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A Model for Selecting Viticultural Sites in the Piedmont Triad Region of North Carolina

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ABSTRACT

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, requiring considerable effort to consistently produce yields of appropriate volume and good quality. The model produced in this research was designed to help guide site selection for V. vinifera vineyards in the North Carolina Piedmont. This is accomplished using a site suitability model and predictive geophysical parameters. The area of interest is Rockingham County, North Carolina. The model consists of four sets of factors each weighted and combined into sub-model composites. These sub-model composites represent the capability/suitability of: topography, soil, land use/land cover, and climate. The four sub-model composites were weighted and combined to produce the final output that summarizes the viticultural site suitability for the study area.

KEYWORDS

Applied Geography, Capability/Suitability, Composite Suitability, Geography of Wine, GIS, Map Algebra, Modeling, Niche Agriculture, Rockingham County, Site Selection, Terroir, Viticulture

INTRODUCTION

The annual economic impact of the North Carolina (NC) wine industry is $1.28 billion (Frank, Rimerman + Co. LLP, 2011). The number of wineries across the state has increased from 55 to 125 in less than a decade (2005 to 2013) (Winslow, 2014). The explosive growth of the wine industry and vineyards in NC is expected to continue well into the future, especially since demand for grapes still outpaces supply (Frank, Rimerman + Co. LLP 2011).

The installation of a vineyard is expensive, time-consuming, and takes considerable effort. A successful grape grower must first match potential vineyard sites to the variety of grape being grown (Wolf, 1995; IAGT, 2011; Jones, Snead, & Nelson, 2004; Poling, E. B. (Ed.). 2007; Sommers, 2008; Wolf, 1995). The establishment period of a vineyard typically takes three to six years, but the first

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two to three years of the period include establishment expenses that are not offset by harvest revenues (Poling, E. B. (Ed.). 2007).

In the Southeastern Atlantic Coastal region, costs to establish a four hectare Chardonnay vineyard on a good site has more than doubled from $24,260 per hectare to $50,000 per hectare over the past two decades (Hobson, 2008; Hobson; IAGT, 2011; Poling, E. B. (Ed.). 2007; Wolf, 1995). These costs do not include purchase of land or preparation prior to vineyard installation. These significant economic and time commitments underscore the importance of choosing a suitable site as a way to ensure success. Choosing a proper site increases the likelihood of maintaining healthy vines and high quality yields. A carefully selected site also reduces risks such as frost, damage from harmful insects, and viral, bacterial, and fungal diseases.

This research presents a model that identifies sites for establishing a *Vitis vinifera* vineyard in the Piedmont Triad region of NC using Rockingham County as the case study. Geospatial datasets were developed from core geophysical factors known to influence vineyard viability. The factors used in this study are grouped by topography (absolute elevation, relative elevation, slope, and aspect), soil (drainage, available water capacity, depth, pH, and texture), land cover, and climate (precipitation, spring frost index, and Pierce's Disease risk—temperature thresholds). The factors were ranked, weighted, and summed to produce physiographic composites using a weighted linear combination (WLC) and geographic information systems (GIS). The composites were combined to produce a final output that represented the ranking of suitable sites for locating vineyards growing *V. vinifera* in Rockingham County, NC. The methodology presented in this paper will provide vital information to agricultural agencies as they strive to ensure the success of future grape growers.

THE LITERATURE: REGIONAL BACKGROUND AND GIS MODELING OF VITICULTURAL SITE SUITABILITY

The Concept of Terroir

Regionality is a fundamental concept in the geography of wine. An important term associated with wine and the concept of regionality is *terroir*. The term *terroir* comes from the French word for "earth" or "soil". It is a viticultural concept that summarizes the set of variables associated with a certain place that, together, impart a local character to its wine. These variables embody both cultural and physical characteristics.

The cultural aspects of terroir relate to the practices of the viticulturist in the vineyard and the winemaker in the winery. Both affect the regional character of a wine and represent the cultural side of terroir. The physical elements of terroir such as climate, geology, soil, land cover, and topography differ from place to place. The complex interactions of physical elements produce unique environments capable of supporting viticulture. The model presented in this research focuses on the physical elements of terroir (Blij, 1983; Cox, 1999; Johnson & Robinson, 2007; Poling, E. B. (Ed.). 2007; Sommers, 2008; Van Leeuwen & Seguin, 2006; Vaudour, 2002; White, 2009; Wolf, 1995).

Wine Regions, Appellation, and Scale

The synoptic scale is used when considering world wine regions such as the Mediterranean Basin or Australia. In contrast, the macroscale is used to delineate sub-regions of the world (e.g., France, Chile, or California). Macroscale environments may also be identified by their combinations of physiographic sub-regions within political units, such as Italy's Piedmonte or South Africa's Western Cape. Most appellations fall within mesoscale regions of between 10km to 100km across. Regionally produced bottles of wine are often described by the appellation, such as Saint-Émilion, Barolo, or Napa Valley.

The microscale is the scale of a group of vineyards, a single vineyard, or even a few rows of vines. There are a few exclusive and very small appellations that fit within this scale (e.g., La Romanée in the Burgundy region of France). Most recent viticultural GIS studies have been conducted at the appellation, between 10km and 100km, using a 10 m spatial resolution (Irimia & Patriche, 2010; Irimia & Patriche, 2011; Jones, Snead, & Nelson, 2004; Jones, Duff, & Myers, 2006; Vaudour, 2002).

Appellations are precisely defined areas representing designations of origin. Wine makers have sole legal rights to the use the appellation name on labels as long as they follow the set rules of winemaking outlined for the appellation in question. The rules might specify the origin(s) and varieties of grapes, the yield of grapes per unit area, the way the vines are trained, pruned, and spaced and length of aging. France's appellation system, known as *Appellation d'Origine Contrôlée* (AOC) provides a practical example in Champagne. Unless a wine originates within a certain boundary and conforms to the rules of the AOC, it may not be labeled "Champagne." Many countries, especially in historic wine regions, have similar appellation systems, such as Italy's *Denominazione di Origine Controllata* (DOC), yet each system's origins and level of legal complexity are unique (Blij, 1983; Johnson & Robinson, 2007).

The American system of appellation, known as the American Viticultural Area (AVA), is administered by the Alcohol and Tobacco Tax and Trade Bureau, or TTB (27 C.F.R § Part 9, 1979). The AVA system is simpler than European appellation standards existing solely to control the use of the name to the growers within the boundaries of the AVA. This differs from the AOC, DOC, and other European systems of appellation which attempt to control quality along with geography. 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. As of January, 13th 2014, there were 211 AVAs in the U.S. (TTB, 2014).

History of NC Wine

North Carolina has a long and storied past as a grape-producing region. The oldest cultivated grapevine in North America is located on Roanoke Island in northeastern NC. Known affectionately as the "Mother Vine," the origin of this Scuppernong vine remains a mystery (Helsley, 2010; Kickler, 2012). The earliest account of grapes growing in North Carolina dates back to 1524. During a trip to the NC coast, Giovanni da Verrazanno, a French navigator and explorer, writes to the King of France "many vines growing naturally," and "without all doubt, they would yield excellent wines." As Europeans settled the state, the production of wine grew. By the mid-1800s, and The Old North State produced more wine than any other state. Prohibition had a devastating effect on the Tar Heel wine industry. By 1930, there were only 383 vines growing in commercial vineyards. By 1969, there were no more wineries producing wine in NC (Helsley, 2010).

In the late 1970s, commercial winemaking resumed across NC, and by 2005, there were 55 bonded wineries. By early 2014, the number had grown to 125, increasing 115% in under nine years (Winslow, 2014). Grape species currently grown commercially in NC are *Vitis aestivalis*, *Vitis labrusca*, *Muscadinia rotundifolia* (formerly *Vitis rotundifolia*), *Vitis vinifera*, and hybrids between these and other native species. *V. vinifera* is the European grape, often termed *Euvitis*. Popular *V. vinifera* varieties include Cabernet Sauvignon, Chardonnay, and Merlot. Because of the shared *V. vinifera* genes, hybrids of *V. vinifera* have similar challenges. The Native American varieties of *V. rotundafolia*, *V. aestivalis*, or *V. labrusca* tend to be less needy, low temperature tolerant, and/or more disease resistant than *V. vinifera.*

Modeling Site Suitability

GIS based studies on the geography of viticulture are consistent in their organization of physical realms: topography, soils, climate and, at times, land cover/land use. Both descriptive and predictive approaches have been used in viticultural studies. Descriptive approaches leverage the concept of terroir to help differentiate one region from another. They also define and elaborate on the physical and cultural character of a region. Predictive methods, on the other hand, use and analyze measurements, focusing on the physical aspects of terroir. They often leverage capability and/or suitability models to identify optimal sites for viticulture (Bowen et al., 2005; Hellman, Takow, Tchakerian, & Coulson, 2011; Imre & Mauk, 2009; Irimia & Patriche, 2010; Irimia & Patriche, 2011; Jones, Duff, & Myers, 2006; Shaw, 1999).

Capability models are based on the Boolean concept of pass/fail (Foss, Ravenscroft, Burnside, & Morris, 2010), while suitability models are combinations of pass/fail and ordinal ranking classification, such as good, fair, and poor. It is common to consider capability as one of the suitability classes. Soil depth, for example, could be ranked based on how well it supports viticulture (e.g., 30cm = fail; 30 - 90cm = fair; > 30cm = good) (Jones, Duff, & Myers, 2006).

Multiple factors can be combined to produce a composite suitability. For example, land cover and soil depth surfaces can be combined in a single composite surface. This can be achieved by classifying surface water, exposed bedrock, and soil type as nominal categories and soil depth as ordinal rankings. Locations that pass are further delineated using ranking constraints. The advantage of the composite suitability approach is that it can provide a range of suitability rather than a simple pass/fail. Weights can also be assigned to factors based on relative importance. In a multi-factor capability/suitability model where soil drainage rate, soil depth, soil pH and soil water holding capacity are combined, relative weights can be assigned to different factors based on their influence. This methodology is a form of WLC (Malczewski, 2000). Although determining a relative weight for each factor is subjective, values can be assigned using input from expert knowledge. In the case of viticulture such guidance can be provided by agricultural extension documentation or other established research (Kurtural, 2010; Kurtural, Dami, & Taylor, 2006; Poling, E. B. (Ed.). 2007; Wolf, 1995; Wolf & Boyer, 2003).

Topographic Suitability

Capturing the variation in viticultural suitability across a region has been a central theme in viticulture literature. Elevation, slope, and aspect are often included in models of viticultural site suitability (Boyer, 1998; Foss, Ravenscroft, Burnside, & Morris, 2010; Irimia & Patriche, 2010; Irimia & Patriche, 2011; Jones, Snead, & Nelson, 2004; Jones, Duff, & Myers, 2006). The data used to derive geospatial datasets for topographic factors come from Digital Elevation Models (DEMs). Over the last decade, more accurate and higher spatial resolution datasets have become readily available. Variations in elevation can be used as a proxy for average temperatures by measuring adiabatic cooling. Higher elevations are unsuitable for grape growing because of their short growing seasons, extreme cold temperatures, and/or frosts occurring during the growing season (Foss, Ravenscroft, Burnside, & Morris, 2010; Irimia & Patriche, 2010; Irimia & Patriche, 2011; Jones, Snead, & Nelson, 2004; Jones, Duff, & Myers, 2006). Cold air is not limited to high elevations since many valley floors experience cold air ponding. Extension documentation recommends using land within the highest 20th percentile elevation in lower elevation counties (Wolf & Boyer, 2003). Relative elevation is also important when considering protection from cold air drainage (Poling, E. B. (Ed.). 2007; Wolf, 1995). A good example is found in an article by Jones et al. (2004) who divide elevation into six graded classes (Table 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 grapevines. When slope is too high, however, it is unsafe to operate agricultural machinery because of tip over hazards. High slope environments also suffer from increased erosion rates, making soil retention problematic. Land with slope of less than 1% is too flat while land with slope greater than 30% is too steep (Jones, Snead, & Nelson, 2004). The optimal range for slope is thought to be 5 to 15% (Irimia & Patriche, 2010; Irimia & Patriche, 2011; Jones, Duff, & Myers, 2006). Jones et al. (2004) offered six graded classes for slope range (Table 2).

Many viticulture studies have partitioned aspect into cardinal and ordinal directions (Foss, Ravenscroft, Burnside, & Morris, 2010; Irimia & Patriche, 2010; Irimia & Patriche, 2011; Jones,

Table 1. Grades for elevation range classes (Jones, Snead, & Nelson, 2004)

Elevation Range (m)	Grade
0 to 61	0
61 to 122	1
122 to 244	2
244 to 305	1
305 to 365	0
> 365	–1

Snead, & Nelson, 2004; Jones, Duff, & Myers, 2006). Mid-Atlantic extension documentation lists benefits to both northern aspects and eastern aspects (Poling, E. B. (Ed.). 2007; Wolf, 1995). Southeastern aspects of the NC Piedmont have also been cited as optimal since they promote lower fungal pressure through quick evaporation of morning dew and warmer winter temperatures which lowers the risk of freeze damage (Spayd, 2012).

Soil Suitability

Soil is a basic consideration when establishing a vineyard. The humid forest soils of the Eastern U.S. are judged by their capacity to govern water drainage and availability. The types of soil found in the NC Piedmont can lead to over vigor where vines produce excess vegetative growth at the expense of fruit quality.

The common soil factors included in models of vineyard site suitability are pH, depth to bedrock, soil drainage, water holding capacity (Jones, Snead, & Nelson, 2004; Jones, Duff, & Myers, 2006; Wolf & Boyer, 2003), and organic matter and texture (Foss, Ravenscroft, Burnside, & Morris, 2010). Two sources for soil data are the U.S. General Soil Map (STATSGO) (Jones, Snead, & Nelson, 2004) and the Soil Survey Geographic Database (SSURGO) (Jones, Duff, & Myers, 2006). STATSGO is macroscale in resolution and would 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; cm of H_20 per cm of soil), depth to bedrock, and pH. All values falling outside of the passing ranges were failed. 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 3).

Table 2. Grades for slope range classes (Jones, Snead, & Nelson, 2004)

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

Land Cover/Land Use Suitability

Land use (LU) was considered in viticultural site suitability studies in Oregon, which has strict zoning laws. Areas not zoned for agriculture were eliminated through masking (Jones, Snead, & Nelson, 2004; Jones, Duff, & Myers, 2006). Planting *V. vinifera* vineyards requires land that has been cleared for several years since there must be a multi-year transition from forest. The transition from forest to cleared land is necessary to reduce the presence of wild grapevine diseases and pests. (Poling, E. B. (Ed.). 2007; Wolf & Boyer, 2003).

Climatological Suitability

Weather readings have been systematically recorded at stations in the U.S. since the end of the 19th century. The records include temperature, precipitation, pressure, and humidity at a given point and time period. Weather is a continuous phenomenon, but the data are recorded at discrete points, making it necessary to interpolate locations with unknown values by using locations with known values.

One method of downscaling from interpolated surfaces is to incorporate an average lapse rate correction using a high resolution DEM. This lapse rate correction methodology can be further improved by using the local mean lapse rates for the period being analyzed (Calvo-Alvarado & Gregory, 1997; Chung et al., 2006; Holden, Abatzoglou, Luce, & Baggett, 2011). There are also high quality datasets of general climate information such as PRISM, Daymet, and WorldClim. These datasets are optimal when available for the required metric and offer resolutions up to 800 m.

Viticultural studies routinely consider temperature and annual precipitation (Hellman, Takow, Tchakerian, & Coulson, 2011; Wolf & Boyer, 2003). Foss et al. limited desirable ranges of precipitation to between 45cm and 85cm per year (2010). Wolf & Boyer (2003), estimate that mature vines can be expected to use the equivalent of between 61cm and 76cm of rain per year. Temperature is the most critical climate value to a region's suitability for growing grapes. If absolute temperatures are too cold, the vines can be damaged or killed. In Oregon, Jones et al. suggested that regions must have average annual winter minimum of −15°C (2004, 2006). In the southeast it has been determined that a region's grape growing capability is limited if there are three occurrences at or below –22°C per decade (Wolf & Boyer, 2003). A commonly cited climate index is the Spring Frost Index (SFI). SFI evaluates the likelihood of a damaging late spring frost. This risk is often a problem in continental climates with late spring cold fronts, which come after the buds have opened. The NC Piedmont experienced economically damaging spring frosts in the 2007 and 2012 growing years. 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." SFI has also been calculated by subtracting the mean monthly Tmin from the mean monthly Tmean (Wolf & Boyer, 2003).

Growing Degree Days (GDD) is a widely used metric summarizing heat accumulation during the growing season, and useful for delineating boundaries between cool, warm, hot, and very hot regions (Amerine & Winkler, 1944; Jones, Duff, Hall, & Myers, 2010). Jones and company summarize Winkler Regions such that Region Ia corresponds to 1500-2000 GDD where only the very earliest ripening grapes are appropriate; Region Ib to 2000-2500 GDD where early ripening grapes can be grown, Region II to 2500-3000 GDD where early to mid-season varieties can be grown, Region III

Table 3. Classes for soil property ranges (Jones, Snead, & Nelson, 2004)

Soil Property	Passing Ranges	# Classes
Soil Drainage	N/A	4
AWHC (cm/cm soil)	0.254 to 0.762	5
Depth(cm)	63.5 to 165	3
pH	5 to 6	4

from 3000-3500 GDD where a wide range of standard varieties can be grown, Region IV to 3500-4000 GDD which they say is favorable to high production, but only acceptable quality wine, and Region V to 4000-4900 GDD which is, "typically only suitable for extremely high production, fair quality table wine or table grape varieties destined for early season consumption"(Jones, Duff, Hall, & Myers, 2010).

Pierce's Disease

Pierce's Disease (PD) is a vascular disease of grapes caused by the bacterium *Xylella fastidiosa*. PD spreads by insect vectors such as the glassy-winged sharpshooter, and initially presents as water stress because it blocks the flow of xylem fluid. Infection of V. vinifera vines with PD typically leads to decline and death within three years (Wallingford, Tolin, Myers, Wolf, & Pfeiffer, 2007). Regional research findings concluded that areas with more than two days below –12.2°C or four days below –9.4°C had no incidence of PD. 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 (Anas, Harrison, Brannen, & Sutton, 2008; Myers, Sutton, Abad, & Kennedy, 2007; Sutton, 2005).

METHODS

Study Area

The study area is Rockingham County, NC (Figure 1) located in the North Central Piedmont. The NC Piedmont is delineated to the east by the fall line at an average elevation of about 60 m above sea level and to the west by the base of the mountains where the average elevation is about 460 m above sea level (NCSCO, 2011). Rockingham County's elevation ranges between 323.2 m and 139.8 m above sea level, placing it centrally within the range of Piedmont elevations. Rockingham County is 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 12 county Combined Statistical Area (CSA). The U.S. Census listed 91,878 residents in Rockingham County in 2013.

Rockingham County is centered between the Yadkin Valley and Haw River AVAs. As well as showing the relationship of Rockingham County to NC's AVAs, Figure 2 reveals the regional clustering of vineyards in the state. The Yadkin Valley AVA has the densest cluster of vineyards and wineries. There is also a recognizable pattern in the Haw River AVA and a growing cluster in and around Rockingham County.

The county has a long history of growing tobacco, which has seen decline due to reductions in smoking and the Tobacco Transition Payment Program (FSA, 2013). It is economically depressed relative to the metropolitan region to its south (Parnell & Johnson, 2012; U.S. Census Bureau, 2013). Since the distillery in Madison opened in 2005 (Piedmont Distillers, Inc., 2014), and since there is a large beer production facility in Eden (Parnell & Johnson, 2012), Rockingham Community College just launched a "Brewing, Distillation and Fermentation" Associates in Applied Science Degree in 2013 (Wilson, 2014; RCC, 2014). Winemaking may further cultivate a professionalization of the adult beverage workforce and offer diversity to the local economy.

Data

Data for Rockingham County were obtained from various government and private sources and organized by themes to produce four sub-models: topography, soil, land cover, and climate (Table 4). Topography data for Rockingham and surrounding counties were obtained from the United States Geological Survey's (USGS) 2012 National Elevation Dataset (NED) 10 m Digital Elevation Models (DEMs) (USGS 2012). The soil data were downloaded from the USDA/NRCS Soil Survey Geographic (SSURGO) Database. Land Cover (LC) data originated from orthoimagery, transportation

Figure 1. Rockingham County, North Carolina

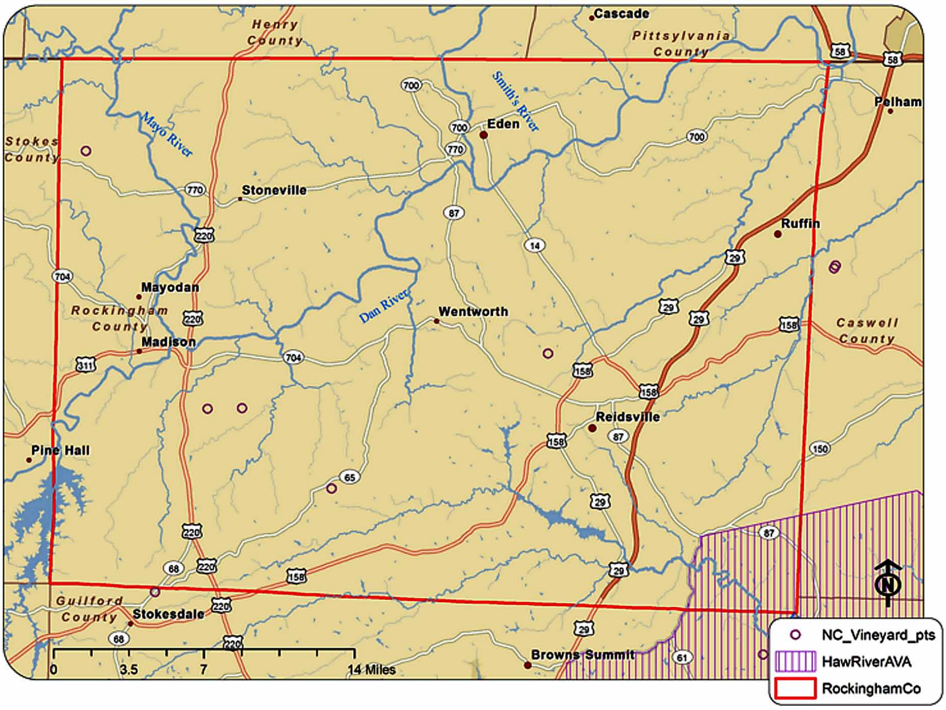
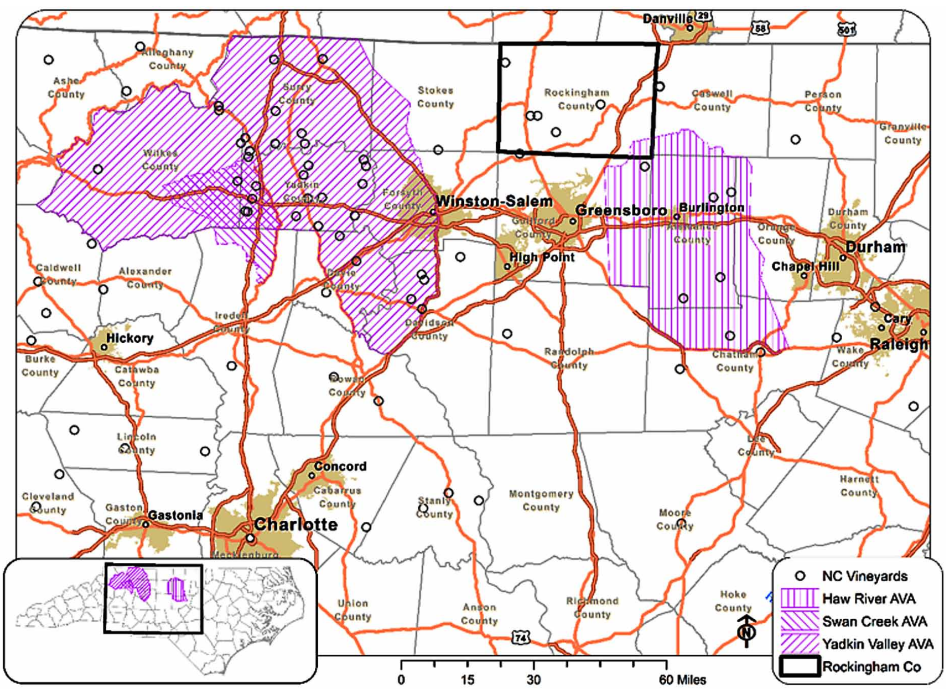


Figure 2. North Carolina viticulture



infrastructure vector files, and SSURGO land cover vector features. The source for orthoimagery was the 2010 three band National Agricultural Imagery (NAIP; FSA 2010). The transportation infrastructure data came from ESRI's 2010 base data and the NCDOT vector files. The bedrock data also came from SSURGO.

The data used for the climate sub-model was both vector point data and raster data. The point data was made up of two weather values, daily TMAX and daily TMIN. The weather station data came from regional National Climatic Data Center (NCDC). The raster data was the DEM mentioned above and a precipitation surface at a resolution of 800 m prepared by the PRISM climate group. This PRISM surface was lapse rate corrected to zero elevation and then re-sampled to a spatial resolution of 10 m using the DEM.

Viticultural Suitability Model

Building on the GIS methods of Jones Snead and Nelson (2004), and using the regional extension documentation of Poling (2007), along with the principles and prioritizations presented by Wolf and Boyer (2003). Factor surfaces were individually graded, weighted, and summed using map algebra into the four sub-model composites: Topography, Soils, Land Cover, and Climate. The grading method consisted of classifying each surface into ordinal classes. Failing classes were given –9999 values; for all other classes, the grades begin with zero for the lowest scoring class and proceeding higher in increments of one (e.g. –9999, 0, 1, 2, and 3). Pass/fail layers acted as masks (e.g. –9999 or 0). Areas failing on any of the factor surfaces failed on the sub-model composite. After classifying and grading all layers, weights were applied and summed to form the four sub-model composites. Relative weights were applied using expert knowledge and research (Wolf & Boyer, 2003). When combining the sub-model composites to form the final output, one weight was applied. The description of how the factor surfaces were graded is covered in the following discussion on the four sub-models. The factors are italicized for clarity.

Topographic Sub-Model

The topographic sub-model consisted of graded surfaces of absolute elevation, relative elevation, slope, and aspect. Elevation consisted of two parts: absolute elevation, then relative elevation. For *absolute elevation*, the elevation data were separated into quintiles. The highest twenty percent of the county's elevations, or the first quintile, was graded highest; the lowest quintile of absolute elevation failed and was graded –9999, while the intermediate classes received intermediate grades. Cold air drains downhill like water, with high cold plateaus and low valley floor areas proving riskier than the upper mid-slope. *Relative elevation* data were used to produce a stream drainage network. The first order Strahler (1957) stream designation was set by classifying streams as those cells which collected the flow from at least 100 other cells, an area of one hectare. A survey of the resulting streams revealed that the second order drainage paths were coincident with much greener grass, indicating soil moisture. In order to summarize the likely flow path of soil water and cold air toward lower relative elevation, the flow paths in the streams network were buffered in meters by subtracting one from their assumed Strahler Stream Order. This factor functions as a mask, such that the area within the buffered drainage network was failed.

Vines have no preference for what percentage of *slope* they grow on, but slope impacts vineyard workers. 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. In humid environments, ponding water can contribute to over-production of vine vegetation. High slope conditions are also problematic because while performing basic vineyard maintenance there is added risk of tipping machinery. Slopes between five and fifteen 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. Slopes which are between five and fifteen percent were graded highest, and slopes above 30 percent were failed; all other slopes received intermediate grades.

Table 4. Data sources

Factor	Source	Resolution	Year	Variable or Table
TOPOGRAPHY				
Absolute Elevation	NED DEM	10 m	2012*	
Slope	NED DEM	10 m	2012*	
Aspect	NED DEM	10 m	2012*	
Relative Elevation	NED DEM	10 m	2012*	
SOIL				
pH	SSURGO	1:24000	2009*	pHWater (Weighted Average, All Layers)
Drainage	SSURGO	1:24000	2009*	DrainClass (All Components)
Depth	SSURGO	1:24000	2009*	Dep2ResLyr (Weighted Average)
Texture	SSURGO	1:24000	2009*	SurfText (All Components)
AWC	SSURGO	1:24000	2009*	awc-r (All Components)
LAND COVER				
Land Cover	NAIP 1m	1m	2010	vegetation cover
Land Cover	ESRI Data & Maps 10 TeleAtlas	vector	2010*	streets, airports, railroads
Land Cover	SSURGO	1:24000	2009*	surface water & bedrock
CLIMATE				
Precipitation	PRISM		2011	Monthly Precip. Apr to Oct
PD Risk	NCDC Regional Stations 1971 to 2010	point	1971 to 2010	Daily TMIN
PD Risk	NED DEM 10 m	point	2012*	
PD Risk	Calvo-Alvarado & Gregory 1997	point	1951 to 1980	Table 1. Mnth. & Ann. Mean Temp. Regression Eq. (pg17)
Growing Season	NCDC Regional Stations 1971 to 2010	point	1971 to 2010	Daily TMIN
Growing Season	NED DEM 10 m	point	2012*	
Growing Season	Calvo-Alvarado & Gregory 1997	point	1951 to 1980	Table 1. Mnth. & Ann. Mean Temp. Regression Eq. (pg17)
Spring Frost Risk	NCDC Regional Stations	point	1971 to 2010	Daily TMIN & Daily TMAX
Spring Frost Risk	NED DEM	10 m	2012*	
Spring Frost Risk	Calvo-Alvarado & Gregory 1997	point	1951 to 1980	Table 1. Mnth. & Ann. Mean Temp. Regression Eq. (pg17)
Temperature	NED DEM	10 m	2012*	Lapse Rate Downscaling
TEMPERATURE MATURITY ZONE				
GDD	NCDC Regional Stations 1971 to 2010	point	1971 to 2010	Daily TMIN
GDD	NED DEM 10 m	point	2012*	
GDD	Calvo-Alvarado & Gregory 1997	point	1951 to 1980	Table 1. Mnth. & Ann. Mean Temp. Regression Eq. (pg17)

* Year of publication

The effects of *aspect* on site suitability in NC are different than in higher latitude regions where southern slopes are preferred (e.g., Oregon). In a region of high humidity, such as NC, there are benefits to receiving eastern exposure from early sunlight which helps burn the dew off of the plants and lowers the risk of fungal infections. The general character of northern aspects is that they stay cooler and slightly wetter than slopes facing other directions. In the NC Piedmont, southwestern aspects are least suitable because of the hot sun at the warmest part of the day. No aspects were failed.

The topographic sub-model factor surfaces were standardized to one, and weights were given to these graded surfaces as follows: 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 factor surfaces were then summed to represent the Topographic Composite Suitability Map (Equation 1). Aspect was degraded to half the value of the other topographic variables (Jones, Snead, & Nelson, 2004; Wolf & Boyer, 2003).

Soil Sub-Model

The soil factors included in the model were soil drainage, available water capacity (AWC), depth to bedrock, soil pH, and texture. The soil drainage factors were taken from the natural drainage class in SSURGO. The natural *drainage* classes below “moderately well drained” were failed, and “well drained” was considered optimal. The *available water capacity* (AWC) factor was taken from the AWC value in SSURGO. Those classes above 0.15 cm/cm AWC were failed, while those classes below 0.10 cm/cm AWC were graded as optimal. Intervening classes received intermediate grades. The soil *depth* factor summarizes the “depth to restrictive layer” value from SSURGO. Those classes with depths of less than 30cm were failed. Areas with depths exceeding three feet were graded as optimal. Intervening classes received intermediate grades. As the soil approaches the extremes of the *pH* scale, nutrients are made unavailable to the vines; the optimal acidity is very close to neutral or slightly acidic. Typically, pH is amended with lime in soils of the NC Piedmont, increasing the pH to a more optimal range. Since this factor is fairly easy to adjust, no classes were failed. Those soils between 6.0 and 6.8 pH were graded as optimal. Grades were decreased as pH varied from this range.

The *texture* of a soil is summarized with the soil triangle, which is a graphic representation of the relative proportions of sand, silt, and clay. Piedmont 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, which are problematic for vineyards due to over-vigor. Soils high in silt (50% and above) were failed. In Figure 3, the soil triangle has been marked with the soils of the study area in the bottom center and the failed texture classes in the lined out area of the bottom right.

The soil sub-model factor surfaces were standardized to one, and weights given to these graded surfaces are as follows: 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 factor surfaces were then summed to represent Soil Composite Suitability (Equation 2). These weights were assigned based on the importance assigned in Table 5 of Wolf and Boyer (2003; Jones, Snead, & Nelson, 2004).

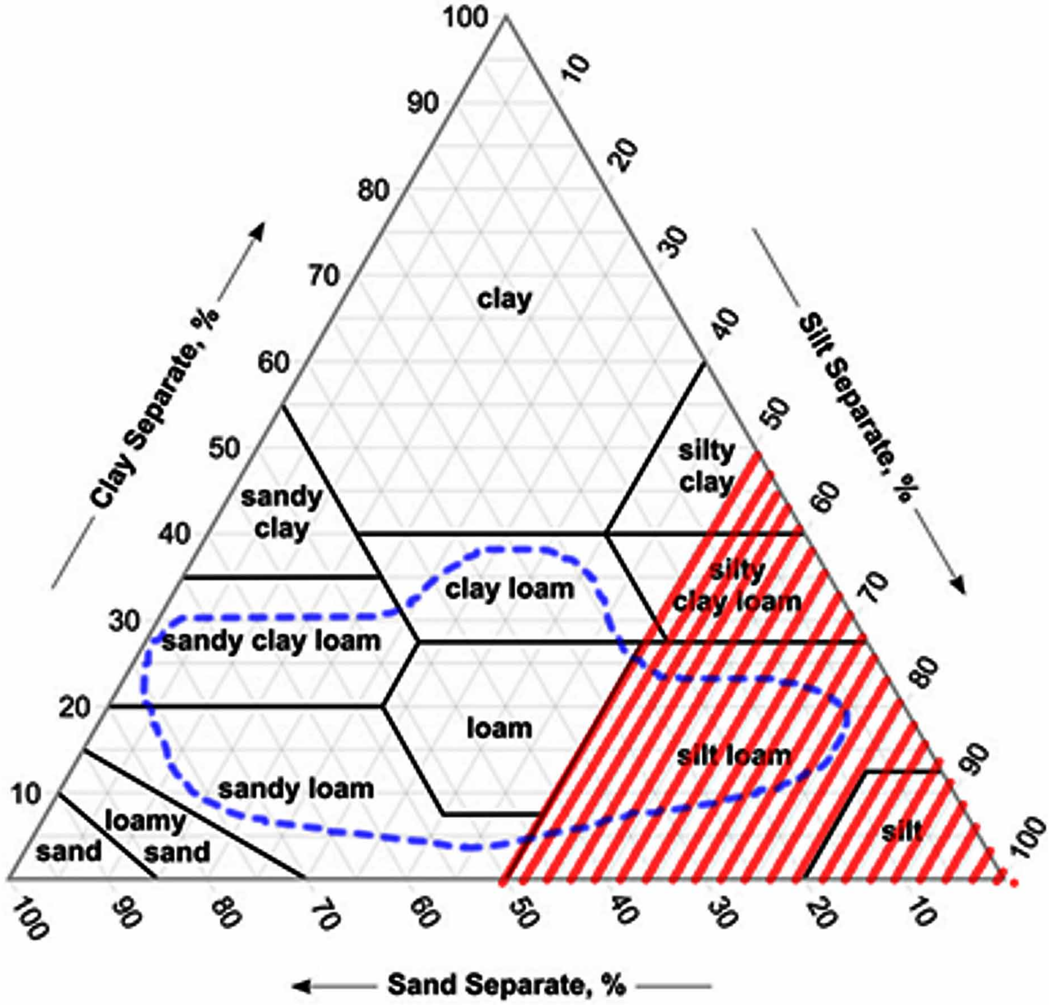
Land Cover/Land Use Variables

Some classes of *land cover* can render land incapable of supporting viticulture, including roads, surface water, and exposed bedrock. Other land cover classes provide degrees of suitability. Land

Equation 1. Topographic Composite Suitability (TComp)

```
{Absolute Elevation (TAE); Relative Elevation (TRE); Slope (TS);
Aspect (TA)}
Tcomp = (100 * 0.4 * TAE/3) + (100 * TRE) + (100 * 0.4 * TS/2) +
(100 * 0.2 * TA/3)
```

Figure 3. Soil triangle with study area soils (blue dashed area) and 50% silt limit (red lines)



that is cleared of forest, such as pasture, is considered optimal prior to planting a vineyard. Land that is forested must be transitioned to cleared land, which is a multi-year process. Land cover was classified into five classes: cleared, forested, water, urban, and bedrock. Cleared land was considered as the optimal land cover, while forested land was considered neutral. The water, urban, and bedrock classes were failed. There is only one layer in the land cover sub-model, so it is also the land cover composite (Equation 3). 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 (Equation 5).

To assess the accuracy of the LC classification scheme, 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 results of this assessment are summarized in Table 5 and show that the land cover classification into cleared and forested was 92.7% accurate if all error points were to be thrown out. One error point was on a cloud, and three were on urban areas, 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 5. Land cover classification assessment results

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

Equation 2. Soil Composite Suitability (SComp)

```
{Drainage (SDR); Available Water Capacity (SAWC); Depth (SDP); pH
(SPH)}
SComp = (100 * 0.4 * SDR) + (100 * 0.3 * SAWC/5) + (100 * 0.2 *
SDP/2) + (100 * 0.1 * SPH/3) + (100 * ST)
```

Equation 3. Land Cover Suitability (LComp)

```
LComp = (100 * LC)
```

Climatological Sub-Model

There are many measures of climate that can be helpful to minimize risk when choosing a site for a vineyard. The variables used in the climate capability/suitability analysis were: mean number of days per decade experiencing at or below –22°C, Spring Frost Index, mean April to October precipitation, and a Pierce's Disease Risk layer derived from mean number of days per year experiencing below –12.2°C and –9.4°C.

Interpolation of Climate Point Data

Because not all of the temperature data were available from PRISM climate group, point-based temperature data was interpolated to temperature surfaces using inverse distance weighting (IDW). 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 and topography should be used to downscale this interpolated surface. The combined IDW-lapse rate-topographic method was to first adjust the climate point data by the station elevation using the average monthly lapse rate, and then the IDW was performed. This interpolated surface was lapse rate and topographically corrected back to the appropriate elevation using a digital elevation model (DEM).

Beginning with the daily minimum and maximum temperature (Tmin; Tmax) at the twenty-eight regional National Climate Data Center (NCDC) stations for the period of 1971 through 2010, mean daily temperature (Tmean) was calculated. Using the forty years of daily data, the Tmean for each month of the year was determined for each of the twenty-eight NCDC stations. IDW interpolations were performed, including the mean number of days below –9.4°C and –12.2°C per year and the mean number of days below –22°C per decade, Tmax, and Tmin. The RMSE for all interpolations was 0.5 or less.

Climate Sub-Model

One climate-based risk for vines is presented by extremely cold temperatures which lead to vine damage. Using the average number of days per decade at or below –22°C to predict this risk, the threshold of three days per decade below this value was considered failing. The entire study area falls outside the climate zone of extreme cold freeze risk. The closest area of extreme freeze risk is on the Appalachian Plateau about 50 km west-northwest. This suggests that the study area is unlikely to experience extreme damaging cold.

As a conservative estimate of growing season length, the frost free period (Figure 4) was used to gauge the length of the season (Wolf & Boyer, 2003), which is the period from the last vernal frost to the first autumnal frost where a frost is understood as any temperature at or below 0°C. In accordance with Jones et al. (2004), the frost free period was graded in four classes (Table 6).

In order to account for spring frost risk, SFI was used. SFI is understood here as the difference between the mean Tmean and mean Tmin values for the month of April, in accordance with the Wolf & Boyer methodology (2003). SFI was calculated using map algebra to subtract the Tmin surface from the Tmean surface (Table 7).

In the absence of a summer drought, NC is higher in precipitation than most wine growing areas. For the purposes of this model, lower average precipitation between April and October was considered a benefit. Using the PRISM mean monthly precipitation data (1971 to 2000), this was adjusted from 800 m resolution to 10 m resolution and then classified (Table 8).

Figure 4. Frost free period

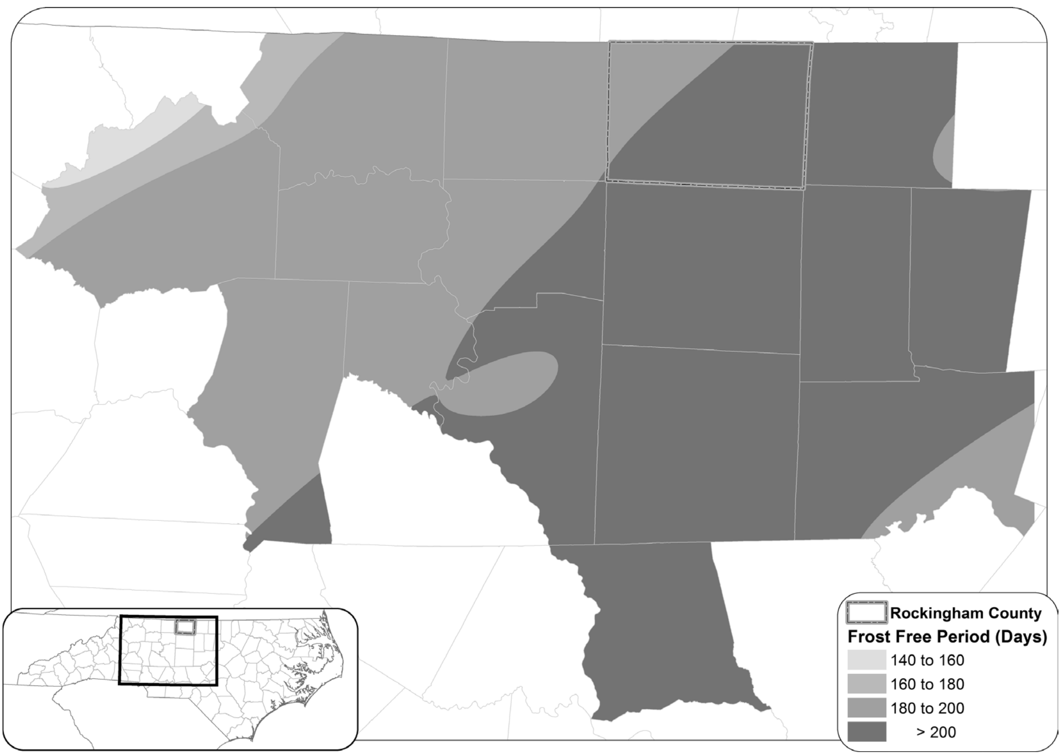


Table 6. Model vineyard site suitability grades for frost free period

Number of Days	Frost Free Period class	Grade
140 to 160	short	0
160 to 180	medium	1
180 to 200	long	2
>200	longest	3

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 (Sutton, 2005). Surfaces were produced summarizing average annual days below the risk thresholds of –9.4°C (Figure 5) and –12.2°C (Figure 6). In order to produce a single PD risk map, the average was taken from these to surfaces by summing the layers using map algebra and dividing by 2. The highest risk is to the south and east of the first composite isotherm, and the isotherms inland and up slope from this represent areas of moderate risk, low risk, and very low risk respectively. This is illustrated and summarized in Table 9.

After the climate factor surfaces were produced, each layer was standardized to one. Since there is no risk in the county for extreme cold and since the frost free period 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 factor surfaces were then summed to represent the Topographic Composite Suitability (Equation 4). Precipitation was reduced against SFI and PD measures based on the logic that there was little variance across the study area.

Final Composite Model

The Topographic, Soil, Land Cover, and Climate Suitability Composite layers were then weighted and summed to produce the Final General Viticultural Suitability Composite (Equation 5), the only weight applied was to reduce Land Cover suitability to the same weight as a soil layer. A model overview can be seen in Figure 7.

Temperature/Maturity Zones

Growing Degree Days (Figure 8) equals the sum of the maximum and minimum mean daily temperatures divided by two; 10°C (50°F) is subtracted, then every day in the period of interest is summed. 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 10 including the Winkler GDD range classes and descriptions.

Table 7. SFI Risk Classes

SFI Classes (°C)	Risk	Grade
< 6.1	Low	3
6.1 to 6.7	Medium	2
6.7 to 7.2	High	1
>7.2	Very High	0

Table 8. Model vineyard site suitability grades for precipitation classes

Precipitation Classes (cm)	Grade
70 to 71	0
71 to 72	1
72 to 73	2
73 to 74	3
74 to 75	4
75 to 76	5

Figure 5. Annual Days at or below –9.4°C

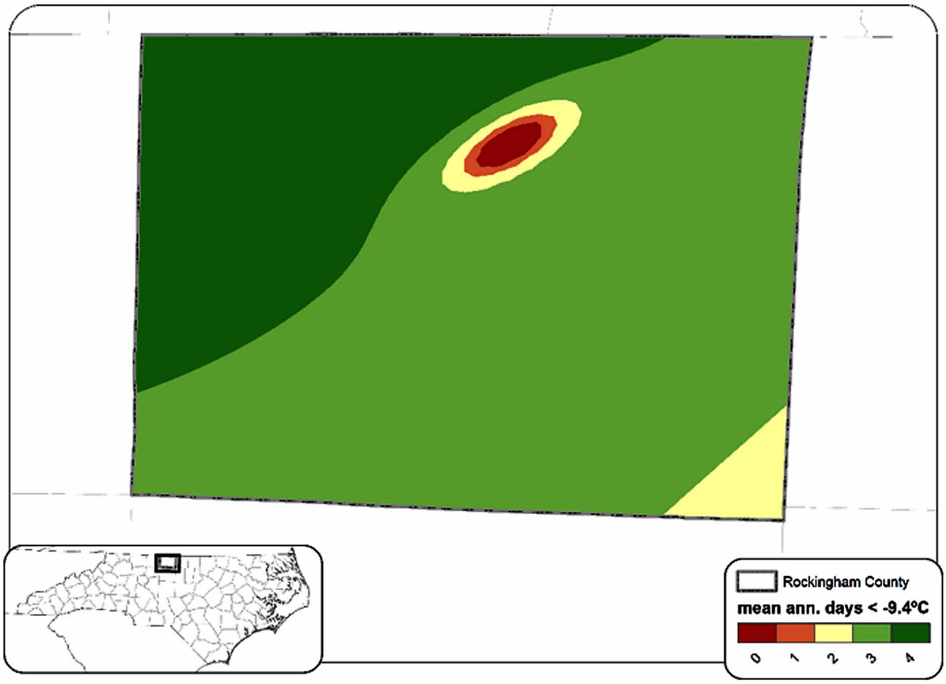


Figure 6. Annual Days at or below –12.2°C

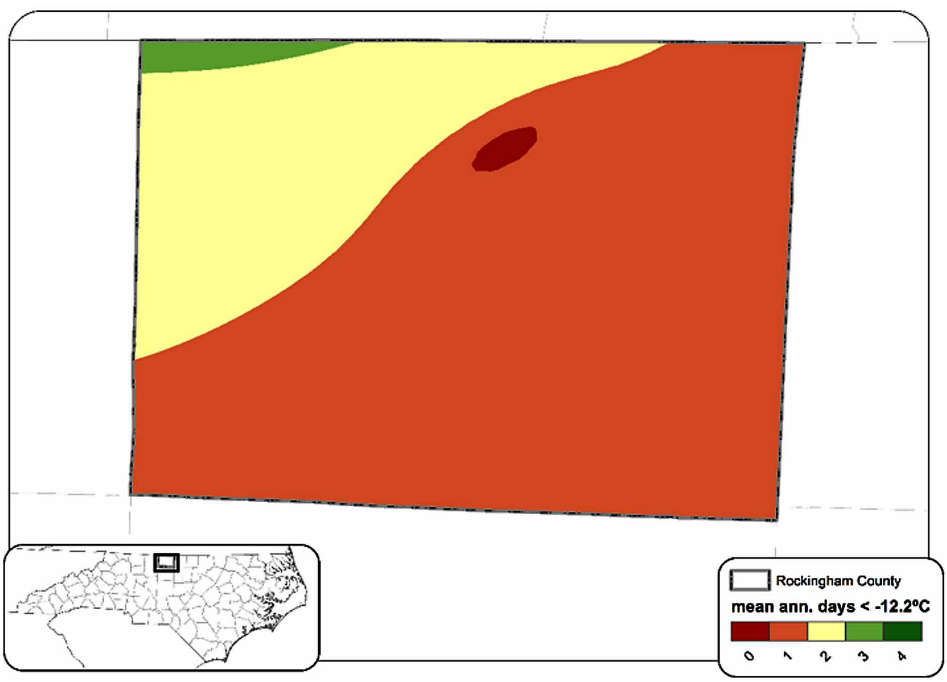


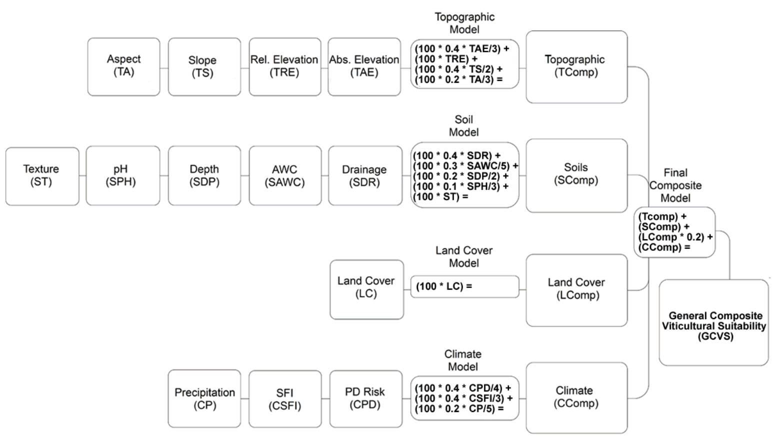
Table 9. Model vineyard site suitability grades for PD Risk classes

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

Equation 4. Climate composite suitability (CComp)

```
{Pierce's Disease Risk (CPD); Spring Frost Index (CSFI);
Precipitation (CP)}
CComp = (100 * 0.4 * CPD/4) + (100 * 0.4 * CSFI/3) + (100 * 0.2 *
CP/5)
```

Figure 7. Model overview



RESULTS

The graded factor surfaces from each layer of the model were analyzed by grade class. 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 factor surfaces interpreted individually first, followed by the sub-model composite.

Topographic Results

Absolute Elevation (Figure 9a.) within Rockingham County falls in the range of 139.75 to 323.17 m above sea level. The most suitable areas for viticulture, based on absolute elevation, are in the northwest corner of the county north of Mayodan, and west of Stoneville and along the central ridge separating the Dan and Haw rivers. This includes areas extending from Stokesdale in the southwest corner to the area which is northeast of Wentworth and northwest of Reidsville. The least suitable areas in the county are in the northeast and the northern half of the eastern border with Caswell County,

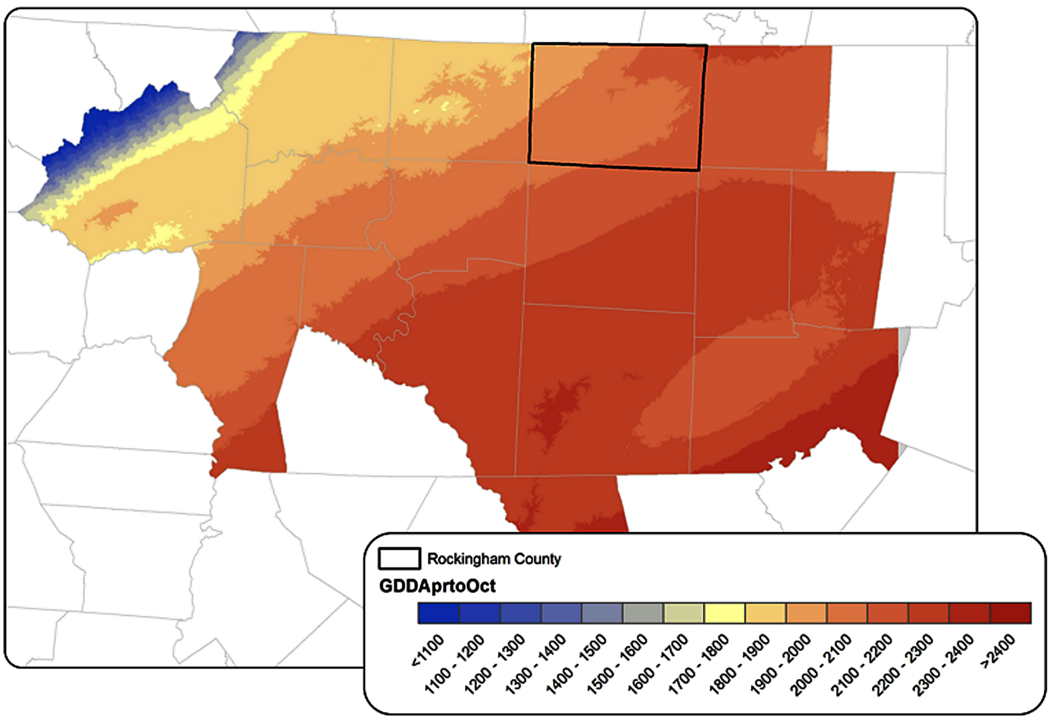
Table 10. Model vineyard site suitability grades for GDD classes

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

Equation 5. General Composite Viticultural Suitability (GCVS)

```
GCVS = TCS + SCS + (0.2 * LCCS) + CCS
```

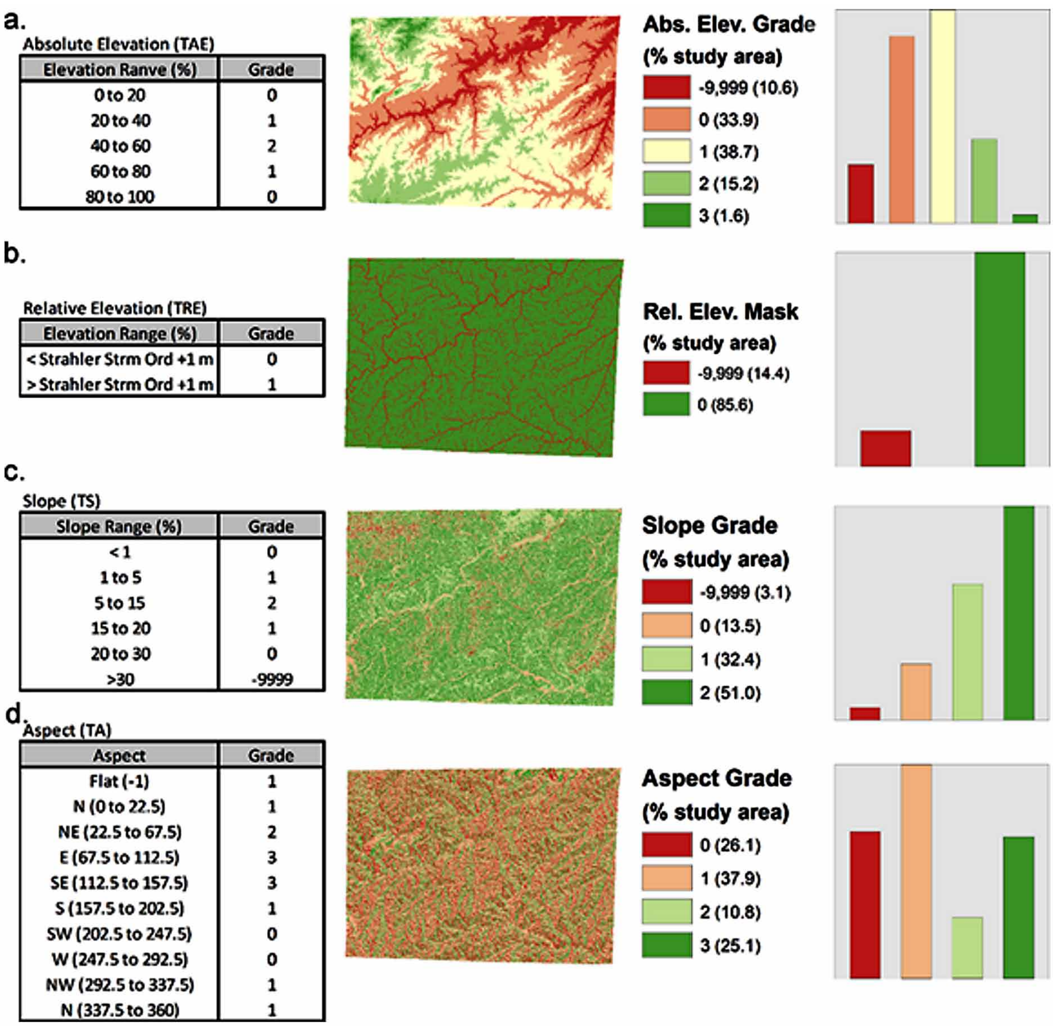
Figure 8. Growing degree days in the Piedmont Triad region of North Carolina



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.

The relative elevation layer (Figure 9b.) is a buffer highlighting proximity to the drainage network. The Dan, Haw, Mayo, and Smith 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.

Figure 9. Topographic model



With regard to slope (Figure 9c.), 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% of the county.

The map of aspect classification (Figure 9d.) shows less of a visually discernible pattern than the other topographic factors. 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 toward 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.

The Topographic Composite Map (Figure 10) illustrates that the best, with regard to topography, areas for viticulture are isolated areas in the northwest corner of the county, especially the ridges around the Mayo River Basin. The broadest area of above average suitability is the drainage divide between the Dan and Haw River Basins. This area extends from the southwest 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% of elevations resulted in the failing of much of the 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% of the county failed due to topographic incapability.

Soils Results

The soil drainage classification (Figure 11a.) shows that the overwhelming percentage of the area in the county, 89.2%, 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% of the county.

There are generally three zones of semi-homogeneity with regard to the pattern of AWC (Figure 11b.). 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 during the Triassic Era. To the northwest and southeast of the failing zone, the soil is generally suitable; the exception is 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% of the county.

The soil depth classification (Figure 11c.) 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% of the county fails due to soil depth, while 68% is in the highest class of suitability.

Very little of the county is excellent with regard to pH suitability (Figure 11d.); 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% of the county falls into the lowest graded class of pH.

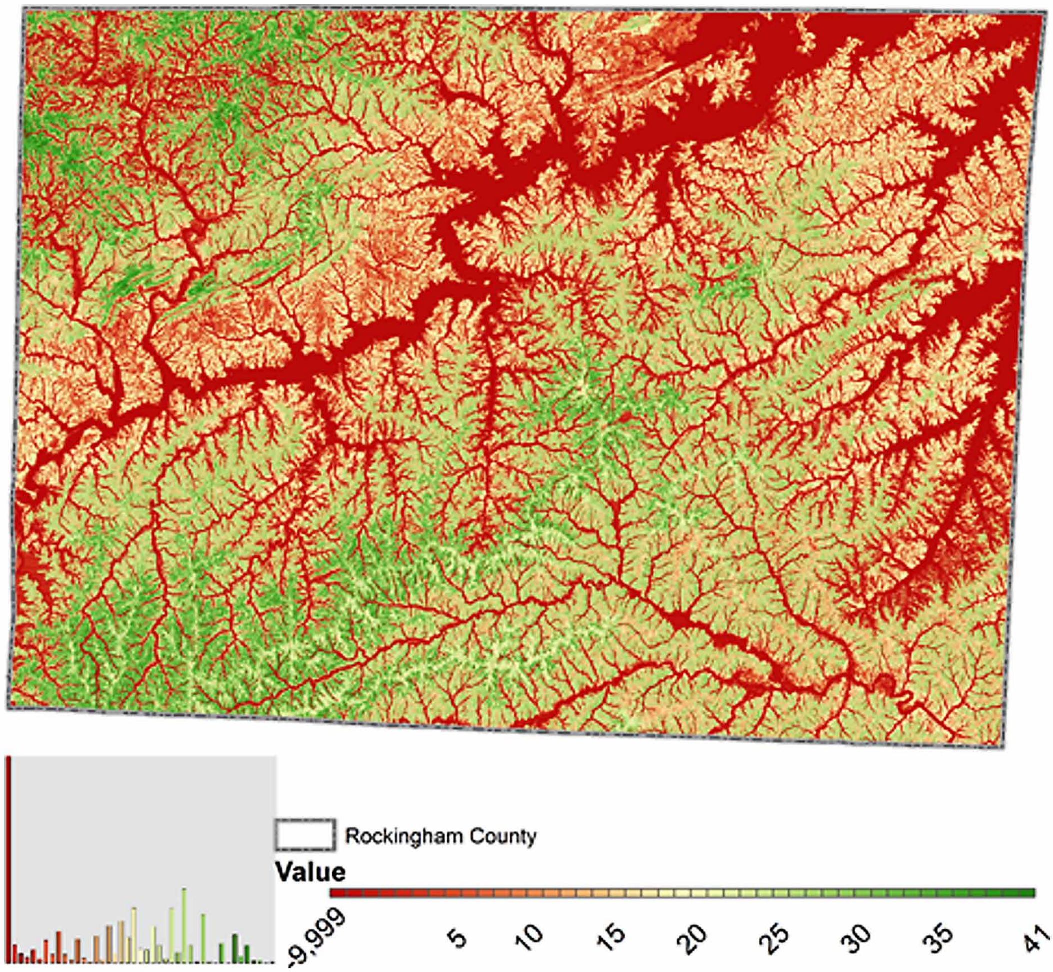
The soil texture classification (Figure 11e.) shows that almost all of the area in the county, 96.7%, has no high percentages of silt and is therefore suitable based on texture. This layer functions as a mask since it is pass/fail. With the exception of a patch of failing area around Eden, the failing areas are related to water features; these areas comprise only 3.3% of the county.

The Soil Composite Map (Figure 12) 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. The values on the Soil Composite Map represent the outcome of the sub-model map algebra equation; 21.3% of the county is failing due to soil incapability.

Land Cover/Land Use Results

The land cover classification (Figures 13 and Figure 14) shows that forested land dominates the study area with 67.8% of the county being forested. The highest rated land cover class, which is cleared land, accounts for 26.3% 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

Figure 10. Topographic sub-model composite



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.

Climatological Results

The precipitation classification (Figure 15a.) 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.

The SFI classification (Figure 15b.) shows that Rockingham County has notable areas graded as moderate, which is one of the lower risk classes for frost in the surrounding counties. 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.

Figure 11. Soil model

a. Drainage (SDR)

Elevation Ranve (%)	Grade
Unknown	-9999
Poorly Drained	-9999
Somewhat Proorly Drained	-9999
Moderately Well Drained	0
Well Drained	1

b. AWC (SAWC)

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

c. Depth (SDP)

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

d. pH (SPH)

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

e. Texture (ST)

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

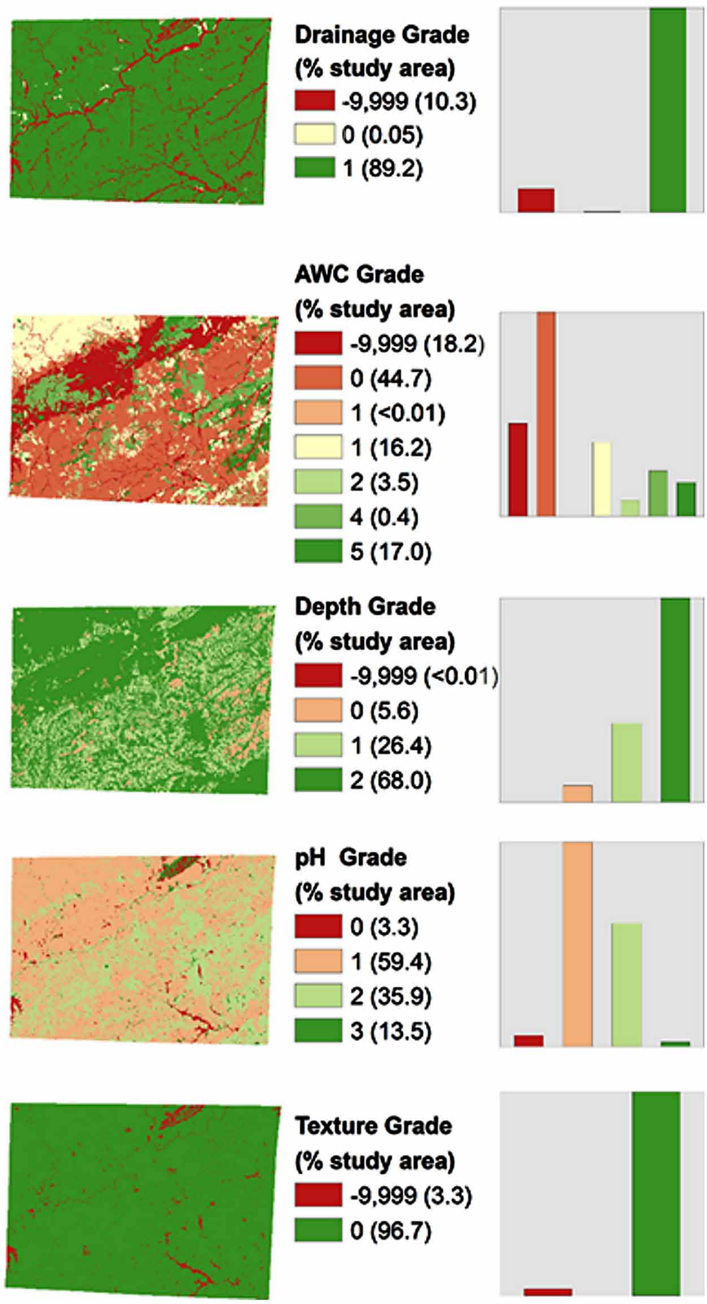


Figure 12. Soil sub-model composite

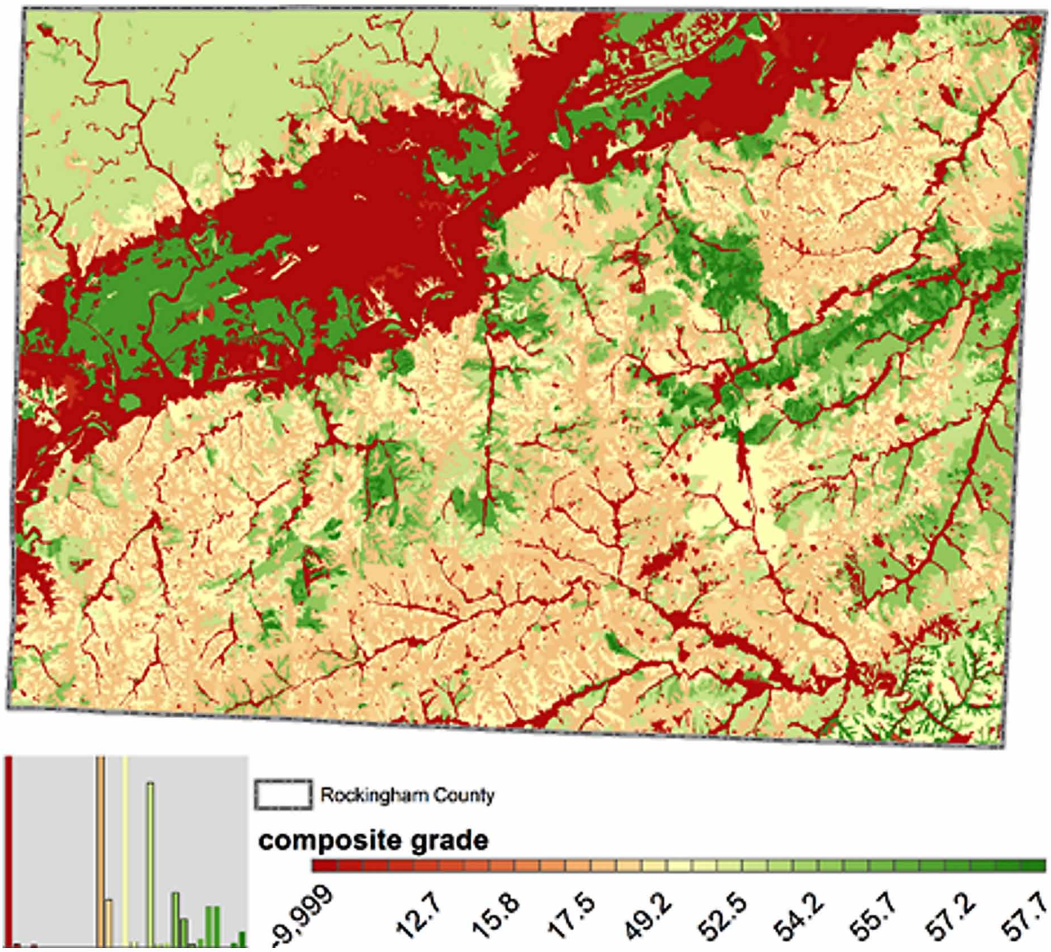


Figure 13 Land cover model

Land Cover (LC)

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

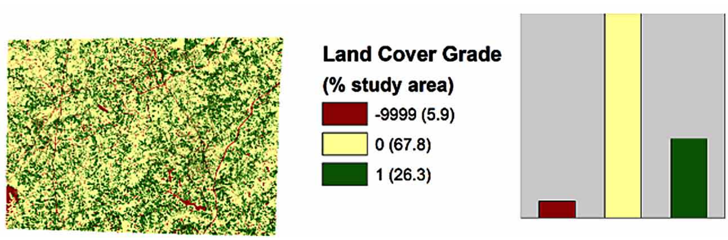


Figure 14. Land cover composite map

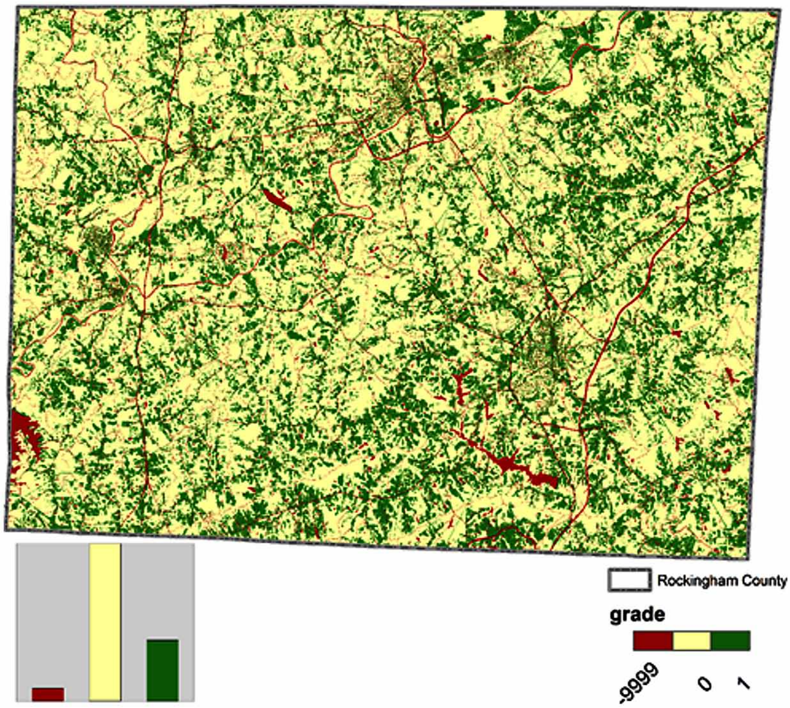
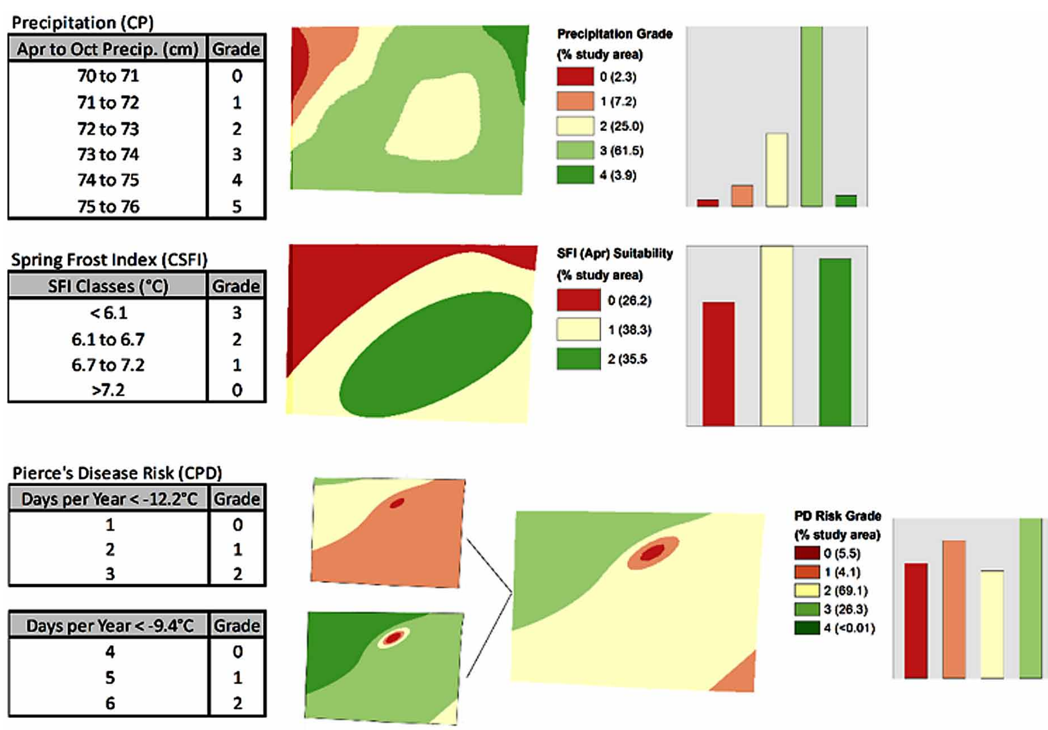


Figure 15. Climate model



The classification of Pierce's Disease (PD) risk thresholds show that Rockingham County falls into a relatively risky area for PD. There is less risk based on the days below –9.4°C (Figure 15c.) and more risk with the –12.2°C threshold (Figure 15d.). These are averaged to produce a single risk layer for PD (Figure 15e.), used in the climate model. There is a single 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.

General Viticultural Suitability Results

The climate composite classification (Figure 16) is the least comprehensible of all of the sub-model composite suitability maps. This is attributable to several factors relating to 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 did not elegantly line up with each other. 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 m to 10 m 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 in the temperature surfaces. 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 (Figure 14).

The final product of the research is a composite viticultural site suitability map (Figure 17). An overall outline of the general viticultural suitability model is presented in Figure 18. This general viticultural suitability map identifies the best areas in the county to grow *V. vinifera* grapes. As emphasized by Jones et al. (2004) ". . . for most potential growers, site selection will involve compromises, in that few sites will possess ideal characteristics in every respect." This is borne out in the results as the highest scoring land in the county was graded 124 of a possible 320 quality points. The best scoring three areas are between Eden, Wentworth, and Reidsville; these falls in the area known as Oregon Hills, the area along Business 29 going north out of Reidsville to Highway 29 and the area around the Historic Chinqua Penn Plantation. The broadest area of general suitability is along the broad ridge running from the southwest corner of the county to the central northeast quadrant and separating the Haw River and Dan River Basins. There is also a sizeable area in the northwest corner of the county and the hills surrounding Mayodan. Approximately 25% of the north western portion of the county has a different climate than the south eastern portion. This suggests that these areas should not share the same AVA if one or more are established in the county in the future. The failing portion of the county amounted to 37.3%, most of which was related to two factors: the soil property AWC and the lowest 20% of absolute elevations in the county.

Temperature Maturity Zonation

To give general insight into the nature of the temperature/maturity zones in the study area, the general viticultural suitability surface was reclassified by GDD. The GDD ranges belonging to the Winkler Regions were used to delineate the different wine climates in the county. Rockingham County falls in to two Winkler Regions (Figure 19), Class II Warm (1667 – 1944 GDD) and the Class III Hot (1944-2222 GDD). Winkler Region II is best for early to mid-season wines and is labeled in blue to gray to red color ramp, while Winkler Region III is more favorable for most standard wine varieties and is colored in the green to tan to red color ramp of the general suitability map (Jones, Snead, & Nelson, 2004). The so called Warm Winkler Region only makes up a small part of the northwest corner of the county, northwest of Mayodan.

Figure 16. Climate composite map

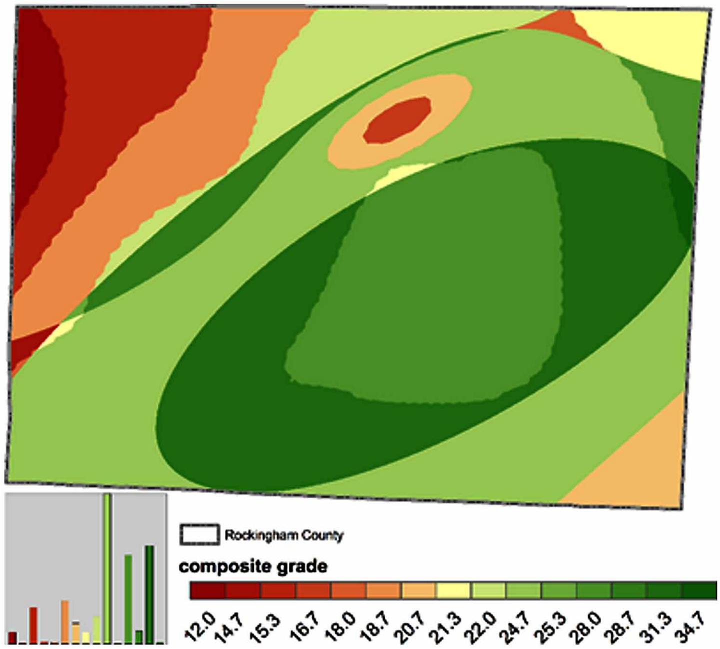
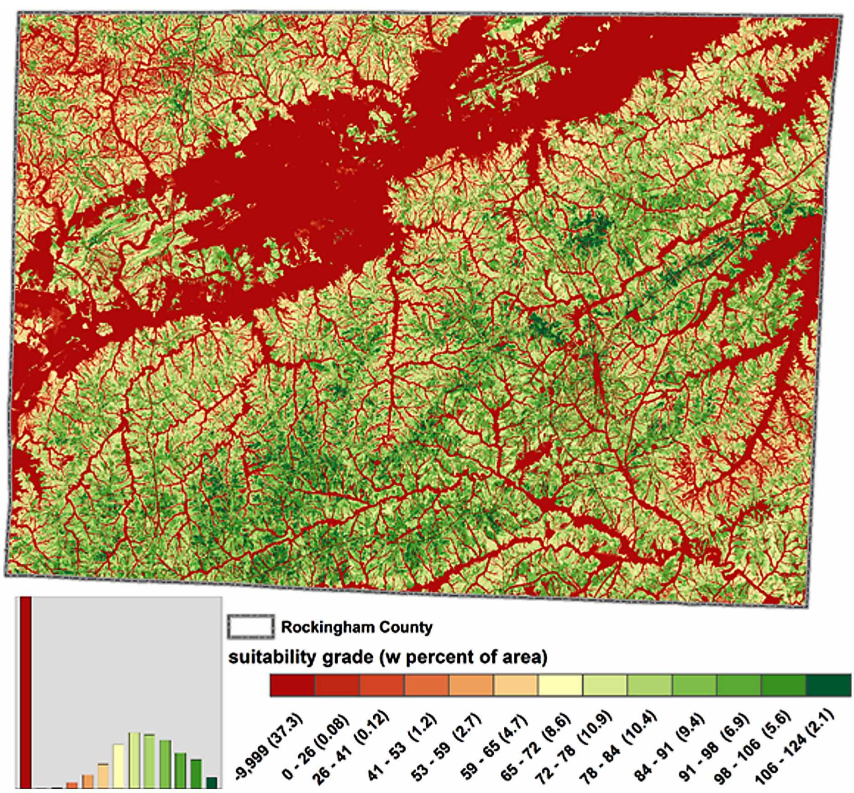


Figure 17. General viticultural suitability composite



Assessment

The assessment of the final composite surface was conducted using existing vineyards within the county to test the assumption of the model (Figure 20). If many failing cells were to fall within these vineyards, it would suggest that the factors need adjustment or that these vineyards would not be successful long term. However, if all vineyards tended to score high on suitability, it would be affirmative for the choices made in the model.

All four known commercial vineyards and one private vineyard in Rockingham County were found by plotting their street addresses then using NAIP imagery to find and trace their boundaries. These vineyards' polygons have been used to clip the final composite output and have been 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, Figure 17.4). After investigation, it was determined that the vineyard in question was bordered by a road, and these two cells were classified as failing because the road was within the 10 m 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 within these vineyards are above the mean for suitability. These are very strong results, indicating that the assessment of both capability and suitability suggest that the model is valid. The aforementioned clipped vineyard plots were statistically quantified and are compared and contrasted in Figure 20 note the histogram.

DISCUSSION AND CONCLUSION

The analysis of environmental parameters used in this research has provided answers to practical viticultural land use questions. While similar methodologies have been pioneered in other wine growing regions, most notably in Oregon, this study tailors such modes of applied research to a new and upcoming wine growing region, the Piedmont Triad Region of North Carolina. For the purposes of the prospective grape grower, the lowest risk areas were identified and delineated. The realms of topography, soils, land cover/land use, and climate are all interconnected. Each of these continuous surfaces present risks to the potential grape grower, and each can be quantified. The practice of following guidance from agricultural extension documentation and expert regional researchers in order to make class distinction and weighting decisions is the key to interpreting the statements of this model. The physical characteristics of the region are very important when identifying optimal sites for vineyards. In high latitudes, for example, the northern aspects are too cold for viticulture, and in lower latitudes, the southwestern aspects may be too warm for viticulture. The researcher must make choices that tailor the model to the environment under study.

One weakness in weighting and summing multiple factor surfaces is the possibility that the factors chosen and the weights applied to them are not appropriate for the end goal. This is why it is important to rely on authoritative sources; the results of this paper are only as successful as the set of extension documents and viticultural studies these claims rest upon. Another weakness relates to scale; using a synoptic scale PRISM precipitation surface for a mesoscale area provides lower precision than desired. The fact that the climate parameters came from different sources is also problematic. The negative impact of this data mashup is revealed in the relatively messy climate composite output. In future work, it would be beneficial to use factors from the same data source and methods developed for the scale of the research. There is no known off-the-shelf climate product available at 10 m, so methodologies to downscale currently available surfaces or the creation of higher spatial resolution surfaces should be investigated further. Regardless of these shortcomings, the results make predictions about risk and they can be tested, albeit over time and/or across space. The factors used in the model are widely accepted but additional research on their influence could improve outcomes.

Since North Carolina falls across the climate boundaries which separate southern grape species from those grown farther north, it is and area rich with research opportunities. The implications of

Figure 18. Viticultural suitability model

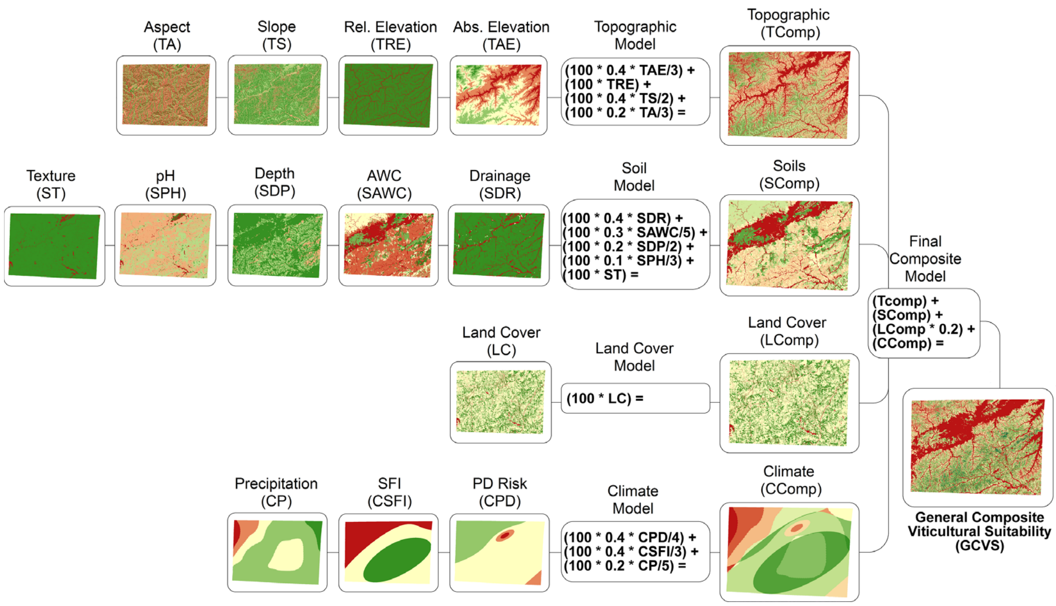


Figure 19. General viticultural suitability composite separated into Winkler regions

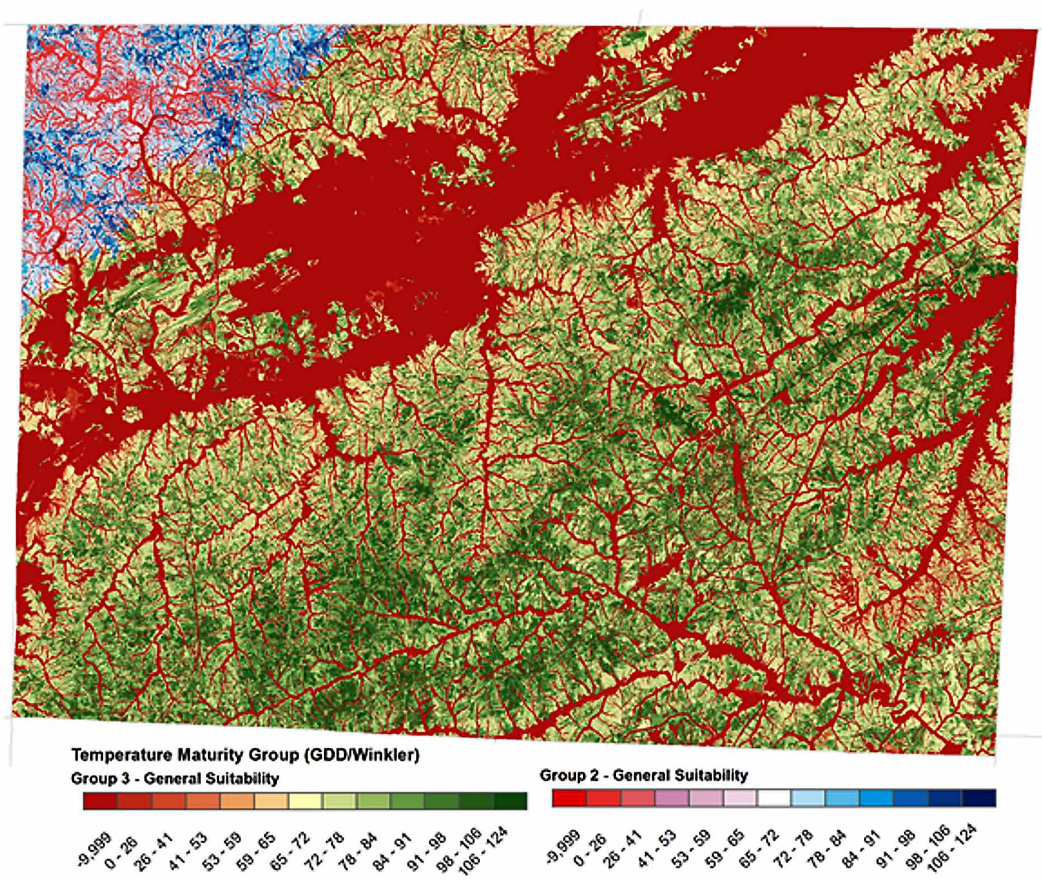
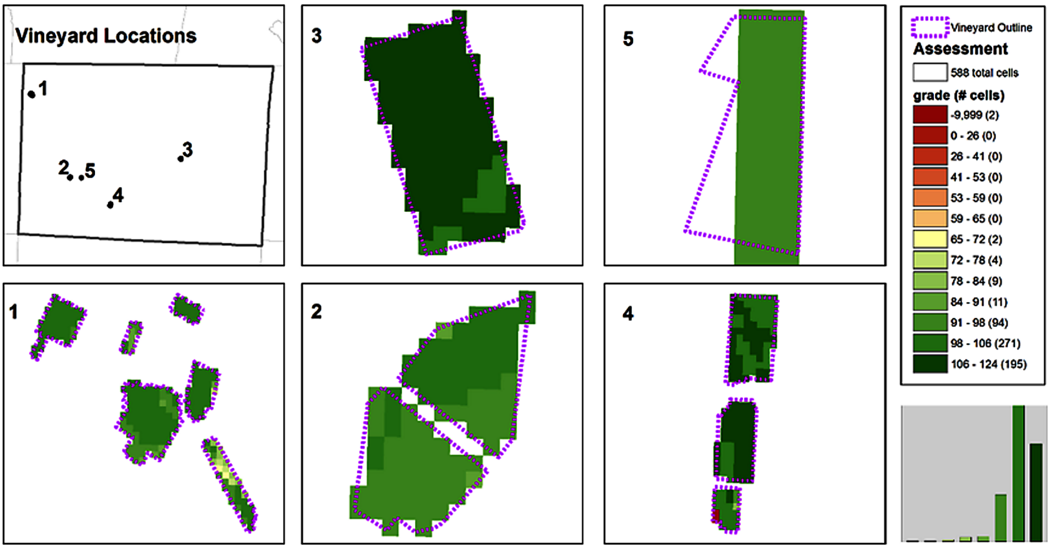


Figure 20. Vineyard assessment



climate change in the region are also important, and provide many research opportunities related to niche agriculture. Future studies could improve upon this model by considering the inclusion of real estate values, PRISM climate surfaces, population studies, surveys of vineyard and winery operators, and demographic information as a way to enhance results. The authors are planning future research to focus on terroir comparisons between the state's AVA's & vineyards. The model developed in this research specifically considers locating a vineyard site for European wine grapes, but it can be applied to other grape species. Outside of viticulture, there are many other niche agricultural crops which could benefit from the methodology presented in this research. For example, some agricultural uses include site suitability for varieties of olives, truffles, or pasture for a variety of herd animals. With the popular focus on local food, local wine has an opportunity to flourish. With the move toward diversification among small farms, viticulture offers a unique opportunity for certain sites. In order to produce consistent crops, new wine growing regions will need to focus on quality and consistency; understanding the risk is a key component to this puzzle. This research helps elucidate the spatial dimensions of these risks in one small area, and is presented in a repeatable way.

REFERENCES

Alcohol and Tobacco Tax and Trade Bureau (TTB). (2012). TTB Wine Appellations of Origin. Retrieved March 26, 2014, from http://www.ttb.gov/appellation/

Amerine, M. A., & Winkler, A. T. (1944). Composition and quality of musts and wines of California grapes. [University of California]. *Hilgardia*, *15*, 493–673.

Anas, O., Harrison, U. J., Brannen, P. M., & Sutton, T. B. (2008, July 18). The Effect of Warming Winter Temperatures on the Severity of Pierce's Disease in the Appalachian Mountains and Piedmont of the Southeastern United States. Retrieved February 12, 2012, from http://www.plantmanagementnetwork.org/pub/php/research/2008/pierces/

Bowen, P. A., Bogdanoff, C. P., Estergaard, B. F., Marsh, S. G., Usher, K. B., Smith, C. A. S., & Frank, G. (2005). Geology and Wine 10: Use of Geographic Information System Technology to Assess Viticulture Performance in the Okanagan and Similkameen Valleys, British Columbia. *GeoScience Canada*, *32*(4), 161–176.

Boyer, J. D. (1998, September 15). *Geographic Analysis of Viticulture Potential in Virginia* (EDTs). Retrieved from http://scholar.lib.vt.edu/theses/available/etd-92198-02524/unrestricted/Boyer.pdf

Calvo-Alvarado, J. C., & Gregory, J. D. (1997). Predicting the Mean Annual Runoff and Suspended Sediment Yield in Rural Watersheds in North Carolina (No. WRRI Project No. 70097) (p. 156). Chapel Hill, North Carolina: Water Resources Research Institute, University of North Carolina Chapel Hill; Retrieved from http://repository.lib.ncsu.edu/dr/bitstream/1840.4/1869/1/NC-WRRI-307.pdf

27. C.F.R § Part 9. Title 27: Alcohol, Tobacco and Firearms, PART 9 American Viticultural Areas (AVAs), § 9 (1979). Retrieved from http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?type=simple;c=ecfr;cc=ecfr;sid=fa02bde2d10fe31ff33f97245a801c3b;idno=27;region=DIV1;q1=american%20viticultural%20areas;rgn=div5;view=text;node=27%3A1.0.1.1.7

Chung, U., Seo, H. H., Hwang, K. H., Hwang, B. S., Choi, J., Lee, J. T., & Yun, J. I. (2006). Minimum temperature mapping over complex terrain by estimating cold air accumulation potential. *Agricultural and Forest Meteorology*, *137*(1–2), 15–24. doi:10.1016/j.agrformet.2005.12.011

Cox, J. (1999). *From Vines to Wines: The Complete Guide to Growing Grapes and Making Your Own Wine* (3rd ed.). Storey Publishing, LLC.

de Blij, H. J. (1983). Geography of Viticulture: Rationale and Resource. *Journal of Geography Journal of Geography*, *82*(3), 112–121.

de Blij, H. J. (1987). Viticulture and Viniculture in the Southeastern United States. *Southeastern Geographer*, *27*(2), 115–130.

Environmental Working Group (EWG). (2013). North Carolina Tobacco Subsidies. Retrieved December 22, 2014, from http://farm.ewg.org/progdetail.php?fips=37000&progcode=tobacco&page=county&regionname=NorthCarolina

Farm Service Agency (FSA). (2010). National Ag. Imagery Program Mosaic. Retrieved December 5, 2011, from http://www.fsa.usda.gov/FSA/apfoapp?area=home&subject=prog&topic=nai

Farm Services Agency (FSA). (2013). Tobacco Transition Payment Program (TTPP). Retrieved December 22, 2014, from http://www.fsa.usda.gov/FSA/webapp?area=home&subject=toba&topic=landing

Foss, C., Ravenscroft, N., Burnside, N., & Morris, D. (2010). Champagne Comes to England: Assessing the Potential of GIS in the Identification of Prime Vineyard Sites in South East England. *RICS Research*, 1–20.

Frank, Rimerman + Co. LLP. (2011). *The Economic Impact of Wine and Wine Grapes on the State of North Carolina - 2009* (Government). Retrieved from http://www.nccommerce.com/Portals/10/Documents/NorthCarolinaWineEconomicImpactStudy2009.pdf

Fridley, J. D. (2009). Downscaling Climate over Complex Terrain: High Finescale (<1000 m) Spatial Variation of Near-Ground Temperatures in a Montane Forested Landscape (Great Smoky Mountains). *Journal of Applied Meteorology and Climatology*, *48*(5), 1033–1049. doi:10.1175/2008JAMC2084.1

Gladstones, J. (2000). Past and future climatic indices for viticulture. *Wine Industry Journal*, *15*(2), 67–73.

Hellman, E. W., Takow, E. A., Tchakerian, M. D., & Coulson, R. N. (2011). Geology and Wine 13. Geographic Information System Characterization of Four Appellations in West Texas, USA. *Geoscience Canada*, *38*(1), 6–20.

Helsley, A. J. (2010). *A History of North Carolina Wine: From Scuppernong to Syrah*. The History Press.

Hobson Jr., F.W., owner of Rag Apple Lassie Vineyards. (2008, November 22). Installation Cost for Vitis vinifera vineyards in the North Carolina Piedmont.

Hobson Jr., F.W., owner of Rag Apple Lassie Vineyards. (2014, February 1). Installation Cost for Vitis vinifera vineyards in the North Carolina Piedmont.

Holden, Z. A., Abatzoglou, J. T., Luce, C. H., & Baggett, L. S. (2011). Empirical downscaling of daily minimum air temperature at very fine resolutions in complex terrain. *Agricultural and Forest Meteorology*, *151*(8), 1066–1073. doi:10.1016/j.agrformet.2011.03.011

Imre, S. P., & Mauk, J. L. (2009). *Geology and wine 12. New Zealand terroir.(Series)(Report): An article from: Geoscience Canada*. GeoScience Canada.

Institute for the Application of Geospatial Technology. the (IAGT). (2011). Vineyard Site Evaluation - Educational Info. Retrieved October 27, 2011, from http://arcserver2.iagt.org/vll/learnmore.aspx

Irimia, L., & Patriche, C. V. (2010). Evaluating the Ecological Suitability of the Vineyards, by Using Geographic Information Systems (GIS). *Cercetări Agronomice În Moldova, XLIII {43}*(1 (141)), 49–58.

Irimia, L., & Patriche, C. V. (n.d.). GIS applications in viticulture: the spatial distribution analysis of slope inclination and slope exposure in Huşi vine growing centre – Huşi vineyard. *Cercetari agronomice in Moldova, 44*(1).

Johnson, H., & Robinson, J. (2007). *World Atlas of Wine (6 Rev Upd.)*. MITCH.

Jones, G. V., Duff, A. A., Hall, A., & Myers, J. W. (2010). Spatial Analysis of Climate in Winegrape Growing Regions in the Western United States. *American Journal of Enology and Viticulture*, *61*(3), 313–326.

Jones, G. V., Duff, A. A., & Myers, J. W. (2006). Modeling Viticultural Landscapes: A GIS Analysis of the Viticultural Potential in the Rogue Valley of Oregon.*Terroir Congress*.

Jones, G. V., Snead, N., & Nelson, P. (2004). Geology and Wine 8. Modeling Viticultural Landscapes: A GIS Analysis of the Terroir Potential in the Umpqua Valley of Oregon. *GeoScience Canada*, *31*(4), 167–178.

Kickler, T. L. (2012). North Carolina History Project : Mother Vine. Retrieved August 25, 2012, from http://www.northcarolinahistory.org/commentary/122/entry

Kultural, K. S., Dami, I. E., & Taylor, B. H. (2006). Utilizing GIS Technologies in Selection of Suitable Vineyard Sites. *International Journal of Fruit Science*, *6*(3), 87–107. doi:10.1300/J492v06n03_07

Kurtural, S. K. (2010). Vineyard Site Selection. Retrieved October 16, 2012, from http://www.uky.edu/Ag/NewCrops/KF_31_02.pdf

Malczewski, J. (2000). On the Use of Weighted Linear Combination Method in GIS: Common and Best Practice Approaches. *Transactions in GIS*, *4*(1), 5–22. doi:10.1111/1467-9671.00035

Myers, A. L., Sutton, T. B., Abad, J. A., & Kennedy, G. G. (2007). Pierce's Disease of grapevines: Identification of the primary vectors in North Carolina. *Phytopathology*, *97*(11), 1440–1450. PMID:18943514

North Carolina State Climate Office (NCSCO). (2011, October 21). Overview | State Climate Office of North Carolina [Government]. Retrieved October 25, 2011, from http://www.nc-climate.ncsu.edu/climate/ncclimate.html#topo

Nowlin, J. W. (2013, May). *A mesoscale geophysical capability/suitability model for Vitis vinifera vineyard site selection in the North Carolina Piedmont Triad region, case study: Rockingham County NC* (Text). Retrieved from http://libres.uncg.edu/ir/uncg/listing.aspx?styp=ti&id=10074

NRCS. (2011a, August 11). U.S. General Soil Map (STATSGO2) Description | NRCS Soils. Retrieved December 6, 2011, from http://soildatamart.nrcs.usda.gov

NRCS. (2011b, August 18). Soil Survey Geographic (SSURGO) Database for Rockingham County, NC. Retrieved October 28, 2011, from http://soildatamart.nrcs.usda.gov

Parnell, A., & Johnson, J. A. (2012). *Assessing the Rockingham County Economic Development Landscape*. Mebane, NC: Cedar Grove Institute for Sustainable Communities.

Piedmont Distillers, Inc. (2014). Piedmont Distillers, Inc. Retrieved December 22, 2014, from http://www.linkedin.com/company/piedmont-distillers-inc-

Poling, E. B. (Ed.). (2007). The North Carolina Winegrape Grower's Guide. Raleigh, NC: N.C. Cooperative Extension Service; Retrieved from http://cals.ncsu.edu/hort_sci/extension/wine_grape.php

PRISM Climate Group. (2011, December 5). PRISM Climate Group, Oregon State U. Retrieved December 22, 2014, from http://www.prism.oregonstate.edu/

Rockingham Community College (RCC). (2014). Brewing, Distillation and Fermentation Associate in Applied Science Degree. Retrieved December 22, 2014, from http://www.rockinghamcc.edu/credit-programs/aas-programs/brewing-distillation-fermentation-technology.htm

Shaw, A. B. (1999). The Emerging Cool Climate Wine Regions of Eastern Canada. *Journal of Wine Research*, *10*(2), 79.

Sommers, B. J. (2008). *The Geography of Wine: How Landscapes, Cultures, Terroir, and the Weather Make a Good Drop (First Trade.)*. Plume.

Spayd, S. (2012, February 5). Aspect as a consideration for site suitability for Vitis vinifera vineyards in the North Carolina Piedmont.

Strahler, A. N. (1957). Quantitative Analysis of Watershed Geomorphology. *Transactions - American Geophysical Union*, *38*(6), 913–920.

Sutton, T. (2005). *Progress Report-Pierce's Disease Risk Zones in the Southeast*. North Carolina State University.

United States Geological Survey (USGS). (2012). The National Elevation Dataset. Retrieved May 1, 2012, from http://ned.usgs.gov/

U.S. Census Bureau. (n.d.). Population estimates, July 1, 2013, (V2013). Retrieved December 22, 2014, from http://www.census.gov/quickfacts/table/PST045213/00

Van Leeuwen, C., & Seguin, G. (2006). The concept of terroir in viticulture. *Journal of Wine Research*, *17*(1), 1–10. doi:10.1080/09571260600633135

Vaudour, E. (2002). The Quality of Grapes and Wine in Relation to Geography: Notions of Terroir at Various Scales. *Journal of Wine Research*, *13*(2), 117–141. doi:10.1080/0957126022000017981

Wallingford, A. K., Tolin, S. A., Myers, A. L., Wolf, T. K., & Pfeiffer, D. G. (2007). Expansion of the Range of Pierce's Disease in Virginia. *Plant Management Network: Plant Health Progress*, (doi:). Retrieved from http://www.grapesandfruit.umd.edu/grapes/Pages/PiercesDiseaseVirginia.pdf10.1094/PHP-2007-1004-01-BR

White, R. (2009). *Understanding Vineyard Soils*. USA: Oxford University Press.

Wilson, J. (n.d.). Rockingham Community College gets OK to launch beer-brewing program. Retrieved December 15, 2014, from http://www.bizjournals.com/charlotte/blog/morning-edition/2013/07/rockingham-community-college-gets-ok.html

Winslow, W. (2014, February 1). *State of the NC Wine Industry*. Presented at the NCWA Annual Conference.

Wolf, T. K. (1995). *The Mid-Atlantic winegrape grower's guide*. N.C. Cooperative Extension Service.

Wolf, T. K. (1998). Site selection for commercial vineyards. *Publication - Virginia Cooperative Extension Service (USA)*. Retrieved from http://agris.fao.org/agris-search/search.do?recordID=US9038695

Wolf, T. K., & Boyer, J. D. (2003). Vineyard Site Selection. Retrieved October 14, 2011, from http://pubs.ext.vt.edu/463/463-020/463-020.html

Wood, S. M. (2013). Ripe for Revenue. *Business North Carolina*, *33*(5), 42–43.

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