Vineyard

SITE SELECTION

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Vineyard Site Selection

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Introduction

Grapes grown in Virginia can be exposed to environmental stresses and biological pests that can reduce crop quality and yields and injure or kill grapevines. Damaging winter temperatures, spring and fall frosts, extremes of rainfall, and higher than optimal summer temperatures occur with regularity in some regions. Other regions may be frequented by hurricanes. Grapevines can be severely injured by certain atmospheric pollutants if grown near the origin of those pollutants. Grapes are also threatened by diseases, certain insects, and by vertebrate animals, including deer and birds. Despite these challenges, grapes are successfully grown in many areas of the state. Vineyard site selection, therefore, greatly affects crop yields, quality and vineyard profitability.

The aim of this bulletin is to describe the principal physical and biological features that affect grape production and which should be evaluated in the site selection process. In practice, most readers will ultimately realize that vineyard site selection involves compromises. Few sites are ideally suited to grape production in all respects. Furthermore, those who wish to establish a winery should also recognize that the best vineyard sites might not necessarily be the most accessible to winery customers. The text is divided into three sections: (I) discussion of the broad, "macroclimate" of Virginia; (II) discussion of local climate or "mesoclimate" and soil factors that have a bearing on site selection; and (III) a description of potential pests and other threats that should also be considered when choosing a vineyard site. The bulletin is primarily intended for wine grape producers, but the basic concepts are also applicable to table grape production.

Climate

Climate refers to the average course of the weather at a given location over a period of years and is measured by temperature, precipitation, wind speed and other meteorological conditions. "Weather" is the state of the atmosphere at a given moment with respect to those same meteorological conditions.

The *macroclimate* refers to the prevailing climate of a large geographic region (many square miles). Most of Virginia is subject to a continental macroclimate. Continental climates have temperature and precipitation patterns that are primarily modified by large land masses (continents). Air temperatures of continental climates can fluctuate rapidly on a day-to-day basis because land does not readily affect or buffer air temperatures.

Maritime climates, on the other hand, are macroclimates that are directly influenced by their proximity to large bodies of water, which are tremendous heat sinks. Water absorbs heat during summer and slowly cools in the fall. Cold air that blows across seas, unfrozen lakes and bays in the fall and winter will tend to warm vineyards on the leeward side of the water. This may extend the growing season, and it may raise mid-winter air temperatures enough to prevent vine damage from low-temperature events. The depth, surface area, and salinity of these bodies of water will largely determine how much heat they can absorb and release before freezing. As air temperatures rise in the spring, large bodies of water will warm slower than the surrounding land. Relatively warm air is cooled as it blows over cold water. The cooled air retards plant development on the leeward side of the water and reduces the risk of spring frost damage. In Virginia, the Tidewater and Eastern Shore counties are subject to a maritime climate due to their proximity to the Atlantic Ocean and the Chesapeake Bay. There are no other bodies of water in Virginia that are large enough to significantly affect regional climate.

The *mesoclimate* or local climate is more specific than the macroclimate. Horizontal distances of as little as 500 feet, such as opposing aspects or hillsides in hill and valley terrain, may affect mesoclimates. The vineyard mesoclimate is influenced by topography, the compass orientation (aspect), the degree of inclination (slope), barriers to air movement, and, to a lesser extent, the nature of ground cover, soil type, and soil moisture.

A third term, *microclimate*, is used to describe the specific environment within and immediately exterior to grapevine canopies. Grapevine canopies consist of shoots and their leaves and the fruit present during the growing season. The microclimate within vine canopies can differ significantly from the climate immediately outside the canopy, particularly with respect to the quantity and quality of sunlight, air temperature, wind speed, and humidity.

Macroscale Site Selection

Many readers will have a narrowly defined interest in vineyard site selection. Landowners, for example, may simply wish to determine if their land is suitable for grape production. Others might ask, "Where in Virginia should I establish a vineyard, and why?" The answers to both sets of questions have some commonalties and, for both, those answers start with a review of the state's macroclimates, particularly the length of the growing season and the occurrence of temperature extremes.

Length of growing season

The length of the growing season will determine whether grapes will ripen or not. Decreasing fall temperatures reduce the capacity of the vine to synthesize sugar and ripen grapes. Ultimately, frost will kill leaves that have not naturally senesced, preventing further sugar accumulation in fruit and perennial portions of the vine. Vineyard sites, therefore, must have sufficient heat and duration of heat to ensure crop ripeness. A minimum of 180 frost-free days is recommended for vineyards in Virginia, although very early-maturing varieties, such as some Muscats and Viognier, may ripen with a season as short as 155 days. The average period from budbreak to fruit harvest ranged from 144 to 179 days for a range of varieties evaluated at Winchester, Virginia (Wolf and Warren, 2000; Wolf and Miller, 2001).

"Budbreak" is defined as the time when the dormant buds open and newly formed leaves are seen. The average length of growing season, conservatively defined by the last average spring occurrence of 32°F to the first fall occurrence of 32°F, is shown in **Figure 1**. Additional frost-free days after harvest are desirable though to permit further gains in carbohydrate accumulation in roots, trunks, and other perennial organs. Regions of southwestern and western Virginia are marginal, on a macroscale basis, for grapes that require 160 or more days of growing season. On the other hand, most sites east of the Blue Ridge have ample growing season length, although as discussed later, local or mesoscale differences may greatly affect the length of the growing season.

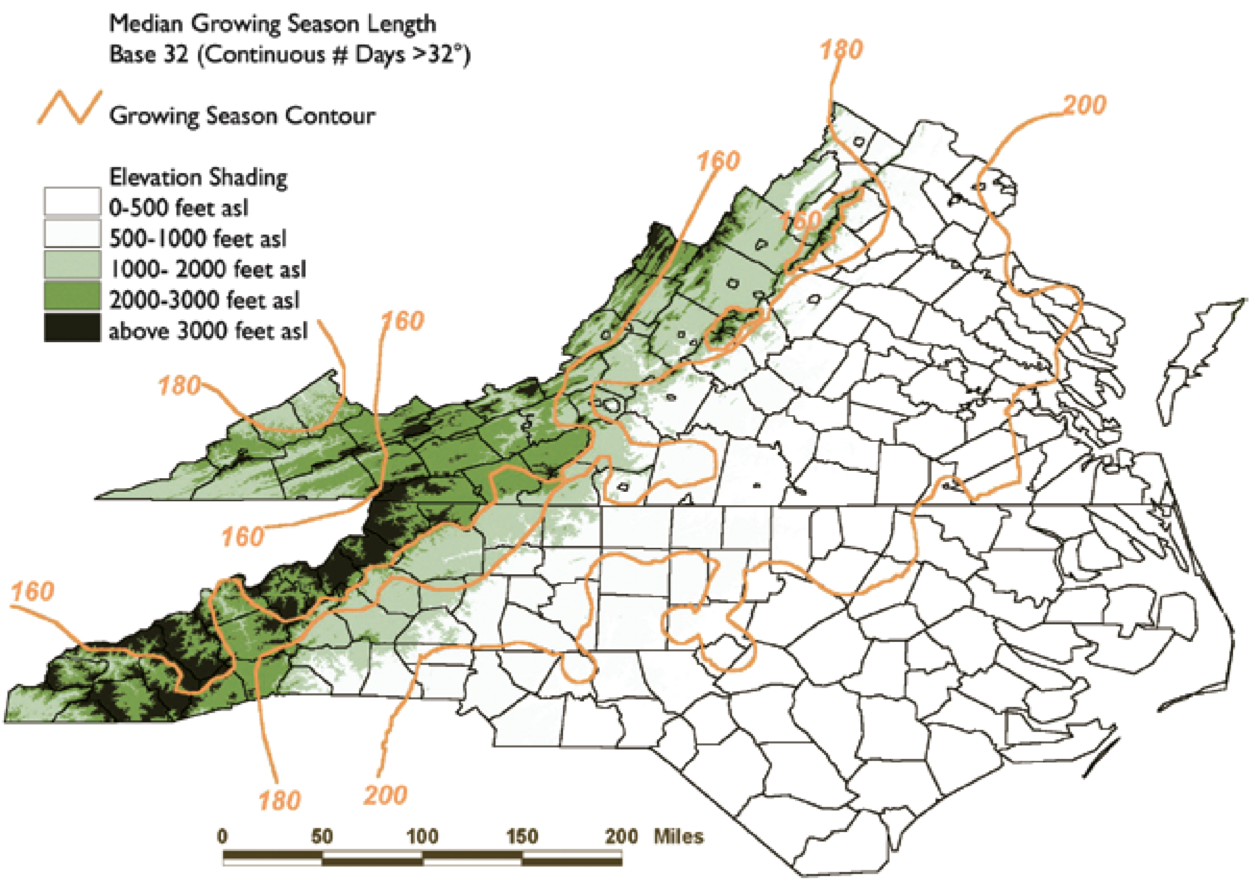


Figure 1. Median growing season-length isolines and elevation shading for Virginia and North Carolina. The isoline values are the median number of frost-free days from spring to fall. A temperature of 32°F is used to define frost-free days although grapevines can, under certain atmospheric conditions, withstand slightly cooler temperatures without injury.

Frost

Depending upon the time of year, grapevines may be injured by fall frosts, winter cold, or spring frost, all of which are defined as low-temperature injury. We will define "frost" injury to occur when buds are fully swollen or leaves are present, and "winter" injury as that injury which occurs when vines lack obvious seasonal growth. Frost injury and winter injury often have similar causes that are associated with topography and meteorological conditions. Those factors are discussed below in greater detail.

Spring frosts chronically injure some vineyards and are more frequent in some parts of the state than in others, even those with good local site selection. The risk of spring frost damage is increased when unseasonably warm weather promotes early budbreak and shoot growth, which is then followed by more seasonable low temperatures. Grape shoots are very susceptible to freeze injury if temperatures dip below 32°F (**Figure 2**). Under very dry air conditions, the injury may not occur until temperatures reach 25°F or 26°F, but shoots would rarely survive lower air temperatures. Spring frosts generally do not kill vines because secondary buds will subsequently break and their shoots will provide sufficient foliage to support the vine; however, secondary buds typically produce shoots with a very low fruiting potential. On the tail end of the season, fall frosts, as mentioned above, essentially arrest further

Figure 2. Frost injury to young shoot.

sugar accumulation. It would be desirable for grapevine leaves to naturally senesce, rather than being frosted off the vines, in order to maximize carbohydrate (sugars and starch) reserves in perennial portions of the vine.

A goal of site selection is to locate sites with a relatively low likelihood of spring and early fall frost. One method of evaluating a site's risk of frost is based on the range between a site's average *mean* and average *minimum* temperatures for a given month. That range, defined for spring months as a "spring frost index" (SFI) by Gladstones (2000), is a measure of the site's continentality, or tendency to produce large fluctuations in temperature over short periods of time. The greater the range, the greater the frost hazard. Budbreak is primarily influenced by air temperature – the warmer the temperature, the earlier the budbreak. Warm weather is only a problem if the warm weather is interspersed with sub-freezing temperatures, which would tend to lower the average minimum temperature for a month, and thereby increase the SFI value. The average mean temperature for a month is based on the daily mean temperature (daily high plus daily low, divided by 2), averaged for all days of that month. The average minimum is simply the minimum daily temperature averaged for all days of the month. Both figures are reported for many Virginia stations by the National Oceanic and Atmospheric Administration (NOAA, 2002). Average April mean and minimum temperatures, as well as corresponding SFIs, are shown for eight Virginia locations in **Table 1**.

Although there is no precisely defined threshold for stating what frost risk is tolerable, SFI values less than 11.0 have *relatively* low frost risk, whereas those of 13.0 or greater are high risk. The Painter (Accomack County) and Norfolk Naval Air Station locations have a relatively low frost risk due to the temperature moderating effects of the ocean and bay, and perhaps to relatively high relative humidity. Mount Weather, at 1720 feet above sea level (asl) on the Blue Ridge, has a low frost risk because it lies within an optimal "thermal elevation belt" described elsewhere in this publication. Dulles Airport, just west of Washington, D.C., lies in a large cold-air basin and that is reflected by its relatively large SFI. Winchester in the northern Shenandoah Valley and Abingdon in Southwest Virginia have strongly continental climates, and elevated SFI values. Farmville (Cumberland County) and Chatham (Pittsylvania County) in the Eastern Piedmont are among the state's most frost-prone sites.

Table 1. Illustration of Spring Frost Index (SFI) for April at eight Virginia locations.

Station	Elevation (feet above sea level)	Average daily mean (°F) for April	Average daily minimum (°F) for April	Spring Frost Index (SFI)	Relative frost risk
Painter	30	56.2	45.9	10.3	Low
Norfolk NAS	33	58.7	49.5	9.2	Low
Mount Weather	1720	49.3	40.2	9.1	Low
Dulles Airport	290	53.1	40.2	12.9	Moderate
Winchester	680	51.7	38.5	13.2	Moderate
Abingdon	1920	52.9	39.3	13.6	High
Farmville	450	56.9	42.5	14.4	High
Chatham	640	53.9	38.7	15.2	High

This region quickly warms in late-winter, but lacks any temperature moderation from large bodies of water, and has relatively little variation in elevation to generate "thermal belts." The SFI may not be precise, but the values shown in Table 1 are consistent with our experiences with spring frost occurrence in Virginia. Although the SFI applies to spring frost, the same technique can be used to gauge a site's risk of fall frost, say in the month of October. Generally, one could expect a strong correlation between spring and fall frost risk.

Frequency of extreme low temperatures

Grapevines can be injured or killed by winter cold. Winter injury has historically been the primary environmental limitation to *Vitis vinifera* varieties in Virginia. Injury may include death of overwintering buds, injury to the vascular tissues of canes, cordons, and trunks, or even complete vine kill (**Figure 3**). The frequency of damaging low winter temperatures will define if grape production is possible and, if so, what the species and variety limitations are to such production. Due to the dynamics of vine cold hardiness (Howell, 2000), it is difficult to say precisely what temperature will cause cold injury to a specific variety on a specific date.

Above the threshold of injurious cold for a given variety, the cooler a region's minimum daily temperatures during fall, the greater the extent of cold acclimation achieved by mid-winter. Cold acclimation refers to the metabolic and visible changes that occur with cold-adapted plants as they transition from a non-hardy condition to a dormant, cold-hardy condition. One visible manifestation of acclimation is the maturation of green, succulent shoots into brown, woody canes. To illustrate air temperature effects on acclimation, varieties grown in New York State will tolerate mid-winter temperatures that are

Figure 3. Riesling vineyard that experienced from -17 to -20°F in February 1996. The lack of growth on these vines in June of 1996 was due to cold injury to the exposed trunks and canes. The only grapevine growth present originates from regions of the trunks close to the ground that had been protected by a layer of snow. The smaller photo (A) is a dormant bud cut cross-sectionally to reveal a cold-injured primary bud, straddled by live secondary buds. Photo (B) is a healthy cane (left) compared to a cold-injured cane (right). The discolored tissue immediately beneath the bark on the injured cane illustrates the injury to the phloem and vascular cambium that can result from low temperature exposure.

about 8°F lower than tolerated by the same varieties grown in Virginia (Pool et al, 1992). Thus, the definition of a critical, injurious temperature in one region will not necessarily apply to warmer or cooler regions.

Experience, as well as numerous controlled freezing tests in Virginia over the past 15 winters, has led to the use of a critical temperature of -8°F as a guide for predicting the onset of significant cold injury in *V. vinifera* varieties. In principle, and practice, if well managed vines are exposed to -8°F, we can anticipate – under central Virginia conditions – seeing appreciable (>50%) primary-bud injury and, perhaps, cane, cordon, and trunk injury, depending on the freeze conditions. The -8°F threshold is not absolute; it will vary by variety, time of year, and as a function of the air temperatures immediately preceding the cold episode. This threshold is fairly representative of a variety with cold hardiness comparable to Chardonnay, and it represents average maximal hardiness as attained by early January. It is also important to understand that the -8°F figure does not imply that injury will be absent at warmer temperatures. In fact, we may see economically significant injury at 10°F in some varieties in some cases, although this is rare. Finally, the occurrence of -8°F events is counted by each cold episode, not necessarily the number of days that experienced -8°F. For example, a cold front that resulted in two consecutive nights at -8°F or lower, would be counted as one occurrence. The frequency of -8°F events, by decade, over a 30-year period is depicted in **Figure 4**. Regions that experience -8°F three or more times per decade would not be considered appropriate for *V. vinifera* production. Parts of western Virginia and southwestern Virginia fall into this category. Two episodes per decade would be of concern and would increase the need for careful mesoscale site selection. The temperature moderating influence of the Atlantic Ocean and the Chesapeake Bay essentially eliminate the potential of a -8°F event in the eastern part of the state. The validity of Figure 4 was demonstrated by a damaging freeze event on February 5-6, 1996. Minimum temperatures during that event (**Figure 5**) correlated very well with long-term records and showed the significance of the Blue Ridge as a barrier to the eastern migration of low

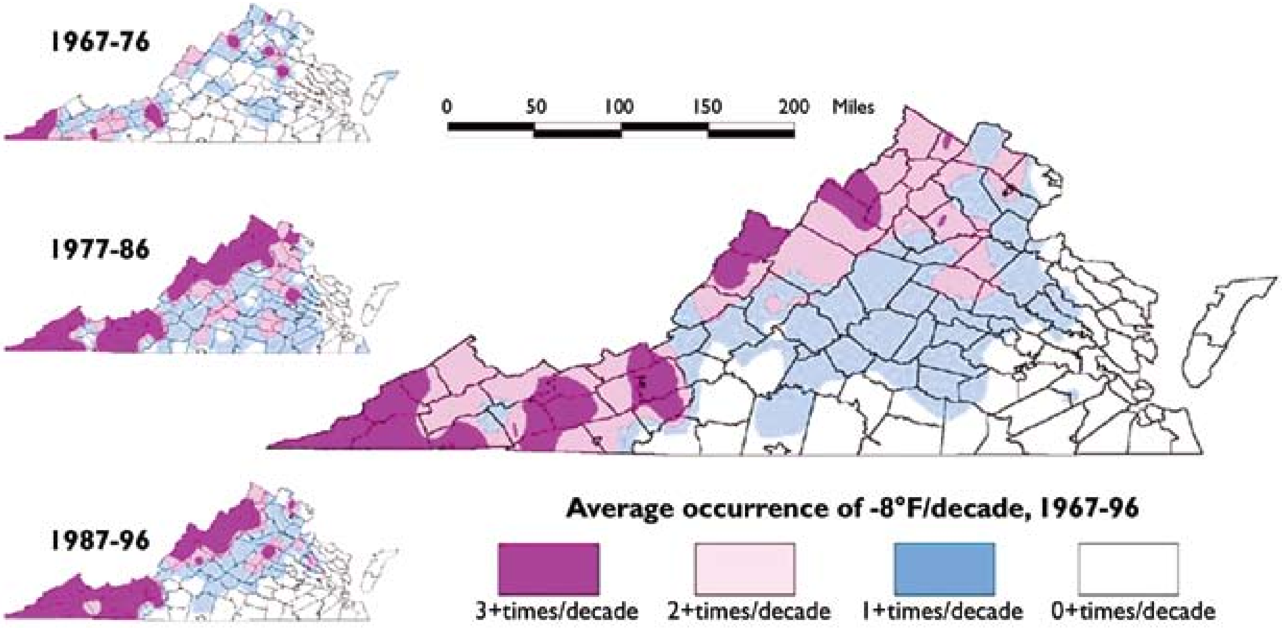


Figure 4. Average number of -8°F episodes per decade in the 1967-1996 period. The large central image is an average of the three smaller, 10-year records.

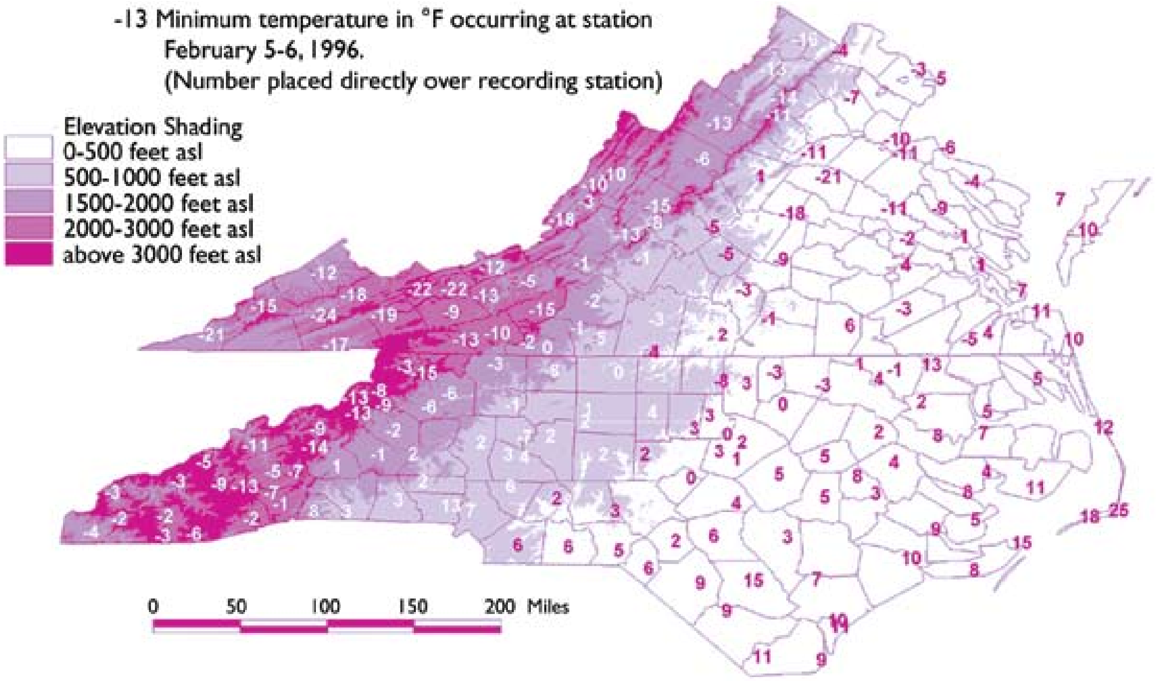


Figure 5. Temperatures recorded February 5-6, 1996, at various sites in Virginia and North Carolina.

temperatures. An exception to that barrier occurred in the northern Piedmont, which experienced an influx of extremely cold air, which was also predicted from long-term records (Figure 4).

The frequency of specified low temperatures can be predicted for a proposed vineyard site on the basis of nearby historical temperature data and knowledge of the proposed site's elevation. The commercial company, SkyBit (http://www.skybit.com/), can provide an historical probability analysis of the frequency of specified temperature(s) at a site based only on the site's location and elevation. SkyBit uses existing temperature data from nearby recording stations and interpolates the expected temperature at the candidate site based on its elevation and proximity to the established stations. This probability assessment can serve as a predictor of future occurrences of the same temperature(s). Such an exercise is illustrated in **Table 2** for three vineyard sites in Northern Virginia. Two of the sites, the Winchester Agricultural Research and Extension Center (AREC) vineyard, and Linden Vineyards (Fauquier County), each have at least 15 years of experience or actual temperature data. The third site (Rappahannock Cellars) is a relatively new vineyard at 860 feet asl on the east side of the Blue Ridge in Fauquier County. All three of these sites would be considered good to excellent from an elevation standpoint. The SkyBit assessment of -4°F and -8°F events at Winchester AREC and Linden Vineyards is a fair approximation of actual experience or actual data (Table 2); however, SkyBit tended to "predict" more cold episodes than actually occurred. For example, SkyBit "predicted" the occurrence of -8°F at Winchester AREC on four occasions between 1990 and 2000. In reality, that low was attained only once (January 19, 1994, -11°F). The three occurrences predicted in 1994 may have related to several occurrences on consecutive 24-hour reporting periods during the same event. For example, the two actual occurrences of -8°F at Linden Vineyards in 1994 occurred as -13°F on one night, followed by -10°F on the following night.

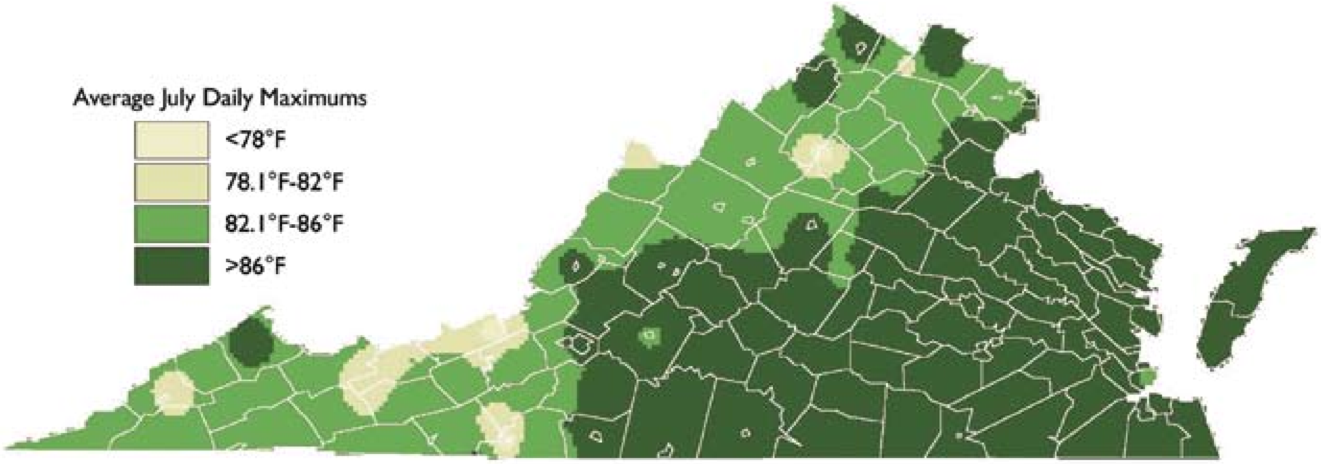
Table 2. SkyBit-generated prediction of low-temperature event (0°F, -4°F, or -8°F) occurrence per year at three Virginia locations in northern Virginia. Comparison is made to actual recorded frequency of -8°F for the Winchester Agricultural Research and Extension Center (AREC) and Linden Vineyards locations.

	Winchester AREC **39.1104N, 78.2822W** **990' elevation**				**Linden Vineyards** **38.8867N, 78.0472W** **1400' elevation**				**Rappahannock Cellars** **38.8362N, 78.1165W** **860' elevation**		
	Predicted			**Actual frequency**	**Predicted**			**Actual frequency**	**Predicted**		
Year	**0°F**	**-4°F**	**-8°F**	**of -8°F**	**0°F**	**-4°F**	**-8°F**	**of -8°F**	**0°F**	**-4°F**	**-8°F**
1981	1	0	0		2	0	0		1	0	0
1982	6	4	2		6	4	1		4	2	1
1983	3	2	0		2	2	1		2	1	0
1984	4	2	1		4	3	2		4	2	1
1985	3	1	1		4	2	1		2	1	1
1986	0	0	0		0	0	0		0	0	0
1987	2	2	0		4	1	0		2	0	0
1988	1	0	0		0	0	0		0	0	0
1989	4	0	0		6	4	0	0	4	0	0
1990	0	0	0	0	0	0	0	0	0	0	0
1991	0	0	0	0	0	0	0	0	0	0	0
1992	0	0	0	0	0	0	0	0	0	0	0
1993	0	0	0	0	0	0	0	0	0	0	0
1994	5	4	3	1	6	5	3	2	5	3	1
1995	0	0	0	0	1	0	0	0	0	0	0
1996	2	2	1	0	3	1	1	0	2	1	1
1997	2	0	0	0	2	0	0	0	0	0	0
1998	0	0	0	0	0	0	0	0	0	0	0
1999	0	0	0	0	0	0	0	0	0	0	0
2000	0	0	0	0	0	0	0	0	0	0	0
Sum	33	17	8		40	22	9		26	10	5

Based on a very limited comparison to actual temperature data, the SkyBit simulations might be somewhat overstating the frequency of low temperature events, but the analysis could nevertheless give some guidance for sites where no historical data are available. Those interested in exploring this service for candidate sites may contact SkyBit and provide the elevation and, if available, the latitude and longitude of the proposed site.

Temperatures from July through October

Temperatures greater than 86°F can reduce the vine's ability to photosynthetically convert carbon dioxide into sugars and other carbohydrates. Nighttime temperatures greater than about 64°F tend to increase the vine's respiration of this energy. In fact, respiration can consume up to 60% of the energy generated by photosynthesis (Iacono et al, 2000). Many Virginia sites have average July *maximum* temperatures in excess of 86°F (**Figure 6**) and some, particularly those in the more humid regions of the Tidewater region, have average July *minimum* temperatures in excess of 64°F (Figure 6). In practical terms, vines grown in such regions would not be as physiologically productive as would vines grown at cooler day and night temperatures.



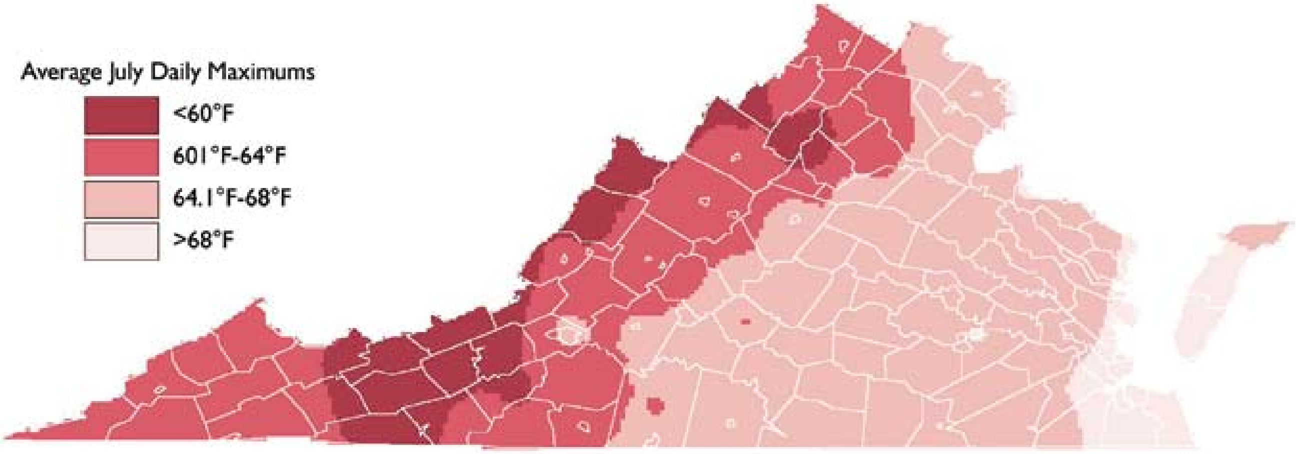


Figure 6. Average July daily maximum (upper) and minimum (lower) temperatures throughout Virginia.

Optimal primary fruit chemistry (sugar/acid concentrations and pH) and, in red-fruited varieties, color development, is promoted by daytime temperatures of 68°F to 77°F and nighttime temperatures of 59°F to 68°F (Coombe, 1987). Gladstones (1992) suggests an optimal mean daily temperature of 64°F to 70°F in the final month of ripening (August through October, depending on location and variety). Most sites in Virginia's Piedmont and Tidewater regions experience an average daily mean temperature greater than 70°F in August (**Figure 7**). Average mean temperatures range from 64°F to 70°F throughout much of this same region in September, except the far southeast portion of the state, which still exceeds 70°F. The average October mean daily temperature is actually cooler than optimal throughout most of the state. The most effective means of locating sites with lower daily temperatures is to increase elevation. This trend is apparent in the data of **Table 3** that show a decrease in average July temperatures (maxima, minima, and means) with an increase in station elevation. However, note that both the recorded low temperature and the length of the frost-free period also decrease with increased elevation. Thus, there is a tradeoff between finding sites with cooler summer temperatures, yet where grapes will ripen and vines will not experience winter injury. The compromise is reached by locating vineyards at increased elevation (discussed below) that also afford excellent cold air movement out of the vineyard.

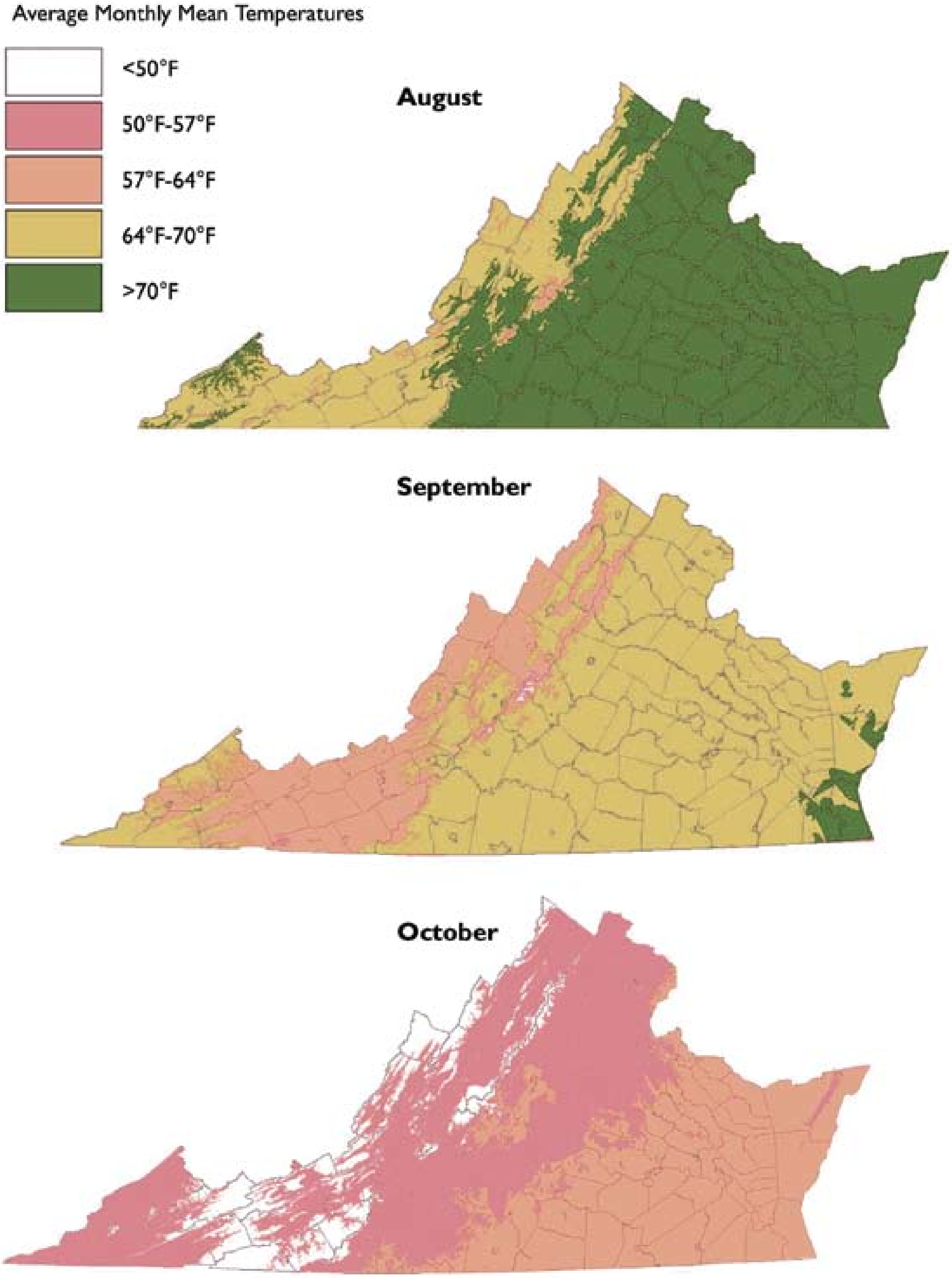


Figure 7. Average daily mean temperatures throughout Virginia for August, September, and October.

Table 3. Selected climatological indices for various Virginia locations. Source: NOAA, Climatography of the United States No. 81: 1971-2000 (http://www.ncdc.noaa.gov/oa/climate/climatedata.html#CLIMATOLOGY)

Station name	County	Elevation (feet, asl)	Recorded low (°F)	Record low date	July daily average max (°F)	July daily average mean (°F)	July daily average min (°F)	Days >90°F (number)	GDD	FFP (days) Base 32°F
Suffolk Lake Kilby	Suffolk	22	-5	21-Jan-85	88.1	78.5	68.8	30	4491	222
Painter 2 W	Accomack	30	-1	2-Feb-71	87.0	78.3	69.5	22	4257	209
Williamsburg 2 N	York	70	-7	21-Jan-85	89.0	78.1	67.1	36	4358	202
Fredericksburg	Spotsylvania	90	-11	22-Jan-84	89.6	77.5	65.4	40	3839	177
Lawrenceville 3 E	Brunswick	137	-10	21-Jan-85	88.3	76.5	64.6	36	3901	179
Warsaw 2 NW	Richmond	140	-6	21-Jan-85	88.1	77.6	67.1	35	4153	195
Ashland	Hanover	220	-11	5-Feb-96	87.1	76.6	66.0	26	3887	191
John H Kerr Dam	Mecklenburg	250	-5	21-Jan-85	89.2	78.4	67.5	40	4270	197
Louisa	Louisa	420	-21	5-Feb-96	86.6	74.4	62.1	27	3359	172
Farmville 2 N	Cumberland	450	-8	21-Jan-85	89.0	77.2	65.4	39	4036	187
Warrenton 3 SE	Fauquier	500	-11	16-Jan-72	84.2	75.0	65.8	24	3502	193
Piedmont Research Stn	Orange	520	-11	5-Feb-96	86.2	76.1	65.9	24	3636	198
Chatham	Pittsylvania	640	-9	21-Jan-85	87.2	75.2	63.2	30	3486	160
Winchester 7 SE	Frederick	680	-18	19-Jan-94	87.1	74.6	62.0	24	3249	167
Charlottesville 2 W	Albemarle	870	-10	19-Jan-94	88.0	76.9	65.8	27	4035	211
Appomattox	Appomattox	910	-14	19-Jan-94	87	75.9	64.7	25	3666	193
Bedford	Bedford	975	-10	21-Jan-85	86.2	75.7	65.1	17	3657	203
Philpott Dam 2	Henry	1123	-10	21-Jan-85	86.8	76.4	65.9	26	3804	190
Lexington	Rockbridge	1125	-12	21-Jan-85	87.1	74.7	62.3	22	3355	168
Roanoke ROA (Airport)	Roanoke	1149	-11	21-Jan-85	87.5	76.2	64.9	28	3870	192
Rocky Mount	Franklin	1315	-11	21-Jan-85	86.5	75.5	64.4	23	3600	180
Stuart	Patrick	1375	-13	21-Jan-85	85.4	74.7	63.9	17	3601	191
Luray 5 E	Page	1400	-14	5-Feb-96	87.9	74.1	60.2	23	3468	157
Pennington Gap	Lee	1470	-25	21-Jan-85	85.7	73.8	61.8	17	3302	158
Staunton Sewage Plant	Augusta	1640	-16	27-Jan-87	83.3	72.1	60.9	12	2865	161
Mount Weather	Loudoun	1720	-15	18-Jan-82	79.9	72.1	64.2	4	2846	188
Abingdon 3 S	Washington	1920	-21	21-Jan-85	85.0	72.8	60.5	13	3174	163
Wytheville 1 S	Wythe	2450	-20	21-Jan-85	83.4	70.8	58.1	8	2670	146
Wise 3 E	Wise	2548	-24	21-Jan-85	82.1	71.4	60.6	2	3044	171
Floyd 2 NE	Floyd	2624	-19	21-Jan-85	80.9	69.5	58.1	3	2421	141
Big Meadows	Madison	3539	-29	20-Jan-94	75.4	66.1	56.7	0	1888	143

Precipitation

The amount of water that grapevines require varies with their age, amount of fruit produced, presence of competitive weeds, and humidity. Mature vines can use the equivalent of 24 to 30 inches of rainfall per year, or 30 or more gallons of water per vine per week in the heat of the growing season (Lakso and Pool, 2001). Mild to moderate drought stress after veraison (onset of final stage of fruit ripening) can help slow vegetative growth and concentrate grape flavors. More severe drought stress, however, leads to reduced carbohydrate (e.g., sugars) production, poor fruit and wine quality, reduced vine vigor, and diminished yields.

Summer rainfall patterns in Virginia are quite variable, but most regions experience deficits of moisture during the height of the summer. That is, the combination of evaporation and plant transpiration of soil moisture exceeds the input from precipitation. When plant available water is exhausted from soils, vines begin to exhibit drought symptoms. Most vineyards in Virginia will benefit from some irrigation almost every year, while others may only require supplemental water in the occasional drought years. One historical index of drought frequency is the Palmer Drought Severity Index (PDSI). The PDSI is a monthly value that indicates the severity of a wet or dry period. The PDSI is simply a meteorological drought index; it does not relate directly to plant performance, but the PDSI can be used in consideration of future water requirements, whether those requirements be urban water reservoir construction or vineyard irrigation. The PDSI generally ranges from -6 to +6. Negative values indicate dry periods while positive values denote wet periods. PDSI values of 0 to -0.5 indicate normal precipitation patterns; -0.5 to -1.0 = incipient drought; -1.0 to -2.0 = mild drought; -2.0 to -3.0 = moderate drought; -3.0 to -4.0 = severe drought; and greater than -4.0 = extreme drought. Similar adjectives qualify the positive deviations from the 0 baseline (i.e., wet spells). Monthly PDSI data for state climatic divisions are available electronically from the National Climate Data Center, and extend back to 1895 (http://lwf.ncdc.noaa.gov/oa/climate/onlineprod/drought/xmgrg1.html). The last 17 years' PDSI data for Virginia's northern climatic division (division #4) are shown in **Figure 8**. Again, the data provide a reasonable representation of the frequency at which drought may have affected grapevines. One argument for installing an irrigation system would be the observed occurrence of six "moderate" to "severe" drought years out of the last 17 (35%).

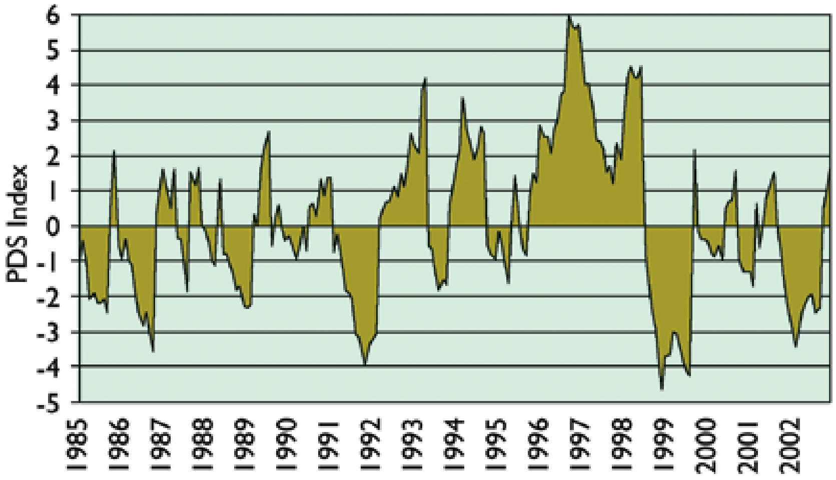


Figure 8. Palmer Drought Severity (PDS) indices for Virginia's northern (division #4) climatic division from 1985 through 2002. Negative values denote dry periods whereas positive values denote wet conditions. See text for a more specific interpretation of the values.

Excess precipitation also adversely affects the quality of grapes. Rain after veraison can significantly increase the splitting and subsequent rotting of grapes. When grapes are ripening, excess rainfall will decrease the sugar content, flavor, and aroma of the grapes and ultimately reduce wine quality. The vineyardist has three measures to counter the negative effects of excess precipitation. The most effective measure is to choose to grow varieties that are relatively insensitive to the ill effects of late-season rains (Wolf et al, 1999). Riesling, Pinot noir, and Zinfandel, for example, are not recommended in Virginia due to their tendency for berry splitting and subsequent rot with rains near harvest. From a site selection standpoint, sites should be evaluated for surface and internal soil drainage to facilitate the removal of excess moisture from the root zone (see Soils below). Finally, precipitation patterns can be evaluated on the macroscale to determine the probability of precipitation in the ripening months of August through October (**Figure 9**). The central and eastern Piedmont and Tidewater regions, for example, all receive more

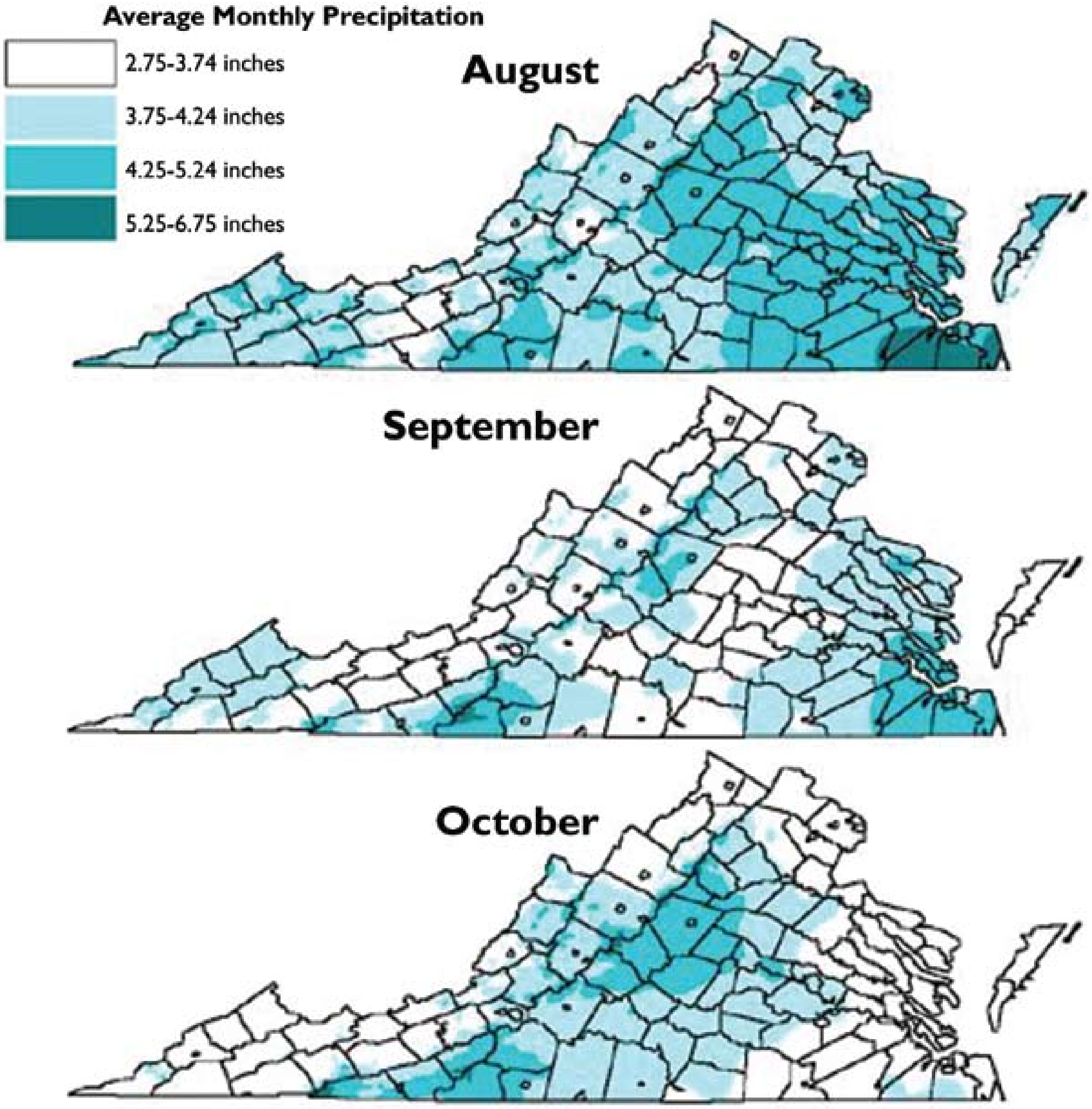


Figure 9. Average monthly precipitation totals for August, September, and October.

rainfall than the Shenandoah Valley does in August (Figure 9). The increased precipitation pattern in the Tidewater region continues for September, but patterns shift in October, with more rainfall in the central and western Piedmont – areas just east of the Blue Ridge.

Mesoscale Site Selection: Elevation and Topography

State maps are helpful in defining the regional basis of vineyard site suitability, but these maps are too general to pinpoint the best site to locate a vineyard. The topography, including the absolute and relative elevations of a particular site, will greatly affect the suitability of a proposed site, particularly in the western Piedmont and mountain regions of the state. The local or mesoscale conditions of a site, including the soils of the site, are the next parameters to evaluate.

Elevation has a profound influence on the minimum and maximum temperatures in a vineyard, particularly in hilly and mountainous terrain. Because frosts and freezing temperatures can so dramatically reduce vineyard profitability, elevation is one of the most – perhaps *the* most – important features of vineyard site suitability. The physics of topographic effects on air temperature are well documented (Geiger, 1966) and its horticultural significance generally well appreciated. Under radiational cooling conditions, with calm winds and clear skies, the earth loses heat to space and cools the adjacent layer of air. If the vineyard is on a slope, the cold, relatively dense air moves downhill (**Figure 10**). This movement can be pronounced in mountainous areas and may even produce local winds. The sinking, cold air displaces warmer air to higher elevations producing thermal inversions and thermal belts. Above these relatively warm belts, air temperature again decreases at an average rate of 3.6°F/1,000 feet of increase in elevation. The sinking, cold air collects in low-lying areas and can create frost pockets. Experience in central Virginia suggests that 80% or more of spring freezes, and many midwinter freezes, are

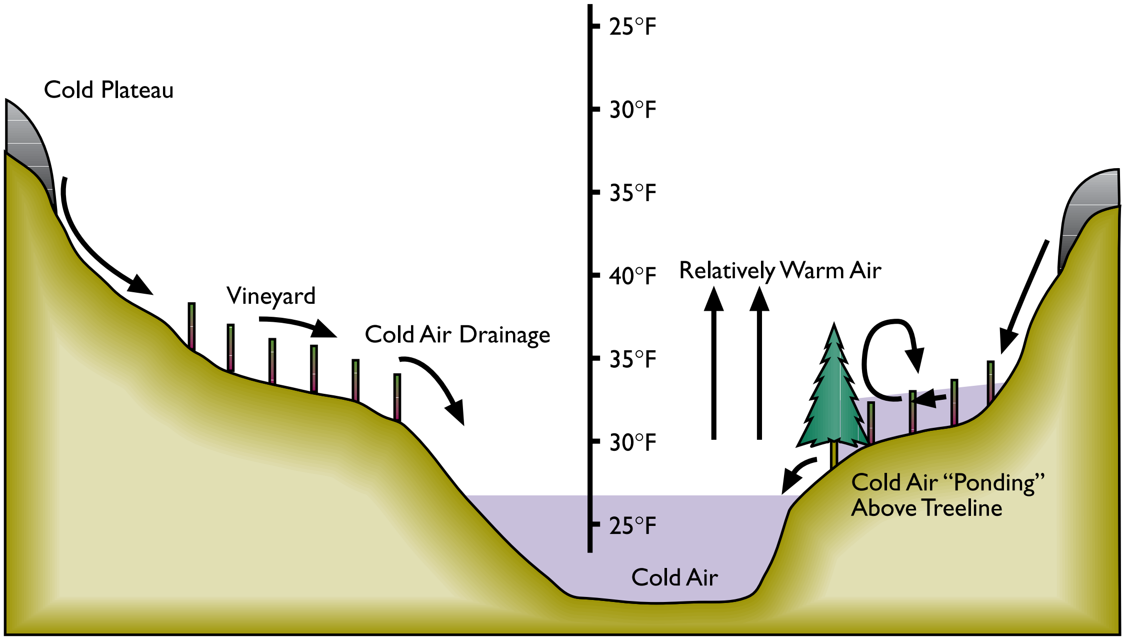


Figure 10. Illustration of site topography effects on air temperatures during a radiational cooling event.

caused primarily by radiational freeze events. Vineyards in low-lying frost pockets are much more prone to spring and fall frost damage, and winter cold injury, than are vineyards that have been established at higher elevations.

As illustrated above, the higher elevations, particularly in the mountainous regions, also afford cooler daytime temperatures during the summer and fruit maturation period of the fall. But the cooler temperatures that are found at higher elevations during fruit maturation can easily become liabilities in winter if the vineyard is situated too high. Air temperature continues to cool with increased altitude above thermal inversions (Figure 10). Those temperatures can be lethal to grapevines, especially with advective freeze events. Advective freezes are characterized by windy conditions in which little or no temperature stratification occurs, except the general pattern of decreasing temperature with increasing altitude. Thus, in most mountain/valley complexes, there is an optimal elevation, sometimes referred to as a "thermal belt," that is most suited for vineyard development. The advantages of increased elevation diminish above this zone, and sites below the zone are subject to increased risk of radiational frosts.

A combination of local experience and research was used to help define the upper and lower limits of the desired thermal belt or zone for the mountain/valley region of Virginia (Wolf and Boyer, 2001). Those limits vary as a function of atmospheric conditions and the profile of the mountain/valley terrain. Generally, the steeper the slope, the more pronounced the temperature differential with changes in elevation. Based on limited grape experience, and a much greater tree fruit experience, we estimated that the upper limits of the thermal belt ranged from 1,500 feet above sea level (asl) in Northern Virginia, to approximately 2,200 feet asl in the southern portion of the state (Wolf and Boyer, 2001). Thus, for Fauquier County, which ranges in absolute elevation from 200 to 2,300 feet asl, the most desirable or "best" elevation range was estimated to be from 680 to 1,500 feet asl. "Good," and "Risky" elevation ranges, reflective of zones that are successively lower and higher than the "best" zones, were also estimated, and are included in the Vineyard Suitability Maps discussed below. In the eastern Piedmont, Tidewater, and Eastern Shore regions, the best guidance on absolute elevation is to simply seek the highest land that the county has to offer. Our definition of "Best" elevation for counties that do not exceed 1500 feet asl is an elevation in the upper 20% range of elevation (e.g., ≥ 520 feet asl in a county that ranges from 200 to 600 feet asl). This is an arbitrary classification. Vineyards may be profitably operated at lower elevations; however, experience would argue that the risk of frost and winter injury increases at lower elevations.

The *relative* elevation of the site is also an important consideration, and must be considered in tandem with absolute elevation. Good relative elevation cannot overcome the risks associated with inferior absolute elevation, but poor relative elevation can significantly reduce the quality of an otherwise good absolute elevation site. The latter situation has occurred with small valleys that are "perched" in mountainous areas. Even though these valleys may fall within the "best" elevation range predicted for a county, they are still "ponds" for cold air drainage and are thus subject to increased frequency of frost and winter injury.

To summarize, the candidate site's absolute and relative elevations are paramount considerations in the site selection process. Optimal, absolute elevation zones exist in mountain/valley complexes, above and below which vineyards should not be established. Superior relative elevations must be sought within these zones. For sites that do not have upper limits to optimal elevation (elevations do not exceed 1,500 feet asl), one should attempt to find vineyard sites that are in the upper 20% of the elevation range. Compromises must occasionally be made with vineyard site selection criteria. The elevation of the candidate site, however, must not be compromised.

Slope

The slope is the inclination or declination that a parcel of land varies from the horizontal, usually expressed as a percentage; a 5-foot fall over a 100-foot horizontal distance would be a 5% slope. Perfectly flat land would have a slope of 0%; a vertical cliff would have a slope of 100%. Slope can be accurately measured with an inexpensive, handheld inclinometer. A slight to moderate slope is desirable because it accelerates the drainage of cold air from the vineyard. As mentioned earlier, cold air is denser than warm air and, much like a fluid, will tend to flow downhill. Generally, the steeper the slope, the faster cold air will drain downhill, assuming there are no barriers to air movement (Figure 10). Land slope also is important for surface and, to some extent, internal soil water drainage. As discussed later, surface and internal soil drainage are extremely important, and a slope is conducive to these movements.

Slopes steeper than about 15%, however, are not recommended because it is hazardous to operate equipment on steep slopes and because of the risk of roll-over or the downhill drift of towed equipment into the vineyard row. Terracing slopes is possible, but adds significantly to vineyard establishment and management costs. Soil cultivation and terraces on steep slopes also increase the risk of soil erosion. Local USDA Farm Services offices have advice on soil erosion control measures.

Aspect

The aspect of a slope refers to the prevailing compass direction which the slope faces (e.g., east, southeast, etc.). Aspect will affect the angle that sunlight hits the vineyard and thus its total heat balance. Aspect is probably more critical in the higher-elevation regions of Virginia or in the northern part of state. Among a site's physical characteristics, aspect is probably least important, being far outweighed by elevation, soil properties, and degree of slope. Even in hot grape growing regions, such as Virginia, vineyards should be exposed to direct sunlight for at least a portion of the day; eastern exposures are probably optimal (Gladstones, 1992). The early morning exposure advances the start of temperature- and light-dependent photosynthesis and results in more rapid drying (as from dew or rain) of foliage and fruit, potentially reducing disease problems. Eastern slopes also tend to be more sheltered from the hot afternoon sun, which might be of some benefit to retain volatile aromatic compounds in fruit. On the other hand, for late-maturing varieties, such as Cabernet Sauvignon or Norton, there may be some advantage to western exposures to promote fruit ripening in the waning heat and daylight of autumn.

Vineyards with southern and western aspects can warm earlier in the spring, and the vines may undergo budbreak earlier than vineyards with northern slopes. The earlier budbreak on southern and western aspects is probably caused more by the warming of soils and roots than by increases in air temperature.

In locations that do not have a danger of spring frost, early budbreak may be desirable because it translates into earlier bloom and harvest of the fruit. In frost-prone areas, such as most of Virginia's Piedmont and mountain regions, early budbreak can increase the potential for frost damage in the spring. For example, growers have reported that the buds break and commence growth up to 7 days earlier for a variety planted on a southern aspect than for the same variety planted on a northern or eastern aspect.

Aspect also has a slight, but measurable effect on winter temperatures. In a long-term Georgia study, minimum temperatures on northerly slopes were 1.0°F to 2.5°F cooler than on the corresponding elevations of southerly slopes during freezes with temperature inversions (Johnstone et al, 1968). In the same study, the frost-free growing season was, on average, about two weeks longer on the slope with the southern aspect than on the corresponding slope with the northern aspect.

There are pros and cons to most vineyard aspects, as summarized in **Table 4**. Fortunately, aspect is probably the least important physical variable of vineyard site considerations. In practice, other factors such as elevation, current land use, and soil characteristics typically dictate which aspect will be used.

Land use

Although current land use is not a direct indicator of vineyard site suitability, it is of prime importance to the feasibility and cost of establishing a vineyard. Land use ranges from the unusable urban areas and bodies of water to prime farmland. While not prime, and potentially quite rocky, some forest land can be cleared for vineyard use. Forests, however, are often in forest vegetation because they are too steep, too rocky, or otherwise unsuited to cultivation.

Vineyard suitability maps

To help in site selection, we have generated maps classifying areas for vineyard suitability. The maps are organized by county and are currently available for about 45 counties in the western Piedmont and mountain regions of Virginia. Similar maps are available in North Carolina. These maps are

Table 4. Relative effects of compass direction (aspect) of vineyard site on vine phenology and physical parameters.

	Aspect			
Parameter	**North**	**South**	**East**	**West**
Time of bud-break	Retarded	Advanced	Retarded	Advanced
Daily maximum vine temperature	Less	Greater	Less	Greater
Speed of foliage drying in morning	-	-	Advanced	Retarded
Radiant heating of fruit	Less	Greater	Less	Greater
Radiant heating of vines in winter	Less	Greater	Less	Greater
Minimum winter air temperatures	Lower	Higher	-	-
Length of growing season	Shorter	Longer	-	-

intended only as general indicators of areas or regions of a particular county that may have greater or lesser potential for commercial grape production. The maps are based on a Geographical Information System in which the individual themes of elevation, land use, slope, and aspect are combined into a single, graphic representation that is scored for overall suitability (**Figure 11**). Roads and streams are included to orient the user. The maps, including background information on their production, can be ordered from the following web site: (http://www.arecs.vaes.vt.edu/arec.cfm?webname=winchester&section=about_us&pid=vitis).

Mesoscale Site Selection: Soils

Soil affects grapevine productivity and wine quality; but soil, like climate, comprises many components. Soil can be described in terms of its depth, parent rock origin, organic matter content, texture, chemical properties, hydrology, and in terms of its microbial and other invertebrate fauna density and diversity. All of these variables may ultimately affect vine growth and wine quality, but precise relationships are not well characterized for all such variables. Furthermore, the confounding influences of vineyard management, climate, varieties and clones, fertilizer and irrigation practices, as well as variation in fruit harvest and winery practices, may easily obscure the more subtle, unique soil contributions to wine quality. For these reasons, and given our relatively brief experience with wine production, the ideal vineyard soil for Virginia is imperfectly defined. Nevertheless, some properties are decidedly more important than others by virtue of their known influence on vine performance, or because some are more easily improved than others (**Table 5**). Each of the criteria listed in Table 5 should be evaluated in the site selec-

Table 5. Soil features and their importance in vineyard site selection in Virginia. Features are listed in decreasing importance to grape productivity and fruit and wine quality.

Soil feature	Importance in site selection[a]	Desirable value	Undesirable value	Ability to modify[b]
Internal water drainage	*****	> 2" / hour	< 2" / hour	+ (tile drainage is possible but expensive
Water holding capacity	****	< 0.10 inch/ inch of soil (?)	> 0.15 inch/ inch of soil (?)	++ (can be increased)
Fertility	****	Low to moderate	Highly fertile	+++ (can be increased)
Effective rooting depth	***	> 3 feet	< 1 foot in the absence of irrigation	-- (deep ripping may increase rooting depth)
Moist bulk density	***	< 1.5 g/cm^3	≥ 1.5 g/cm^3	-- (can be decreased)
Texture (relative proportion of sand, silt and clay)	***	Loam, sandy loam, sandy clay loam, etc.	High proportion of silt (>50% silt)	---
Soil pH	***	6.0 – 6.8	< 5.0	+++ (can be adjusted)
Organic matter	**	1.0 – 3.0%	> 5.0%	+++ (can be increased)
Soil organisms	**	Variable	? [c]	+++ (can be increased)
Parent material	*	Granite, sandstone	See text	---
Surface composition	*	Uncertain	See text	---

[a] Relative importance, with multiple asterisks indicating greater importance in site selection process.

[b] Relative ease of adjustment:, where +++ denotes readily adjusted and -- indicates difficult to ---, increasingly impossible, to practicably adjust.

[c] A question mark (?) indicates a proposed or otherwise uncertain value.

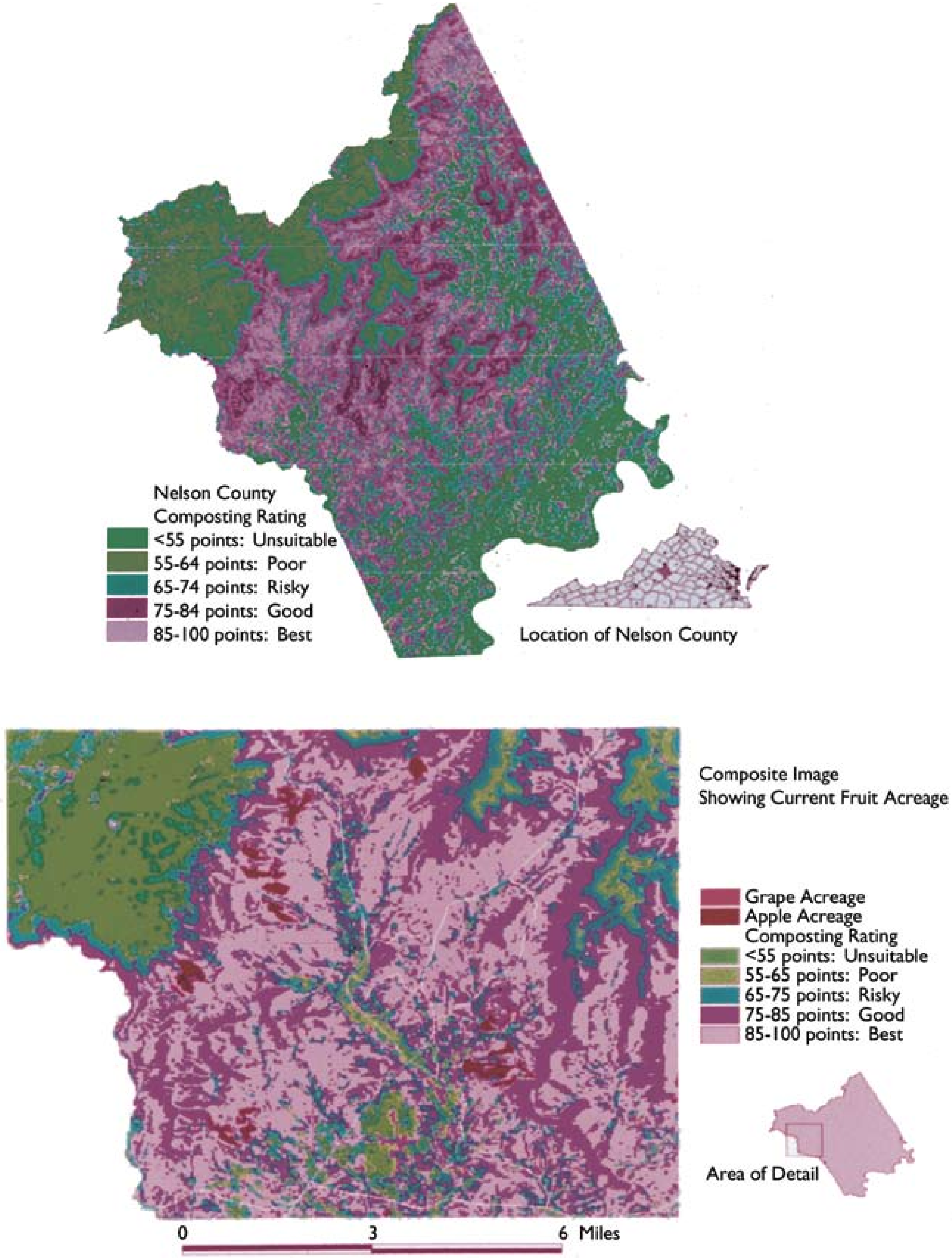


Figure 11. Example of a Geographical Information System (GIS) approach to mapping of vineyard suitability for Nelson County, Virginia. The "composite rating" is a synthesis of elevation, slope, land use, and other features which, collectively, help define the site's suitability for grape production. The red areas visible in the zoomed images are actual tree fruit operations that were geo-located on the GIS data set.

tion process. One should realize, however, that like above-ground features, few soils will be ideally suited for all criteria. Soils cannot be evaluated independently of the other vineyard site considerations discussed in this bulletin, and some compromises in soil quality may be necessary so that the vineyard site selection process does not become too exclusive. The criteria of Table 5 are discussed below in what we believe is a descending order of importance.

Sources of soils data

The principal, published source of detailed soils data is the U.S. Department of Agriculture (USDA) Soil Conservation Service's soil survey. This information is published by county and can usually be found at local Virginia Cooperative Extension (VCE) offices, through the USDA Natural Resources Conservation Service (NRCS) offices, or on the Web (http://soils.usda.gov/). The soils data provide detailed soil maps to identify soil series, with descriptive information on each soil series and sub-classification found in the county. Users with geospatial mapping experience and software also can obtain digital soils data from the NRCS Web-based Soil Survey Geographic (SSURGO) Database (http://www.ftw.nrcs.usda.gov/ssur_ftp.html). Detailed, site specific information can be obtained by physically digging pits with a backhoe on the candidate property and evaluating the soil profile for color, depth, texture, bulk density, and degree of existing plant rooting. Serious investigators may wish to involve a professional soil scientist in this investigative process. Purchase of the candidate property can be made contingent upon an acceptable soil report.

Soil moisture

The best vineyard soils are those that permit deep and spreading root growth and provide a moderate supply of water, released incrementally over time (Seguin, 1986). Soils to be avoided include those that are compacted and severely restrict rooting, soils that are chronically or seasonally water-logged, and soils that are extremely droughty (in the absence of irrigation).

Excess moisture leads to surplus vegetative growth, increased fruit acidity, and diluted fruit and wine flavors. Fruit rots are increased by berry splitting and by the more favorable disease conditions that exist within the dense canopies of overly vigorous vines.

At the other extreme, drought stress can lead to insufficient vine growth and reduced yields, impaired fruit ripening, and sunburning of fruit. In the absence of supplemental irrigation, deep, well-drained soils afford a reservoir of moisture that can be exploited by vines over an extended dry period. Considering the erratic nature of summer rainfall patterns in the mid-Atlantic region, the grower should anticipate a surplus of summer rainfall, but be prepared to supplement that precipitation with irrigation during droughts.

Finding a soil that accommodates our irregular water supply entails identifying deep, well-drained soils. In other humid regions (e.g., Bordeaux), that goal has been achieved by establishing vineyards on alluvial deposits. Even clayey soils can produce world-class wines, as demonstrated in the Pomerol appellation of Bordeaux, if these soils are well drained.

The topography of a site will have a bearing on the underlying soil hydrology. With undulating topography, the superior vineyards sites will typically be situated on convex land patterns – features that tend to shed surface water, rather than collect it. Concave land forms – swales, ravines, or gullies – are usually areas of water import, and soils in these zones may be deeper due to erosion from higher ground. Thus, locating vineyards on convex land patterns is an excellent means of restricting water availability to the vines.

Soil moisture is affected by both the rate of internal water drainage (permeability[1]) and by the retention, or water-holding capacity of the soil. Permeability is perhaps the most important consideration in a candidate vineyard's soil. "Good drainage" refers to the speed with which free soil moisture drains from the soil profile. Deep soils with good porosity or pore spaces drain better than do those that are dense and compacted or those with textural discontinuities that limit water movement. Permeability rates are determined in part by soil texture. Sands, for example, typically drain faster than clayey or silty soils do; however, sandy soils have very low water holding capacities and may lead to drought stress sooner than would soils with higher proportions of clay or silt. Thus, we seek a compromise; soils that drain well, yet have reasonable water holding capacity. Texturally, loams, loamy sands, and sandy loams would generally fit this description (see **Texture**).

A visual indication of the quality of internal soil drainage is soil color, a sometimes subtle feature that is best observed by digging pits and examining the face of the pit. Well-drained soils allow deep infiltration of oxygen and will appear uniformly brown, yellow, orange, or otherwise "bright" to some depth (4 feet or more). Poorly drained soils may appear mottled with shades of gray or blue and may have off-odors. Clues to the quality of soil drainage may also be obtained by examining the native vegetation on the proposed site. Well-drained soils support well established grass sod, most agronomic crops, and mixed forest, whereas perennially wet soils often support sedges, willow, or sycamore, and may have poorly developed sod, or the sod is spongy during wet weather.

Soil-survey data present permeability data in inches of water movement per hour through a moist soil. A speed of 2 inches or more per hour is a good candidate soil (Table 5). One useful rule of thumb is to reject soils that are not suitable for a conventional, gravity-fed septic field.

Available water capacity, or Plant Available Water (PAW), is defined as the difference between the amount of soil water at field capacity and the amount at the wilting point. Soil moisture at or below the wilting point is held with such high tension that most plants cannot extract it from the soil. Water in excess of field capacity is drained out of the soil profile by gravity. Available water capacity is commonly expressed as inches per inch of soil and is a function of soil texture and organic matter content. Sands and sandy soils hold relatively little moisture, whereas clays and silts contain a large reservoir of PAW. Typical PAW values range from 0.10 to 0.20 inches of water per inch of soil profile (e.g., Poplimento series, 30% to 60% clay). Suitable PAW values for Virginia vineyard soils have not been researched. If one accepts the premise that "surplus" moisture is a greater problem in the mid-Atlantic than is moisture "deficit", one would seek a soil that has a relatively low PAW. We propose that PAW values of 0.1 inch per inch of soil or less are superior to 0.15 or greater inches per inch of soil (Table 5). Greater water-holding capacity would be desirable, however, in the absence of irrigation.

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[1] "Permeability" is a qualitative measure of water movement (e.g., rapid, moderately rapid, etc.) and is typically estimated by NRCS from soil texture or other means. Hydraulic conductivity is a more specific measure of a material's (e.g. soil) ability to transmit water under standard conditions and units. Hydraulic conductivity is assessed under saturated soil conditions and is called "Saturated Hydraulic Conductivity" or Ksat. Ksat and permeability values may be very similar for a given soil; however, Ksat values are considered more precise.

Soil depth

Soil depth is important for providing a buffer against drought. A deep soil (e.g., > 3 feet) offers a greater volume of potential soil moisture than does a shallow soil (e.g., < 12 inches). Grapevines can be grown on shallow soils; however, these vines will be the first to suffer drought stress if supplemental water is not available by irrigation. Deeper soils also allow grapevines to develop a large, perennial root structure, which in turn fosters a large, productive above-ground framework.

Bulk density

Bulk density is the mass, or weight, of dry soil per unit of bulk volume and is expressed in g/cm^3 or kg/m^3. In practical terms, bulk density is a measure of the compactness of soil. Naturally or mechanically compacted soils interfere with internal water drainage and may restrict root growth. Bulk-density values of about 1.6 g/cm^3 or more are restrictive to root growth of most plant species, including grape (van Huyssteen, 1988). Suitable values would be < 1.5 g/cm^3 (Table 5). Bulk-density data are typically included in the soil surveys; however, the procedures for determining bulk density are not complicated and can be found in agronomy handbooks.

Soil fertility

Fertility should be evaluated in the site selection process, but this criterion is less important (Table 5) because fertility can be modified. On a relative scale, low to moderately fertile soils are superior to highly fertile soils for producing high-quality grapes and wine. Evaluation consists of the collection of soil samples, analytical testing by a state or commercial service, and interpretation of results. Soil testing reveals the availability of plant essential nutrients, soil pH, cation exchange capacity (CEC), and the percentage of organic matter. Good vineyard soils provide an adequate and balanced supply of macro- (N, P, K, Ca, Mg) and micro-nutrients, have moderate CEC values, and have a pH within the optimal range for the intended species of grape (Wolf, 1993). Most of these features can be modified by soil amendments. Exceptions are CEC, and the rare situation where one or more nutrients may be at supra-optimal levels. For example, soils with high organic matter content (> 3%), may release excessive amounts of nitrogen that could cause excessive vegetative growth of vines.

Organic matter

Organic matter contributes porosity, structure, nutrients, and moisture. It also aides in supporting a diverse microbial and invertebrate (e.g., earthworms) ecology. Organic matter provides a pool of slowly available nitrogen to support vine growth. Mineral soils – those which by definition contain less than 20% organic matter – typically range from <1% up to 5% organic matter in Virginia. Organic matter values greater than 5% may be counter-productive in that excessive nitrogen that is released by organic matter decomposition may lead to supra-optimal vine growth. Organic matter values of 3% to 5% may also lead to surplus growth, but if all other properties are acceptable, the vineyardist might simply choose to accommodate the expected greater growth by decreasing vine density or by using more elaborate training systems. Soils that have been exploited by deficit farming or that are inherently low in organic matter can be profitably amended with compost, green manures, or other forms of organic matter and, therefore, should not be rejected as vineyard soils.

Soil texture

Texture refers to the relative proportions of sand, silt, and clay – the essential triad of soil textural classification (**Figure 12**). While there are interesting ideas on how texture affects wine quality, the direct effects are poorly defined. Indirect effects on soil hydrology are probably more important than more subtle direct effects (Van Leeuwen and Seguin, 1994). For example, sands and soils with a qualifying sandy prefix (e.g., sandy loam) will have better drainage characteristics and a lower PAW capacity than will clays or silty loams. The interested reader might wish to peruse some of the Web-based soil hydraulic "calculators" that allow a rapid calculation of a soil's hydraulic properties based on an input of the candidate soil's percentage proportions of clay and sand. An example of such a calculator can be found at: wilkes.edu/~boram/grphtext.htm.

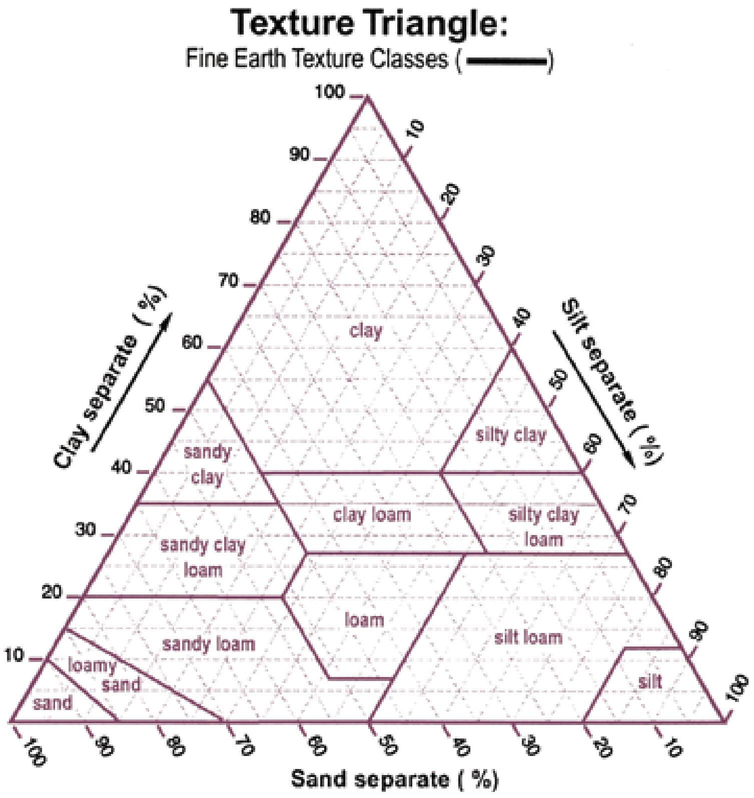

Figure 12. Soil triangle used to describe soil texture. Soil that consists of 50% sand, and 25% clay would be described as "sandy clay loam."

Soil biology

"Healthy" soils contain a rich diversity of plant and animal species, most of which are inconspicuous but some of which (e.g., earthworms) are easily observed. While some soil animals and fungi can cause disease in grapevines, the vast majority of soil fauna and flora is essential to nutrient recycling and mineralization of organic matter. The maintenance of this living aspect of the soil is essential to the maintenance of a healthy vineyard. Unfortunately, many of our farming practices (e.g., tillage, use of pesticides, crop monoculture, and soil compaction by machinery) tend to reduce diversity. Commercial labs can evaluate soil microbial diversity and provide an interpretation and action plan to increase diversity if the soil bioassay is low for a particular soil organism functional group (e.g., fungi vs. bacteria). Unfortunately, the interpretation of soil biological properties is an emerging science and is not sufficiently advanced to make cultural recommendations for potential and existing vineyards.

Soil origin

The principal residual soils of Virginia are derived from granite, limestone, sandstone, and shale. In many cases the soil will consist of some mix of these four types. The parent rock from which soil is derived may indirectly affect grape production through the availability of nutrients or by affecting soil hydrology. Soils derived from granite, for example, are considered superior to soils derived from greenstone (i.e., Catoctin) by virtue of having less silt, a coarser structure, and therefore a lower PAW capacity. Limestone soils dominate some areas of the Shenandoah Valley. If deep (4 feet or more), these soils can lead to very vigorous vine growth, as demonstrated with grape variety trials at the AREC in Winchester (Wolf and Miller, 2001), a site dominated by Frederick-Poplimento series soil. On slopes (classified as "C" or "D" series in soil-survey maps), the limestone soils may be very suitable for vineyards. All other factors being equal, the soil parent material has no measurable *direct* effect on grape and wine quality in Virginia (Table 5).

Surface characteristics

In some grape regions the surface composition of soil directly impinges on grape and wine quality. A stony surface can be important for absorbing and redirecting heat to the vines during the cooler nights of autumn. This feature might be worth considering in the cooler areas of western and southwestern Virginia but would be less important in the Piedmont and eastern Virginia, where heat is typically in excess of vine requirements. In either case, it may be very difficult to find a stony surface concomitant with other, more important, vineyard features.

Nematodes and other soil-borne pathogens

Sites that are in woods or that were previously planted to other fruit crops including grapes, should be evaluated for the presence of nematodes and other soil-borne grape pathogens. Nematodes are small, wormlike parasites and several genera, notably *Xiphinema*, can transmit destructive viruses to grapevines. Soil sampling for nematodes and sample submission instructions can be obtained through local Virginia Cooperative Extension offices. A passive control option involves planting and maintaining non-host plants, such as perennial grass, to the site for up to several years before grapevines are planted to depress the nematode populations. A more active approach involves planting a series of green manure crops, including a brassica (Rapeseed, *Brassica napus*, cv. 'Dwarf Essex'), that releases a chemical that is toxic to nematodes when the crop is incorporated into the soil. Detailed instructions on the use of this biocontrol measure can be obtained from Virginia Cooperative Extension offices. Soil fumigation or treatment with nematicides is a third alternative, but one that carries potential risks, both to the user and to the overall soil biology. Fumigation is therefore not recommended.

Other potential soil-borne pathogens include the oak root fungus (*Armillaria mellea*), which has the potential to infect grapevines in areas where affected oaks, peaches, or other hardwoods previously grew. We have not, however, found documented cases of this disease in Virginia vineyards.

Potential Vineyard Pests and Other Threats

We have focused on the physical and climatological requirements of vineyards up to this point. Beyond that, consideration must also be given to biological and abiotic threats that can affect grapes. These include diseases, certain insects, nematodes and vertebrate pests, and specific atmospheric pollutants. Vineyard operators must also be sensitive to neighbors who might be concerned about commercial vineyard operations, especially pesticide spraying.

Diseases

Pierce's Disease

Pierce's Disease is a destructive, bacterial disease that affects all bunch grapes in the warmer regions of the southern United States, including Virginia westward through parts of Texas and into California. The disease has been observed in Northampton and James City counties since 1990. Pierce's Disease (PD) is caused by a bacterium (*Xylella fastidiosa*), which is transmitted from vine to vine and from alternative host plants to vines principally by leafhoppers, which are small, winged insects. In disease-susceptible vines, the water conducting tissues of the grapevine are blocked either by the bacteria or by defensive gums produced by the vine. This blockage leads to the characteristic disease symptoms: leaf scorching, wilting, defoliation, and eventual death of the vine (**Figure 13**).

At least two factors may be contributing to the appearance of PD in southeast Virginia. One obvious factor is the fact that susceptible grapes were introduced into southeast Virginia in the 1980s. A second possibility is that a series of warmer than average winters has led to a northward movement of the disease occurrence in the southeast. Cold winter temperatures are thought to limit the extent of bacterial development within the vine. Areas that have an average minimum January temperature of 30°F or *less*, are thought to be less at risk of PD than areas with higher winter temperatures (Fell and Purcell, 2001). If we look at the historical, 30-year January average minimum isotherm (**Figure 14**), the documented cases of Pierce's Disease fall to the south (warmer side) of this line in Virginia, while areas to the north and west of the isotherm have remained *apparently* free of the disease. Note that the 30°F isotherm of Figure 14 is based on a 30-year record. If the 30°F isotherm is redrawn with data from only the 1997 through 2001 winters, the high-risk zone moves significantly farther north – a reflection of the warmer winters during that time.

If the 30°F isotherm is relevant, commercial grape production will be risky in a large portion of Virginia's Tidewater and along the southern borders, west to the Blue Ridge. Growers continue to profitably grow grapevines in areas of Virginia that experience PD, and their experiences might reinforce the notion that prudent variety choice (e.g., minimizing Chardonnay) and aggressive management of alternative host plants are keys to sustaining profitability. Nevertheless, these growers suffer increased costs and loss of production when infected vines die.

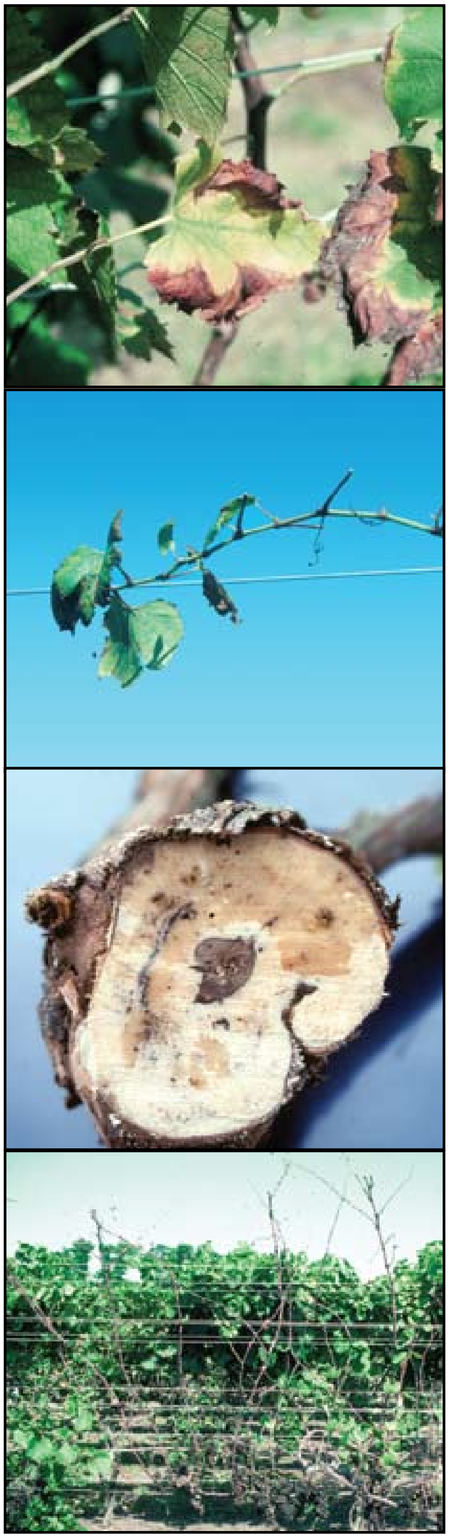

Figure 13. Symptoms of Pierce's Disease. From top: marginal leaf scorch; shedding of leaves, often with petioles adhering to stems; young trunk cut cross-sectionally to reveal darkened inclusions in xylem; and severely affected vine showing loss of vigor and defoliation.

North American Grapevine Yellows

North American Grapevine Yellows (NAGY) is another destructive disease of grapes whose incidence varies within the state. Affected vines typically die within 2 or 3 years of symptom onset, and some Chardonnay vineyards have experienced annual losses of 5% or more of the original planting, with attrition rates approaching 30% over a 5- to 10-year period. NAGY has been observed throughout the state, but the most frequently affected vineyards lie within eyesight of the Blue Ridge. The disease is caused by phytoplasmas, single-celled organisms similar to bacteria but lacking rigid cell walls. Leafhoppers, and possibly some related insects, are thought to transmit phytoplasmas from wild grapevines or other hosts into the vineyard, and possibly from vine-to-vine

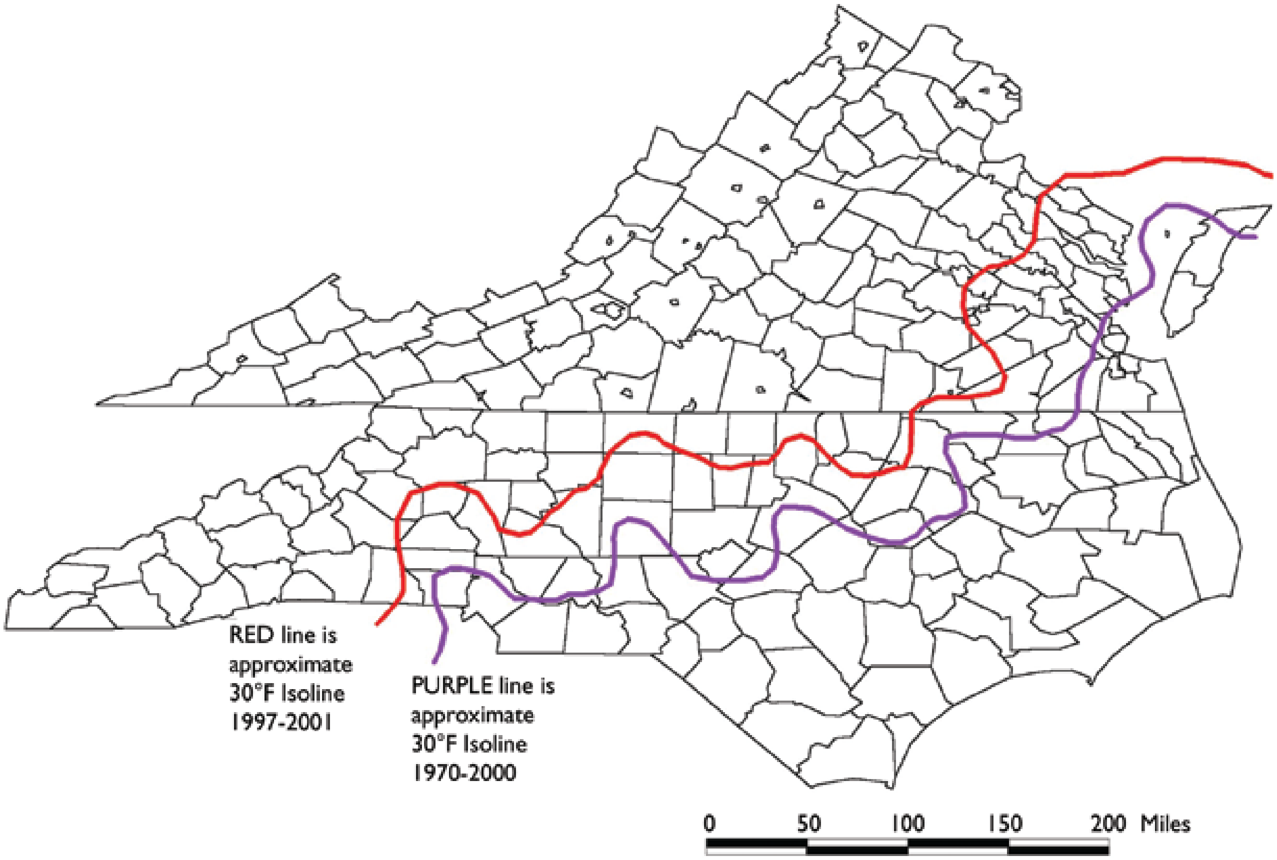

Figure 14. Average January minimum of 30°F isotherm based on 30-year (1970-2000) record (purple line) and on a more recent 5-year period (1997-2001, red line). Regions to the north of these lines experience colder average January minimum temperatures, whereas regions to the south experience warmer average January minimum temperatures.

within the vineyard. To date, wild grapevines (*Vitis cordifolia* and *V. riparia*) have been the most consistent alternative hosts detected, and an abundance of these species appears to increase the frequency with which cultivated vines are diseased. Chardonnay and Riesling are highly susceptible, but other varieties have also expressed the disease in vineyard sites prone to the disease. Symptoms of NAGY are often confined to one or several shoots of the vine in the first year, followed by a comprehensive involvement of the vine in the second or third season (Wolf et al, 1994). Specific symptoms include withering of clusters at or after bloom, rolling and yellowing of leaves, shoot-tip dieback, and failure of shoot stems to uniformly develop the brown bark of canes called periderm. Shoot stems may express a blue-gray cast and the stems often droop due to lack of internal lignification (**Figure 15**).

Given the incomplete knowledge of insect vectors and alternative hosts for NAGY, it is not possible to say precisely where the disease will or will not occur. Based on vineyard surveys, the vineyards that are *most* at risk of NAGY are Chardonnay vineyards that are situated within eyesight of the Blue Ridge and that are closed bounded by woods that contain an abundance of wild grapevines. The association with the Blue Ridge may, in time, be found to rest with the abundance of wild grapevines and perhaps specific vectors that inhabit this ecosystem.

Deer, raccoons, opossums, and birds

Vineyard site selection should also consider the proposed site's proximity to other threats and pests that may adversely affect the vineyard. Among the vertebrate pests, whitetail deer, raccoons, opossums, and various species of birds are of primary concern. Deer browse the shoots and ripening fruit. The injury to shoots is particularly troublesome in young vineyards where the shoots are being trained as trunks. The loss of fruit can be significant, with nearly complete loss over a short period of feeding if the deer population is high. Deer depredation is greatest in remote vineyards located near woods or other cover; however, deer damage can occur in any vineyard in Virginia. Commercial chemical repellents, bars of soap, human hair, and permit shooting all offer a measure of deer damage reduction. Experience, however, suggests that electric fencing may be the only effective means of excluding deer, and some growers have resorted to 11-foot high woven fencing to exclude deer. Plans for electric and woven fences for deer exclusion are available from several sources, including Virginia Cooperative Extension offices. Many Virginia vineyards use electric fencing in conjunction with solar-powered chargers. Fencing, if properly constructed, offers the added benefit of excluding small animals, such as raccoons and opossums, which can also cause significant fruit loss.

Figure 15. Symptoms of North American Grapevine Yellows on Chardonnay. Vine in top photo shows poor wood maturation, downward rolling leaves, leaf yellowing, and cluster abortion in August. A representative shoot from a nearby healthy vine was cut and placed on the affected vine to contrast the appearance of affected and healthy shoots. Photo on bottom is a close-up of affected cluster in June.

Birds

Birds can cause significant fruit loss, and sites located near roosting areas, such as trees and overhead power lines, are vulnerable, as are areas in eastern Virginia where flocking, migratory birds can be particularly troublesome. Vineyards located near turkey habitat can also experience significant fruit loss to these protected animals. Audible and visible scare devices are commercially available and include recorded distress call broadcasters, propane cannons, plastic, reflective ribbon, and various balloons and other props that mimic predators. Each of these devices appears to offer some measure of protection, but none is entirely effective on its own. Bird netting is expensive and cumbersome to apply and remove, but does offer near-complete protection. Some growers have had good success in netting only the two sides of vertically shoot-positioned canopies. This minimizes the problems with shoots growing through the netting, and allows sprayer and mower operations to continue after netting.

Black walnuts and butternuts

The roots of black walnut (*Juglans nigra*) and butternut (*Juglans cinerea*) trees produce a compound called juglone that inhibits the growth of certain plants including grapevines. Grapevines can be killed when they absorb juglone. Vines affected by juglone will have weak growth and wilting, pale or yellowed leaves (**Figure 16**). Their occurrence in the vineyard is superimposed on the radiating root system of the offending trees (Figure 16). Research has not clearly shown how juglone causes the inhibition of growth and/or plant death, but the alteration or inhibition of oxygen uptake and photosynthesis are suspected. Exercise caution when designing your vineyard around these trees. We recommend removing trees near the proposed vineyard by a margin of twice the height of the tree. For example, if the trees are 60 feet high, keep the vines at least 120 feet from the base of those trees. If you intend to remove the tree, do not plant vines in the area of the root system for several years. The roots will continue to release juglone until they are completely decomposed.

Figure 16. Symptoms of juglone toxicity in Chardonnay vines grown close to a black walnut tree, leaves of which are visible in photo on top.

Figure 17. Hydrogen fluoride injury on Syrah leaves.

Neighboring properties

Consideration must also be given to your immediate neighbors in the site selection process. Equipment such as air-blast sprayers and bird-scare cannons are noisy and can disturb neighbors. Neighbors are increasingly concerned about pesticide drift from vineyards onto their property. Natural windscreens planted at the vineyard edge, and spray drift reduction technologies will help reduce offsite drift.

Conversely, certain herbicides may severely damage the vineyard if they drift in from neighboring property. In particular, 2,4-D and other phenoxy-type herbicides are often used for broadleaf weed control in pastures and no-till corn planting. In its more volatile form, 2,4-D can drift some distance and cause severe damage to the vineyard. Although long-range drift is possible, the damage observed in Virginia vineyards has typically resulted from application to fields immediately upwind of the vineyard. For this reason, it is important to know the herbicide use patterns of your immediate neighbors and to alert them to your grape growing enterprise. Applicators are ultimately responsible for ensuring that off-target drift does not occur.

Hydrogen Fluoride

Grapevines are sensitive to hydrogen fluoride (HF) (**Figure 17**), a colorless, odorless gas that is released by some industrial processes, notably the heating of fluoride-containing soils in brick manufacture. We have limited but dramatic experience with HF damage to Virginia vineyards. Vineyards should not be located within 2 miles of brick kilns, ceramic producing facilities, and metal smelting facilities unless these facilities are equipped with HF abatement devices. The Virginia Department of Environmental Quality (DEQ) issues permits for HF discharge by industries and can be contacted to determine if a particular industrial facility has a discharge permit for HF.

Other pollutants

Other atmospheric pollutants that may affect vines in Virginia include sulfur dioxide and ozone; the latter produces a dark stippling on leaves termed oxidant stipple. Both gases are produced directly or indirectly by fossil fuel consumption, notably transportation and electricity generation. Unlike HF, these pollutants are typically produced by non-point sources, and thus site selection is not effective as a means of avoiding adverse effects. The variety Chambourcin is one of the most sensitive varieties to oxidant stipple, but symptoms can be ameliorated by maintaining optimal nitrogen levels in the vine. To date, we do not have good data to indicate what impact these symptoms have on grape production or quality.

Conclusions

Virginia's diverse topography and varied climate, the state's wildlife and biological pests, and several anthropogenic pollutants offer commercial grape producers a challenging environment in which to produce quality fruit. The aim of this publication is to outline the nature of these threats so that the vineyardist can minimize if not totally eliminate risk. If the litany of potential problems appears overwhelming, the reader should be reminded that the contemporary Virginia grape and wine industry, as a whole, has been successfully growing grapes for over 20 years. The quest for an "ideal" vineyard site may take years and will ultimately involve compromises. Certain features, such as elevation, soil drainage (internal and surface), and length of growing season must never be compromised. Others, such as the vineyard's aspect, disease pressure, or some soil features, can be accepted as less than ideal, in that choice of variety, soil amendments, and other inputs can be incorporated to modify certain features.

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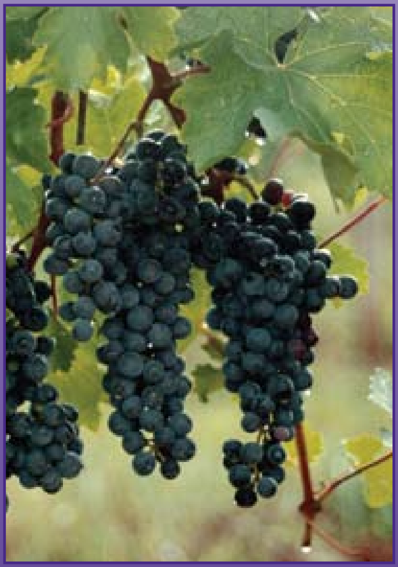

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