DEPARTMENT OF ENVIRONMENTAL PROTECTION
WATER RESOURCE MANAGEMENT
NEW JERSEY GEOLOGICAL SURVEY

ABSTRACT

A Geographic Information System (GIS) suitability model was prepared for the Warren Hills American Viticultural Area (AVA) to produce a wine-grape-growing suitability map (fig. 1). This suitability model defines some of the location factors important to grape cultivation including slope, aspect, solar radiation, geology and land-use then synthesizes the data illustrating where wine grapes have a favorable opportunity to grow and ripen. The resulting map provides an inventory of land suitability for growing wine grapes in the Warren Hills AVA. Eight vineyards from four wineries and one commercial vineyard surveyed for this study were determined to be situated on land favorable for viticulture. Six of the eight vineyards are located on land classed as highly favorable whereas two are on land that is moderately favorable. This data may be used by new and established vintners to find the best wine-grape-growing sites in the Warren Hills AVA. It might also be used to target areas for farmland preservation, tourism and economic development. This map presents input data, methodology and model results.

INTRODUCTION

Wine-grape growing is a relatively new venture in this region of the state. The first wine grapes were planted here by two wineries in 1981 and the area was designated as an AVA in 1988 by the Alcohol, Tobacco, Tax and Trade Bureau, U. S. Department of the Treasury. It is one of three federally designated AVAs in New Jersey. The area was recognized as an AVA because of its unique characteristics which make it very suitable for wine-grape cultivation. This wine-growing region is shaped by diverse geology and topography. Emergent wine-grape growing areas like the Warren Hills AVA typically face a trial-and-error stage of finding the best regions to grow grapes and the best variety of grape to match the land (Jones and others, 2004).

Suitability modeling is a representation of physical factors and their effects to enable determinations of potential or desirable outcomes. Models are used to increase understanding about natural systems and how they react to varying conditions. The objective is to produce a suitability model to ascertain where the best "terroirs" are for growing wine grapes in the 226-square-mile Warren Hills AVA based on a set of predetermined factors. Terroir is a French word that wineries have borrowed to denote the special characteristics that the geography, geology and climate of a specific site impart to particular variety of grapes.

GIS has proved to be a useful tool in modeling other viticultural regions in the United States, including areas in California, Oregon, New York, Virginia, and Missouri. Assessing a site's physical characteristics is most likely the single most important process that any potential grape grower will encounter when starting out (Jones and others, 2004). Great care must be used when selecting a vineyard site because it is probably the most important decision to be made out of thousands of decisions needed for a successful vineyard (Jordan and others, 1980).

Raster data-sets hold information in pixels rather than polygons, enabling one to make a very precise analysis. In this case, raster data is used to facilitate the measurement of cells, specifying the size of each land-use area. This made possible a cross analysis with other pertinent data based on the geographical features of slope, aspect, solar radiation, geology and land use. A composite grid was created with the model inputs using the weighted overlay tool in ESRI's ArcGIS software. The composite grid was then clipped using a land-use data layer to produce a spatial depiction of possible vineyard sites within the Warren Hills AVA. A ranking system was subsequently developed for the areas ability to grow wine grapes.

Interpretation of the map data requires discretion. Selection criteria for the map are simplified from the more complex conditions on the ground resulting from microclimate, soil and land use.

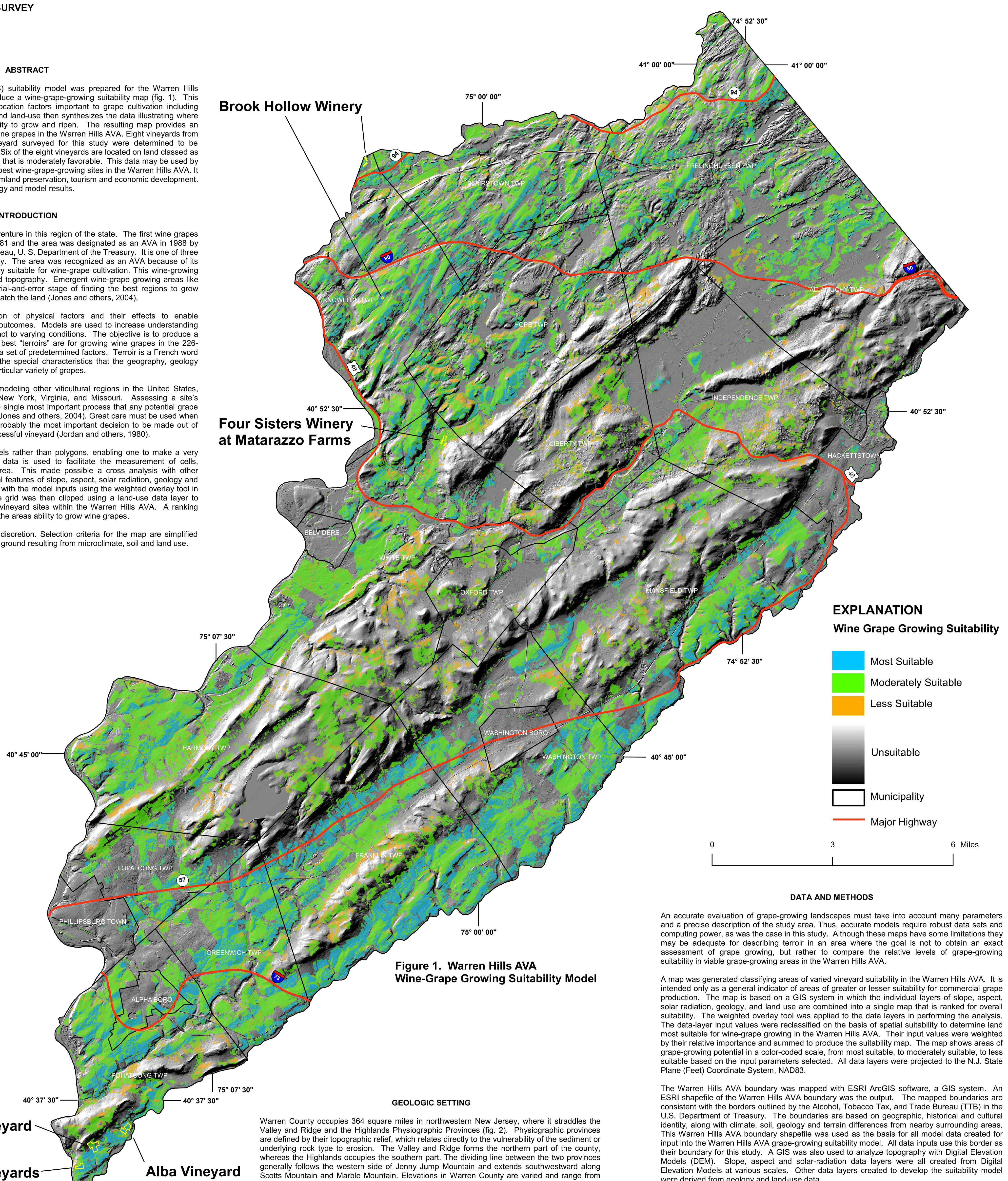
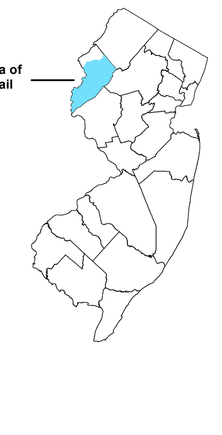


Figure 1. Warren Hills AVA
Wine-Grape Growing Suitability Model



BACKGROUND

New Jersey winemaking dates back to at least 1767 when two New Jersey vintners were recognized by London's Royal Society of the Arts and awarded 200 pounds each for producing the first bottles of quality wine by colonial agriculture (McCormick, 1962). Edward Antill of Piscataway was credited first for making wine from the vineyard he established on the banks of the Raritan River close to New Brunswick in what was formerly the community of Raritan Landing. The Renault Winery is one of the oldest continuously operating wineries in the United States. It was established in 1864 by Louis Renault and is in operation to this day in Egg Harbor City, Atlantic County. In Passaic County, Alfred Speer experimented with wine-grape growing on his hilltop farm west of the Passaic River in the City of Passaic and Clifton. By 1869, he was producing wine and Speer's New Jersey Wine Company and Speer's Vine Culture Company were formed. He was very successful at making and selling port wine made from the European Oporto grapevines (Lotz, 1987). By the early 1880's, with 60 acres of vines planted, he had the largest vineyard and winery in New Jersey and one of the largest on the east coast (Clayton, 1882). Speers' Oporto grapevines were grown in soil overlying the iron-rich Passaic Formation of the Piedmont Physiographic Province. Welch's Grape Juice Company got its start in 1869 in Vineland, Cumberland County, when physician and dentist Thomas Bramwell Welch and his son Charles processed the first bottles of "unfermented wine" to use in their church's communion service (www.Welchs.com).

According to an 1891 national survey by the Board of Viticultural Commissioners of California, 163 grape growers in New Jersey cultivated at least 553 acres in grapes. There were 71 wine makers in New Jersey identified in this survey (Johnston, 1891). This productive wine-making time did not last long. Prohibition began in 1919 with the passage of the Volstead Act devastating the U.S. wine industry. Only three wineries in New Jersey survived this dry period by producing sacramental wines for religious services, medicinal tonic and non-alcoholic grape juice. The New Jersey wine industry has made a strong comeback in recent years. From 1981 to 2010, the number of wineries in the state grew from 9 to 40 (NJ Dept. of Agriculture, 2010). In 2003, the winery and vineyard industry in the state was valued at $36 million (Gorman, 2003). In 2006, New Jersey wineries produced an estimated 1.67 million gallons (6.33 million liters) of wine (Hodgen, 2008). In 2007, New Jersey was fifth in wine production in the United States, producing more than 40 different varieties, from dry and semi dry to sparkling, fruit, and dessert wine (NJ Dept. of Agriculture, 2010). In 2007, 192 farms grew grapes on 1,043 acres statewide (USDA, 2009, table 32).

WARREN COUNTY AND THE AVA

In 2007, Warren County boasted 25 farms with vineyards, more than any county in the state. With 116 acres planted in grapes, it ranked second in New Jersey only to Atlantic County with 207 acres planted (USDA, 2009, table 32).

Most of Warren County is included in the Warren Hills AVA except for the area to the northwest of the Paulins Kill. The boundary description of this AVA is as follows: From the junction of the Delaware and Musconetcong Rivers, at the southern tip of Warren County it extends northeastward along the Musconetcong River about 32 miles, where it intersects the Warren County-Sussex County line. It then progresses northwestward along that county line for about 10 miles before turning generally southwestward along the Paulins Kill to the Delaware River to the beginning point (Alcohol, Tobacco, Tax and Trade Bureau, 1988). For purposes of this study, the boundary of the AVA was mapped generally to the Paulins Kill, although a small section of land just northwest of the Paulins Kill was added to include a second and third vineyard belonging to a winery with another vineyard within the AVA boundary.

GEOLOGIC SETTING

Warren County occupies 364 square miles in northwestern New Jersey, where it straddles the Valley and Ridge and the Highlands Physiographic Provinces (fig. 2). Physiographic provinces are defined by their topographic relief, which relates directly to the vulnerability of the sediment or underlying rock type to erosion. The Valley and Ridge forms the northern part of the county, whereas the Highlands occupies the southern part. The dividing line between the two provinces generally follows the western side of Jenny Jump Mountain and extends southwestward along Scotts Mountain and Marble Mountain. Elevations in Warren County are varied and range from 1,560 feet above sea level on Kittatinny Mountain to 160 feet above sea level along the Delaware River. Middle and Upper Proterozoic rocks of the Highlands (1,400 to 600 million years ago, mya) underlie a series of northeast-trending ridges (listed from northeast to southwest): Jenny Jump Mountain, Marble Mountain, Scotts Mountain, County House Mountain, Pohatcong Mountain, Upper Pohatcong Mountain, and Allamuchy Mountain. These ridges are separated by broad, northeast-trending valleys underlain by Paleozoic sandstone, dolomite, limestone, and shale of the Kittatinny Valley sequence. Paleozoic sediments (560 to 420 mya) are the bedrock of the Valley and Ridge in Warren County. These sedimentary rocks underlie the large, open expanse of moderate topographic relief between the Highlands and Kittatinny Mountain. Prominent northeast-trending relief characterizes Kittatinny Mountain, part of the Valley and Ridge that is underlain by dense and resistant Paleozoic conglomerate and quartzite (Monteverde and others, 1994). Although bedrock dominates much of the landscape of Warren County, significant glacial deposits overlie the valleys.

WARREN HILLS AVA CHARACTERISTICS

Generally, the Warren Hills AVA is considered very favorable for wine growing because of several factors that when combined provide good growing conditions for wine grapes. The mountain ranges trending from northeast to southwest and the parallel intervening valleys give it a southeast or southern exposure (fig. 2), considered to be excellent for wine-grape growing at this latitude because of the enhanced solar radiation. These slopes also provide abundant air flow, lessening the chances of frost pockets. The AVA also contains ample limestone, shale and sandstone derived soils considered favorable for wine grape growing.

The borders of the Warren Hills AVA are formed by the Delaware River to the west, the Musconetcong River to the south and the Paulins Kill to the north. These riparian areas provide a slightly warmer microclimate than areas away from the rivers. The constant wind movement near water helps to prevent frosts in the spring and fall. This wind also can dry off the leaves and fruit after rainfall, helping prevent to disease (Hedrick, 1919). Many of the established wine growing regions of the United States are situated near bodies of water to take advantage of their moderating effect on climate (Hedrick, 1919).

Climate can also be a limiting factor to wine grape growing. The local growing season in the AVA averages 180 days. Grapevines may be injured by fall frosts, winter cold, or spring frost, all of which are defined as low-temperature injury (Wolf and Boyer, 2009). Extreme cold is damaging to most grapevines, and temperatures below 0° F are especially dangerous to Vinifera grapevines. For example, the winters of 1989 and 1994 had temperatures of -15 to -20° F in some parts of the AVA. One winery reported hundreds of vines killed in 1989 due to this extreme cold and another vintner reported the loss of multiple acres of grapevines in 1994. In 2009, one vintner reported vine damage during a late May frost. This has been a deterrent to vintners growing Vinifera in the Warren Hills AVA.

The Warren Hills AVA is planted with the three types of wine grapes available for wine making in this part of New Jersey. The cold hardy Labrusca or Native American varieties (1) including Concord, Niagara, and the Cynthiana or Norton grapes are grown here. The popular French-American hybrid grape varieties (2) including Vidal, Frontenac, Leon Millet, Seyval, Marechal Foch, Cayuga White, Baco Noir, Chambourcin and Traminette, are also grown here. These hybrid varieties provide cold hardiness and a more appealing flavor than the Native American varieties. There are also some plantings of Vinifera or European varieties at two wineries in the southern part of the AVA near the confluence of the Delaware and Musconetcong Rivers. The temperatures in this area are typically a few degrees warmer than elsewhere in the AVA. This slight temperature difference makes it possible to grow Vinifera in the southern part of the AVA on south-facing slopes. Vinifera varieties (3) include Chardonnay, Cabernet Sauvignon, Shiraz, Pinot Grigio, Malbac, San Grievan, Cabernet Franc, Pinot Noir, Barbera and Riesling.

DATA AND METHODS

An accurate evaluation of grape-growing landscapes must take into account many parameters and a precise description of the study area. Thus, accurate models require robust data sets and computing power, as was the case in this study. Although these maps have some limitations they may be adequate for describing terroir in an area where the goal is not to obtain an exact assessment of grape growing, but rather to compare the relative levels of grape-growing suitability in viable grape-growing areas in the Warren Hills AVA.

A map was generated classifying areas of varied vineyard suitability in the Warren Hills AVA. It is intended only as a general indicator of areas of greater or lesser suitability for commercial grape production. The map is based on a GIS system in which the individual layers of slope, aspect, solar radiation, geology, and land use are combined into a single map that is ranked for overall suitability. The weighted overlay tool was applied to the data layers in performing the analysis. The data-layer input values were reclassified on the basis of spatial suitability to determine land most suitable for wine-grape growing in the Warren Hills AVA. Their input values were weighted by their relative importance and summed to produce the suitability map. The map shows areas of grape-growing potential in a color-coded scale, from most suitable, to moderately suitable, to less suitable based on the input parameters selected. All data layers were projected to the N.J. State Plane (Feet) Coordinate System, NAD83.

The Warren Hills AVA boundary was mapped with ESRI ArcGIS software, a GIS system. An ESRI shapefile of the Warren Hills AVA boundary was the output. The mapped boundaries are consistent with the borders outlined by the Alcohol, Tobacco Tax, and Trade Bureau (TTB) in the U.S. Department of Treasury. The boundaries are based on geographic, historical and cultural identity, along with climate, soil, geology and terrain differences from nearby surrounding areas. This Warren Hills AVA boundary shapefile was used as the basis for all model data created for input into the Warren Hills AVA grape-growing suitability model. All data inputs use this border as their boundary for this study. A GIS was also used to analyze topography with Digital Elevation Models (DEM). Slope, aspect and solar-radiation data layers were all created from Digital Elevation Models at various scales. Other data layers created to develop the suitability model were derived from geology and land-use data.

After site visits, commonalities among eight vineyards belonging to four commercial winery vineyards and one commercial vineyard were mapped. New Jersey Department of Environmental Protection aerial photography (2007) was used to map the vineyards. An ESRI shapefile was created based on this information. The locations of 20 additional farms with vineyards in the AVA were not available and their information is not included in this study (USDA, 2009).

SLOPE

Slope is an important feature in modeling grape-growing regions. It influences the angle of incoming solar radiation, soil moisture, wind exposure, and cold air drainage (Sommers, 2008). Air flow is a critical factor for productive vineyard sites because it channels cold air downslope to be replaced by warmer air from above. Since slopes help to remove cold air, they are excellent sites to grow grapes (Wolf and Boyer, 2009). Excessive slopes are difficult for machinery to access thus affecting the viability of vineyards on steep ground. This factor was taken into consideration in the development of the model. Access for machinery on slopes of as much as 12 percent works well, is increasingly difficult on 13–19 percent slopes and is difficult on slopes exceeding 20 percent (Jordan and others, 1980). Moderate slopes are considered optimal for vineyards because they avoid most frost damage and problems with tractors and mechanical harvesters. Table 1 shows slopes categorized into suitability classes for the model.

Table 1. Slope suitability rating

Slope Percentage	Suitability	Remarks
Less than 1	Low	Poor air drainage
1-2%	Moderate	Readily accessible for machinery
3-12%	High	Readily accessible for machinery
13-19%	Moderate	Machinery access increasingly difficult with increasing slope
20-100%	Low	Machinery access very difficult

This slope raster file for the model was created using the slope tool in ESRI's ArcMap Spatial Analyst extension. The slope tool calculates the maximum rate of change between each cell and its neighbors. Every cell in the output raster has a slope value. The lower the slope value, the flatter the terrain; the higher the slope value, the steeper the terrain. For the model, the slope was expressed as a percentage.

The slope data layer used in the suitability model was created using LiDAR (Light Detection and Ranging) raster DEMs. LiDAR data is remotely-sensed high-resolution elevation data collected by an airborne collection platform. The first and larger land-area raster data layer was clipped out of the NJDEP Digital Elevation Model for the New Jersey Highlands Planning and Preservation Areas. LiDAR was flown over approximately 1675 square miles of Passaic, Sussex, Bergen, Morris, Warren, Hunterdon, and Somerset Counties in New Jersey and a small part of Orange County, New York, with a Root Mean Square Error (RMSE) of 18.5 centimeters vertically and 95 percent confidence level. The Warren County part of the Highlands DEM within the Warren Hills AVA was clipped and mosaicked with a smaller and similar LiDAR study of Western Warren and Sussex Counties New Jersey (2009), which is within the Warren Hills AVA border in the northwest of the AVA but excluded from the Highlands LiDAR DEM data to produce the data-set. After the two LiDAR data layers were mosaicked together, the slope was generated from this combined raster-grid file and normalized to a 5 x 5 foot cell size (fig. 3).

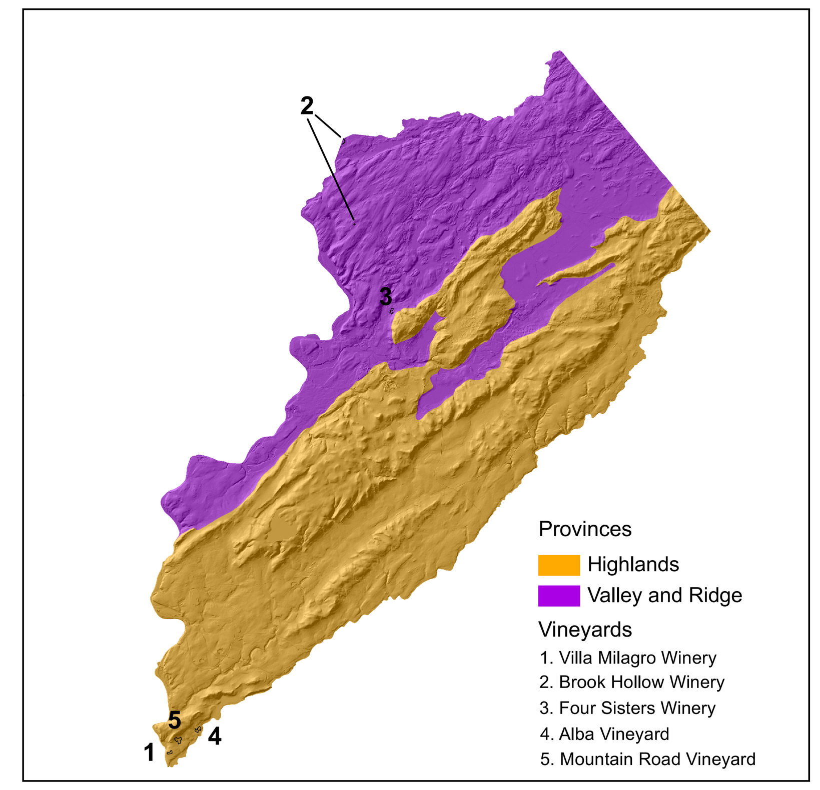


Figure 2. Warren Hills AVA Vineyards, Physiographic Provinces

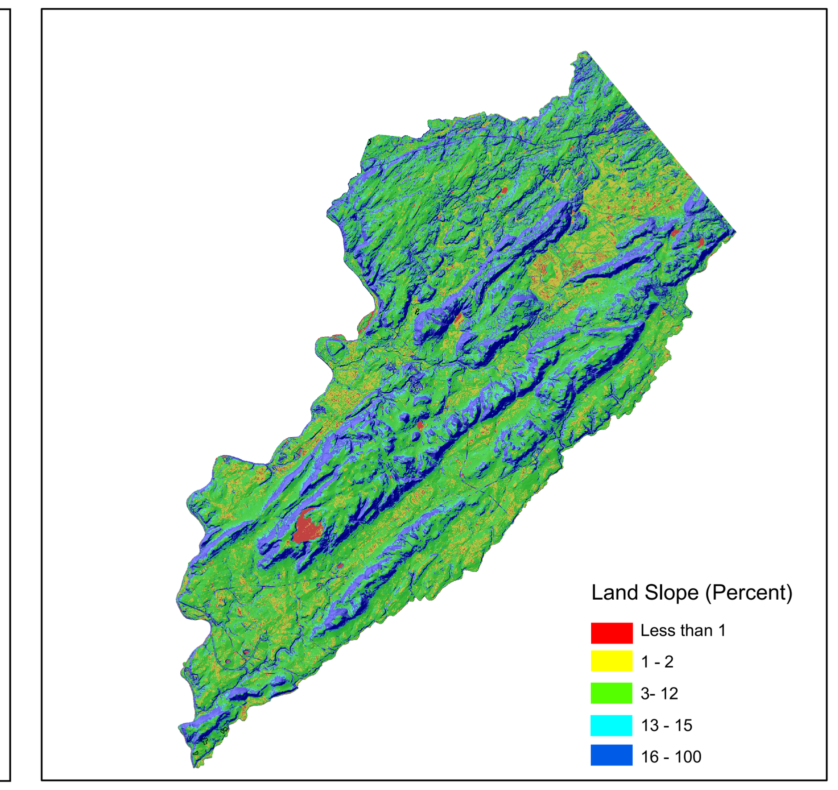


Figure 3. Warren Hills AVA Slope

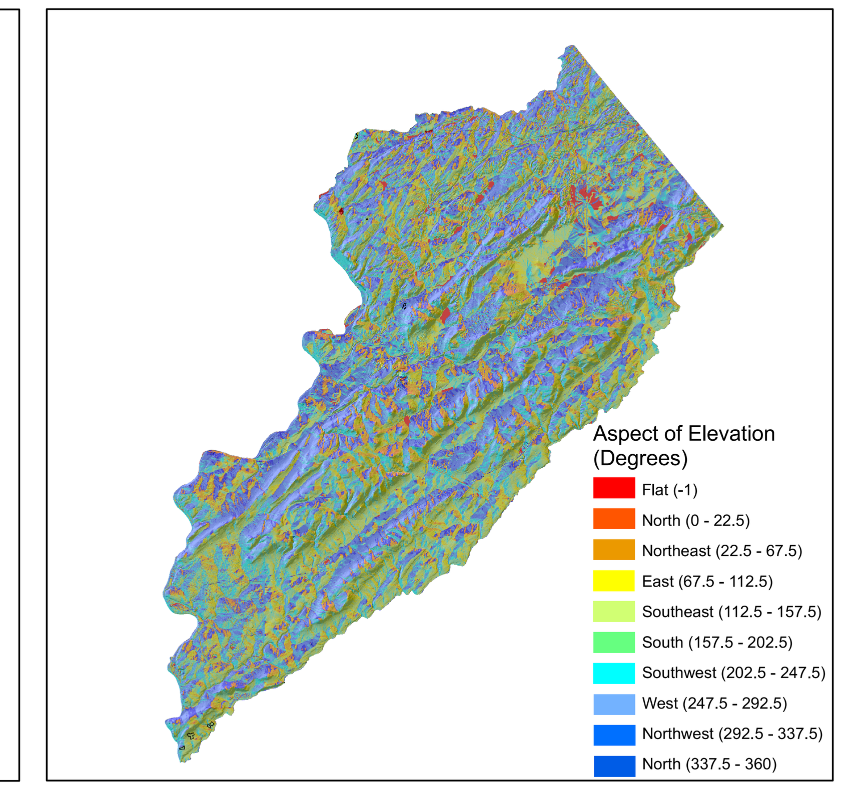


Figure 4. Warren Hills AVA Aspect

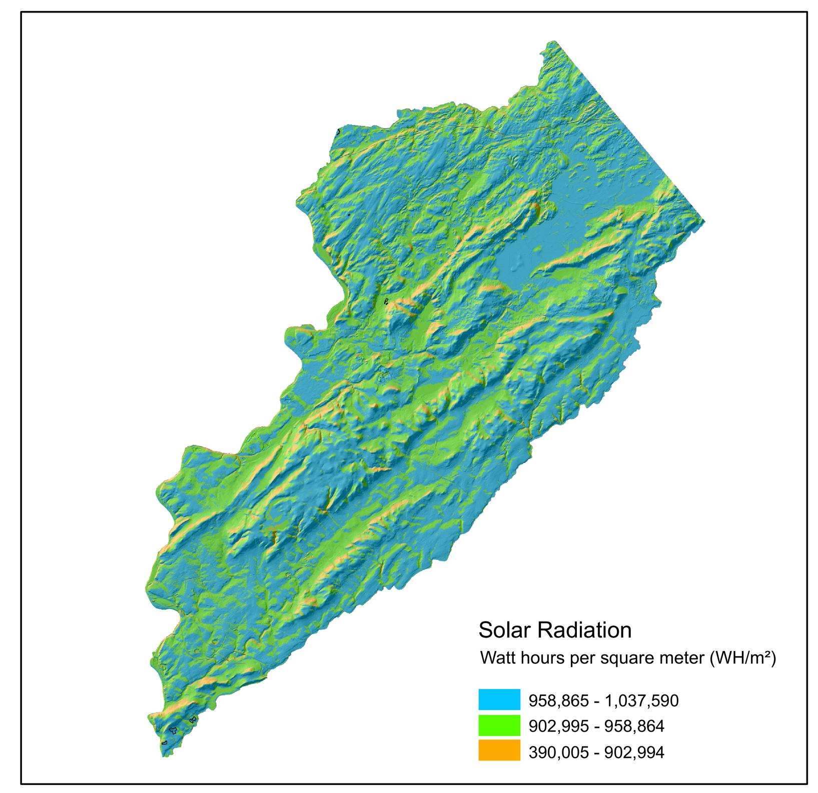


Figure 5. Warren Hills AVA Solar Radiation

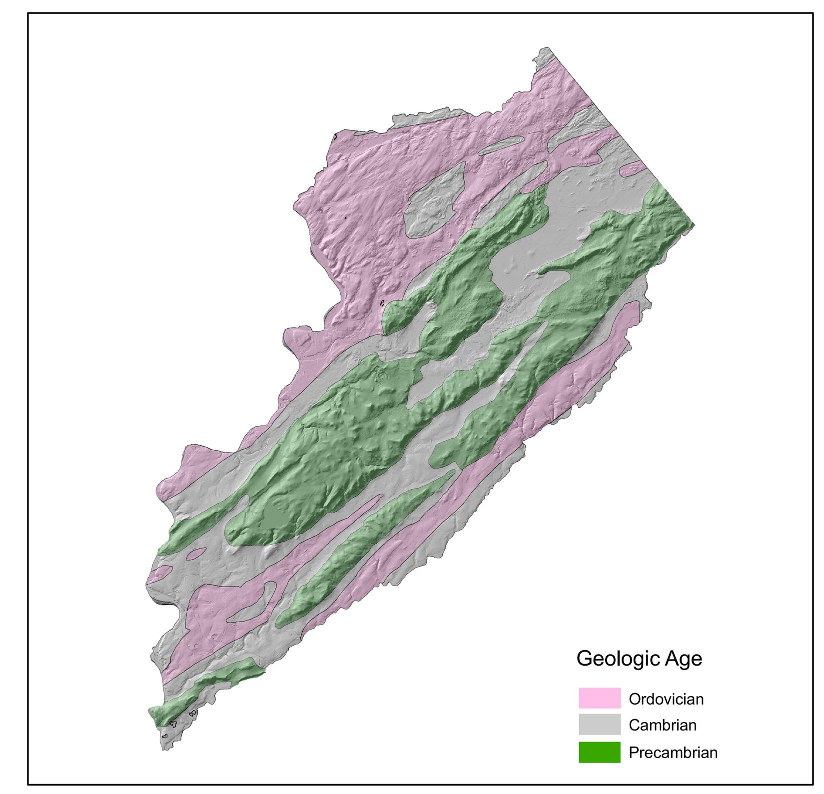


Figure 6. Warren Hills AVA Major Age Units

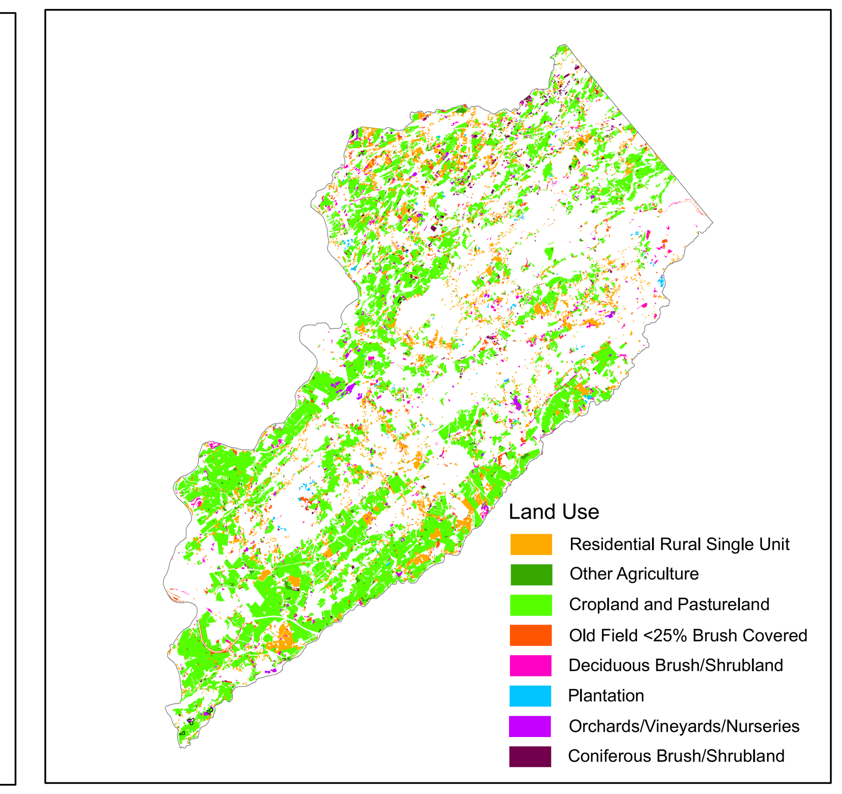


Figure 7. Land Use Related to Warren Hills AVA Suitablity

ASPECT

The aspect of the landscape is typically used to define the direction toward which the slope is facing. Wine grapes can and have been grown on all aspects in the Warren Hills AVA. But some aspects are more suitable for wine-grape growing than others. It is commonly known that a southern exposure is milder and is the best for grape growing at this latitude. Early and later grapes facing south are less likely to suffer from frost damage because in general southern slopes provide a longer growing season. All Vinifera currently grown by wineries and vineyards surveyed for this study are planted on southern slopes. Frost damage can be severe on steep eastern slopes because the rays of the direct sun may strike frozen plants which may then be injured by rapid thawing. However, early morning sun exposure on east slopes initiates the start of temperature and light-dependent photosynthesis, resulting in more rapid drying of foliage and fruit from dew or rain, reducing fungal disease problems (Wolf and Boyer, 2009). Eastern slopes also tend to be better sheltered from the hot afternoon sun, further benefiting grapes. North and west slopes retard the leafing and blooming period, protecting grapes from spring frosts but it is well known that they can be damaged by fall frosts and may fail to ripen enough before harvest because these areas are slightly cooler and have a shorter growing season than south slopes. It is also slightly colder on these slopes in winter, which could be more hazardous during extreme winter cold. Vineyards surveyed for this study in the Warren Hills AVA are situated on slopes facing east, southeast, south, southwest and west. None of the vineyards are on north slopes.

The aspect of a land area can be derived from a raster surface such as a DEM. The aspect algorithm used in creating the aspect-data layer identifies the steepest down-slope direction from each cell to its neighbors. The values of the output-data layer are compass direction of the aspects, or the compass direction a hill faces (Burrough, 1998).

The aspect data layer was generated from an NJDEP Digital Elevation Grid for New Jersey (10 meter x 10 meter cell size) originally generated from U.S. Geological Survey (USGS) DEM files. From this grid, an aspect raster grid with slope direction was generated (fig. 4). Wine grapes grown on certain aspects have a better chance of success in the Warren Hills AVA. The most suitable are on slopes facing east, southeast, south, southwest and west. These are the slopes on which wine grapes are currently being grown successfully. Northeast and northwest slopes are given a medium suitability ranking. North slopes are given a low-suitability ranking. The aspect raster grid file used was created in ESRI's ArcMap Spatial Analyst extension.

SOLAR RADIATION

"Growing grapes requires careful consideration of the microclimate of the selected location. Growing conditions for grapes are determined largely by the solar radiation received at the site. The sun is the primary energy source for practically all biological processes on the earth. Solar radiation has a direct affect on the air and soil temperature, transpiration, soil moisture and atmospheric humidity, etc." (Pirzadeh, 2011).

The amount of solar radiation received at a site varies widely with slope and aspect of the area, particularly in hilly and mountainous areas. "The accumulated seasonal solar radiation tends to be lower on slopes facing north, north east and north west and higher for the slopes facing south" (Pirzadeh, 2011).

An area solar-radiation analysis calculates incoming solar radiation from a raster surface. An NJDEP Digital Elevation Grid for New Jersey (2007), (10-meter x 10-meter cell size) derived from USGS DEM files was used to calculate the insolation throughout the entire Warren Hills AVA landscape during a growing season (fig. 5). A 199-day growing season was chosen to calculate the solar radiation. This 199-day period begins on April 1, 2009 and ends on October 17, 2009. These dates were selected because grape-vine buds in the Warren Hills AVA typically begin to swell in early April, when daytime temperatures commonly climb to around 50° F. The first widespread frost may occur sometime between late September and late October and ends the wine-grape-growing season. October 17 is selected as the date ending the growing season because this is the date of the first widespread frost of the 2009 growing season in the Warren Hills AVA. The Area Solar Radiation tool in ESRI's ArcMap Spatial Analyst Extension was used to create the solar radiation raster data layer.

The classification system used to determine the values for reclassification of solar radiation is based on the natural-breaks criteria in the GIS software. The classes are based on natural groupings inherent in the data. ArcMap identifies break points by picking the class breaks that best group similar values together and maximizes the differences among classes. The features are divided into classes whose boundaries are set on pronounced breaks in the data values. Three classes are identified for the model. The solar radiation values identified are units of watt hours per square meter (WH/m²). It is assumed that the higher the watt hours per square meter, the higher the suitability for grape growing. For the model, 390,005 to 902,994 is considered to be low suitability, 902,995 to 958,864 is considered medium suitability, and 958,861 to 1,037,590 is considered high suitability.

GEOLOGY

Geology is an important factor in grape growing. Wine grapes can be grown in soils derived from many types of geologic formations but some are clearly superior to others. A geologic raster data layer with a 5-foot cell size was created based on generalized bedrock geology data for the Warren Hills AVA at 1:1,000,000 scale (fig. 6). The geologic map is by the New Jersey Geological Survey (2007). Geologic commonalities were derived by identifying the type of bedrock geology each vineyard is situated on. A database was created with bedrock geology attributes for each vineyard. Subsequently, input parameters for the model were developed based on the type of bedrock.

Three of the four commercial winery vineyards in the study have vineyards situated on limestone-derived soil while one is located on shale-derived soil. The one vineyard in the study without a winery is located predominantly on limestone soil but also contains a small proportion of vines planted on soils derived from sandstone and granite. For the suitability analysis performed in this map, limestone and shale-derived soils are treated as high-suitability soils for wine-grape growing. Soils derived from marble, granite and gneiss are treated as moderately suitable as few vineyards were found in these geologic areas.

LAND USE

Land-use data was used to create a mask to find sites where grape growing is not only possible but productive. Unsuitable areas were removed from the suitability-model data using the land-use mask. The land-use data layer created for this study was generated from NJDEP 2002 Land Use/Land Cover data. The process involved selecting the chosen data from the 2002 Land Use/Land Cover, then converting the data to a raster data file using ESRI's ArcMap Spatial Analyst. The land use raster mask includes: Residential, Rural, Single Unit, Other Agriculture, Cropland and Pastureland, Old Field (<25 percent Brush Covered), Deciduous Brush/Shrubland, Plantation, Orchards/Vineyards/Nurseries/Horticultural Areas, and Coniferous Brush/Shrubland, (fig. 7). These land uses are considered the most favorable for grape growing and are deemed suitable because they are also readily converted to vineyard sites. Other land uses are less conducive to grape growing. For example, Urban Land, Wetlands, Agricultural Wetlands Modified, Forested Lands, Impervious Cover and Standing Water are considered unsuitable for vineyard sites and are omitted from the viable land-use data layer mask.

The decisions regarding which land use types to use, with the exception of Forests, was fairly obvious. Forests are an exception. Although some forested areas are probably fully capable of supporting grapes, the cost of land clearing and preparation could be prohibitive.

MODEL PARAMETERS

A weighted overlay analysis was used to create the wine-grape-growing suitability model map to find the best locations for growing wine grapes in the Warren Hills AVA. The weighted overlay tool enables calculation of a multi-criteria analysis among several raster data sets. After deciding what raster data sets to use, the model input rasters for this study were reclassified, weighted equally, and then combined using the weighted overlay tool. To create the suitability model, four raster data sets were used in the weighted overlay analysis. They are slope, aspect, solar radiation and geology.

The raster layers were reclassified by choosing where each one was to be segmented. The information on where to segment is based on previous studies and discussions with vintners in the Warren Hills AVA. The fields for weighting the rasters were then chosen. The effect of the raster is a given weight comparable to the other rasters for the model data criteria as a percentage of 100. For this suitability model, each of the four rasters, slope, aspect, solar radiation, geology was given a 25-percent weighting or equal value. Much debate centers around the most important physical factors for wine grape growing. For this study, all four factors used in this model are considered equally important. After the weighted overlay model was run, three classifications were chosen, based on natural breaks. The classifications are: most suitable, moderately suitable, and less suitable. The land use raster data was used to mask out the viable grape-growing lands and a final ESRI grid raster file was generated for the Warren Hills AVA with a 10 x 10-meter pixel size, whereas other areas were classified as unsuitable and show up as shades of gray on the map.

CONCLUSIONS

Methodology used in this research attempts to determine the most suitable areas to grow wine grapes in the Warren Hills AVA for the benefit of present-day and future growers. This approach improves the knowledge base of wine-grape-growing landscapes in the Warren Hills AVA by generating a GIS suitability model. This model could be adapted and used in other areas of New Jersey to help understand the terroirs of different parts of the state more accurately. This research may merit further study. More information on soil ph, soil depth, soil drainage and climate would further refine and update the suitability model.

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NEW JERSEY DEPARTMENT OF ENVIRONMENTAL PROTECTION

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by

Ted Pallis, Mike Girard and Mark French

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