aspect in the Southeast, because regional extension documentation lists benefits to northern aspects and eastern aspects (Wolf 1995; Poling 2007), while the predictive studies favor southern and western aspects. What is certain is that the manner of weighing aspect should be considered based on the impact imparted by aspect on local climate. Jones et al. (2004) chose five classes for aspect: 0–89, 90–134, 135–224, 225–269, 270–360 degrees and graded them 0 through 2 (Table 3). The optimal aspect class was 135-224 (SSE, S, and SSW), which was assigned a grade of 2, while the failing classes were between 270–90 (W, NW, N, NE, and E), which were assigned a grade of -1.

Table 3. Grades for aspect range classes (Jones et al. 2004)

Aspect Range (°)	Grade
0 – 89	0
90 – 134	1
135 – 224	2
225 – 269	1
270 – 360	0

It is important to note that aspect modifies the physical nature of a vineyard site in complex ways. First, it is hard to reduce all aspects to eight classes and apply quantities equitably to them; second, aspect works in concert with slope in such a way so that as slope approaches zero, aspect has a lower unique impact on the terroir of a site; thirdly, zero aspect, which is horizontal land, has no aspect effect. On the local scale, aspect is commonly considered on the basis of its impact on insolation and temperature. This is why it is commonly weighed higher toward southern and western aspects in the cited studies. Each aspect has benefits and disadvantages, however the eastern aspects have the advantage of early morning sun, which means dew evaporates sooner than other aspects; conditions providing drier leaves and fruit should indicate lower fungal loads, especially in humid environments (Wolf 1995; Poling 2007). Northern aspects which are out of the question in many high latitude appellations might be beneficial in the warm humid Southeast, because they are cooler and tend to correct for early warm spring days which can cause early bud break on warmer aspects. Another benefit to northern aspects is that cooler summer night temperatures produce grapes with higher acid content and aromatics, both beneficial to wine quality. Southwest aspects are the driest and hottest in this region, which can be helpful to correct for higher rainfall rates in the growing season, by reducing soil water, but are generally least favorable because of the excessive afternoon temperature and tendency for earlier bud break. These facts make aspect more problematic to grade than other topographic variables like elevation or slope (Wolf and Boyer 2003). In North Carolina, southeast aspects have been cited as optimal for their all-round set of benefits, mostly for the quick evaporation of morning dew which promotes lower fungal pressure, but also for warmer absolute low winter temps, causing less freeze damage (2012 Sara Spayd, Extension Viticulture Specialist & Professor NCSU).

The method used by Jones et al. (2004) to calculate topographic site suitability was to sum the elevation, slope, and aspect scores into one layer. The result was a composite topographic site suitability map. Similar processes were used in other predictive studies with variation in the number of classes, boundaries between classes, and calculation methods (Irimia and Patriche 2010; Irimia and Patriche 2011; Jones, Duff, and Myers 2006).

Soil Suitability

Soil is one of the most basic considerations for proper situation of a vineyard. The presence of too much available water in the soil is a primary topic of concern in the Southeast. In the humid warm North Carolina Piedmont, the soil can contribute to a tendency toward over vigor, which is common in the region. This means that the vines produce so much vegetative growth that the fruit suffers at the expense of making leaves and stems. The term terroir is rooted in the soil, and while high quality wine grapes are grown in a broad range of soils, it is this substance which anchors the vines and provides many of the basic nutrients of life. The primary orders of Piedmont soils are typically formed of very old and highly leached residuum of the Appalachian Mountains and even older mountains which have denuded well below their former elevations to become the rolling hills and low mountains of the Piedmont Region.

The common soil parameters included in GIS models of vineyard site suitability are: pH, depth to bedrock, soil drainage, water holding capacity (Jones, Snead, and Nelson 2004; Jones, Duff, and Myers 2006; Wolf and Boyer 2003), organic matter and texture (Foss et al. 2010). Two common sources for soil data in the U.S. are the U.S. General Soil Map (STATSGO) (Jones, Snead, and Nelson 2004) and Soil Survey Geographic Database (SSURGO) (Jones, Duff, and Myers 2006). STATSGO is macroscale in resolution and would, therefore, be appropriate for scale extent of a state (NRCS 2011a). SSURGO is mesoscale in resolution and would be a better source for a county extent scale defined as 1:12,000 to 1:63,000 (NRCS 2011b).

In the Jones et al. (2004) study, four soil variables were considered: soil drainage from poor to excessive, available water holding capacity (AWHC; inches H_20 per inch of soil), depth to bedrock (inches), and pH. Drainage was considered most important, and the layer was given twice the value of the other layers by weighting it 0.4, and all other soil layers were weighted 0.2, then these layers were scaled by weight and summed into a final soil suitability layer (Table 4).

Table 4. Classes for soil property ranges (Jones et al. 2004)

Soil Property	Pass Range	# Classes
Soil Drainage	N/A	4
AWHC (in./in. soil)	0.1 to 0.3	5
Depth(in.)	25 to 65	3
pH	5 to 6	4

Land Cover/Land Use Suitability

Land use (LU) was considered in some viticultural site suitability studies in Oregon where there are strict zoning laws. These laws limit areas that can be used for agriculture. The areas that were not zoned for agriculture were masked out of the classification (Jones, Snead, and Nelson 2004; Jones, Duff, and Myers 2006). Land Cover (LC) is also tacitly considered by all studies, even if not stated explicitly; it was considered, per se, because certain classes of LC are delineated by soil properties, such as surface water or exposed bedrock. There could also be value to considering areas of previous anthropogenic soil modification such as nutrient depletion, loss of top soil, or horizon compaction. These data used for classification of LU in Oregon were apparently based on zoning maps, which are based on polygon vector files produced by government sources.

With regard to planting *V. vinifera* vineyards, land that has been cleared for several years is optimal, since there must be a multi-year transition if moving from a forest. This period of transition from forest to cleared land is necessary to greatly reduce presence of wild grape vine diseases, pests such as root eating soil organisms. During this period, there is also a change in the microbial & fungal ecologic webs which transition to a being more compatible with a ground cover rather than trees. This period also allows for the complete breakdown and clean up the organic material left from the tree leaf and small root litter. This means that if one is purchasing land to plant a vineyard, they will have the expense of clearing the land, along with the time until the soil has been cleared of pathogens. (Wolf and Boyer 2003; Poling 2007)

Climatological Suitability

Weather readings have been recorded in a systematic and organized manner in the U.S. since the end of the 19^{th} century. Throughout the twentieth century, a system of weather stations, often at airports, was established, and over time, the sensor network has been developed and improved. The records of temperature, precipitation, pressure, and humidity recorded by these stations exist over an increasingly long period. The shortcoming of point based weather data is that weather happens continuously over space yet the data is only recorded at points. The production of continuous weather and climate maps requires the estimation of these phenomena in the area between where the point data is collected, and the process by which this is accomplished is known as interpolation.

The most common simple interpolation methods for climate variables are inverse distance weighting (IDW) and nearest-neighbor; yet these cannot take account of the topographic or orographic effects of complex terrain on the nature of temperature across space. In order to do that, three higher level data sets of interpolated climate data are PRISM, Daymet, and WorldClim. All three of these systems have a resolution of about 800 meters. In the Eastern U.S., all of these systems are in good agreement with each other. Of these methods of interpolation, PRISM is the most commonly cited and generally lowest in error. PRISM takes into account distance and elevation, but also expert knowledge such as the local effects of proximity to coastal zones, local terrain features which drastically affect climate such as orographic barriers, and areas where temperature inversions are common. The biggest flaw of these systems when used to high resolution interpolation is their 800 meter granular scale or resolution.

One particularly promising method of temperature interpolation which can be useful when high resolution is desired is a combination of IDW and the Lapse Rate method. This method involves the correcting of the point station data to a plane based on the mean adiabatic lapse rate and the station elevation. The interpolation is performed with IDW on that plain surface, and then this surface is corrected back to elevation. This is done at high resolution using a DEM at the desired elevation. (Chung et al. 2006). This regional interpolation method would also benefit from the mean lapse rates of the region, and especially those with mean monthly lapse rates (Calvo-Alvarado and Gregory 1997; Table 5).

Table 5. Monthly Mean Adiabatic Lapse Rate with a change in elevation (Calvo-Alvarado and Gregory, 1997)

Month	°C per 100M, Є=0.2
January	–0.42
February	–0.44
March	–0.51
April	–0.51
May	–0.51
June	–0.54
July	–0.57
August	–0.56
September	–0.55
October	–0.48
November	–0.49
December	–0.42

Several useful climate indexes have been created to estimate viticultural suitability. They are all based on temperature since it is critical to the phenology of the vine and resultant fruit quality. These include growing degree days (GDD), biologically effective degree-day (BEDD), growing season temperature (GST), spring frost index (SFI) , dryness index (DI), coolness index (CI), and heliothermal index (HI) (Gladstones 2000; Hall and Jones 2010, Jones and Davis 2000; Tonietto and Carbonneau 2004; Wolf and Boyer 2003). Of all these, GDD is by far the most common method of describing viticultural suitability, and it has the added benefit of few inputs, requiring only average daily maximum and minimum temperatures. At U.C. Davis, Winkler (1974) used GDD to place grape growing regions into five classes (Table 6).

Table 6. Winkler GDD Scale (1974)

GDD Range °C (°F)	Class
< 1388 (2500)	coolest
1388 - 1667 (2500 – 3000)	cool
1667 - 1944 (3000 – 3500)	warm
1944 - 2222 (3500 – 4000)	hot
>2222 (4000)	very hot

SFI evaluates the likelihood of a damaging late spring frost which is certainly a problem in the North Carolina Piedmont and is advocated within the region as a useful tool (Wolf and Boyer 2003). This can be a problem in the Piedmont, which is influenced by spring cold fronts sometimes after the buds have opened. This was especially evident with the economically damaging spring frosts in the 2012 and 2007 growing years.

DI, CI, and HI are often used in Australian Studies (Hall and Jones 2010), but their values are especially useful in combination to characterize clusters of worldwide wine growing areas into similar climate (Tonietto and Carbonneau 2004). This type of analysis would lend itself toward comparative studies in viticulture where the Piedmont Triad wine growing region is being compared to another region on the basis of temperature and precipitation regimes.

The parameters of climate considered most commonly in GIS studies of viticulture are measures of precipitation and temperature. Precipitation is considered on the basis of yearly rainfall (Foss et al. 2010; Hellman et al. 2011; Wolf and Boyer 2003). Low levels of precipitation may be adjusted for by irrigation, while high levels of precipitation may reduce the viticultural suitability of a given area. Mature vines can be expected to use the equivalent of between 61 and 76 cm (24 and 30 inches) of rain per year (Wolf and Boyer 2003). Foss et al. limit precipitation to a range of 45 to 85 cm (17.7 to 33.5 inches) per year (2010).

Temperature is the most critical independent variable as to a region's suitability for growing grapes. There are a number of temperature based variables considered in the literature; these include average annual minimum temperature, average annual maximum temperature, average annual temperature, growing degree days (GDD), frost free period, last spring frost, first fall frost (Hellman et al. 2011; Jones, Snead, and Nelson 2004; Jones, Duff, and Myers 2006) Spring Frost Index (Wolf and Boyer 2003). Other parameters of interest are average date of last frost, average date of first frost, the variability of those two dates, number of frost free days (the growing season), annual mean temperature, and depending on polar hemisphere, mean temperature of July or January (Foss et al. 2010; Wolf and Boyer 2003). The most important temperature control is the average annual minimum temperature, because if temperatures are too cold, the vines can be damaged or killed. In a study from Oregon, Jones et al. suggests an average annual winter minimum of –15°C (5°F) for failing land based on too cold a climate (2004, 2006). Wolf and Boyer with Virginia Extension suggest that areas where there are three occurrences at or below -22°C (-8°F) per decade as the limit for capability (2003). This second threshold mates well to another climate based viticultural hazard in the Southeast which is Pierce's Disease.

Gladstones (2000) states that, "It follows that the range between a spring month's average mean temperature and its average lowest minimum directly measures frost risk, if any, for vines." He used °C when he stated that, "Indices below about 11 shows a low risk, those above 13 a high risk." Wolf and Boyer (2003) used °F and the monthly Tmean and Tmin for their method. Both of these methods have been developed to gauge the risk of frost damage in the spring. Wolf and Boyer use the average monthly minimum temp and Gladstones uses the average lowest temp for the month. This would appear to give pretty different results. The Wolf and Boyer (2003) method seems easier, while the Gladstones method seems to highlight the risk more thoroughly. (Gladstones 2000; Wolf and Boyer 2009). The differences and similarities of the grades are shown in Table 7.

Table 7. SFI classes (Gladstones 2000, Wolf and Boyer 2003)

Gladstones SFI °C(°F) Wolf and Boyer °F{°C}	Risk
<11 (19.8) {6.1}	High
11 - 12 (19.8 - 21.6) {6.1 - 6.6}	Medium High
12 - 13 (21.6 - 23.4) {6.6 - 7.2}	Medium
>13 (23.4) {7.2}	Low

Pierce's Disease

Another important temperature variable, the threshold marking the existence of Pierce's Disease (PD), was not covered in any of the predictive studies. Pierce's Disease is known to be spread by insect vectors such as the glassy-winged sharpshooter (Figure 1; Wood and McBride 2001). There is no cure for PD which typically results in the loss of the vine. This disease is commonly considered in the extension documentation for the

Southeast US, and research is underway regarding a method for how to predict this line using two temperature based thresholds; these are the number of days below either -9.4°C (15.1°F) or -12.2°C (10°F) per year. In the findings of a research study conducted out of North Carolina State University, areas where there were more than two days with temperatures lower than -12.2°C or more than four days with temperatures below -9.4°C had no incidence of PD. Furthermore, the research suggests PD risk thresholds be set at mean annual values of 1, 2, and 3 days below -12.2°C, and 4, 5, and 6 days below -9.4°C. In the North Carolina Piedmont, the areas south and east of these lines are progressively higher risk for experiencing PD (Sutton 2005).

Using 41 weather stations across three states, areas of risk were illustrated for the entire Southeast for two time periods—1972 to 1997 and 1997 to 2005. Due to climate change, there was a major advance of Pierce's Disease risk between these two time frames. The risk area moved up slope and inland from the coast across the Southeast (Sutton, 2005; Anas et al, 2008; Myers et al, 2007). The maps produced in this research were at the synoptic scale and therefore too low in resolution for the scale of the Rockingham County.

Figure 1. Glassy-winged sharpshooter on a grape leaf,
By: Peggy Greb, USDA - ARS (K9664-1)

Temperature/ Maturity Zones

One common way of characterizing the spectrum of interim climates is by describing climate range in terms of ordinal classes of grape varieties that could be grown in a given temperature regime. Jones describes four temperature/maturity regimes (cold, intermediate, warm, and hot) graded with variables of GDD (Winkler et al. 1974), frost free period, last spring frost, and first fall frost. GDD was calculated using a 10°C (50°F) base and adding up the days (by hour) above 10°C between April and October, then this layer was graded with breakpoints in 25 point increments (Table 6). The frost free period is understood as the days between the last spring and first fall frosts. The dates of these frosts were based on a temperature reading of 0°C (32°F), along with important average phenological dates such as bud break and veraison taken from historic regional data (Table 8). The original GDD layer of four classes was then summed with the frost free period layer, and then the frost dates were applied to the GDD to form a composite temperature/maturity group composite layer.

Table 8. Frost Free Period (Jones et al. 2004)

Days	Grade
140 - 160	-2
160 - 180	-1
180 - 200	0
>200	1

In the spring, once the primary buds have broken and the shoots start to grow, the grapevine is in a high risk state for frost damage. This can occur from two situations, first there could be an early warm spell so the buds can begin their growth too early, so that if temperatures come back down to the normal temperature range which could include nights below 0°C (32°F), there could be a frost with tender growth exposed. The second possibility is that the temperatures could warm at the normal rate, bud break occur at the normal time and then there could be a late frost. Depending on the state of development of the new growth, some below freezing temperatures may be tolerated, but a night in the mid 20s could really start to cause damage. Secondary buds are not as productive as primary buds, and the grape quality of secondary bud grapes is inferior to that of the primary growth grapes. Therefore, it is important to assess the frost risk so that the vineyard operator may choose varieties which are mated to the environment and/or prepare the vineyard to try and withstand a threatening frost event.

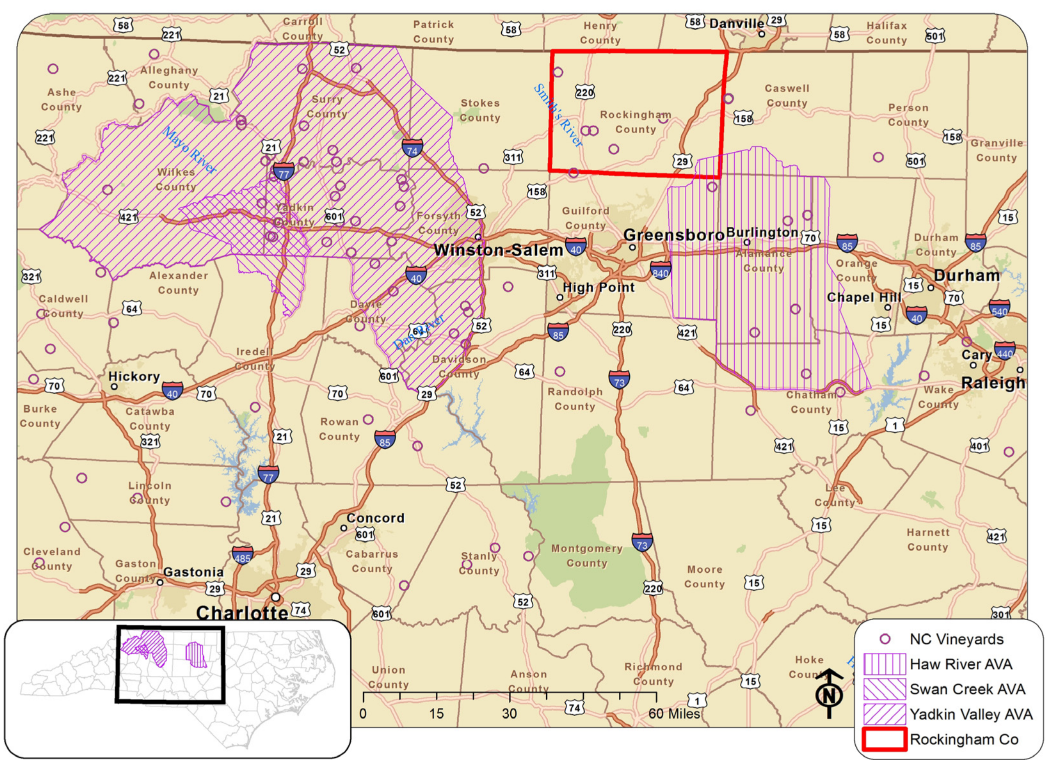
CHAPTER IV

STUDY AREA

The study area for this research is Rockingham County, North Carolina located in the North Central Piedmont. The North Carolina Piedmont is delineated to the east by the fall line at an average elevation of about 60 meters (200 ft) above sea level and to the west by the base of the mountains where the average elevation is about 460 meters (1500 ft) above sea level (NCSCO 2011). Rockingham County's elevation ranges between 323.2 and 139.8 meters (1060.4 - 458.7 ft) above sea level, placing it centrally within the range of Piedmont elevations. It is primarily rural and agrarian with a 2010 Census population of 93,329. Its two largest cities are Reidsville and Eden, each containing about 15,000 residents. Smaller but notable towns include Madison, Mayodan, Stoneville, and Wentworth, the county seat. Rockingham County borders Stokes County to its west, Virginia counties of Henry, Patrick and Pittsylvania to its north, Caswell County to its east, and Guilford County to its south. This puts Rockingham County in close proximity to the Virginian cities of Martinsville and Danville and falls within the Greensboro-High Point Metropolitan Statistical Area and the Piedmont Triad Combined Statistical Area (CSA). This study area is centered between the Yadkin Valley and Haw River AVAs. While still few compared to the state's three AVA's, there are a growing number of commercial wineries and vineyards in and immediately surrounding

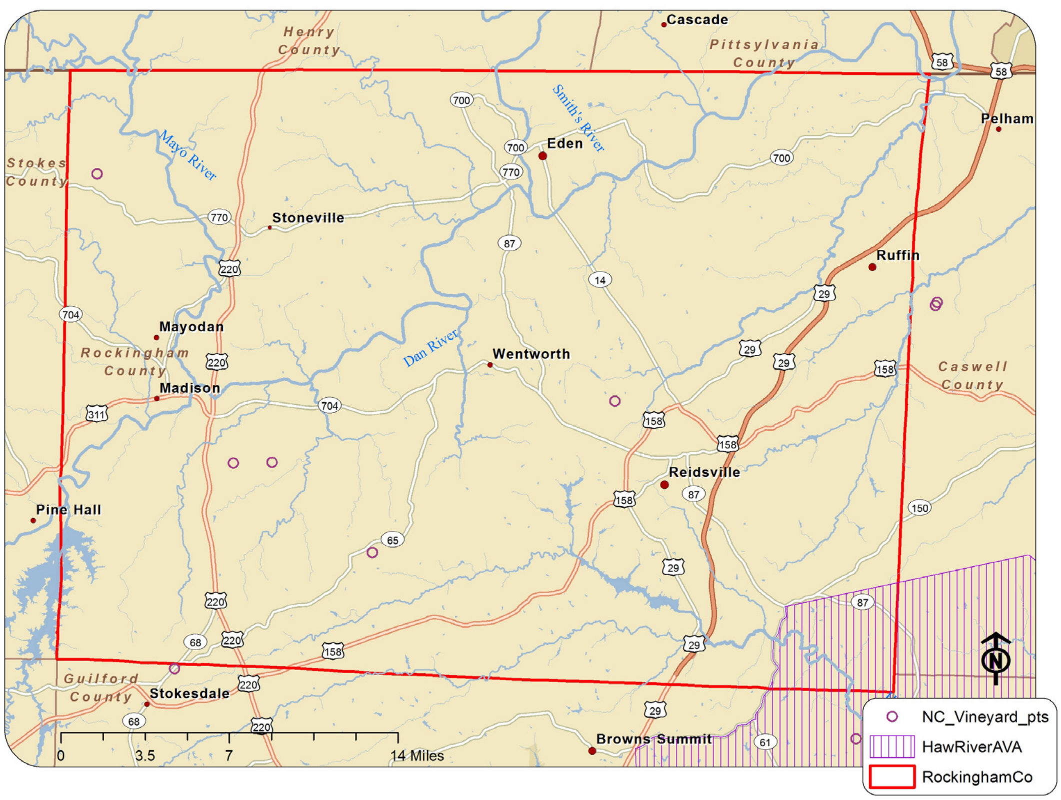
Rockingham County. All of these AVAs are found in and around the Piedmont Triad 12 county CSA, which is colloquially known as the Triad. This is not to be confused with the Triangle which lies 90 miles to east-south-east and consists of the cities of Raleigh, Durham, and Chapel Hill. The Triad gets its name from the three largest cities in the region which are Greensboro, Winston-Salem, and High Point. Burlington is a notable partner as a Triad city as well. The Yadkin Valley and the Swan Creek AVAs are primarily to the west of Winston-Salem while the Haw River AVA is centered on Burlington, east of Greensboro. The study area county and its proximity to these major cities and AVA's can be seen in Map 1.

Map 1. North Carolina Viticulture



As well as showing the relationship of Rockingham County to North Carolina's AVAs, Map 1 reveals the regional geographic pattern of the clustering of vineyards in the state. The Yadkin Valley AVA and especially the area in and around Yadkin County have the densest cluster of vineyards and wineries in the state. While looser and less dense, there is also a recognizable pattern to the cluster of vineyards and wineries in the Haw River AVA. There is also a growing cluster in and around Rockingham County (Map 2).

Map 2. Rockingham County, North Carolina



There is a synergy to the clustering of any specialized economic endeavor, and vineyards and wineries are no exception. There are physical, cultural, and economic reasons for these clusters of vineyards and their location in the area surrounding the cities of the Triad (Taplin 2011). One of the most important resources to any business is customers, and the wineries of the Yadkin Valley certainly benefit from their proximity to the Triad population center and, to a somewhat lesser extent the population centers of the Triangle (Raleigh, Durham, Chapel Hill) and Charlotte. Based on the location of Rockingham County's proximity to the Triad, there appears to be a similar population resource available to its vineyards. There seems to be the economic possibility of more wine commerce in this area, but there is a critical mass of wineries needed before this can be realized. To begin to ignite the synergistic drivers of regional viticultural economic engines, such as the case in the Yadkin Valley, Rockingham County, may need at least double the number of current commercial vineyards and wineries. This is a non-quantified guess. When the Yadkin Valley was at this size in the late 1990s, the wine industry began to grow more quickly there. Once the AVA was formally established, there was another growth spurt. This suggests the wine industry in and around Rockingham County should consider establishing an AVA, maybe even before they double in size.

CHAPTER V

DATA

High quality research results are dependent on high quality data; the old adage that garbage in produces garbage out is a fitting metaphor when it comes to the data to be used for GIS research. This demand for quality, of course, must inevitably be balanced against the difficulty involved in acquiring increasingly high quality data. There is a point where the effort involved in the collection and/or creation of the data is greater than the value of higher quality. More is not always better, because at some point, it would take so much effort to do the survey that the cost-benefit ratio would be too low. Choosing the number of soil samples to take when considering surveying the soil across a 40 acre field is an example. It could likely be commonly agreed that to take a sample of soil to full depth in each square foot of the survey area is more effort than is reasonable under any conceivable agricultural scenario. For those who are trying to think of an example to prove some point about making generalizations, let's increase the area to the typical size of a North Carolina county. Keeping these ideas in mind and considering the size of the study area, the choices of data sources are weighted toward availability and especially those sources made available at the scale of the county.

There are many sources available in North Carolina for elevation data. An example of a high quality and contemporary data set unique to the state is provided by the North Carolina Floodplain Mapping Program. One major shortcoming of this data for this study, however, is that this dataset doesn't extend far into Virginia. This is problematic because the Rockingham County study area borders Virginia and some processes in this research required consideration of a buffered area around the study area. It was therefore important to use a data set that was not limited to the state of North Carolina, or more specifically, a dataset useful for the region in and around the Piedmont Triad in both North Carolina and Virginia. For this reason, the data used for the topographic variables are the National Elevation Dataset (NED) 10 meter Digital Elevation Models (DEMs) in geo .tif format (USGS 2012). These were collected for Rockingham County, NC and the surrounding counties from the Geospatial Data Gateway, a service of the NRCS. These counties were added to a mosaic, and the sinks were filled; all topographic analysis was performed with this filled DEM.

Soil surveys are created at different times, by different soil professionals, and they tend not to perfectly mate at the borders of counties. This makes the county a good study area when using soil surveys. The USDA has two products available which generalize the soil characteristics produced by soil surveys; these are STATSGO and SSURGO. If multiple counties were analyzed, the STATSGO database might be most appropriate because it is prepared for the 1:250,000 scale, and it is available at the scale of the state. The Soil Survey Geographic (SSURGO) Database is described as being prepared for the 1:24000 scale (NRCS 2012). Since the granular scale of this study is 10 meters, and since the soil surveys making up the data of SSURGO are performed at the county scale, it was the best choice for the study area. SSURGO was the data set used for soil values in this research.

Land Cover data used for this research originated from orthoimagery, transportation infrastructure vector files, and SSURGO soil data. The most available high resolution source of leaf-on orthoimagery is the National Agricultural Imagery (NAIP; FSA 2010). Year 2010 imagery was used because it was the most recent available data. The transportation infrastructure data came from ESRI ArcGIS 10.1 and NCDOT vector files. The bedrock data came from the previously mentioned SSURGO Dataset.

The data used for the climate variables was point and raster data. The point data was made up of two weather values, daily TMAX and daily TMIN. There are many networks of weather stations with daily temperature and precipitation data. The weather station data used in this study came from regional National Climatic Data Center (NCDC) weather stations which have daily records between 1971 and 2010. The raster data was the previously mentioned filled DEM, and precipitation data was taken from 800M PRISM data which was re-sampled to 10 meters for the precipitation parameter surface.

CHAPTER VI

METHODS

The variables that were considered in the model fall into four realms: topography, soils, land cover, and climate. Each of these realms is considered separately in its own sub-model. For each of these sub-models, there are one or more parameters which have been classified and graded as parameter surfaces. The basic organization of the model is that the parameter surfaces speak to the goodness of an area as a *V. vinifera* vineyard location, first on an individual basis then combined at the sub-model basis, then finally by combination of all sub-models. In order to represent these parameter surfaces, first maps were produced for each parameter surface individually, and then these parameter surfaces were standardized, weighted, and combined into a sub-model composite using the map algebra concept. The sub-model composite maps were then combined into a comprehensive General Suitability Composite summarizing *V. vinifera* capability/suitability in the county. In order to evaluate which land should be optimal for the spectrum of *V. vinifera* varieties, a temperature/maturity group layer was created and used to clip the final general suitability output into temperature/maturity group zones.

Capability is defined in three ways by the Merriam-Webster online dictionary, “1. the quality or state of being capable; also: ability; 2. a feature or faculty capable of development : potentiality; 3. the facility or potential for an indicated use or deployment;" two of the definitions given for suitability are, "1. adapted to a use or purpose; 2. able, qualified." For the purposes of this project, *capability* means the reasonable ability of the study area to be used as a *V. vinifera* vineyard on a cell by cell basis. Those areas which are capable were graded for their relative suitability. For the purposes of this model, higher suitability equates to lower risk of adverse physical phenomena negatively impacting the vineyard operation. There were one or more classes of suitability given for each parameter. Parameters which are considered in two classes, such as pass/fail, are purely capability based parameters while those with multiple classes of passing grades are suitability parameters. All failing grades, or areas found to be incapable, are graded with a -9999, neutral is marked zero and beginning with one, and progressively higher grades represent the most desirable area. Any area which fails on any model was failed in the final output. There are certainly cases where cells that have been marked incapable by the model and therefore failed will grow vines. Likewise, there will be examples that have been marked capable and may even be given higher suitability grades but are for some reason could not support a vineyard. The goal has been to minimize such errors to the extent that this is possible when capability and/or suitability of physical phenomena are considered at the scale of the study.

Topographic Variables

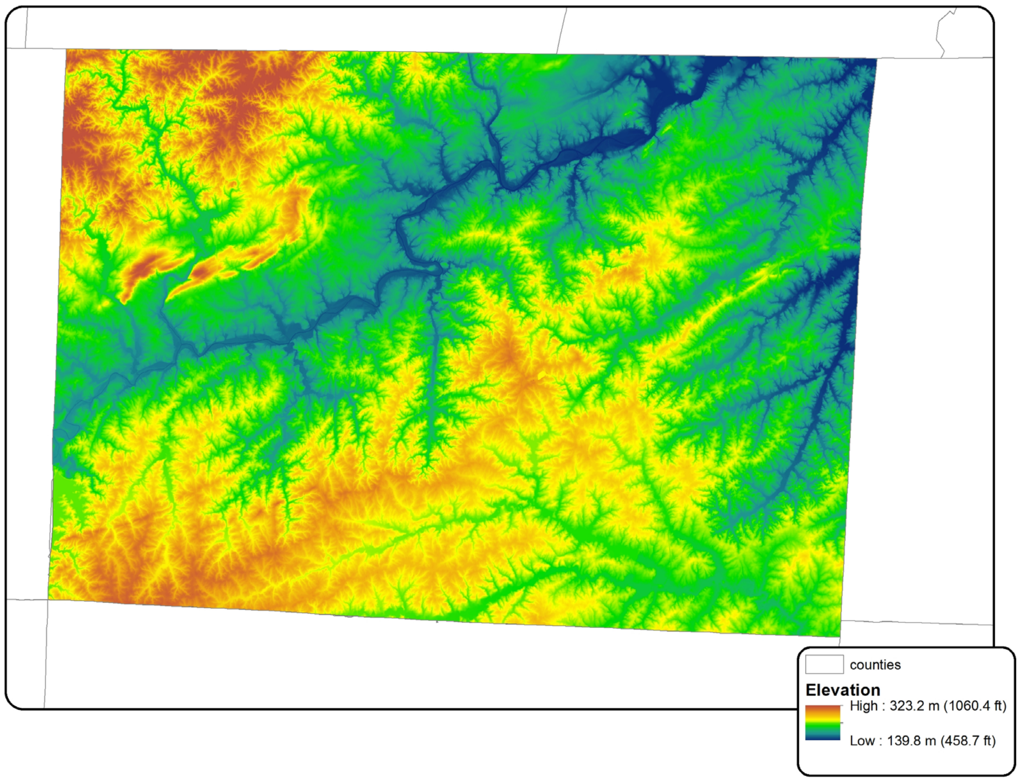
The topographic sub-model consists of graded surfaces of absolute elevation (Map 3), relative elevation, slope, and aspect. These metrics were graded individually into parameter surfaces and were standardized, and they will be combined with a map algebra equation into a topographic sub-model composite.

Since the maximum absolute elevation of Rockingham County falls below the 1500 ft threshold outlined by Tony Wolf (Wolf and Boyer 2003), it is important to seek higher absolute and relative elevations. In order to do this, elevation is considered in two parts—first absolute elevation, and then relative elevation. For absolute elevation, the county data were separated into quintiles. The highest twenty percent of the county's elevations, or the first quantile, was graded highest, and the lowest quantile of absolute elevation failed. The intermediate three classes were graded accordingly. This is summarized in Table 9 (Map 3).

Table 9. Model vineyard site suitability grades for absolute elevation quantiles

Elevation Range (%)	Grade
0 - 20	-9999
20 - 40	0
40 - 60	1
60 - 80	2
80 - 100	3

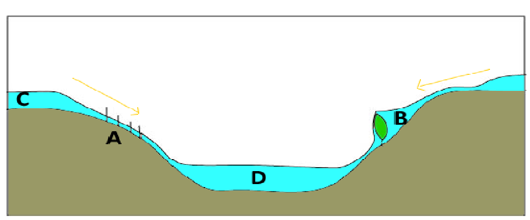
Map 3. DEM (Absolute Elevation)



Surfaces which collect cold air and water are less desirable for viticulture in this region. Cold air and water both collect in surface concavities (Figure 3); therefore, convexities will be considered optimal for vineyards. The drainage network would by definition be the path of drainage of water from a surface and would therefore be the most likely place for water to collect. Relative elevation for this model will be judged by proximity to convexity, which is simply modeled with the drainage network.

This parameter surface has been considered by creating a buffered flow accumulation raster. The Strahler stream order was set by classifying first order streams as those cells which collected the flow from at least 100 other cells. Testing showed that this would equal about one hectare of area. This, of course, is an exaggerated view of where one would find perpetual running water, but it should illustrate markedly wetter and more frost prone areas since both water and cold air act as fluids and are pulled into lower areas. Upon completion of this stream network, a survey of the streams was performed, and the first order streams were found to be less likely than the higher orders to represent the location of streams, therefore only second order and higher streams were considered for this parameter surface. After looking at the NAIP orthoimagery, greener grass was observed to occur first along those streams classified as second order by this system, therefore the flow paths in this raster were buffered in meters by subtracting one from their Strahler Stream Order to summarize the likely flow path of cold air and accumulation of excess soil water (Table 10) toward lower relative elevation (Map 4). Since this parameter surface is pass/fail it functions as a mask; the area within the buffered stream area fails with a grade of -9999, while the remaining area receives a neutral grade of zero.

Figure 2. Cold Air Drainage

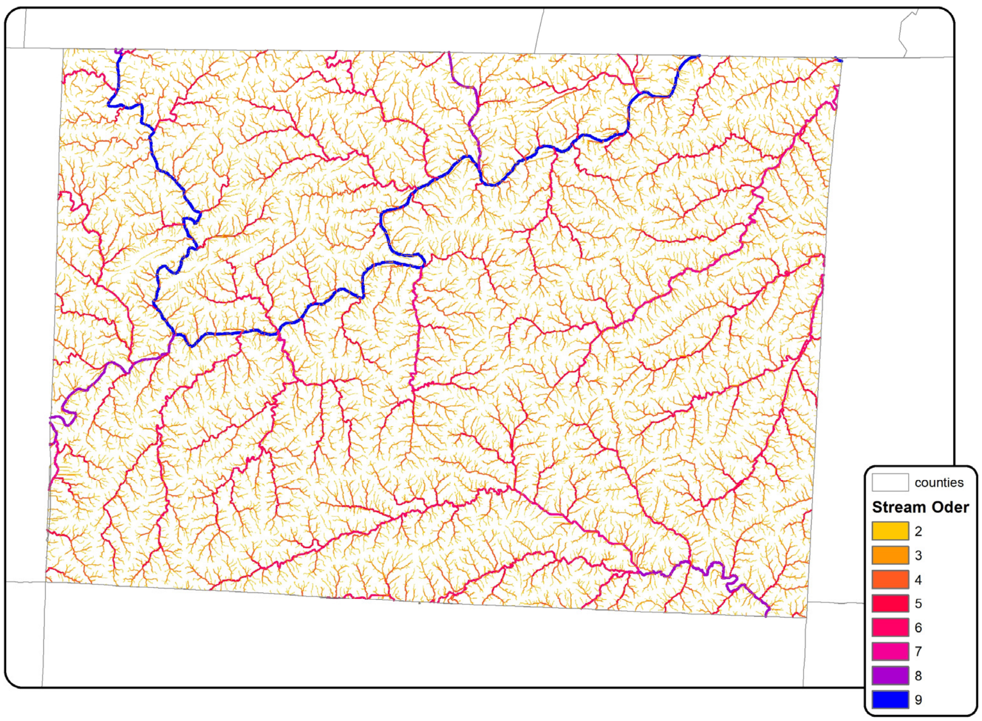


A: good vineyard site, B: perched cold air pond behind tree,
C: cold air on plateau, D: cold air pond in valley.

Table 10. Model vineyard site suitability buffer for relative elevation via Strahler stream order starting from 100 cell accumulation

Strahler Stream Order	Buffer (meters)
1	0
2	1
3	2
n	n-1

Map 4. Relative Elevation (aka Proximity to Stream Network)

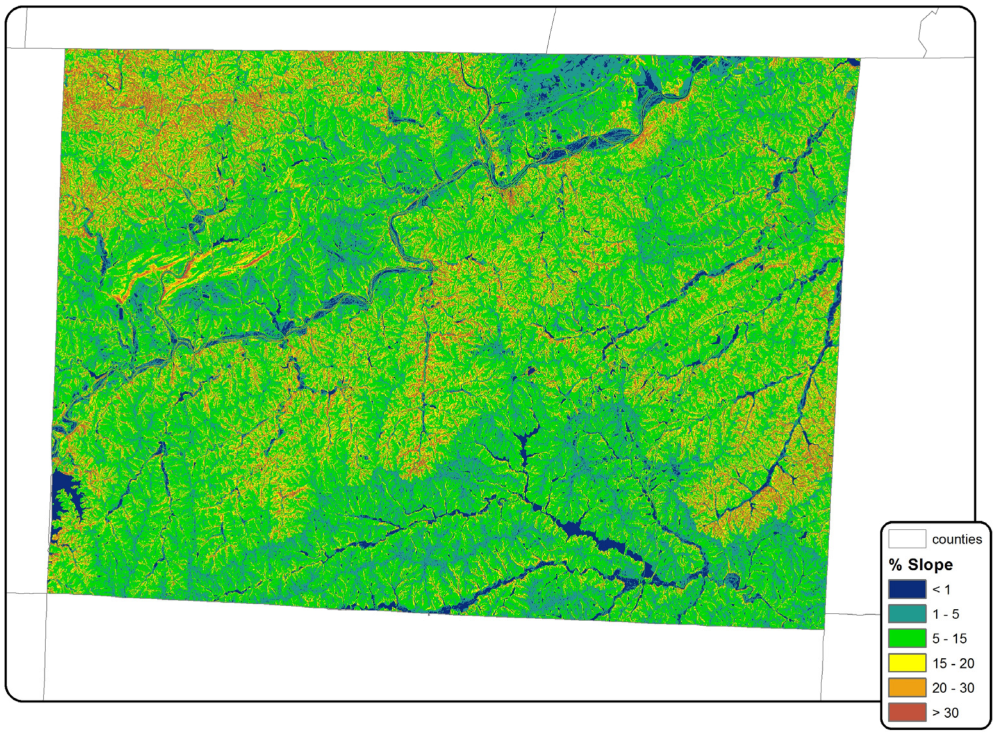


Slope is the amount of rise over a given run. Vines have no preference for what slope they are growing on, per se, but slope matters a lot to vineyard operators. While some degree of slope is better than flat land, high slope is problematic as well. In low slope terrain, where the land is practically flat, there is a tendency for cold air and water to collect. Ponding cold air can give rise to greater frost hazard. Ponding water can contribute to over production of vine vegetation. High slope conditions are also problematic because performing basic vineyard maintenance is difficult enough without the added risk of tipping machinery. Slopes which are between 5 and 15 percent tend to shed excess water and cold air, yet are navigable by most standard equipment and are therefore assumed to be optimal for viticulture. For the slope parameter surface, this range will be graded highest, and slopes above 30 percent will fail. All other slopes will receive intermediate grades. This is summarized in Table 11 (Map 5).

Table 11. Model vineyard site suitability grades for slope range classes

Slope Range (%)	Grade
< 1	0
1 - 5	1
5 - 15	2
15 - 20	1
20 - 30	0
>30	-9999

Map 5. Slope

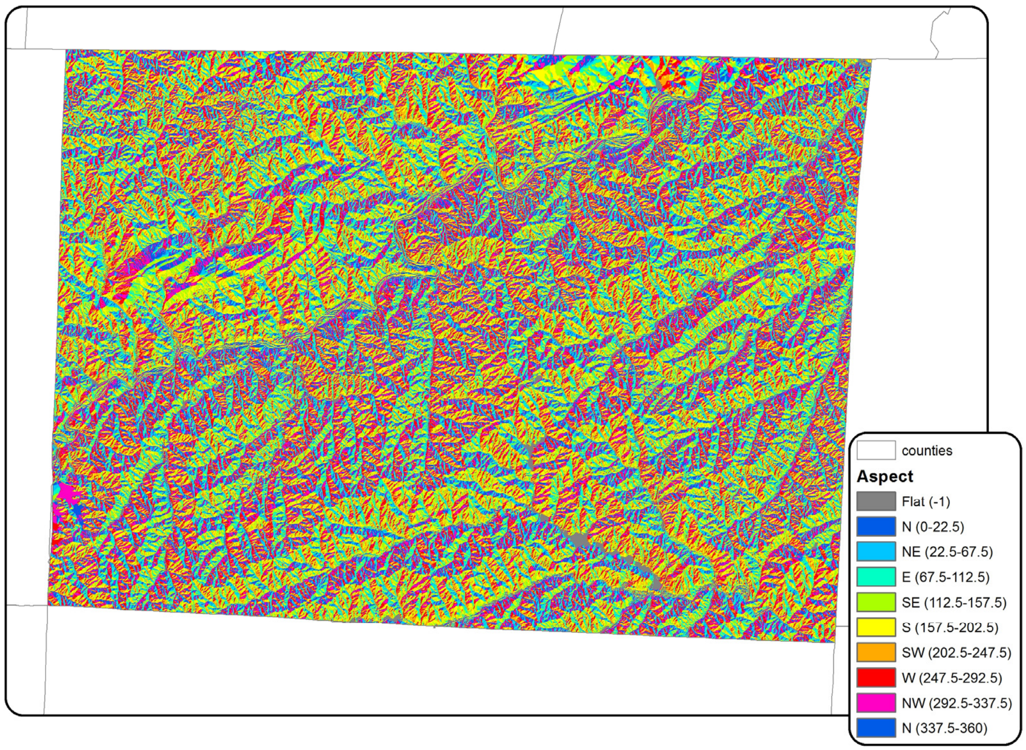


The effects of aspect on site suitability in North Carolina are different than in the other areas where predictive GIS based viticultural suitability studies have been done. This model used aspect in three ways; first, for the general model, eastern, northeastern, and southeastern aspects were considered optimal. This is because in this region of high humidity, it was postulated that there is a benefit to the early sun in two ways. First, eastern aspects get the first sunlight, which should burn the dew off the leaves and fruit faster than other aspects. Second, it means morning sun, as opposed to mid-day or afternoon sun, which is very intense and hot in this region. The general character of northern aspects is that they stay cooler and slightly wetter than slopes facing other directions. The southwest aspects are very hot and least suitable because of the hot sun at the warmest part of the day. No aspects were failed. This is summarized in Table 12 (Map 6).

Table 12. Model vineyard site suitability grades for aspect general model, Spring frost risk, and insolation class classes

Aspect	General Grade	Spring Frost Risk Grade	Insolation Class
™Flat (-1)	1	4	Very Hot
N (0-22.5)	1	1	Warm
NE (22.5-67.5)	2	1	Warm
E (67.5-112.5)	3	2	Hot
SE (112.5-157.5)	3	3	Hot
S (157.5-202.5)	1	4	Very Hot
SW (202.5-247.5)	0	5	Very Hot
W (247.5-292.5)	0	3	Very Hot
NW (292.5-337.5)	1	1	Warm
N (337.5-360)	1	1	Warm

Map 6. Aspect

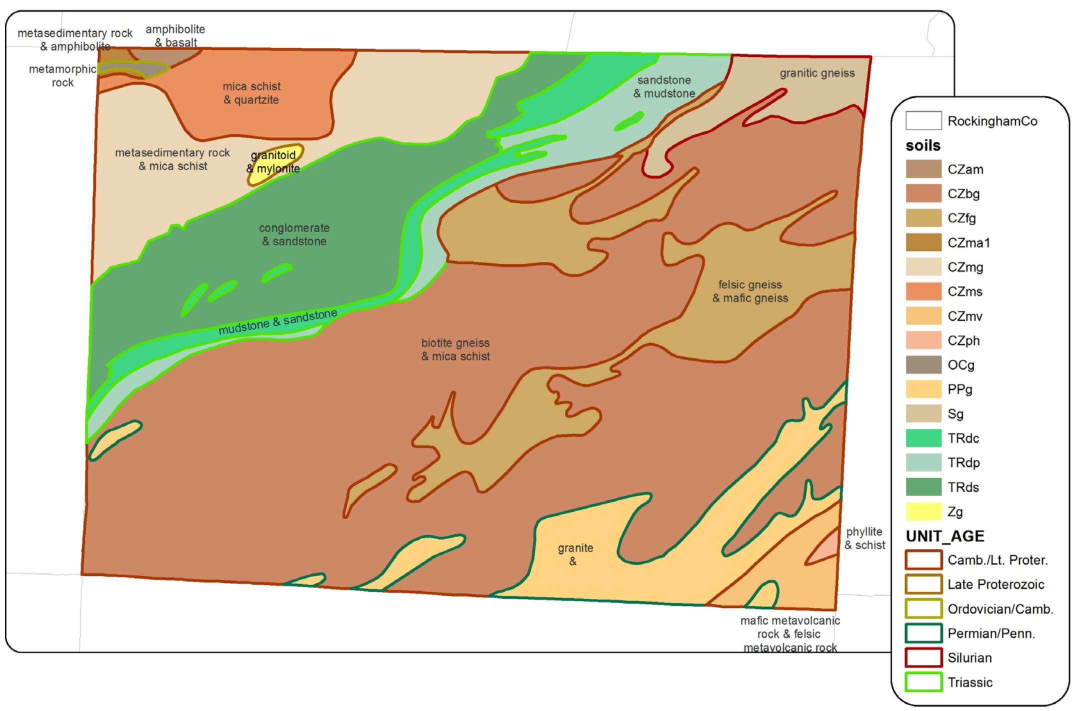


After the topographic parameter surfaces were produced, each layer was standardized to one. Absolute Elevation was weighted 0.4, Relative Elevation functioned as a mask, Slope was weighted 0.4, and Aspect was weighted 0.2; these standardized and weighted parameter surfaces were then summed to represent the Topographic Composite Suitability Map.

Soil Variables

Soil is more than dirt; it is the substance that the vine roots grow in; it is a combination of mineral and organic matter which provides nutrients, water, and an anchor to the vines. One of the broadest ways to consider the way soils vary across space is by looking at how their parent material varies across space (Map5). For viticulture, more than this general view is needed. The soil parameters considered in this model are soil drainage, available water capacity (AWC), depth to bedrock, soil pH, and texture. These parameter surfaces were graded individually and then combined in a soil sub-model composite.

Map 7.General Soil Map



The soil drainage parameter was taken from the natural drainage class value in SSURGO. Those natural drainage classes below "moderately well drained" were failed, and "well drained" was considered the optimal class. This is summarized in Table 13.

Table 13. Model vineyard site suitability grades for soil drainage classes

Slope Range (%)	Grade
Unknown	-9999
Poorly drained	-9999
Somewhat poorly drained	-9999
Moderately well drained	0
Well Drained	1

The available water capacity (AWC) parameter was taken from the AWC value from SSURGO. Those classes above .15 cm/cm AWC were failed, while those classes below 0.10 cm/cm AWC were graded as optimal. Intervening classes received intermediate grades. This is summarized in Table 14.

Table 14. Model vineyard site suitability grades for AWC classes

AWC cm/cm	Grade
<0.10	5
0.10 - 0.11	4
0.11 - 0.12	3
0.12 - 0.13	2
0.13 - 0.14	1
0.14 - 0.15	0
>0.15	-9999
unknown	-9999

The soil depth parameter summarizes the effective rooting depth by taking the "depth to restrictive layer" value from SSURGO. Those classes with depths less than 30 cm (1ft) were failed. Areas with depths exceeding 3 feet were graded as optimal. Intervening classes received intermediate grades. This is summarized in Table 15.

Table 15. Model vineyard site suitability grades for soil depth classes

Depth Range cm (~ft)	Grade
<30 (<1)	-9999
30 - 60 (1 - 2)	0
60- 90 (2 - 3)	1
>90 (>3)	2

The soil pH parameter summarizes relative acidity or alkalinity of the soil. As the soil approaches the extremes of the scale, different nutrients are made unavailable to the vines, so the optimal acidity is very close to neutral. Typically pH is amended once when the vines are planted. With the soils of the Appalachian Piedmont that always means increasing the pH, since the remaining soils are typically acidic in this region. This is usually accomplished with amendments such as lime. Since this parameter is fairly easy to adjust, no classes were failed. Those soils between 6.0 and 6.8 pH are optimal, and grades decrease as pH varies away from this range. This is summarized in Table 16.

Table 16. Model vineyard site suitability grades for soil pH classes

pH range	Grade
unknown	0
<4.7	0
4.7 - 5.4	1
5.4 - 6.1	2
6.1 - 6.8	3
>6.8	2

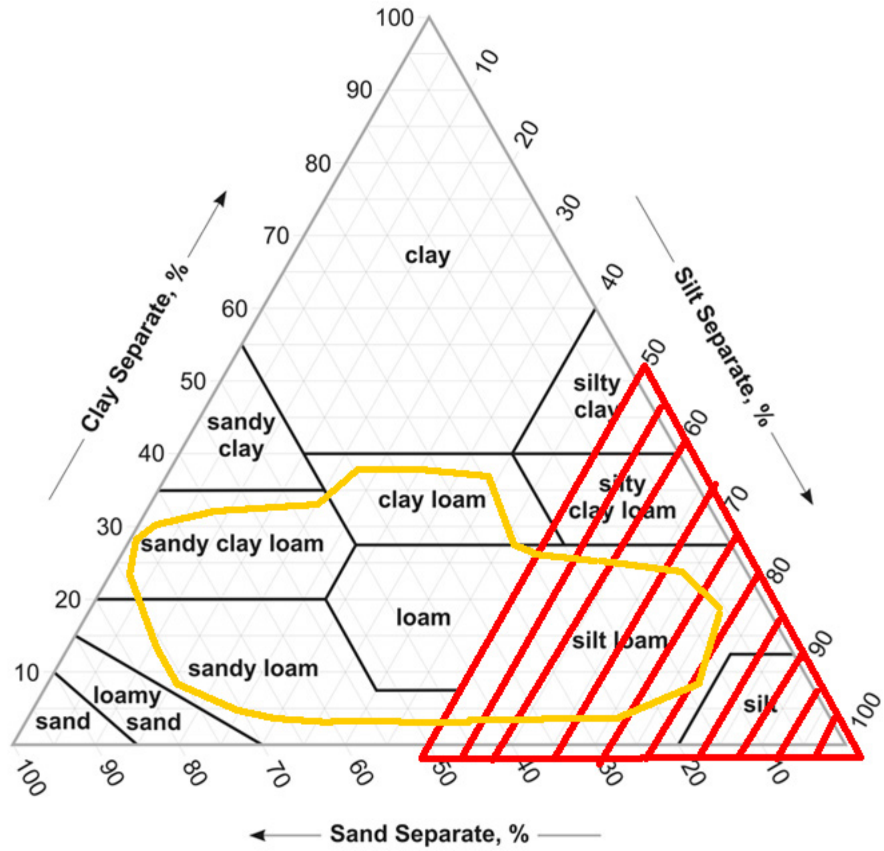
The soil texture is the relative proportion of sand, silt, and clay particles which make up the soil. This is summarized with the soil triangle which is a graphic representation of the relative proportions of these three constituent particle sizes (Figure

2). In this region of the North Carolina Piedmont, those soils with a high percentage of silt tend to be found in alluvium along the stream network. This zone is associated with highly productive bottom land soils but is problematic for wine grape vines due to their propensity to be over vigorous in such soils (Wolf and Boyer 2003). Because of the tendency of alluvial plains to be highly fertile and high in silt, the soils in this region with more than 50% silt have been failed in the model. This parameter is pass or fail, above 50 % silt is failing, and below 50% silt is passing. In Figure 3, the soil triangle has been marked with the soils of the study area in yellow and the failed texture classes in red; this is also summarized in Table 17.

Table 17. Model vineyard site suitability grades for texture by percent silt

% silt	Grade
>50%	-9999
<50%	0

Figure 3. Soil Triangle with Study Area Soils and 50% Silt Limit



After the soil parameter surfaces were produced, each layer was standardized to one. Soil drainage was weighted 0.4, AWC was weighted 0.3, Soil Depth was weighted 0.2, Soil pH was weighted 0.1, and Soil Texture functioned as a mask; these standardized and weighted parameter surfaces were then summed to represent the Soil Composite Suitability Map.

Land Cover/Land Use Variables

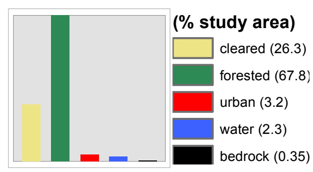
Land cover is important to vineyard site location. Some classes of land cover can be considered as incapable of supporting agriculture all together, such as roads, surface water, or exposed bedrock. Other areas have varying degrees of suitability. Cleared land is optimal, since there must be a multi-year transition period if moving from forested to cleared land cover. For the purposes of this model, land cover was classified into five classes: cleared, forested, water, urban, and bedrock. The water and exposed bedrock land cover classes will be derived from soil data provided by USDA in the SSURGO database. The urban class was made up of transportation infrastructure, such as roads, railroads, and airports which came from North Carolina Department of Transportation & ESRI. The cleared and forested classes were developed from NAIP imagery. This imagery was degraded from 1 meter to 10 meter and followed by a supervised classification. Cleared land was considered as the optimal land cover, while forested land was considered neutral. The water, urban, and bedrock classes were failed. This schema is summarized in Table 18 (Map 8; Figure 4).

There is only one layer in the Land Cover sub-model so it is also the Land Cover Composite Map layer. There is a need to weight this sub-model composite against the others in the final output. In order to reduce the influence of Land Cover to that of a soil layer, the Land Cover Composite map is weighted at 0.2 in the final map algebra equation.

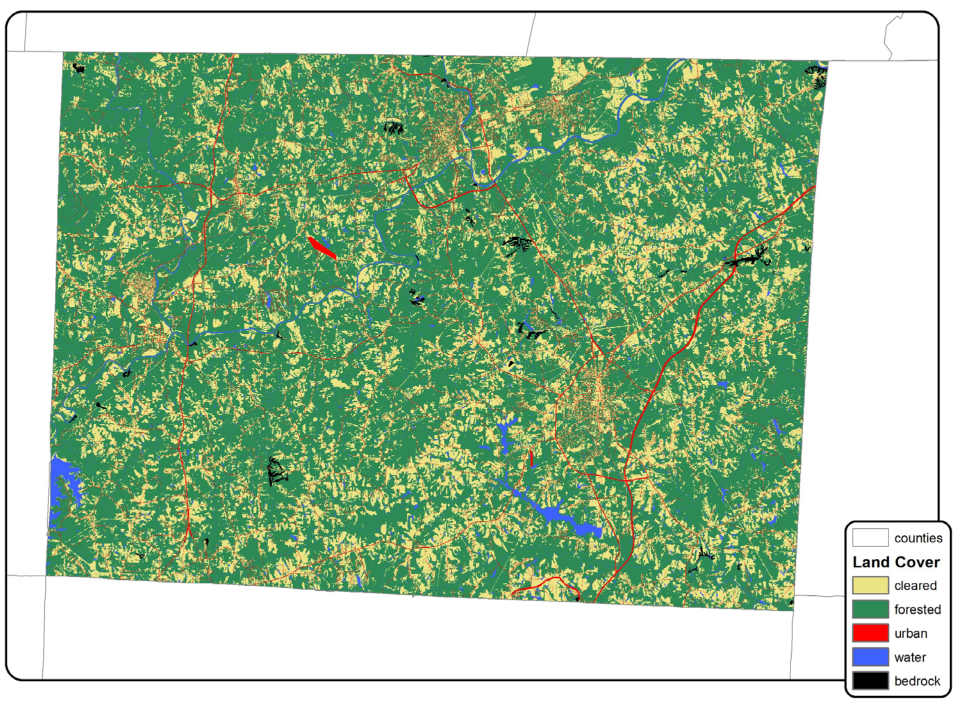
Table 18. Model vineyard site suitability grades for land cover classes

Land Cover Class	Grade
Cleared	1
Forested	0
Water	-9999
Urban	-9999
Bedrock	-9999

Figure 4. Land Cover Classification Chart



Map 8. Land Cover Map



Climatological Variables

There are many measures of climate that can be helpful to minimize risk when choosing a site for a vineyard. The consideration of climate is central to modeling viticulture with GIS. There are four sections to the climate model; first is a discussion of the interpolation methods for point based data, then there is the sub model summarizing capability/suitability, then a map summarizing Pierce's Disease risk, then a map summarizing the temperature/maturity regions in the study area. The variables considered for capability/suitability analysis are: mean number of days per decade experiencing at or below -22°C, Spring Frost Index, mean April to October precipitation, and finally, mean number of days per year experiencing below -12.2°C, and -9.4°C were used to create a Pierce's Disease Risk layer. The Temperature/Maturity regional map considered GDD using Winkler's thresholds (1974).

Interpolation of Climate Point Data

Point based temperature parameters were interpolated to temperature surfaces. In order to perform all of the interpolation processes for the needed parameters at the 10 meter resolution, and based on simplicity and the discrete nature of the surface, inverse distance weighting was chosen for the interpolation method. Because the stations are far apart and the intervening topography is known to influence the temperature, it was concluded that a method which considers atmospheric adiabatic lapse rate should be used as well. The combined method was to first adjust the climate point data by the station elevation using the average monthly lapse rate, then interpolation was performed on this flat plain. Then the final surface is produced by correction of the plain back to the topographic surface using a DEM. Beginning with the daily minimum and maximum temperature (Tmin; Tmax) at the 28 regional National Climate Data Center (NCDC) stations, for the period of 1971 through 2010, mean daily temperature (Tmean) was calculated. Then, using the 40 years of daily data, the Tmean for each month of the year was determined for each of the 28 NCDC stations.

In order to select the best IDW based model, the data was investigated in ESRI ArcGIS Desktop, Geostatistical Wizard. The Tmean for the period between April and October was calculated. In keeping with Waldo Tobler's first law of Geography, "Everything is related to everything else, but near things are more related than distant things," and since all 28 NCDC stations are in and around the Piedmont Triad, all stations were used to weigh the IDW. Using the optimize function to choose the power of the IDW, the optimal power was 3.035. Then, based on a trial and error process of choosing the weighting neighborhood with the lowest error, the neighborhood shape for weighing distance was changed from a circle to an ellipsoid of .33 by 1 ratio which was oriented at an angle of 157°. These modifications lowered the RMSE to under 0.5°C and the mean error was reduced below 0.1°C. This elongated window at a northeast to southwest orientation giving the lowest error makes logical sense because of the general train of the mountains and average west to east movement of weather systems over the area.

These IDW parameter settings were used for all temperature based interpolations performed for all point data at these 28 NCDC stations in this study, including the interpolation of the mean number of days below -9.4°C and -12°C per year, the mean number of days below -22°C per decade, Tmax, Tmin, and Tmean..

Climate Sub-Model

One climate based risk for vines is presented by extremely cold temperatures which can severely damage the vines and even kill the vine back to the graft. The average number of days per decade at or below -22°C is predictive of this risk. The threshold of three days per decade below this value was considered failing because of the long term risk of vine wood loss due to extreme freeze damage. Those areas which experience 1 or 2 days per decade below this threshold were degraded accordingly; this is summarized in Table 19.

Table 19. Extreme Cold classes

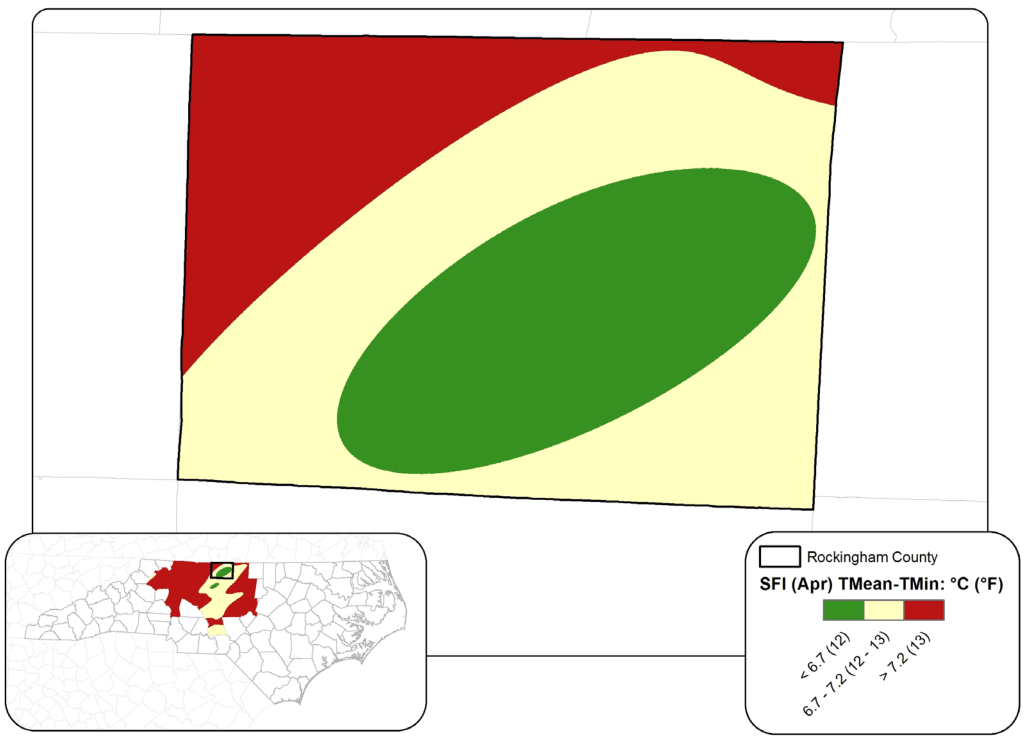
Days per Decade Below -22°C	Risk	Grade
>3	High	-9999
2-3	Medium	0
1-2	Low	1
<1	Very Low	2

To account for the risk of spring frost, the SFI was used to create a frost risk layer. From the lapse rate adjusted/IDW interpolated/DEM corrected Tmax and Tmean surfaces, the SFI was calculated using map algebra to subtract the Tmin surface from the Tmean surface. The resulting raster was the SFI parameter surface. Based on regional extension documentation, the SFI parameter surface was classified and graded (Wolf and Boyer 2003). This grading of SFI classes is summarized in Table 20 (Map 9).

Table 20. SFI classes (Gladstones 2000)

GDD Classes °C (°F)	Risk	Grade
< 6.1 (11)	Low	3
6.1 - 6.7 (11 - 12)	Medium	2
6.7 - 7.2 (12 - 13)	High	1
>7.2 (>13)	Very High	0

Map 9. SFI Classes



Temperature/Maturity Zones

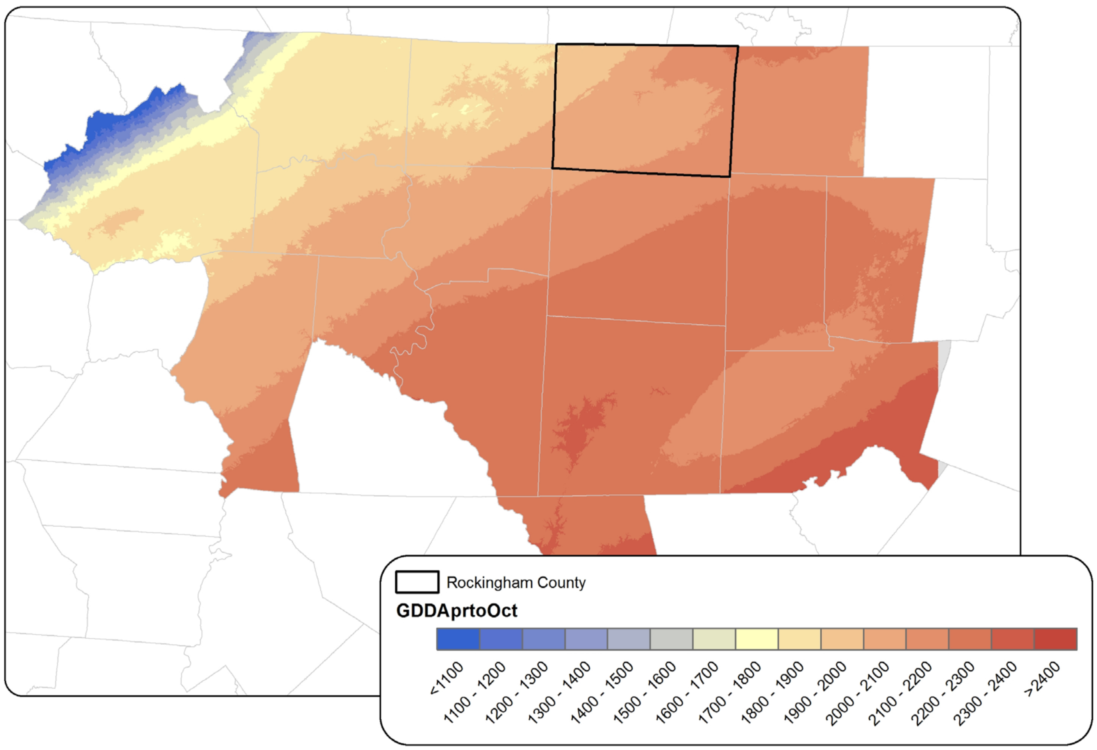
The Growing Degree Day (GDD) is a commonly used method of understanding temperature/day accumulation across a time span. The typical time span considered for viticulture in the northern hemisphere is the growing season from April 1st to October

31st. The GDD represents the sum of the daily mean temps over a base temperature for each day over this period. For this model, GDD equals the sum of the maximum and minimum mean daily temperatures divided by two; 10°C (50°F) is subtracted, then the sum every day in the period of interest. The lapse rate and IDW interpolated Tmax and Tmin surfaces were used for this. No classes of GDD are considered failing. Winkler's GDD ranges have been used for classification of the study area into temperature and maturity zones. This summarized in Table 21 (Map 10).

Table 21. Model vineyard site suitability grades for GDD classes

GDD Classes °C (°F)	Winkler GDD Class (1974)	Temp. Mat Class
< 1388 (2500)	Very Cool	0
1388 - 1667 (2500 - 3000)	Cool	1
1667 - 1944 (3000 - 3500)	Warm	2
1944 - 2222 (3500 - 4000)	Hot	3
>2222 (4000)	Very Hot	4

Map 10. GDD

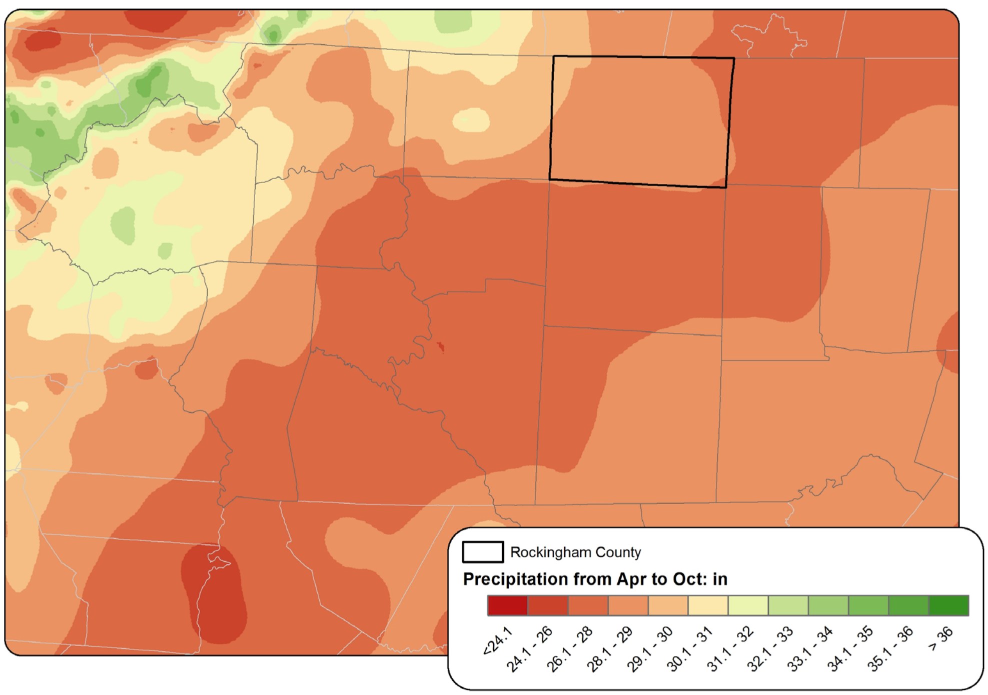


Like all plants, vines have minimal precipitation requirements. In North Carolina, these are rarely a concern, and it is more common to have too much rain in the absence of a summer drought. Grape vines are typically thought of as a plant which thrives in semi-arid locations, and irrigation can completely make up for drought periods. Irrigation is also suggested for the establishment period of the vineyard, because young vines are still building root systems. For this model, lower average precipitation between April and October was considered a benefit and was graded accordingly. Using the PRISM mean monthly precipitation data (1971 to 2000), this was adjusted from 800 meters resolution to 10 meters resolution and then classified. This is summarized in Table 22 (Map 11).

Table 22. Model vineyard site suitability grades for precipitation classes

Precipitation Classes cm(in)	Grade
70 - 71 (27.6 - 28)	0
71 - 72 (28 - 28.3)	1
72 - 73 (28.3 - 28.7)	2
73 - 74 (28.7 - 29.1)	3
74 - 75 (29.1 - 29.5)	4
75 - 76 (29.5 - 29.9)	5

Map 11. Precipitation (Apr to Oct)

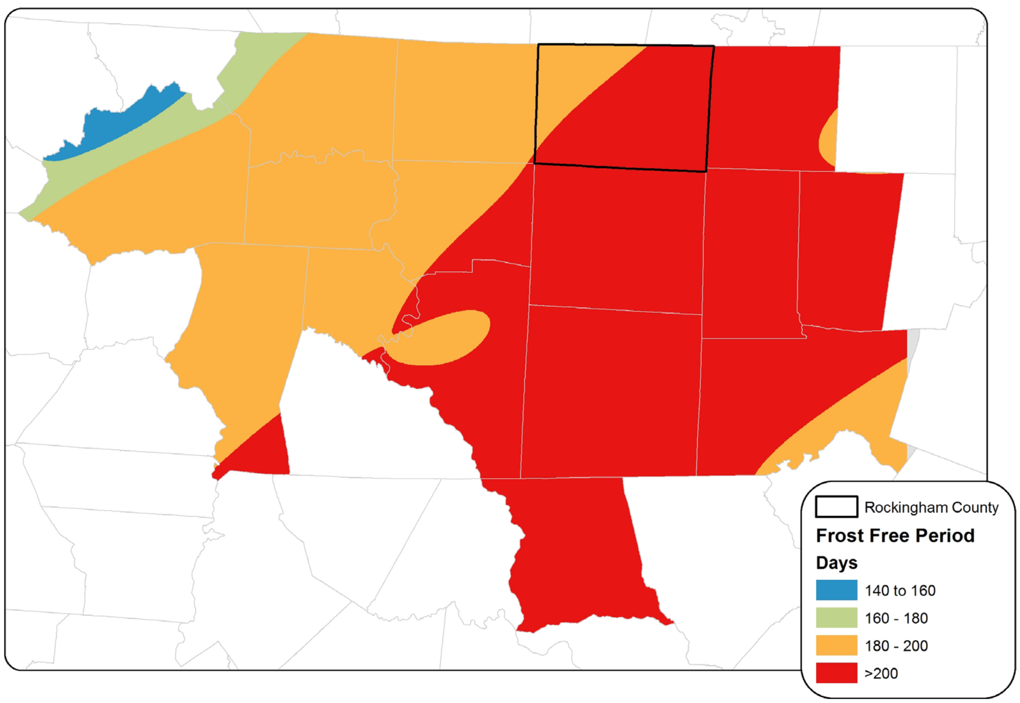


Grapes take a certain amount of time to develop on the vine, so the growing season length must be long enough for this to occur. One way of measuring the growing season length is by the frost free period. In accordance with Jones and others (2004), the frost free period was graded in four classes. This is summarized in Table 23 (Map 12).

Table 23. Model vineyard site suitability grades for frost free period

Number of Days	Season Length	Grade
140 to 160	short	0
160 to 180	medium	1
180 to 200	long	2
>200	longest	3

Map 12. Frost Free Period



Pierce's Disease

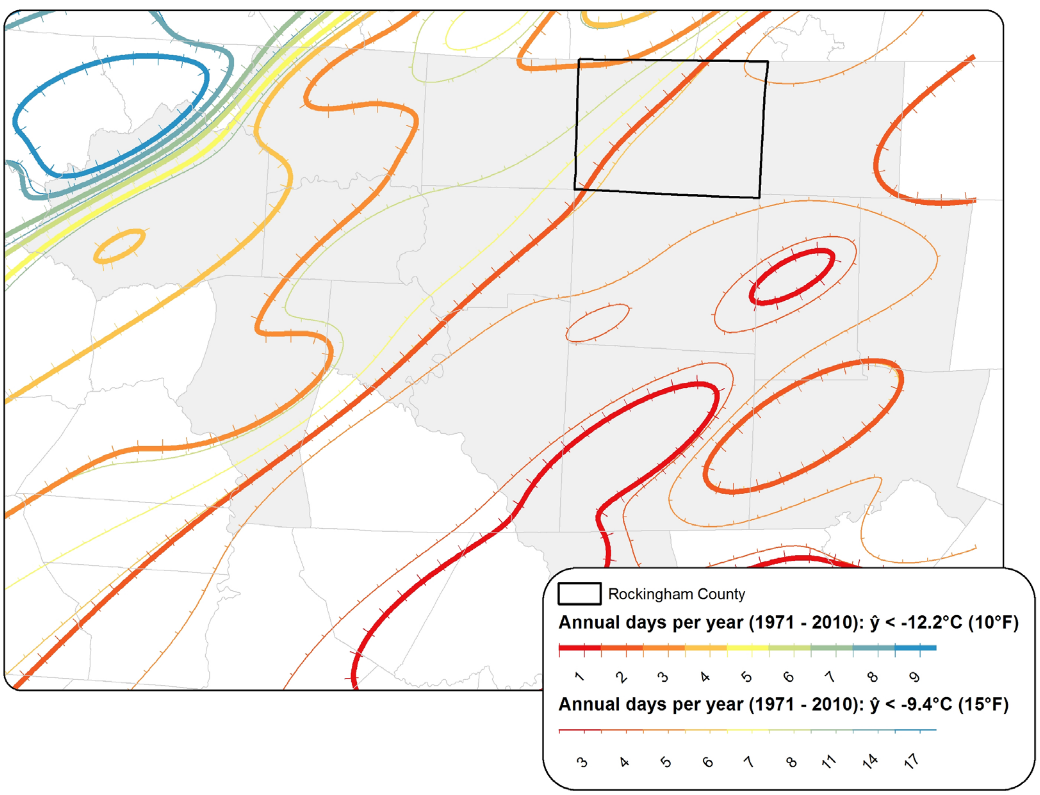
The mean number of days per year spent below both -9.4°C and -12.2°C are used as algorithms for predicting the Pierce's Disease risk. Maps were produced summarizing average annual days below the risk thresholds of -9.4°C and -12.2°C. The risk areas are delineated by one, two, and three days below -12.2°C and four, five, and six days below

-9.4°C. The highest risk is to the south and east of the first composite isotherm, and the isotherms inland and up slope from this will represent areas of moderate risk, low risk, and very low risk respectively. This is illustrated in Map 13 and summarized in Table 24.

Table 24. Model vineyard site suitability grades for PD risk classes

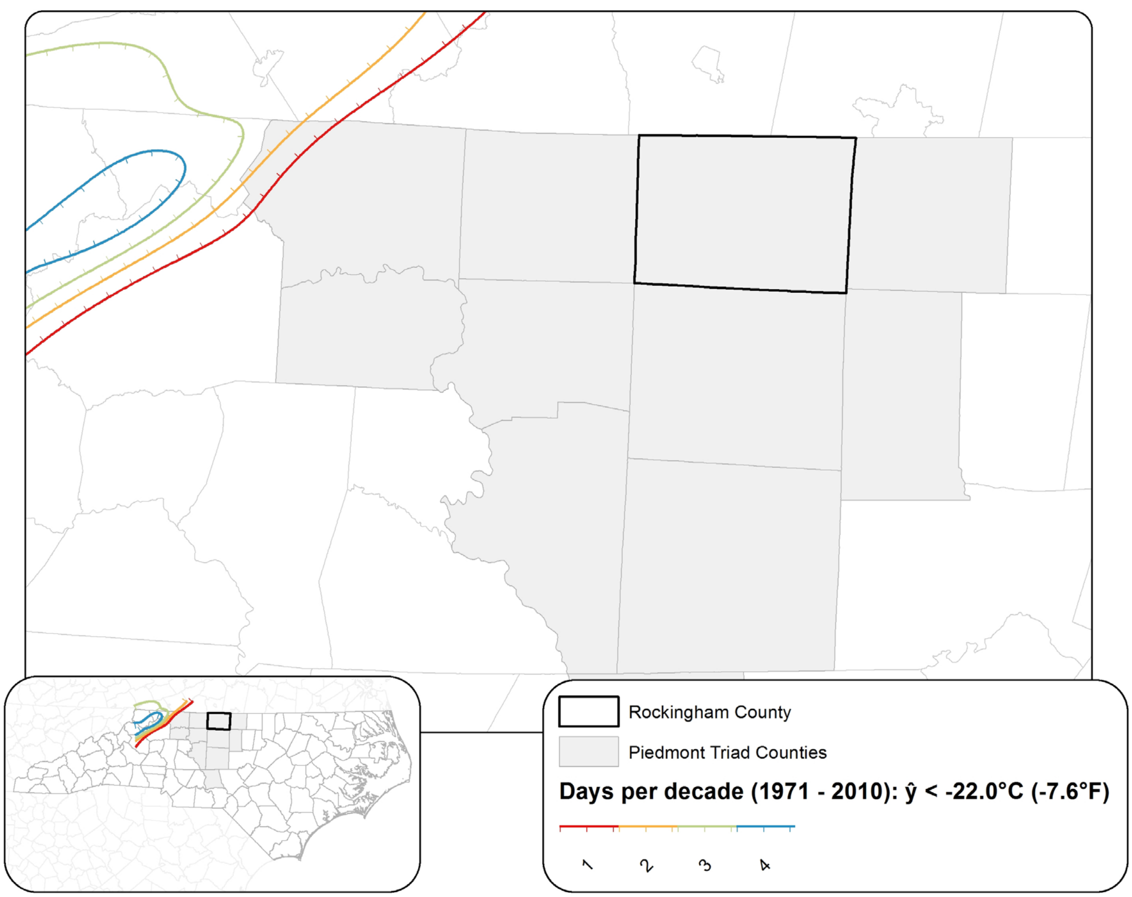
Days per Year	Below	Grade
1	-12.2°C	0
2	-12.2°C	1
3	-12.2°C	2
4	-9.4°C	3
5	-9.4°C	4
6	-9.4°C	5

Map 13. Isotherms for Annual Days below-9.4°C and -12.2°C



The entire study area falls outside the climate zone of extreme cold freeze risk. This is the risk of experiencing -22°C .To illustrate the distance from zones where such risk exists, the closest area of extreme freeze risk is the northwest corner of Surry County and the Northwest third of Wilkes County (Map 14). This suggests that the overwhelming percentage of area for the entire Piedmont Triad Region, much less Rockingham County, is unlikely to experience extreme cold that would severely damage dormant vines in winter.

Map 14. Extreme Cold Risk Classes



After the climate parameter surfaces were produced, each layer was standardized to one. Since there is no risk in the county for extreme cold and since the growing season length is above the needed minimum amount, these metrics will not be used in the Climate classification model. Pierce's Disease risk was weighted 0.4, Spring Frost Index was weighted 0.4, and Precipitation was weighted 0.2; these standardized and weighted parameter surfaces were then summed to represent the Topographic Composite Suitability Map. The Temperature/Maturity Group Map will consist solely of the GDD map.

CHAPTER VII

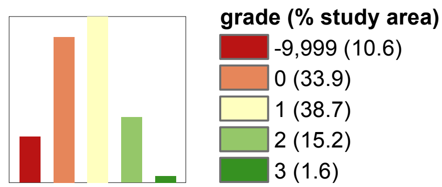
RESULTS

The parameter surfaces from each layer of the model were analyzed by grade class. Classification charts were produced to illustrate the proportion of the area that fell in each class. The results are organized by sub model below, with the parameter surfaces interpreted individually first, followed by the sub model composite. All failing suitability grades were given a score of -9999, while passing grades increase from neutral, graded with zero, with the highest score being the most desirable class.

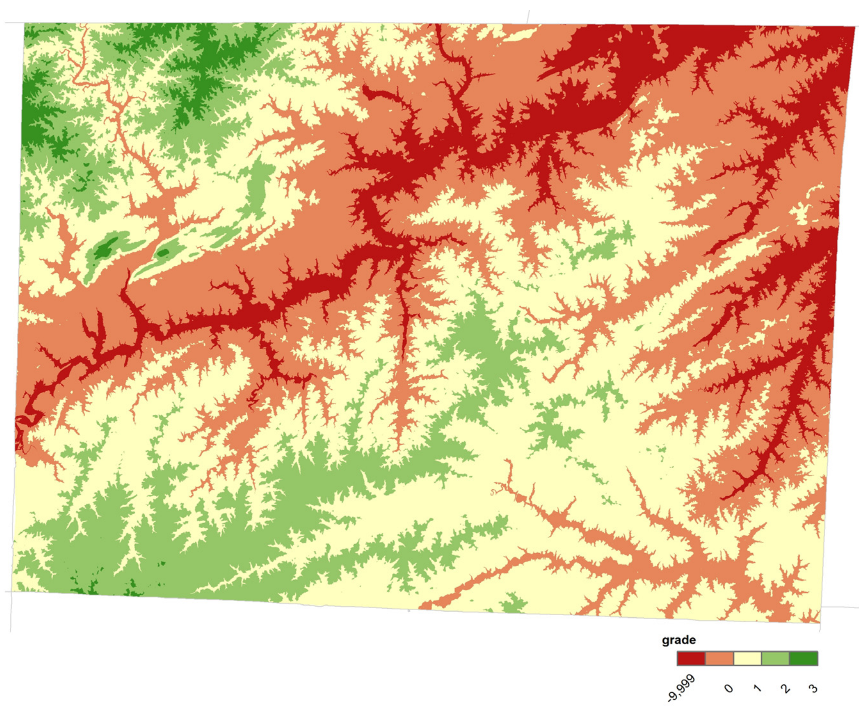
Topographic Results

Absolute Elevation within Rockingham County falls in the range of 139.75 to 323.17 meters (1060 - 458 ft.) above sea level. In looking at the map, it becomes apparent that there is higher ground in the northwest corner of the county, north of Mayodan, and west northwest of Stoneville. There is also a broad ridge of moderately higher elevations extending from the southwest corner of the county just north of Stokesdale toward the northeast to Wentworth including western portions of Reidsville. This ridge separates the Dan River and Haw River Drainage Basins. The Dan River Valley, and to a lesser extent the Mayo, Smith's, and Haw River Valleys are prominent physiographic features revealed by absolute elevation layer. In the southern portion of the county are the headwaters of the Haw River, which feed into the Haw River AVA as it leaves Rockingham County in the southeast corner. Eden, in the northeast portion of the county, is in the Dan River Valley at the lower end of elevations in the county. The most suitable areas for viticulture, based on absolute elevation, are in the northwest corner and the ridge areas extending from the southwest corner to the central portion of the county. The least suitable areas in the county are in the northeast and the northern half of the eastern border with Caswell County, as well as immediately along the Dan River and its major tributaries along the eastern border with Caswell County. The absolute elevation classification resulted in the failing of 10.6% of the county (Map 15; Figure 5).

Figure 5. Absolute Elevation Classification Chart

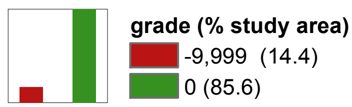


Map 15. Rockingham County Absolute Elevation Classification



The relative elevation layer buffers proximity to the drainage network. The Dan and Haw Rivers and their local tributaries are apparent in the dendritic stream pattern. The drainage divides also become apparent producing an entirely different pattern than absolute elevation. The most suitable area, with regard to relative elevation, will be along these stream divides. This is a pass/fail layer, so it functions as a mask. The relative elevation classification resulted in the failing of 14.4 percent of the county (Map 16; Figure 6).

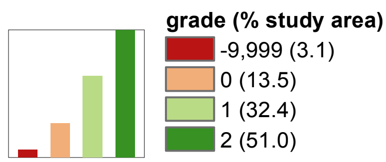
Figure 6. Relative Elevation Classification Chart



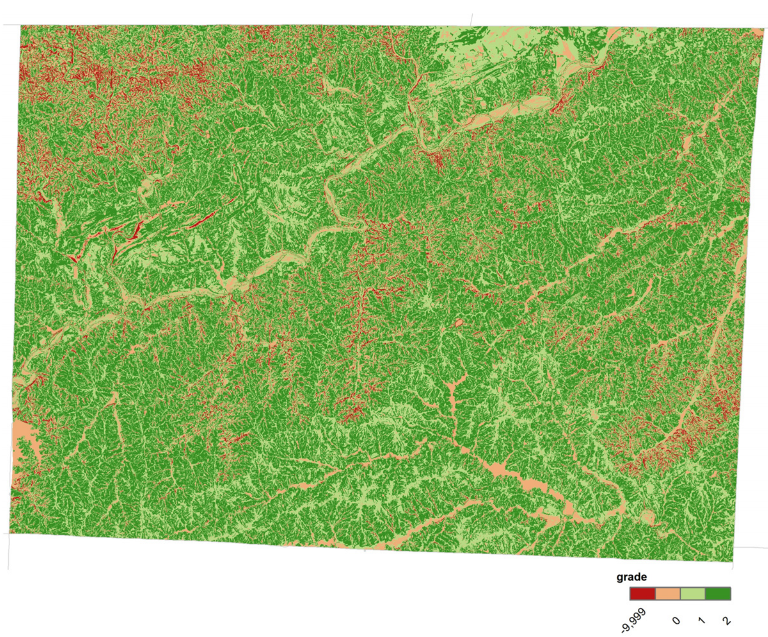
Map 16. Rockingham County Relative Elevation Classification

The slope map shows some notable patterns. With regard to slope, the northwest portion of the county has the densest area of high slope land. This renders much of the land in this area incapable for viticulture. There are also two other dense regions of failing high slope land, one in the center of the county and one in the southeast corner; both of these are along areas of drainage which flow northward to the Dan River. The slope classification resulted in the failing of only 3.1 percent of the county (Map 17; Figure 7).

Figure 7. Slope Classification Chart

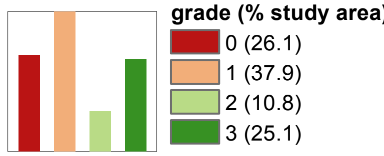


Map 17. Rockingham County Slope Classification

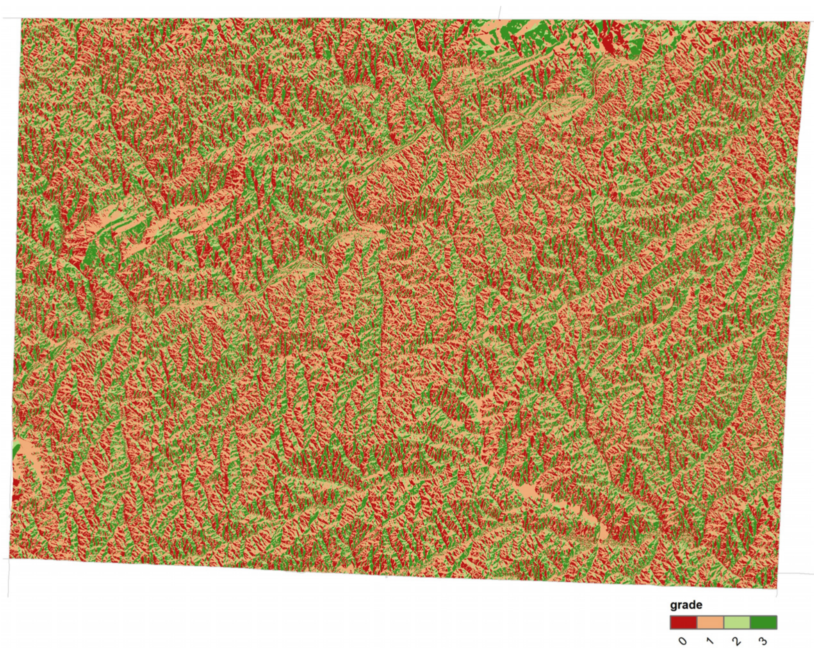


The map of aspect classification shows less of a visually discernible pattern than the other topographic parameters. This is likely due to the high resolution of the DEM used to classify aspect. This could also be the result of the geomorphic character of an old landscape in a humid temperate environment resulting in a well-developed dendritic stream morphology which creates a complex set of aspects. The aspects with the greatest frequency are centered on the southeastern and southern facing slopes. This face would be expected because of the general train of the Appalachian Mountains in the northeast to southwest directions and also because the mountains are rising to the northwest, and elevations are dropping to the southeast at least in the broad multi-county perspective; no aspects were failed in this model, while 26.1 percent of the county falls in the lowest graded class (Map 18; Figures 8).

Figure 8. Aspect Classification Chart

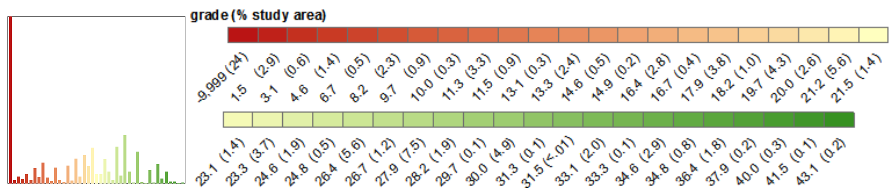


Map 18. Rockingham County Aspect Classification

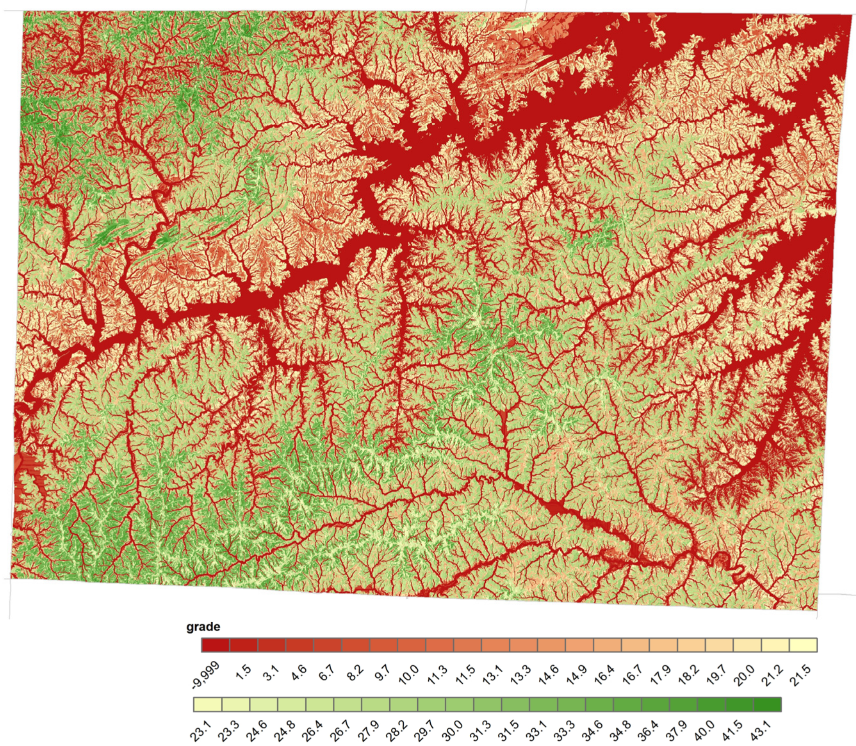


The Topographic Composite Map illustrates that the best areas for viticulture are isolated areas in the northwest corner of the county, especially the ridges around the Mayo River Basin. The broadest good area is the drainage divide between the Dan and Haw River Basins. This area extends from the southeast corner of the county to the middle of the county. Two notable patterns on the map are interesting. First, if the northwest portion of the county, especially within the Mayo River drainage basin, was not so topographically rough, it would have scored highest in topographic suitability. Secondly, the decision to fail the lowest 20 percent of elevations resulted in the failing of much area along the Dan River which otherwise may have passed. The values on the Topographic Composite Map represent the outcome of the sub-model map algebra equation; overall, 24 percent of the county failed due to topographic incapability (Map 19; Figure 9).

Figure 9. Topographic Sub Model Composite Classification Chart



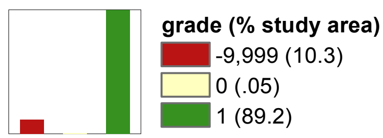
Map 19. Rockingham County Topographic Composite Map



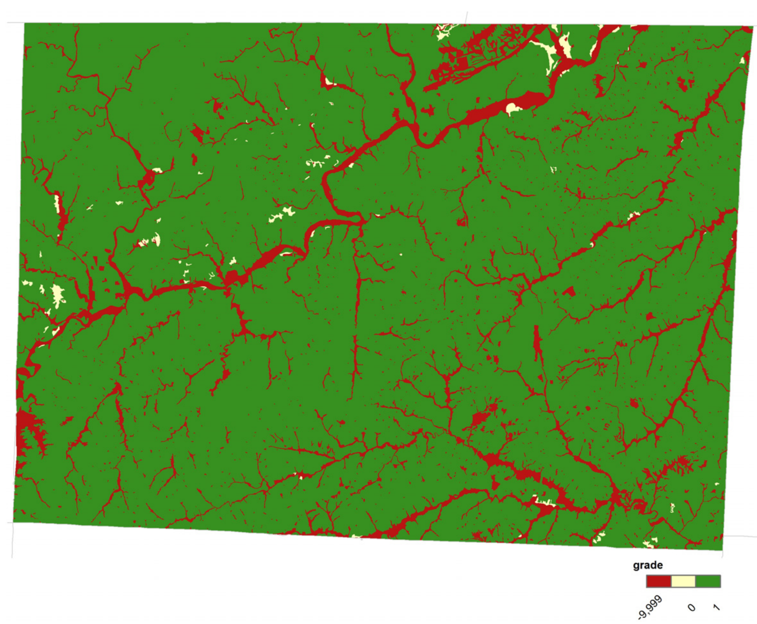
Soils Results

The soil drainage classification shows that the overwhelming percentage of the area in the county, 89.2 percent is well drained and, as it relates to drainage, is highly suitable for viticulture. The areas that fail are likely already failed by the stream network or other undesirable soil properties related to being on alluvial plains; these areas comprise 10.3 percent of the county (Map 20; Figure 10).

Figure 10. Drainage Classification Chart

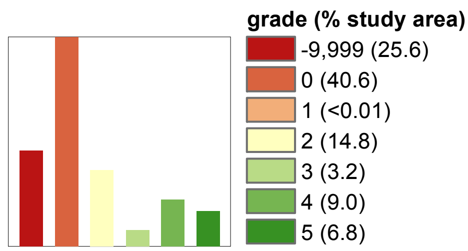


Map 20. Rockingham County Soil Drainage Classification

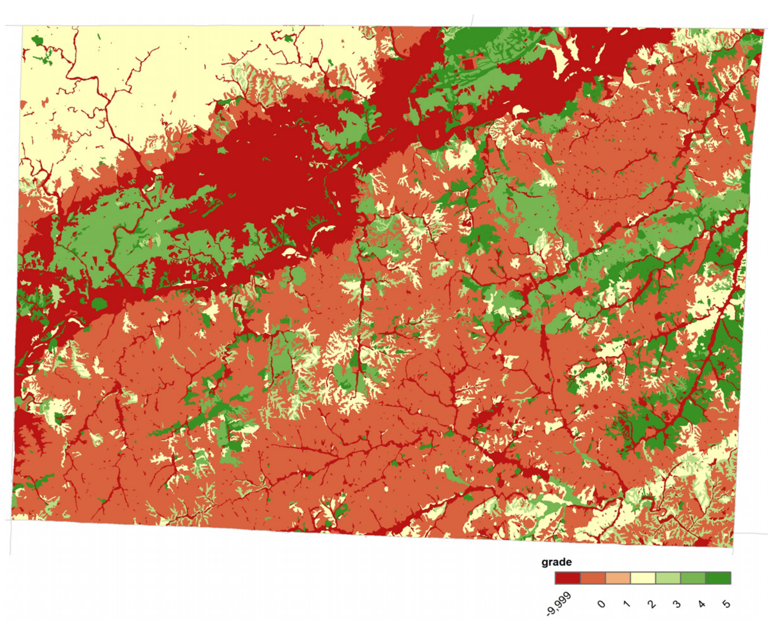


There are generally three zones of semi-homogeneity with regard to the pattern of AWC. There is a sizable and generally homogeneous area of the county which fails to be capable due to high AWC; this failing zone is immediately northwest of the Dan River, which flows along its southern edge. This region is part of a geologic basin formed from lake mud in the Triassic Era. To the northwest and southeast of the failing zone, the soil is generally suitable, except right along the alluvium of the drainage network. There are patches of soil with excellent AWC suitability interspersed within all three primary bands of suitability. The failing area for AWC encompasses 25.6 percent of the county (Map21; Figure 11).

Figure 11. AWC Classification Chart

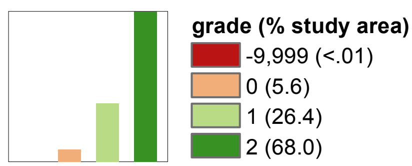


Map 21. Rockingham County Soil AWC Classification

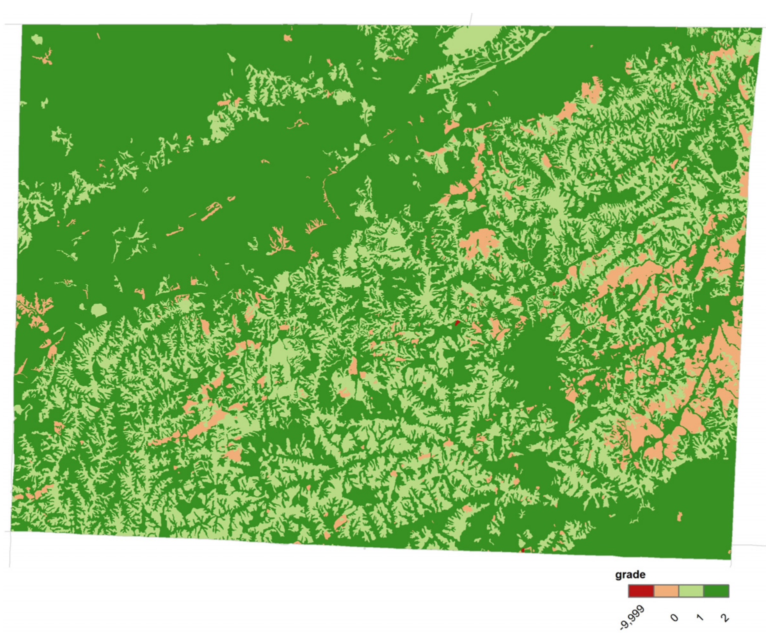


The soil depth classification shows that there are almost no failing areas due to soil depth in the county. The deepest soils tend to be in the northwest and southeast portions of the county, with a broad band of intermediate depth soil along the central ridges in the area between the Haw and Dan Rivers. Less than .01 percent of the county fails due to soil depth, while 68 percent is in the highest class of suitability (Map 22; Figure 12).

Figure 12. Depth Classification Chart

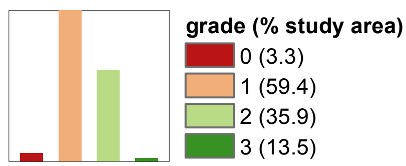


Map 22. Rockingham County Soil Depth Classification

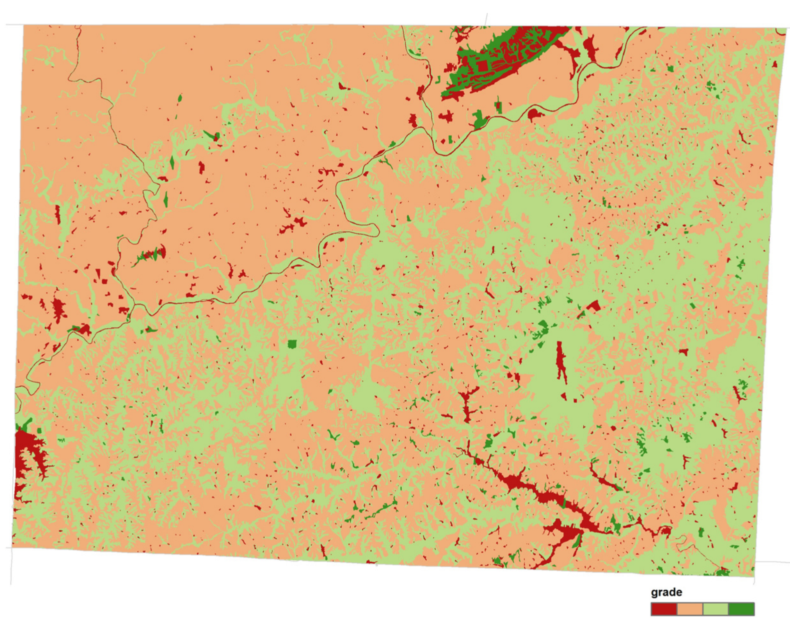


Very little of the county is excellent with regard to pH suitability; none of it fails, however. The areas in the lowest class of pH suitability are likely already failed by the stream network or other undesirable soil properties. There are moderately good areas of pH located primarily between the Dan and Haw Rivers. Less than 3.3 percent of the county falls into the lowest graded class of pH (Map23; Figure 13).

Figure 13. Soil pH Classification Chart

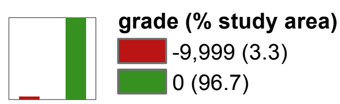


Map 23. Rockingham County Soil pH Classification

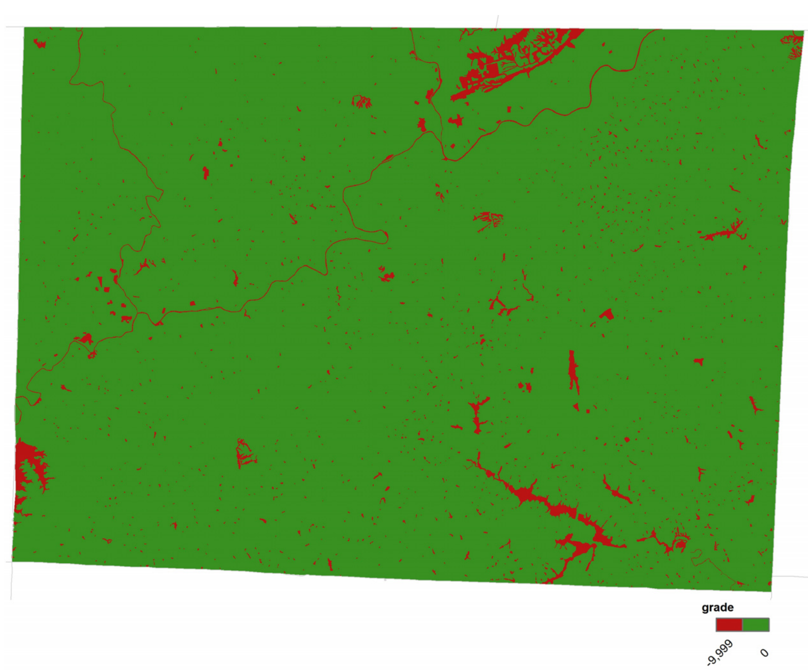


The soil texture classification shows that almost all of the area in the county, 96.7 percent, is absent of high percentages of silt and is therefore suitable based on texture. This layer functions as a mask since it is pass/fail. With the exception of a patch of failing area around Eden, the failing areas are related to water features; these areas comprise only 3.3 percent of the county (Map 24; Figure 14).

Figure 14. Soil Texture Classification Chart

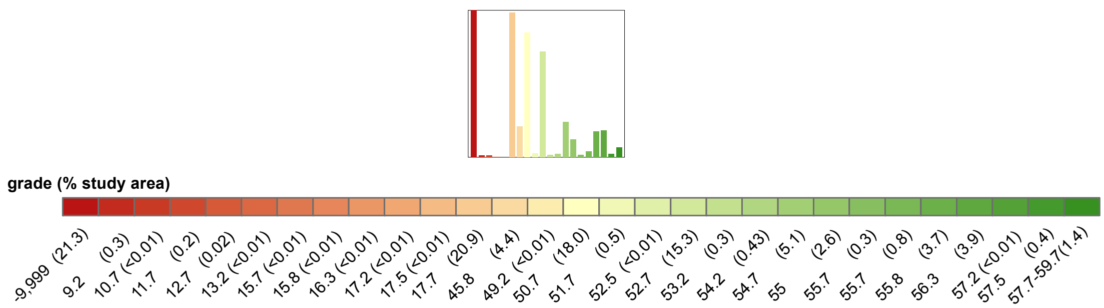


Map 24. Rockingham County Soil Texture Classification

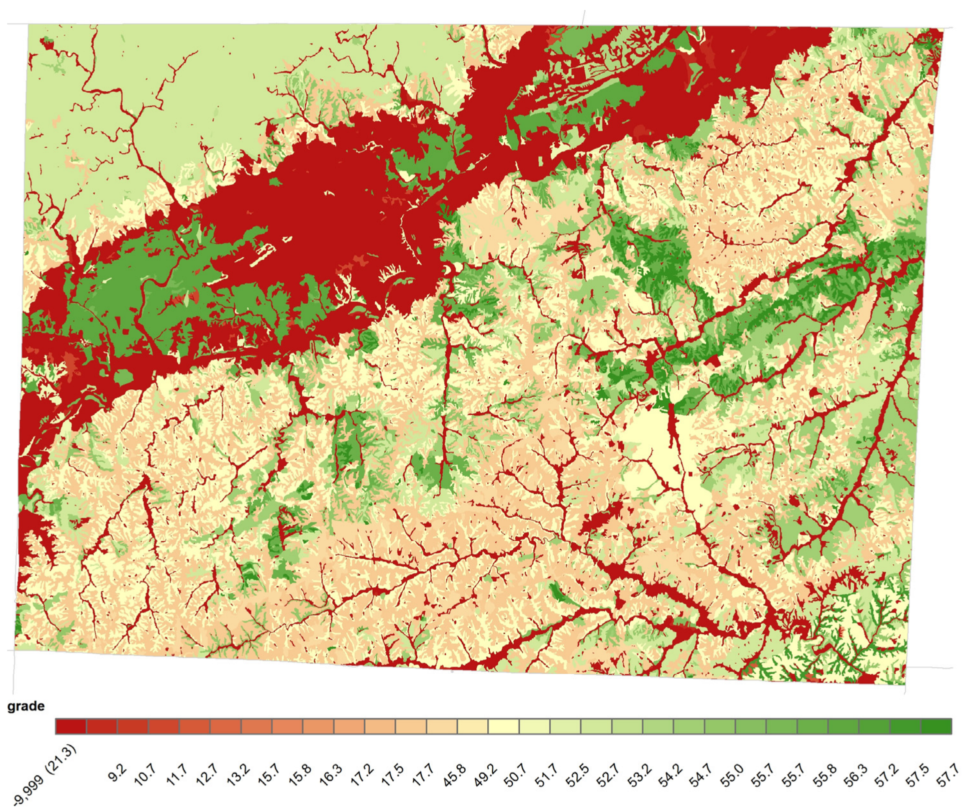


The Soil Composite Map illustrates that the northwest portion of the county has the most spatially homogeneous area of suitable soils, while there is a band of failing soils associated with the Triassic Basin that was failed primarily due to high AWC to the immediate northwest of the Dan River. All other failing areas tend to be on alluvial plains associated with the drainage network. There are large patches of high composite suitability grades; these are generally so graded because of their AWC grade. The values on the Soil Composite Map represent the outcome of the sub-model map algebra equation; 21.3 percent of the county is failing due to soil incapability (Map 25; Figure 15).

Figure 15. Soil Sub Model Composite Classification Chart



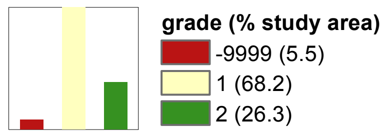
Map 25. Soils Composite Map



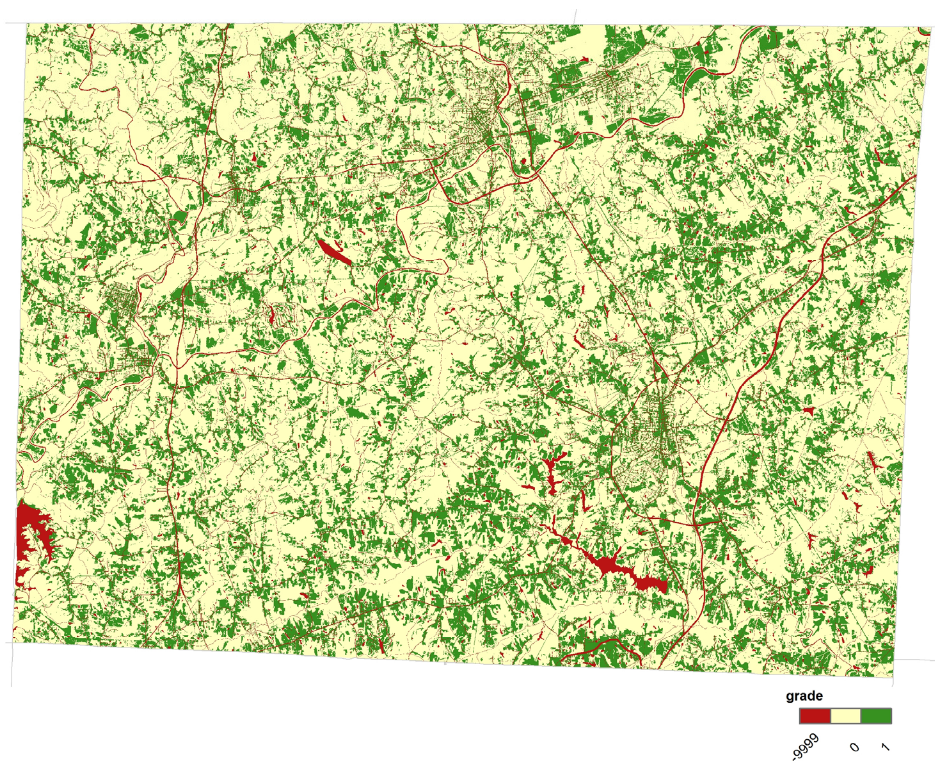
Land Cover/Land Use Results

The land cover classification shows that forested land dominates the study area with 67.8 percent of the county being forested. The highest rated land cover class, which is cleared land, accounts for 26.3 percent of the county. This means that it would be required to clear the land of trees and understory then plant a cereal crop for several years on many sites that are otherwise good for viticulture. This multi-year period of transition from forest to cleared land and the expense of clearing the land reduce the value of forested land. The failing classes account for just fewer than 6% of the area in the county (Map 26; Figure 16).

Figure 16. Land Cover Sub Model Composite Classification Chart



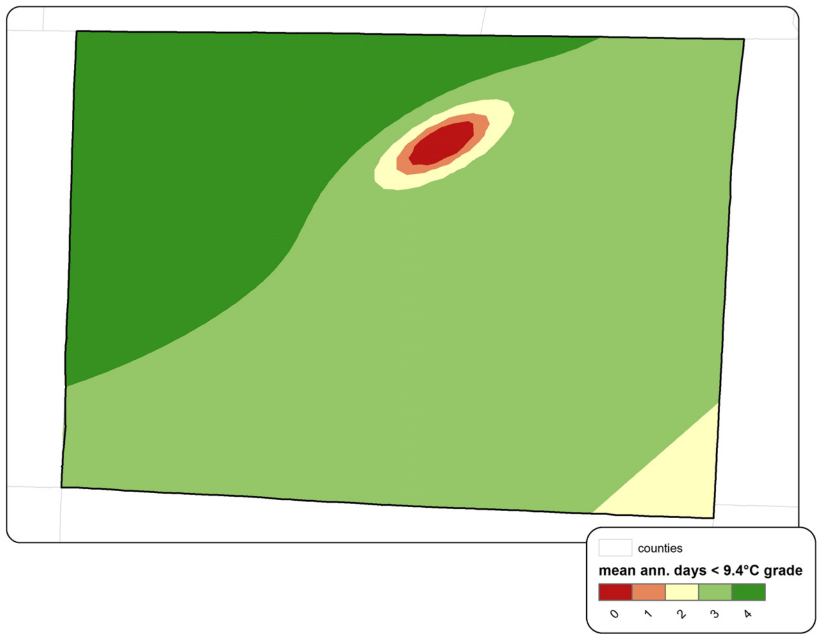
Map 26. Land Cover Composite Map



Climatological Results

The Classification of Pierce's Disease (PD) risk predictor thresholds show that Rockingham County falls in a relatively risky area for PD. There is less risk based on the days below –9.4°C and more risk with the –12.2°C threshold (Maps 27 & 28). To produce a single risk layer for PD, the average grades were taken and this combined PD classification will be used in the model (Map 29). There is a climate data point which causes some error; this is evident in the north central portion of the county. No areas were failed due to this risk, but it is apparent from the northwest to southeast trend that the cooler and hence less PD risky areas are in the northwest portion of the county (Maps 27, 28, & 29; Figure 17).

Map 27. Pierce's Disease Risk: Mean Annual Days <–9.4°C Classification



Map 28. Pierce's Disease Risk: Mean Annual Days <–12.2°C Classification

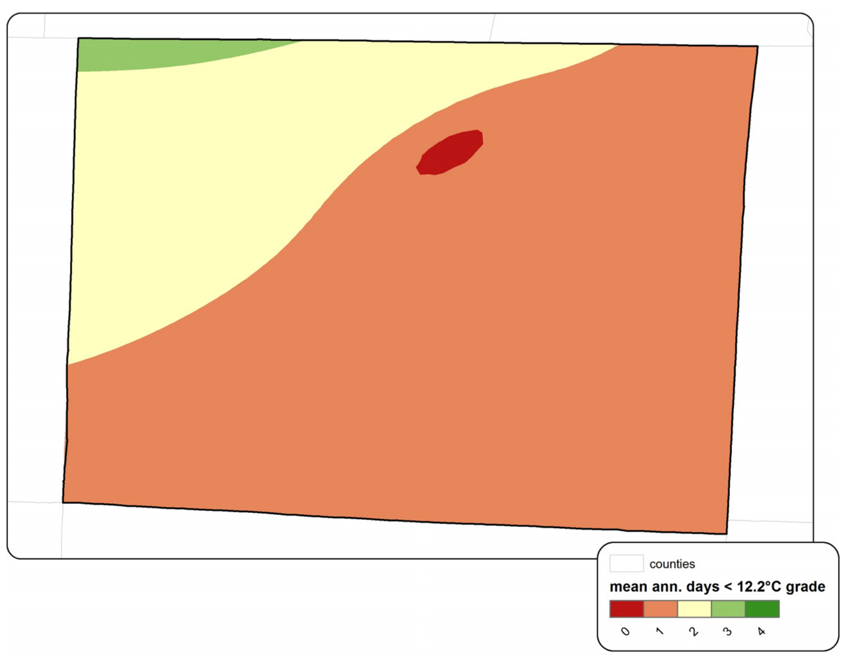
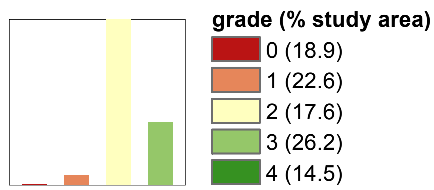
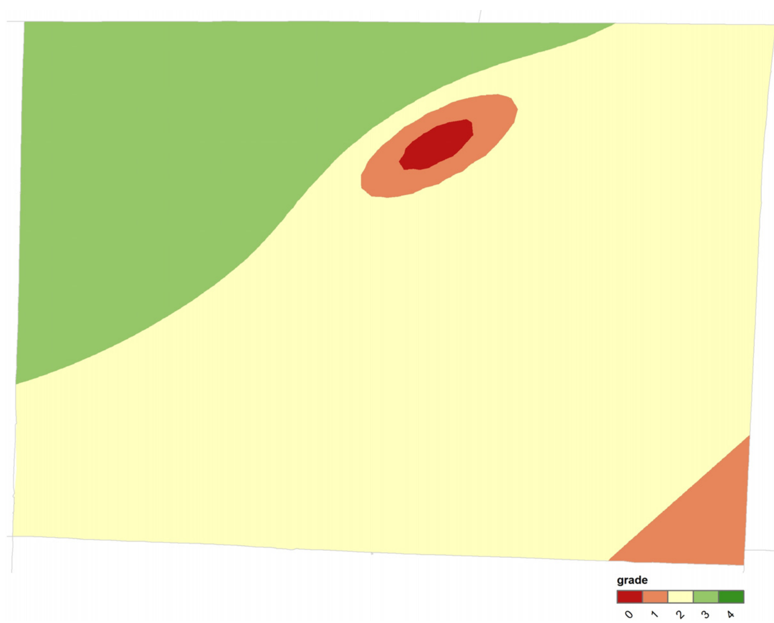


Figure 17. Combined Pierce's Disease Classification Chart

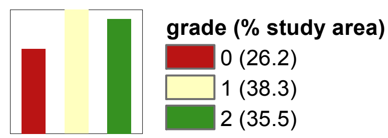


Map 29. Combined Pierce's Disease Classification

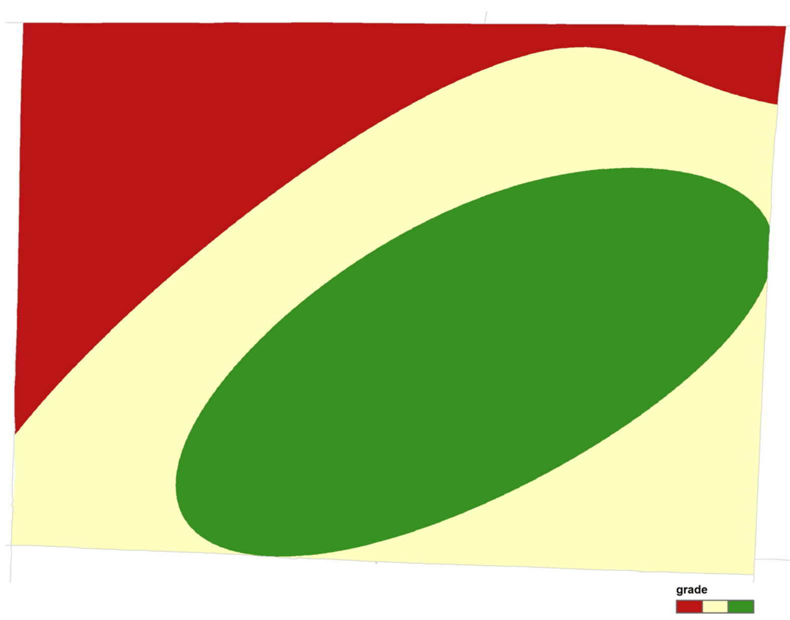


The SFI classification shows that Rockingham County has notable areas graded as moderate, which is one of the lower risk classes for frost. This area is primarily in the south center of the county extending to the southern border just north of Stokesdale, then northwest diagonally to the eastern border close to Ruffin. This area represents 35.5% of the county. The northwest corner of the county, in a strip along the northern border of the county is an area of high SFI risk. No area fails due to SFI (Map 30; Figure 18).

Figure 18. SFI Classification Chart

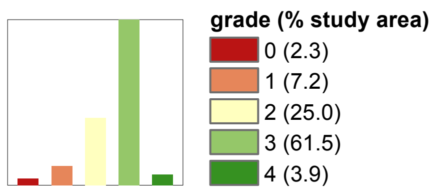


Map 30. SFI Classification

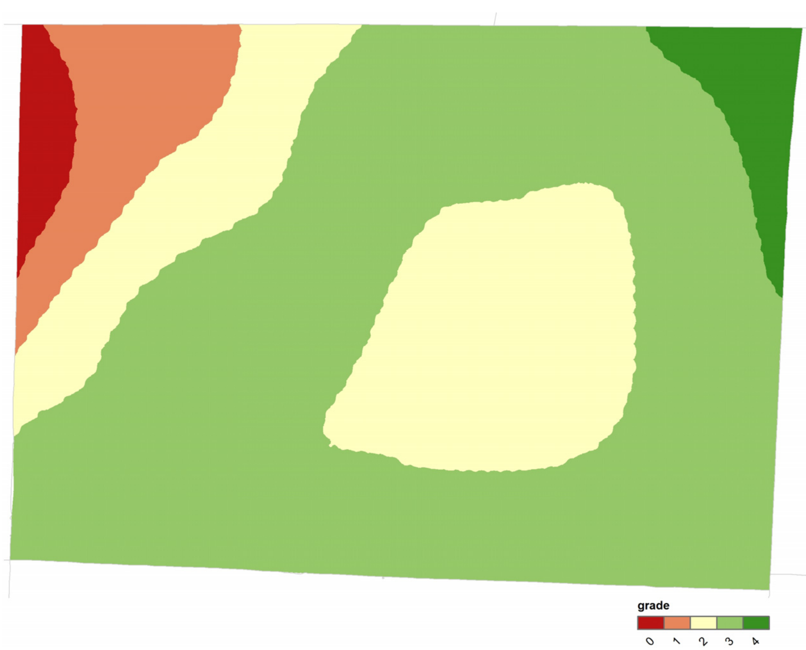


The precipitation classification shows that the northwest portion of the county is wetter than the northeast, and the middle has an intermediate value. No area is failed due to precipitation, but in this humid region, less precipitation is generally more desirable, especially during the growing season. Therefore, the grades have an inverse relationship with the amount of precipitation where less precipitation gets a higher grade (Map 31; Figure 19).

Figure 19. Mean Precipitation (Apr to Oct) Classification Chart

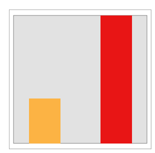


Map 31. Rockingham County Mean Precipitation (Apr to Oct)



The frost free period illustrates that the northwest corner of the county has a shorter growing period than the rest of the county. This layer is sometimes used to classify temperature/maturity zones, however in this model, it was used to confirm the GDD trend. Rockingham County has a sufficient growing season length for almost any *V. vinifera* grape (Map 32; Figure 20).

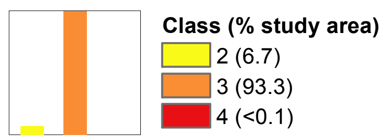
Figure 20. Frost Free Period Classification Chart



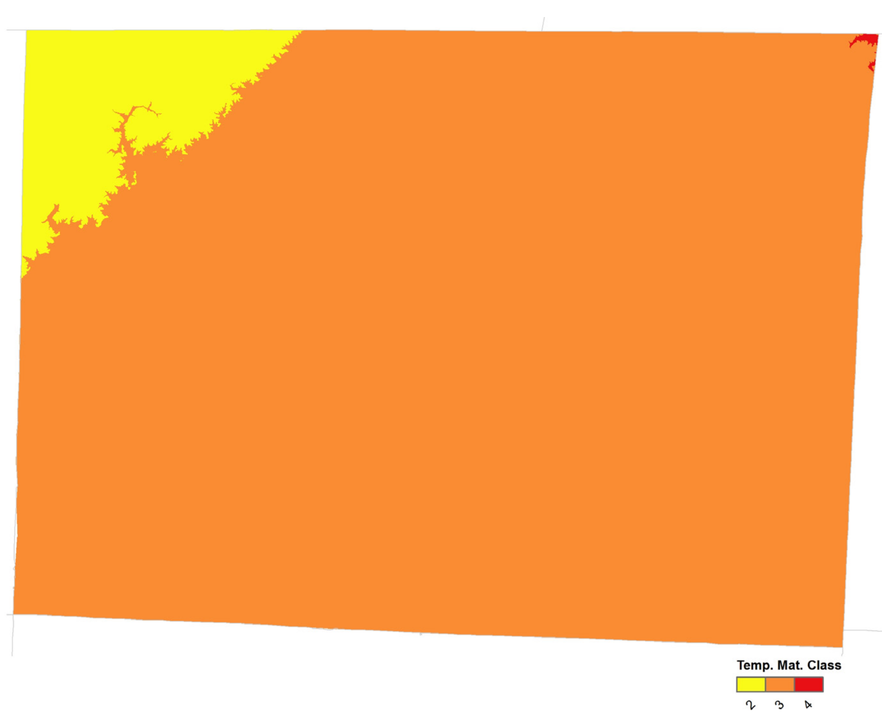
Map 32. Rockingham County Frost Free Period

The GDD classification illustrates that the extreme northwest portion of the county has a lower accumulation of degree days than the rest of the county. This layer is used to classify temperature/maturity zones rather than for general suitability. This is confirmed with the frost free period classification. None of the county area falls in a failing GDD class (Map 33; Figure 21).

Figure 21. (GDD) / Temperature/Maturity Group Classification Chart



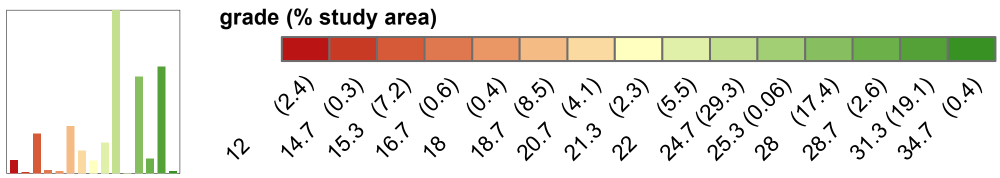
Map 33. (GDD) / Temperature/Maturity Group Class Map



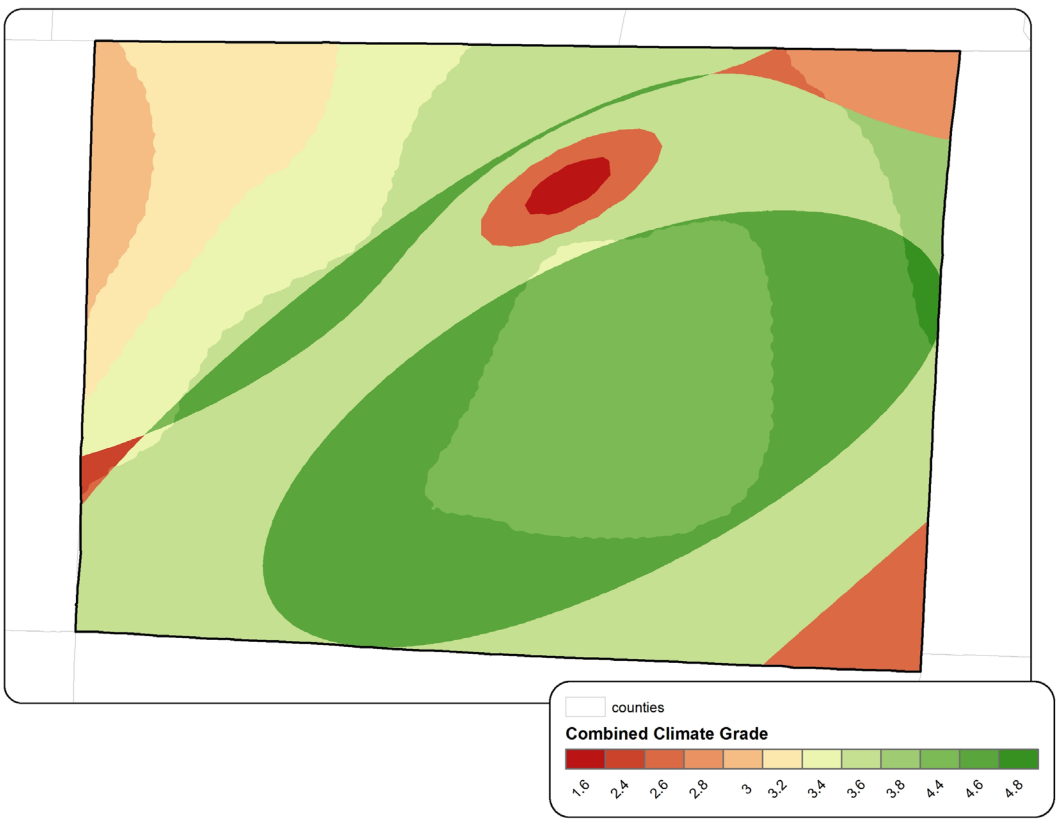
The climate composite classification is the least comprehensible of all of the sub-model composite suitability maps. This is attributable to several factors relating the source of the climate data. The fact that the data for precipitation came from monthly mean PRISM data while all other layers were produced from a custom lapse rate adjusted IDW interpolation is the most important reason why the layers didn't line up with each other elegantly. Without following the same methodology as PRISM, this is to be expected. There is also the fact that the precipitation layer resolution was changed from 800 meter to 10 meter resolution which becomes obvious along the edges of the precipitation classes. Also, the set of climate stations used for PRISM may be different than the NCDC stations used here. Even with its flaws, a general trend can be seen. This trend shows that the county's central ridge that divides the Haw River and Dan River Drainage Basins appears to have the best climate for *V. vinifera*. This is due in large part to the area with desirable SFI values. The values on the Climate Composite Map represent the outcome of the sub-model map algebra equation; none of the county is failing due to climate incapability (Map34; Figure 22).

The temperature/maturity group classification is made up solely by the GDD classification layer (Map 33; Figure 21).

Figure 22. Climate Composite Classification Chart



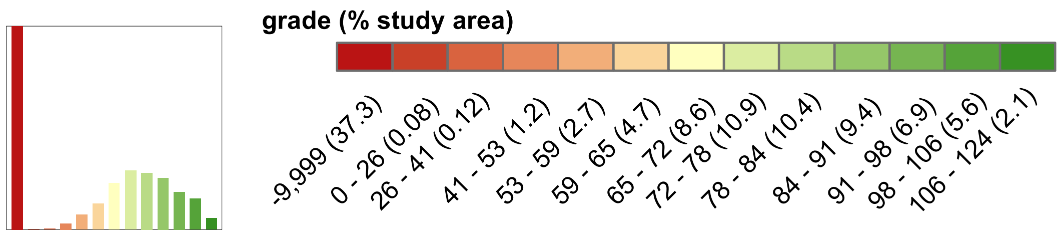
Map 34. Climate Composite Map



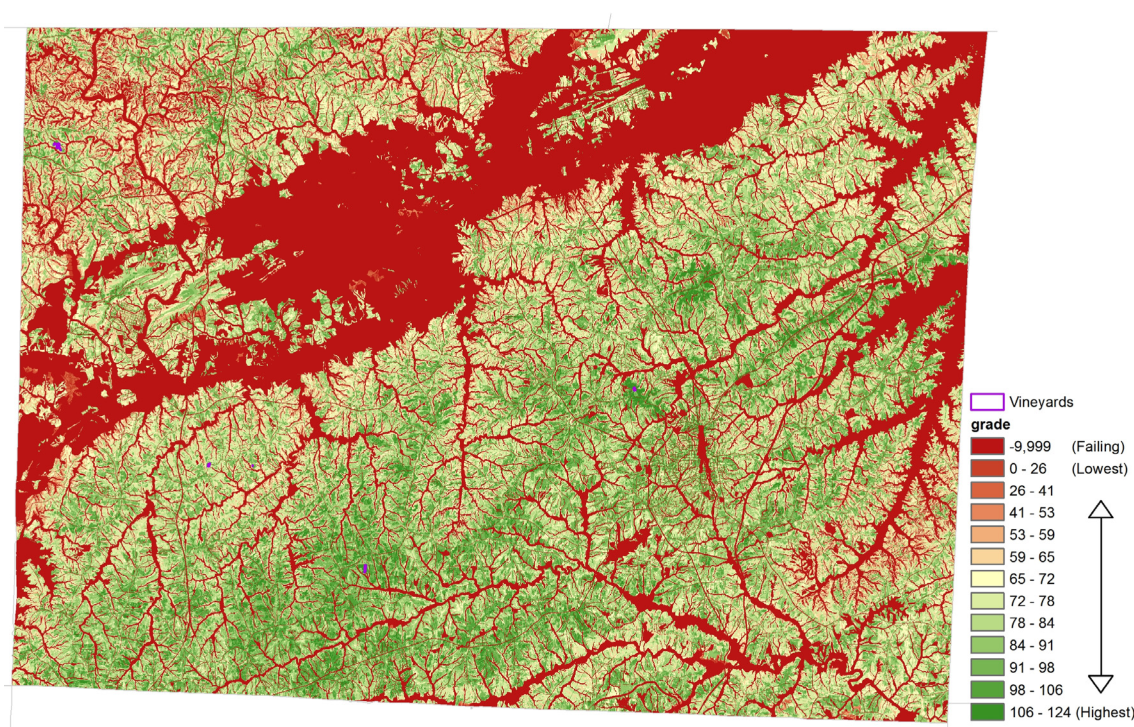
Final Results

The four sub-model composite maps were combined using map algebra resulting in a general suitability map for *V. vinifera* site selection (Figure 24). This general suitability classification illustrates that the ridge from the southwest corner of the county to the center northeast quadrant is the best area for growing *V. vinifera* grapes. There is also a sizeable area in the northwest corner of the county and the hills surrounding Mayodan. The failing portion of the county amounted to 37.3 percent, most of which was related to the soil property AWC and the lowest 20% of absolute elevations in the county (Map35; Figure 23).

Figure 23. General Suitability Composite Classification Chart



Map 35. General Suitability Composite Classification Map



The general suitability map for *V. vinifera* site suitability was then clipped using the Temperature/Maturity group suitability map to produce a general suitability map divided by Temperature/Maturity Group (Map 36).

Map 36. Temperature/Maturity Suitability Composite Classification Map

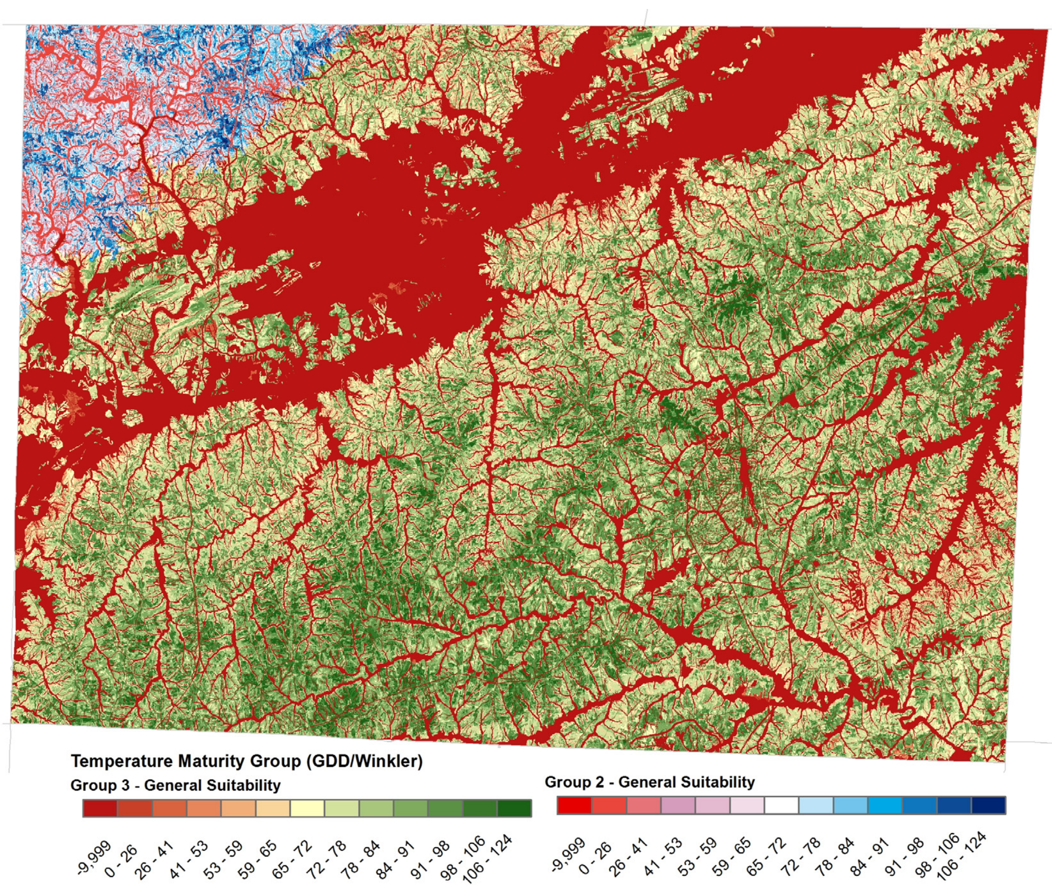
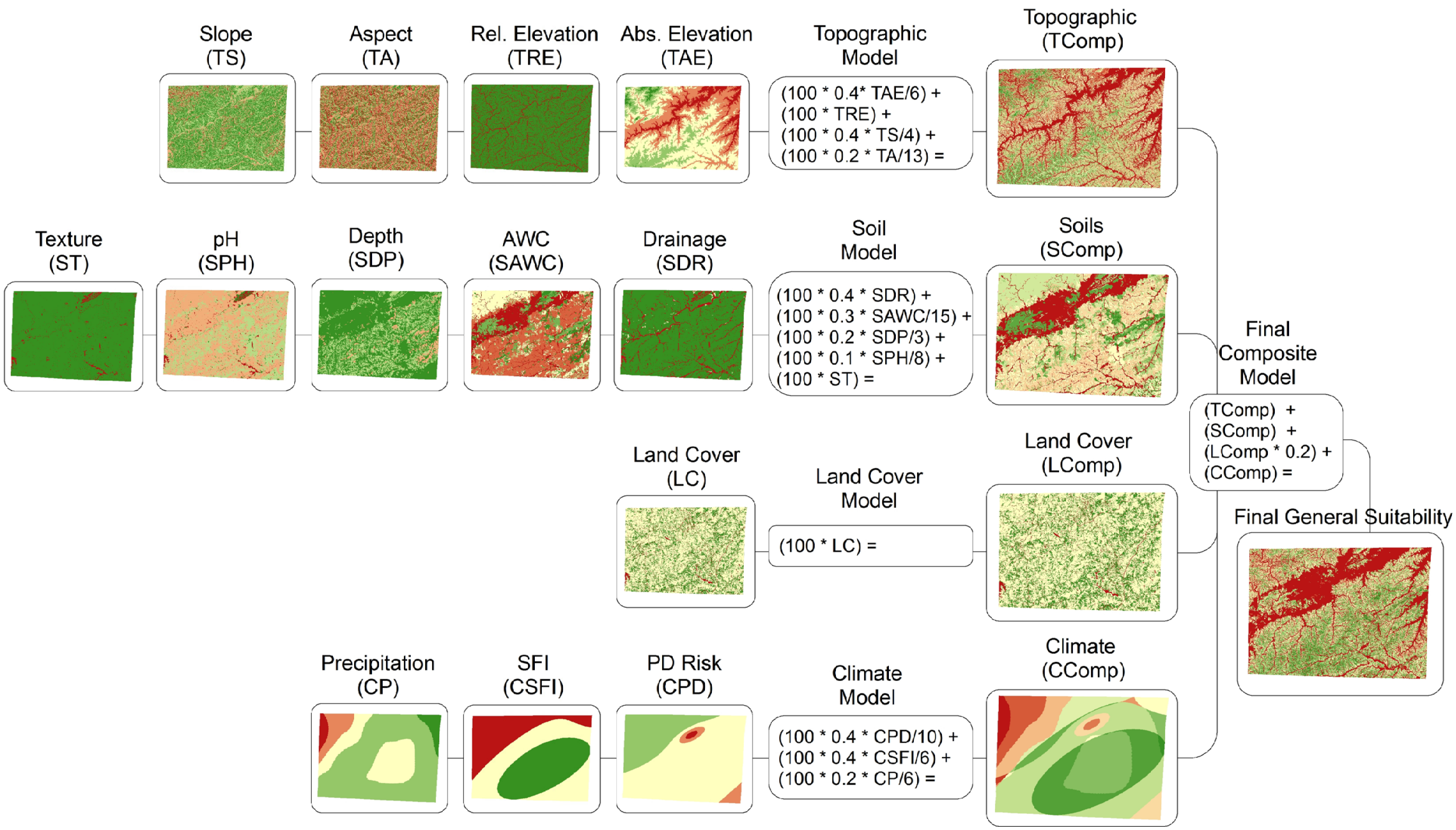


Figure 24. Model Summary Diagram



CHAPTER VIII

ASSESSMENT

The DEM, SSURGO, transportation vector files, orthoimagery, and climate data which make up the base data for this model are all from reputable sources and assumed to be the most accurate and readily available data. Three different assessments have been performed to help validate the assumptions and assertions made in the model. First, the Land Cover sub-model has been assessed as to the accuracy of the supervised classification. Secondly, polygons for all commercial vineyards within the county were compared to the areas that were failed by the model. Finally, these same vineyard polygons were compared to the areas which passed, and the level of suitability is noted.

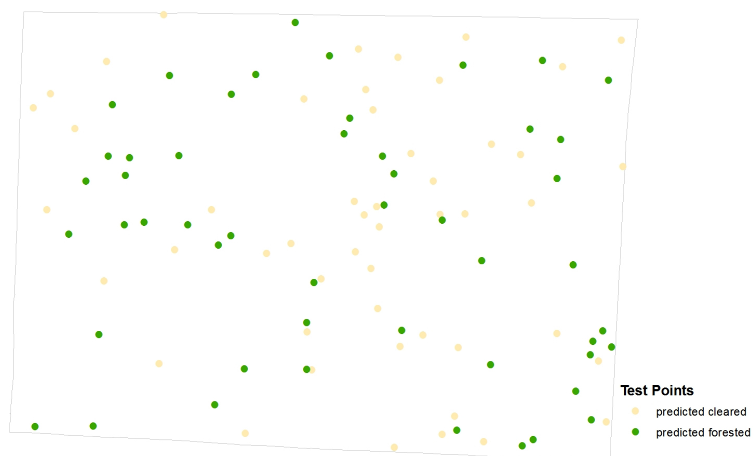
The Land Cover sub-model consisted of a supervised classification of reduced resolution NAIP orthoimagery. The original NAIP imagery was 1 meter resolution and was then degraded to 10 meter at which point a supervised classification was performed and classified into two classes, forested and cleared. Then, vector files were used to determine the positions of water, exposed bedrock, and transportation infrastructure. The final product of the sub-model was a classified image with five classes: forested, cleared, urban (transportation infrastructure), exposed bedrock, and water. To assess the accuracy of this classification, test points were chosen by a stratified random sampling which included 50 points within each of the two classes of forested and cleared. The original

NAIP imagery and a leaf off orthoimagery dataset from the same year (2010) were used to assess accuracy. The errors are mostly attributable to the fact that intermediate classes of forest or cleared land make it impossible to accurately classify all land into one of these two classes. This is the case, first, because the two classes are somewhat ambiguous when it comes to the variety of land cover classes present in nature. For instance, take the case of a fence row separating two fields; the row has trees, but these are not a forest, and this class makes up a small part of the volume of the landscape. The same can be said about a field with multiple small trees. It is woodland, which topologically can be understood to fit between the classes of forest and cleared land. The second problem is that the urban class was taken from the vector data which represented this class with transportation infrastructure. So, where there is a large warehouse, this can be said to be an urban class, yet since it is not transportation infrastructure it was not classified as urban. Therefore, all urban structures other than transportation structures were classified as either cleared or forested. This can be said to be a shortcoming of the land cover classification in general but not really an error in classifying all land as either cleared or forested. The results of this assessment are summarized in Table 25 (Map 37 & 38) and show that the Land Cover classification into cleared and forested was 92.7% accurate if all error points are thrown out. One error point was on a cloud, and three were on urban area all of which had been classified as cleared land; if the urban points are assigned to the cleared class, the assessment shows as 92.9% accurate.

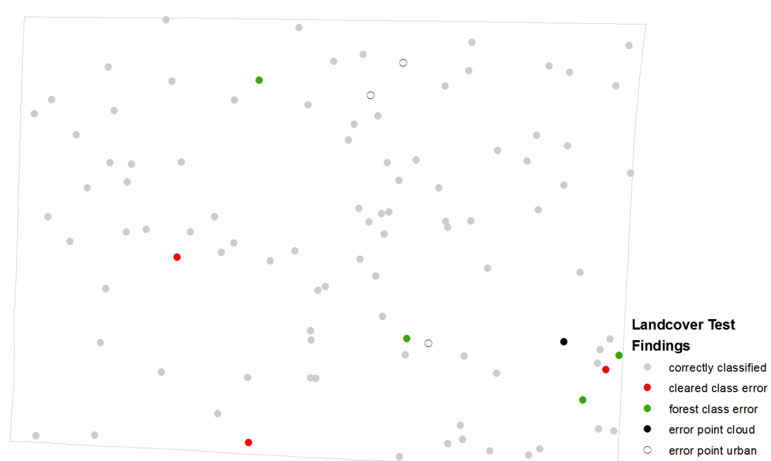
Table 25. Land Cover Classification Assessment

		Measured: Cleared	Measured: Forested	Error Points
Predicted	Cleared	43	3	4
	Forested	4	46	

Map 37. Land Cover Assessment - Stratified Random Sample Test Points



Map 38. Land Cover Test Findings

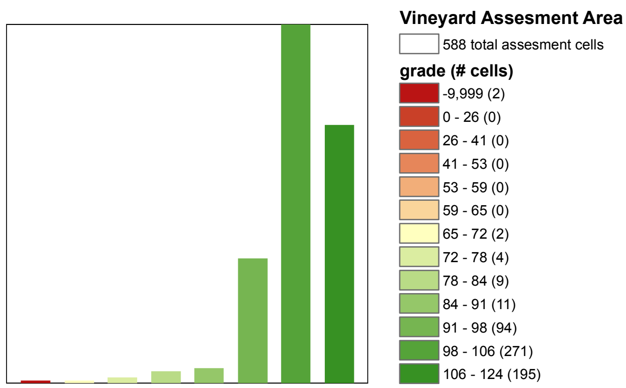


The second assessment task was to use existing vineyards within the county to test the assumption of the model. This test illustrates the grades given by the model to these vineyards and can be used to test the parameter grading regime. If many failing cells were to fall within these vineyards, it would suggest that the parameters need adjustment or that these vineyards would not be successful long term. However, if all vineyards tended to score high on suitability, it is affirmative for the choices made in the model.

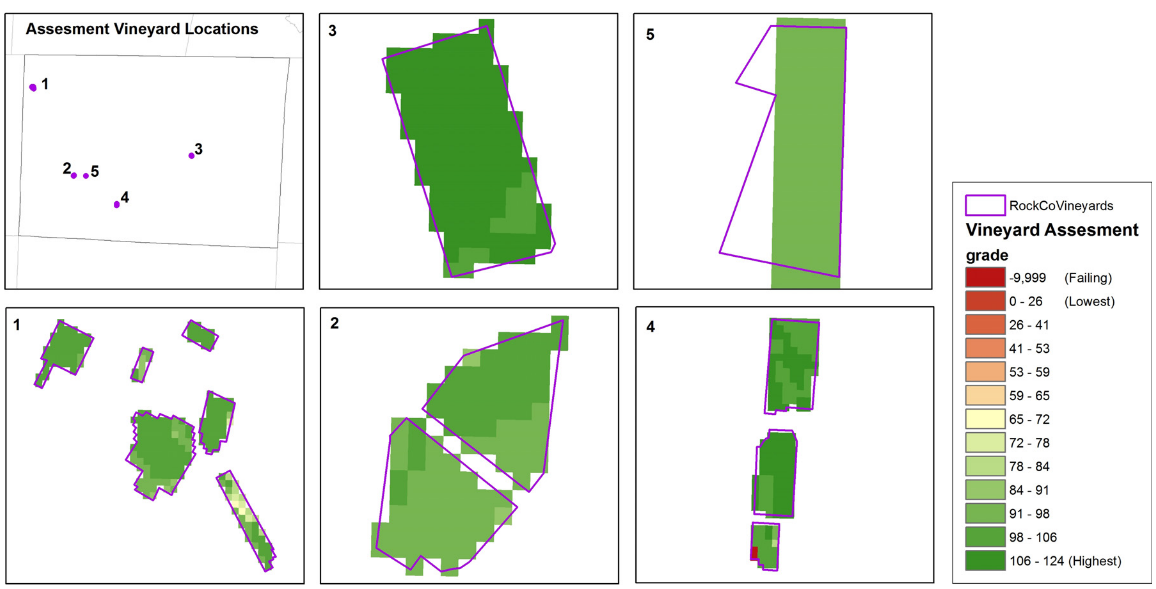
All known commercial vineyards (four) and one private vineyard in Rockingham County were found by plotting their street addresses with points and then using NAIP imagery to find and trace their boundaries. These vineyards' polygons have been used to clip the associated 10 meter raster cells of all layers and investigated for capability and suitability. There were 588 cells total within these vineyards. In the capability assessment, two cells from these 588 were in the failing class (Note: the two failing cells are on vineyard map 4; Map 40). After investigation, it was determined that the vineyard in question was bordered by a road, and these two cells were classified failing because the road was within the 10 meter resolution of the raster image, therefore it was partially clipped along the border of the vineyard. In the suitability assessment, there are no cells in the lowest six of twelve classes in any of the vineyards. All cells falling within these vineyards are above the mean for suitability.

These are very strong results indicating that the assessment of both capability & suitability suggest that the model is valid. The aforementioned clipped vineyard plots were statistically quantified and are compared and contrasted below (Map 39; Figure 25).

Figure 25. Vineyard Suitability Assessment Classification Chart



Map 39. Vineyard Suitability Assessment Map



CHAPTER IX

CONCLUSIONS

Findings

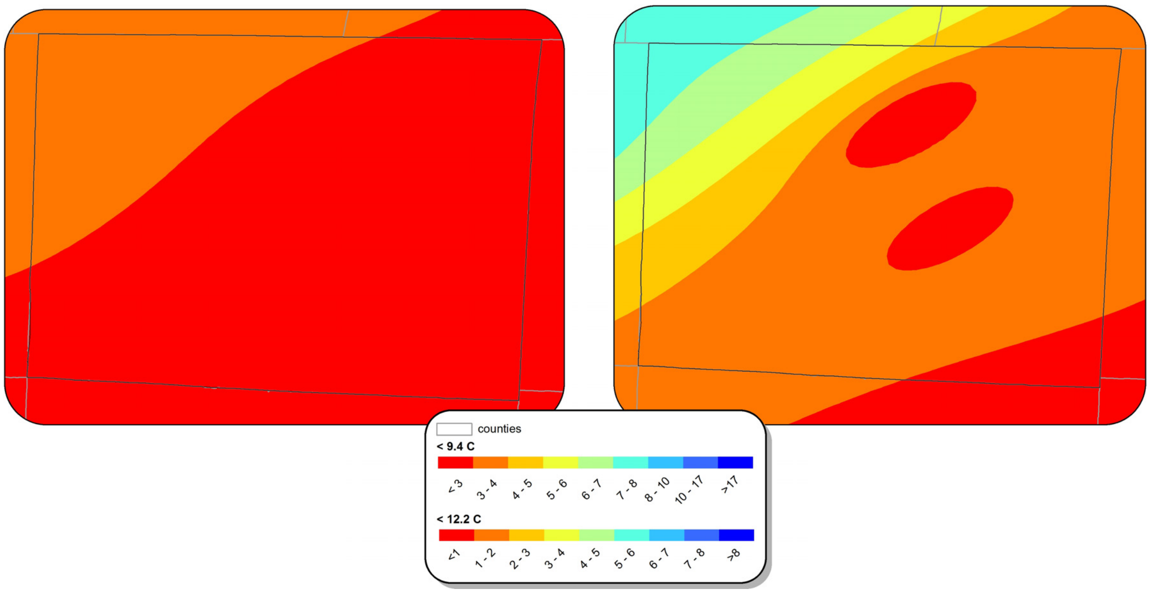
The primary goal of this research was to summarize site suitability for *V. vinifera* vineyard establishment in the North Carolina Piedmont using the case of Rockingham County. This goal has been accomplished, and according to the results of the model and its assessment, it has been determined that there are suitable areas for growing *V. vinifera* grapes in this region. The strongest form on the final map (Map 36) is the contiguous failing area which generally runs from the southwest to the northeast direction across the county; this failing region is primarily the result of two parameters, one each from the topographic sub-model and the soils sub-model. The topographic parameter causing failure was due to low elevations along the Dan River Valley since the lowest 20% of the county was failed based on cold air drainage. The soil parameter causing the failure was AWC, as soils with AWC > .15 were considered failing. These soils tend to retain too much water, which causes excessive vine vigor, a major regional problem for viticulturists of the Southeastern U.S.

The areas containing the best grades tended to be much more dispersed and much smaller in land area than the large contiguous failing area. The densest areas of good suitability tend to be located in three regions of the county. The first, most distinct, and best of these three regions are found between Reidsville, Eden, Wentworth, and Ruffin. In this area, there is a cluster of three very dense zones of suitability. These three zones are the Oregon Hill area, along Business Hwy. 29 north of Reidsville, and in the area surrounding the Chinua Penn Historic Plantation. The second region is the area along the central portion of a broad ridge which partly separates the Haw and Dan River Basins to the southwest of Wentworth and Reidsville. This drainage divide area provides many good sites, in a broad area extending from the southwest toward Stokesdale. The third region of good suitability is on the hills surrounding Madison and Mayodan and the region to their immediate northwest, which was the area that was expected to have the densest collection of high grades for suitability before the model was performed. The steep slopes of the northwest corner and higher rainfall rates and a riskier spring frost profile contributed to the difference between the expected outcome and the model findings.

One convincing aspect of the distribution of the classes across the land is the normal distribution which shows up in the final classification frequency histogram (Figure 24). This normal curve on the frequency distribution is consistent with natural distributions, hinting that the choices made in the model are in keeping with the expectations found with natural physical phenomena. The likelihood that all parameters of the model will be at their highest values at any one spot on the map is unlikely as seen in the small right foot of the histogram. Likewise, the likelihood that all parameters in the model will be at their lowest values at any one place is small as seen in the small left foot of the curve. The likelihood that most areas will have an intermediate sort of suitability is perfectly reflected in that the middle of the curve shares position with the mean suitability scores.

As to the shortcomings of the model, one highly influential physical phenomenon which is not considered thoroughly in the model is that of climate change. Within the climate submodel, the period that the temperature parameters were taken spans 40 years (1971 to 2010), yet the last 10 years of this period were much warmer by every measure than the previous thirty. Most importantly for European grapes are that winters have had consistently fewer days of very cold temperatures below two important thresholds <–9.4°C and <–12.2°C (10°F and 15.1°F). The direct impact that this has on growing European grapes in the area relates to the survival of a particular vector for the pathogen known as Pierce's Disease, which is deadly to the vines. To illustrate the gravity of the situation for *V. vinifera* vineyard operators in Rockingham county, if the temperature parameters from the model had been taken from the numbers for the period of 1997 to 2010, most of the area to the southeast of the Dan River would fail to be capable for *V. vinifera* because none of that area averaged more than a day below –12.2°C in this time period (Map 40). The areas on this map represented in red would fail.

Map 40. Mean Annual Days below Pierce's Disease Risk Thresholds
2000 to 2010 (Left Map = <–12.2°C; Right map = <–9.4°C)



This one fact is the most alarming finding of the whole study, and it was not even directly related to the final products of the research, nor was it a planned finding. If the climate change seen in the last ten years becomes permanent, then the areas where we can easily grow *V. vinifera* grapes in NC will have moved to the north and west from where much of our current commercial vineyards are planted. This fact that 2000 to 2010 decade has been very warm will not change the outcome of this research. The model stands as it is, using a 40 year window for a reason; this is a long period, even longer than the normal 30 year window. This period takes many of the important climate cycles into consideration so that the average over time is preserved as the important value. If there is continual warming in the future, or if there is no more warming and the current mean temperature regime is the new normal, then Pierce's Disease will likely make *V. vinifera* incapable in this area, requiring vineyards to switch to varieties based on native grape species which are resistant to PD, such as Norton, Black Spanish, Blanc Du Bois, and Rotundifolia. If, however, this is a warm decade, and we settle back to something that is more like a typical decade of the last 40 years, then the model will stand as is; only time will tell.

Discussion

The assessment of this model by comparing the predictions of the model with the extant vineyards shows that the concept appears to be valid. This is because all of the vineyards within the study area are located on land which is predicted to be above average in suitability. This is made evident because only two cells out of 588 within the assessment vineyards were planted in a zone classified failing by the model; furthermore, this error was attributed to a road bordering the vineyard. A good long term test of accuracy for this model will need to involve the comparison of performance of vineyard sites based on their unique physical terroir over many growing seasons. Over this long a term, it will also become apparent if Pierce's Disease grows to be limiting for *V. vinifera* in this region.

Based on the recent climate change and implications for Pierce's Disease high risk areas south and east of the Dan River in Rockingham County, North Carolina, it would seem like a reasonable practice for the vineyard operators in this region to have a diversity of grape varieties which are Pierce's Disease resistant. Hybrids of *V. vinifera* and *V. arizonica* being produced by Andy Walker at UC Davis, which are resistant to PD, are one option which shows much promise. These are said to be very close to the European grapes in flavor and color profiles. While *V. vinifera* based varieties may be popular because of their oenological qualities and historic domination of the marketplace, there are several other economically viable wine grape varieties which are hybrids of PD resistant Native American grape species. Many of these native varieties have *V. vinifera* like taste profiles and are proving to be less burdensome on the vineyard operators along the Gulf Coast and in Virginia and Missouri due to their less demanding spray routines. These grapes containing native parentage include varieties like Norton, Black Spanish, and Blanc Du Bois. There is always *M. rotundifolia* as well, which is a major contributor to the North Carolina wine industry; even if it has a non-vinifera flavor profile, there is a good market in the Southeast U.S. for sweet wines produced from this grape.

Regardless of what the future holds for *V. vinifera* in the Piedmont of North Carolina, this research presents a good case for GIS as a useful tool to help consider the capability and/or suitability of a region for vineyard location.

Final Products

The products of this research include composite suitability maps covering the four physical realms of vineyard site suitability: topography, soils, land cover, and climate. Using the concepts of Map Algebra, these four maps have been summed to produce a combined composite physical site suitability map. This map should be useful to understand the general patterns of suitability for *V. vinifera* within the study area. Finally, this combined map was clipped with the temperature/maturity group classes to produce a comprehensive map which summarizes *V. vinifera* suitability by temperature/maturity group. Along with all of these maps, the study area has been statistically described to report the percentage of area falling into twelve suitability classes. These classes are to be understood as ordinal in nature, communicating relative suitability. There is no assumption of ratio based properties such as magnitude. In other words, the highest graded class cannot be said to be twice as good as the middle class. The final output is a composite made of composites; its ordinal nature has the sole purpose of highlighting areas where many types of physical phenomena combine to suggest suitability.

The layers of this model have been incorporated into a shared web map (NOTE: this web can be used in ESRI: ArcGIS Desktop, ArcGIS Explorer Desktop, ArcGIS Online, ArcGIS Explorer Online, as well as the ArcGIS mobile app for iPhone, Android and Windows Mobile.):
http://www.arcgis.com/home/search.html?q=nowlin%20mesoscale%20viticulture

The eventual plan is to use this process to produce such a map for each county in the North Carolina Piedmont, then for each North Carolina AVA. Maps produced using these processes should be very helpful for those interested in establishing *V. vinifera* vineyards in the North Carolina Piedmont, consultants, and extension agents. Funding will be necessary to complete this task.

Future Research

There is a wealth of opportunity for future GIScience based research which could benefit viticulture, both in the Southeast in general and North Carolina Piedmont in particular. Whatever research follows in this vein, one important improvement to the research involves better data. Daily PRISM data would provide a more rigorous data source for all climate data used in this model. If this research is extended, a grant for this needed data should be written. PRISM data for daily normals for each of the 365 days of the year was quoted at ~ $10,000, by the PRISM group. This data could increase the accuracy and ease with which this research could be completed elsewhere.

The first logical extension of this model is that it should be completed for all counties falling within the Piedmont Triad Region of North Carolina and the results in those counties compared and contrasted with the results of Rockingham County. This could yield good suggestions about future possible AVA areas and lead to clarification on how the model can be corrected and/or calibrated for different locations.

This research area could be expanded even further and performed for the whole Southern Appalachian Piedmont Region and then the greater Southern Highlands Region including the Ozarks and Ouachita Mountains. This would further increase the area within which the model could be useful. In the act of expanding this model, while determining if there are parameter calibrations that should be made, this process could reveal some basic universal truths about how viticultural suitability changes over large areas and how to weigh suitability in a multivariate physical parameter space. It would at the least ensure that this model could be effective for other counties within this multistate region. Also, rather than limiting the model to a political boundary, it could be scaled up to the macro and synoptic scales and scaled down to the microscale in order to provide a multi-scale model.

One particularly important and ongoing body of research investigates which grape varieties may best be matched to a particular region. With the aid of GIS based multi-scale models, this place-to-varietal matching research should compare established wine growing regions world-wide to this region to determine which grape varieties are known to perform well within the regional topographical, climatological, and soil parametric matrices common to the region.

Based on the finding that climate change is resulting in increased Pierce's Disease risk in the North Carolina Piedmont, it would be interesting to consider the suitability of the Piedmont for those varieties of grapes which are resistant to Pierce's Disease. Many of these varieties which show particular promise for the region are native to North America and, presumably, could be modeled in a similar fashion to the model presented in this study.

Another important aspect of viticulture not considered in this research which is important to a holistic understanding of the subject in a regional context are the impact of local cultural practices. The study of the viticultural and oenological culture practices of North Carolina as compared to other regions could be fruitful to marketing the region and standardizing behaviors around what practices are most successful economically. This research could determine the cultural components of terroir not included in this physical model and outline what is unique to North Carolina’s wine industry.

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APPENDIX A

LIST OF CLIMATE DATA STATIONS

STATION Number	STATION NAME
GHCND:USC00310090	ALBEMARLE NC US
GHCND:USC00310286	ASHEBORO 2 W NC US
GHCND:USC00310982	BOONE NC US
GHCND:USC00311239	BURLINGTON FIRE STATION NUMBER 5 NC US
GHCND:USC00311515	CARTHAGE WATER TREATMENT PLANT NC US
GHCND:USC00311677	CHAPEL HILL 2 W NC US
GHCND:USC00311700	CHATHAM WTP NC US
GHCND:USC00312238	DANBURY NC US
GHCND:USC00312515	DURHAM NC US
GHCND:USC00312631	EDEN NC US
GHCND:USC00312740	ELKIN NC US
GHCND:USC00313625	GREENSBORO PUMP STATION NC US
GHCND:USC00313919	HAW RIVER 1 E NC US
GHCND:USC00314063	HIGH POINT NC US
GHCND:USC00314464	JACKSON SPRINGS 5 WNW NC US
GHCND:USC00314496	JEFFERSON NC US
GHCND:USC00314675	KING NC US
GHCND:USC00314938	LENOIR NC US
GHCND:USC00314970	LEXINGTON NC US
GHCND:USC00315743	MOCKSVILLE 5 SE NC US
GHCND:USC00315890	MOUNT AIRY 2 W NC US
GHCND:USC00316256	NORTH WILKESBORO NC US
GHCND:USC00317097	RANDLEMAN NC US
GHCND:USC00317202	REIDSVILLE 2 NW NC US
GHCND:USC00317516	ROXBORO 7 ESE NC US
GHCND:USC00317548	RURAL HALL NC US
GHCND:USC00317615	SALISBURY NC US
GHCND:USC00317618	SALISBURY 9 WNW NC US
GHCND:USC00317656	SANFORD 8 NE NC US
GHCND:USC00317924	SILER CITY NC US
GHCND:USC00318292	STATESVILLE 2 NNE NC US
GHCND:USC00318519	TAYLORSVILLE NC US
GHCND:USC00318694	TRANSOU NC US
GHCND:USC00318964	WADESBORO NC US
GHCND:USC00319555	W KERR SCOTT RESERVOIR NC US
GHCND:USC00319675	YADKINVILLE 6 E NC US

GHCND:USC00319704	YANCEYVILLE 4 SE NC US
GHCND:USC00441614	CHATHAM VA US
GHCND:USC00442245	DANVILLE VA US
GHCND:USC00443267	GALAX RADIO WBRF VA US
GHCND:USC00443272	GALAX WATER PLANT VA US
GHCND:USC00445300	MARTINSVILLE FLT PLANT VA US
GHCND:USC00445453	MEADOWS OF DAN 5 SW VA US
GHCND:USC00446692	PHILPOTT DAM 2 VA US
GHCND:USC00447338	ROCKY MOUNT VA US
GHCND:USC00447925	SOUTH BOSTON VA US
GHCND:USC00448170	STUART VA US
GHCND:USC00449301	WYTHEVILLE 1 S VA US
GHCND:USW00003758	DURHAM 11 W NC US
GHCND:USW00013723	GSO PIEDMONT TRIAD INTERNATIONAL AIRPORT NC US
GHCND:USW00013728	DANVILLE REGIONAL AIRPORT VA US
GHCND:USW00093783	BURLINGTON ALAMANCE REGIONAL AIRPORT NC US
GHCND:USW00093807	WINSTON SALEM REYNOLDS AIRPORT NC US

APPENDIX B

LIST OF ASSESMENT VINEYARDS

Name	latitude	longitude	website	Acreage
Autumn Creek V.	36.49	-80.01	www.autumncreekvineyards.com	5.22
Boulder V.	36.35	-79.93	http://cloerfamilyvineyards.com/	2.12
Chinqua Penn V.	36.38	-79.70	http://www.chinquapenn.com/	2.69
Riverbirch V.	36.31	-79.85	http://www.riverbirchvineyards.com/	4.12
Plott Hound V.	36.35	-79.90	none	0.12

APPENDIX C

LIST OF LAND COVER ASSESMENT POINTS

OID	predicted	assesed	Notes	Lat	Long
1	cleared	cleared		36.3988372	-79.726894
2	cleared	cleared		36.3270816	-79.786649
3	cleared	cleared	error point (urban)	36.5137477	-79.711956
4	cleared	cleared		36.4778427	-79.732639
5	cleared	cleared		36.3434246	-79.727412
6	cleared	cleared		36.2707762	-79.66251
7	cleared	cleared		36.381727	-79.746616
8	cleared	cleared		36.4868633	-80.004032
9	cleared	cleared		36.2584562	-79.672809
10	cleared	cleared		36.4485251	-79.608371
11	cleared	cleared		36.4636003	-79.983039
12	cleared	forested	cleared class error	36.2580729	-79.837783
13	cleared	cleared		36.3049904	-79.910629
14	cleared	cleared		36.4851779	-79.790985
15	cleared	cleared		36.4772527	-80.018045
16	cleared	cleared		36.3174987	-79.659851
17	cleared	cleared		36.267737	-79.535567
18	cleared	cleared		36.455467	-79.632963
19	cleared	cleared		36.3803435	-79.821294
20	cleared	cleared		36.4405835	-79.522717
21	cleared	cleared	error point (urban)	36.491628	-79.738859
22	cleared	cleared		36.4484634	-79.700515
23	cleared	cleared		36.4159987	-79.747646
24	cleared	cleared		36.5277477	-79.654813
25	cleared	cleared		36.3630474	-79.775125
26	cleared	cleared		36.3871238	-79.800909
27	cleared	error	error point (cloud)	36.327278	-79.57732
28	cleared	cleared		36.5412869	-79.90934
29	cleared	cleared		36.5082355	-79.57371
30	cleared	forested	cleared class error	36.3821879	-79.898232
31	cleared	forested	cleared class error	36.308858	-79.541995

32	cleared	cleared	error point (urban)	36.3256511	-79.689312
33	cleared	cleared		36.2538322	-79.638173
34	cleared	cleared		36.4124048	-79.72904
35	cleared	cleared		36.4094293	-79.867681
36	cleared	cleared		36.4069033	-79.739382
37	cleared	cleared		36.5190086	-79.745529
38	cleared	cleared		36.4157129	-79.599082
39	cleared	cleared		36.3014965	-79.782701
40	cleared	cleared		36.2495504	-79.712614
41	cleared	cleared		36.5092382	-79.956931
42	cleared	cleared		36.4083793	-80.005815
43	cleared	cleared		36.5264285	-79.524495
44	cleared	cleared		36.4985612	-79.676932
45	cleared	cleared		36.3603906	-79.957506
46	cleared	cleared		36.3176705	-79.708532
47	cleared	cleared		36.4301342	-79.681842
48	cleared	cleared		36.3706273	-79.73342
49	cleared	cleared		36.4080093	-79.65491
50	cleared	cleared		36.4075299	-79.676023
51	forested	forested		36.3854781	-79.861679
52	forested	cleared	forested class error	36.3287991	-79.707386
53	forested	forested		36.2511917	-79.605979
54	forested	forested		36.4586833	-79.57506
55	forested	forested		36.3990914	-79.887701
56	forested	forested		36.3017953	-79.786979
57	forested	forested		36.3220542	-79.547182
58	forested	forested		36.3333691	-79.787362
59	forested	forested		36.3606747	-79.781119
60	forested	forested		36.2620613	-79.9654
61	forested	cleared	forested class error	36.501364	-79.831507
62	forested	forested		36.4658168	-79.600942
63	forested	forested		36.3738938	-79.563842
64	forested	forested		36.2614737	-79.660696
65	forested	forested		36.4440633	-79.937188
66	forested	forested		36.3986274	-79.940974
67	forested	forested		36.5368942	-79.798737
68	forested	cleared	forested class error	36.3183225	-79.531458

69	forested	forested		36.2553851	-79.596523
70	forested	forested		36.2773698	-79.863666
71	forested	cleared	forested class error	36.288374	-79.561061
72	forested	forested		36.432249	-79.57785
73	forested	forested		36.3128959	-79.549164
74	forested	forested		36.3762057	-79.640912
75	forested	forested		36.2690057	-79.548078
76	forested	forested		36.4879507	-79.851889
77	forested	forested		36.5144054	-79.769637
78	forested	forested		36.5087147	-79.657439
79	forested	forested		36.3920989	-79.987377
80	forested	forested		36.4280076	-79.973336
81	forested	forested		36.4321191	-79.940521
82	forested	forested		36.3918999	-79.851345
83	forested	forested		36.4799721	-79.951742
84	forested	forested		36.4722408	-79.752376
85	forested	forested		36.4466675	-79.724392
86	forested	forested		36.3058943	-79.632827
87	forested	forested		36.4614816	-79.756996
88	forested	forested		36.5001144	-79.90418
89	forested	forested		36.5122384	-79.590723
90	forested	forested		36.4450328	-79.954852
91	forested	forested		36.403573	-79.673992
92	forested	forested		36.4137	-79.722806
93	forested	forested		36.434842	-79.714766
94	forested	forested		36.4004828	-79.924371
95	forested	forested		36.4460363	-79.895676
96	forested	forested		36.3292978	-79.538775
97	forested	forested		36.3241994	-79.961426
98	forested	forested		36.4991747	-79.535246
99	forested	forested		36.261532	-80.014095
100	forested	forested		36.3016721	-79.839222

APPENDIX D

LIST OF ACRONYMS

(AOC)	Appellation d'Origine Contrôlée
(AVA)	American Viticultural Area
(AWC)	Available Water Capacity
(BEDD)	Biologically Effective Degree-Day
(CI)	Coolness Index
(CSA)	Combined Statistical Area
(DEMs)	Digital Elevation Models
(DI)	Dryness Index
(DOC)	Denominazione di Origine Controllata
(GDD)	Growing Degree Days
(GIS)	Geographic Information Systems
(GST)	Growing Season Temperature
(HI)	Heliothermal Index
(IDW)	Inverse Distance Weighting
(LC)	Land Cover
(LU)	Land Use
(NAIP)	National Agricultural Imagery Program
(NCDC)	National Climatic Data Center
(NED)	National Elevation Dataset
(PD)	Pierce's Disease
(SFI)	Spring Frost Index
(SSURGO)	Soil Survey Geographic Database
(STATSGO)	U. S. General Soil Map
(Tmean)	Mean Daily Mean Temperature
(Tmean)	Mean daily Maximum Temperature
(Tmin)	Mean daily Minimum Temperature