Chapter 4

Vineyard Site Selection

Grapes grown in North Carolina are sometimes exposed to unfavorable climatic conditions and biological pests that can reduce crops and injure or kill grapevines. Climatic threats include low winter temperatures, late spring frosts, excessive summer heat, and unpredictable precipitation. Biological pests include fungal pathogens and insects that attack the foliage and fruit of vines, as well as birds, deer, and other wildlife that consume fruit and shoots. Vineyard site selection greatly affects both the frequency and severity of these problems and is one of the most important factors affecting profitability in viticulture.

This chapter has been greatly expanded to address a critical issue in site selection: damaging spring frost. Your first and best defense against damaging spring frost is to avoid sites that are subject to repeated spring frosts. The information added to this section will help you understand the types of weather events that will damage succulent new grape shoots, critical temperatures for cold injury, and how a site's relative elevation, or local relief from a valley bottom, affects cold air drainage. This information will help you use a new methodology to assess the frost risk of potential vineyard sites. Planting less susceptible winegrape varieties, using cultural practices that reduce the likelihood of frost damage, and even installing mechanical devices for frost control are also discussed in this chapter.

In practice, vineyard site selection involves compromises, as few sites are ideally suited to grape production. Furthermore, there are two general categories of individuals who will choose a site for vineyard establishment: those who already own their land, and those who are seeking to purchase land on which to grow grapes. The concepts described in this publication apply to both categories. However, you will have more options if you use vineyard site-selection concepts to purchase land specifically for grape production than if you are restricted to choosing the best location on a site that you already own. If you are interested in eventually establishing a winery, recognize that the best vineyard sites might not necessarily be the most accessible to potential customers.

Climate and Topography

Climate refers to the long-term prevailing weather of a region or site. The climate of a vineyard is influenced by temperature, precipitation, winds, and other meteorological conditions. The proximity of large land forms (for example, mountains) and large bodies of water also affects a site's climate. Climate and topography are discussed together because topography has such a profound impact on the local climate of a vineyard.

The importance of site selection becomes clear when we examine the climatic factors that can adversely affect grape production and grape quality in this region.

1. EXTREME HEAT can reduce grape and wine quality, particularly after the onset of rapid fruit ripening (véraison). In general, wines produced from grapes grown in a hot climate can lack the fruitiness and complexity characteristic of wines from the same variety grown in a cooler climate. Many sites in North Carolina, particularly those of the piedmont and coastal areas, experience very hot growing seasons. Selected climatological indices for 12 Carolina cities are shown in Table 4.1. Use the data of Table 4.1 only for relative comparisons. Climatological data from your own vineyard site can differ significantly from those of nearby weather reporting stations, particularly in the case of temperature extremes.

A commonly used index of the relative warmth of a grape-growing region is the cumulative growing degree days (GDD) between April 1 and October 31. That index was refined for grapevines at the University of California, Davis, and was used to define five regions (1 to 5) (Winkler et al., 1974). Using that system, we can see that many of the sites listed in Table 4.1 would be classified as regions 4 or 5. Another viticultural index of a region's temperature is based on the mean temperature of the warmest month—July in our case (Smart and Dry, 1980). Using that index, almost all of North Carolina would be classified as a very hot grape-growing region, with the exception of town of Jefferson.

2. FLUCTUATING TEMPERATURES characterize winters in North Carolina, except perhaps in the coastal areas. Occasionally, temperatures are cold enough to injure vines, particularly the cold-tender *Vitis vinifera* varieties. The potential for cold-injury is increased when relatively warm autumns and early winters are followed by rapid or extreme temperature drops in midwinter.

3. SPRING FROSTS that occur after grapevines have broken bud and commenced shoot growth are not uncommon. Frosts can kill shoots and significantly reduce the fruit crop for the year. The problem is most acute when unseasonably warm temperatures promote earlier-than-normal budbreak and shoot growth. Spring frosts do not generally kill the vine; secondary shoots soon break bud and produce sufficient foliage to maintain vine health. Even a second frost can be compensated for by growth of latent buds on the vine. However, secondary shoots typically have less than half the fruiting potential of primary

Table 4.1 Selected Climatological Indices for 12 Locations in North Carolina[a]

	Elevation	Temperature in July[a]			Record	# Days Minimum Temperature Lower than 0° F			Days With Temperature		UCD		
Location	(ft)	Max	Min	Ave	Low (F)	1970-79	1980-89	1990-99	>90° F	<32° F	GDD[b]	Class[c]	MTWM[d]
Jefferson	2,770	81.3	58.0	69.7	-15	8	5	5	1.3	127.6	2561	2	warm
Asheville	2,240	84.3	63.5	73.9	-17	6	3	3	11.3	81.2	3560	4	very hot
Hendersonville	2,160	84.3	63.7	74.0	-14	5	2	2	11.9	88.5	3500	3	very hot
Marion	1,466	86.7	65.0	76.1	-11	2	1	0	23.4	85.1	3614	4	very hot
Morganton	1,160	88.7	64.6	76.7	-9	1	2	2	40.8	91.2	3982	4	very hot
W Kerr Scott R.	1,070	87.7	63.4	75.6	-10	4	2	4	32.8	108.2	3682	4	very hot
Mt. Airy	1,041	86.3	64.0	75.2	-10	4	5	6	27	102.4	3932	4	very hot
Shelby	920	87.6	66.0	76.8	-11	0	2	0	35.4	77.2	4423	5	very hot
Reidsville	890	88.2	66.4	77.3	-9	4	3	4	30.5	82.7	4171	5	very hot
Yadkinville	875	88.1	64.6	76.4	-8	4	3	4	40.9	93.2	4225	5	very hot
Lexington	750	89.1	67.1	78.1	-6	1	3	0	43.3	80.6	4565	5	very hot
Raleigh-NCSU	400	87.9	69.4	78.7	-6	0	2	0	37.3	63.3	4770	5	very hot

[a] NOAA U.S. Climate Normals for NC, 1971-2000 (information in this table provided by Ryan Boyles, State Climatologist and Director, State Climate Office of North Carolina) "
[b] Cumulative Growing Degree Days (50° F base) for the period from April 1 through October 31 "
[c] Heat summations for climatic regions are 1=less than 2,500 degree-days; 2=2,501 to 3,000 degree-days; 3=3,001 to 3,500 degree-days; 4=3,501 to 4,000 degree-days; 5= 4,001 or more degree-days "
[d] Mean Temperature of the Warmest Month (July) system of classification of grape growing regions (Smart and Dry, 1980); less than 69.8° F (warm); 69.8 to 73.2° F (hot); and greater than 73.4° F (very hot). "

For more information on climatic data, contact Ryan Boyles, State Climatologist and Director, State Climate Office of North Carolina, sco@climate.ncsu.edu, 1005 Capability Drive, Suite 240, Research III Building, Centennial Campus, Box 7236, North Carolina State University, Raleigh, North Carolina 27695-7236 shoots, and latent "base" buds usually have no preformed fruit clusters. Spring frosts are especially damaging in early budburst *vinifera* varieties like Chardonnay. Other interspecific hybrid varieties (for example, Seyval and Vidal blanc) often have very fruitful secondary and base buds. Thus, the consequences of a frost are not as severe with most hybrid varieties as they are with *vinifera* varieties.

4. A HOT, HUMID GROWING SEASON promotes the incidence of disease. Excessive moisture in the fruit maturation period (late August to early October) often causes berry splitting and fruit decay.

Climatologists refer to the climate of a large geographic region as the *macroclimate* of that region. Most of North Carolina, for example, is dominated by a *continental macroclimate*. Continental climates have temperature and precipitation patterns that are modified by large land masses (continents). For example, most high-pressure frontal systems that affect our region have first moved across Canada or the Midwest. One feature of a continental climate is air temperatures that can fluctuate rapidly from day to day because land does not readily affect, or buffer, air temperatures. *Maritime climates*, on the other hand, are macroclimates directly influenced by their proximity to large bodies of water. Basically, warm water tends to warm colder air, and cold water cools warmer air. Water absorbs heat from the sun and releases that heat and moisture to the atmosphere. Thus, cold air that blows across seas, unfrozen lakes, and other large expanses of water in the winter is warmed and, in turn, warms air temperatures on the leeward side of the water. The moisture absorbed over open water is also likely to affect precipitation patterns on the leeward side. The depth and salinity of bodies of water determines, in part, how much heat they absorb and how much heat they can release before freezing. As air temperatures rise in the spring, large bodies of water warm at slower rates than the surrounding land. Air is thus cooled as it blows over cold water. The cooled air retards spring plant development on the leeward side of the water and reduces the risk of frost injury. The fruit-growing regions bounding the Great Lakes benefit from their proximity to those deep, expansive lakes. Similarly, the temperature-moderating influence of the North Sea contributes to the success of grape growing in northern Germany at a latitude comparable to that of Hudson Bay in Canada. In North Carolina, the tidewater and eastern shore counties are subject to a maritime climate because of their proximity to the Atlantic Ocean. No other bodies of water in North Carolina are large enough to affect regional climate significantly.

Mesoclimate, or the local climate of a site, is more specific than the macroclimate. The mesoclimate is primarily the climatic conditions within 10 feet of the ground. Climatologists frequently use the term *microclimate* to describe the climate in this zone; however, we will reserve the term *microclimate* to describe, in the next paragraph, an even more specific climate. A site's mesoclimate is affected by factors such as the compass orientation of the site (aspect), the degree of inclination (slope), the relative elevation, and the barriers to air drainage.

Microclimate as used here refers to the very specific environment within grapevine canopies. Grapevine canopies consist of the shoots—stems and leaves—present during the growing season. The microclimate within vine canopies can be significantly different from that outside the canopy, particularly with respect to the quantity and quality of sunlight, air temperature, wind speed, and humidity. Typically, the interior region of dense vine canopies will be shaded, will be more humid, and will have slower air movement than will the climate on the exterior of the vine canopy. Experienced grape growers recognize the impact of canopy microclimate on fruit quality and use canopy management practices that promote a favorable canopy microclimate. (See chapter 7.)

Temperature

Grapevines require a minimum of about 165 frost-free days to mature their crop and to cold-harden (acclimate) their tissues before a killing frost occurs. Most sites in North Carolina's lower mountains, foothills, and piedmont will meet that minimum requirement, but it would be wise to review available information on the average growing season for the locations you are evaluating (Perry, 1998c).

Once you know that a site meets the minimum growing season, you need to consider three other aspects of temperature in selecting a vineyard site: the potential for spring and fall frosts, midwinter low temperatures, and summer heat.

Frosts

A goal of site selection is to locate sites with a relatively low likelihood of spring and early fall frost (Wolf and Boyer, 2003). Spring frosts chronically injure some vineyards and are more frequent in some parts of the state than in others, even those with good site selection. The expanded section, *Avoiding Spring Frost Damage,* beginning on page 44, explains the potential seriousness of spring frost damage to vines, offers you a way to evaluate the potential for problems on a particular site, and discusses passive and active systems (discussed in chapter 11, *Spring Frost Control)* to minimize potential damage.

Early fall frosts affects grapevines by arresting sugar accumulation; it is 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 (Wolf and Boyd, 2003). Generally, you can expect a strong correlation between occurrences of spring and fall frost (Wolf and Boyd, 2003). Sites having relatively low frost risk in spring should also be less prone to frosts in fall. The same active frost protection techniques described in chapter 11, *Spring Frost Control,* for managing radiation frosts (both hoar frosts and black frosts) in the spring can be applied to prevent leaf damage on sites that are prone to early fall frosts. This can be done to improve cane hardening and improve the vine's winter hardiness.

Minimum Winter Temperatures

One of the chief limitations to grape production in this region is damage to vines resulting from severe midwinter low temperatures. Cold injury can include the usual cane tip dieback, death of dormant buds, and the occasional death of canes and trunks. The temperature required to injure vines varies with the variety, the specific tissue, the time of the season, and the particulars of the low-temperature episode (prior temperatures, cooling rate, low temperature attained, and duration of the cold). It is therefore impossible to state precisely what temperature is required to injure vines. Experience, as well as numerous controlled freezing tests in Virginia, have 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 (Wolf and Boyer, 2003). When well-managed vines in central Virginia are exposed to -8°F, growers can expect to see greater than 50 percent primary-bud injury and perhaps cane, cordon, and trunk injury, depending on the freeze conditions (Wolf and Boyer, 2003). As stated in chapter 3, before committing to planting *vinifera* grapes in a given location in North Carolina, consult the climatological maps found on the North Carolina Wine and Grape Council's Web site (http://www.ncwine.org/siteSuitability/siteSuitability.html). The maps provide important details on the average occurrence of temperatures of -8°F per decade (1970 to 2000). In Virginia, Tony Wolf does not advise commercial production of *V. vinifera* in regions that experience -8°F three or more times per decade.

Like spring radiation frosts, midwinter low temperatures are significantly affected by the relative and absolute elevation of a vineyard site. Cold air ponds in low areas as readily in the winter as it does in late spring or early fall. It is not surprising, therefore, that many vineyards that chronically suffer spring frost injury also suffer frequent winter cold injury. Thus, the concepts of air drainage that apply to frost protection also apply to avoiding winter injury.

Winter cold injury can be significant at altitudes greater than 2,000 feet. A vineyard at such a high elevation is more subject to advective freezes and generally gains little benefit from temperature inversions.

Maximum Summer Temperatures

Maximum rates of photosynthesis in grape leaves occur from 85 to 90°F. Unless the growing season is short, there is little advantage in exposure to higher temperatures. Many locations in North Carolina routinely exceed this temperature range on many days during the growing season. High daytime temperatures, coupled with high night-time temperatures, can reduce fruit pigmentation, aroma, and acidity and cause rapid development of sugars, reduced acids, and very high pHs with some varieties. As a consequence, the juice is often unbalanced with respect to sugar, acid, and pH (Jackson and Schuster, 1987).

One of the goals of a recent research effort at the Upper Piedmont Research Station in Reidsville has been to identify *vinifera* and hybrid varieties that will hold their acidity while achieving a 22+ Brix level. In this relatively warm growing region of the central piedmont, we have been impressed by Tannat (*vinifera*) in regard to its fruit chemistry:

- ❑ Titratable Acidity (TA) levels (as a percentage of tartaric acid) have averaged 0.9 over the three-year period, 2003 to 2005.
- ❑ Brix levels have averaged 20.6.

Table 4.2. Comparison of Characteristics of 14 Winegrape Varieties for Harvest Dates, and Average Yield and Fruit Quality Components 2003 to 2005 at the Upper Piedmont Research Station in Reidsville[a]

Variety	Harvest Date 2003	Harvest Date 2004	Harvest Date 2005	Tons/acre (mean)	Tons/acre (standard deviation[c])	Brix (mean)	Brix (standard deviation[c])	pH (mean[d])	pH (st dev[c])	Titratable Acidity[d] (mean)	Titratable Acidity[d] (standard deviation[c])
Cabernet franc cl. 332	Sept 3	Sept 13	na	1.60	0.27	19.37	2.13	3.96	0.11	0.47	0.08
Chardonnay cl. 76	Aug 29	Aug 25	Aug 28	2.43	1.28	19.60	0.00	3.84	0.12	0.56	0.06
Chardonnay cl. 96	Aug 27	Aug 25	Aug 28	4.29	1.58	19.63	0.61	3.91	0.10	0.56	0.06
Merlot	Sept 3	Sept 1	Sept 5	3.96	0.51	18.47	1.31	3.84	0.08	0.42	0.07
NC74CO44-32	Sept 8	Sept 1	Sept 1	2.44	0.62	22.35	1.75	3.57	0.14	0.69	0.02
NY 73.0136.17	Sept 24	Sept 1	Sept 12	4.06	0.93	18.03	0.90	3.64	0.09	0.64	0.06
Petit Verdot	Sept 24	Sept 21	Sept 18	3.03	0.68	20.27	1.65	3.74	0.17	0.66	0.05
Sangiovese	Sept 8	Sept 13	Sept 18	4.39	1.11	18.00	1.85	3.83	0.14	0.55	0.06
Seyval blanc	Aug 25	Aug 20	Aug 22	4.24	1.50	20.03	0.05	3.67	0.10	0.57	0.03
Syrah	Sept 8	Sept 21	Sept 18	3.56	0.81	16.53	0.82	3.91	0.11	0.51	0.09
Tannat	Sept 24	Sept 5	Sept 12	4.28	0.79	20.57	0.66	3.56	0.15	0.91	0.13
Tempranillo	Aug 29	Sept 13	Sept 12	2.47	0.53	18.50	1.88	4.13	0.07	0.69	0.08
Traminette	Sept 24	Aug 25	Sept 5	3.11	1.25	19.57	0.40	3.82	0.09	0.59	0.09
Viognier	Aug 29	Sept 1	Aug 28	1.43	0.67	20.17	1.11	4.04	0.06	0.54	0.05

[a] Winegrape vineyard planted in 2001 to test various varieties/selections for adaptability to upper piedmont, North Carolina (elevation 890 ft, 36° 23' N; 79° 42' W); spacing is 7 ft in-the-row and 10 ft between rows; low bilateral cordon training with pruning to 17 to 18, 2-node spurs spaced roughly 4 to 5 in. apart per vine (or 8 to 9 spurs per cordon); canopy management practices consisted of shoot positioning, thinning and selective leaf removal on the north side *(the VSP trellis requires extensive canopy management techniques because it is not designed to handle the vigor of NC growing conditions)*. All varieties are on 3309C rootstock.

[b] Titratable acidity as % tartaric acid.

[c] Standard deviation measures the amount of variation in the data; lower standard deviations indicate that data values over the three years were within a range close to the reported mean.

[d] We gratefully acknowledge the contributions of Joanna Foegeding, Research Analyst, Food Science, NC State University, who conducted the analysis procedures for juice pH and TA.

- pH levels have averaged 3.56
- Yields have averaged 4.3 tons per acre for the same period (Table 4.2).

Gladstones (1992) suggests an optimal mean daily temperature of 64 to 70°F in the final month of ripening (August through October, depending on location and variety). For three years at this research vineyard in the central piedmont, we monitored the relationship between heat accumulated during the 30 days prior to harvest (using a base of 71.6°F), and readings for pH, TA, and Brix (Table 4.3). The heat units for the 30 days prior to harvest were 126, 32, and 210 units for the years 2003, 2004, and 2005, respectively. In the warmest seasons (2003, 2005), the TA levels for Chardonnay cl.76 were lower than in 2004 (relatively mild temperatures in August), but the seasonal trends in TA were not as clear-cut for the other Chardonnay clone (cl. 96), Merlot, or Viognier (Table 4.3). A reasonable standard for percent TA is from 0.6 to 0.9 (Amerine, 1980), and it may be viewed as a concern that the acid contents for all each of these *vinifera* varieties were *below 0.6* TA, except Chardonnay cl.76 in 2004 and Chardonnay c1.96 in 2003. Perhaps more alarming were the undesirably high pH levels recorded for all of the winegrape varieties and selections tested in this central piedmont location, with the exception of Tannat which had an average pH of 3.56 over three years (Table 4.2). Tannat's pH is relatively close to being in an acceptable range for full-bodied red wines (Table 4.4). Tannat is a variety that has become Uruguay's flagship red varietal wine, and it is important to note that this South American country's humid climate and heavy soils promote excessive vigor in most varieties (causing a

Table 4.3. Comparison of Selected *Vinifera* Winegrape Varieties for Harvest Dates, Yield Performance, and Fruit Quality Components for 2003, 2004, and 2005 Seasons at the Upper Piedmont Research Station at Reidsville[1]

	Harvest Date[2]			Tons per Acre			Brix			pH			Titratable Acidity (% Tartaric Acid)		
Variety	2003	2004	2005	2003	2004	2005	2003	2004	2005	2003	2004	2005	2003	2004	2005
Chardonnay cl. 76	Aug 29	Aug 25	Aug 28	0.78	2.61	3.89	19.6	19.6	19.6	4.00	3.78	3.73	0.53	0.65	0.50
Chardonnay cl. 96	Aug 27	Aug 25	Aug 28	2.06	5.34	5.48	18.9	20.4	19.5	3.88	3.81	4.04	0.61	0.59	0.48
Merlot	Sept 3	Sept 1	Sept 5	3.41	4.64	3.83	17.8	20.3	17.3	3.81	3.95	3.76	0.52	0.38	0.37
Tannat	Sept 24	Sept 5	Sept 12	4.27	3.32	5.26	19.7	20.7	21.3	3.76	3.51	3.40	0.80	1.09	0.83
Viognier	Aug 29	Sept 1	Aug 28	1.21	0.74	2.33	18.6	21.0	20.9	3.98	4.13	4.01	0.62	0.50	0.51

[1] Winegrape vineyard planted in 2001 to test various varieties/selections for adaptability to upper piedmont in North Carolina. Spacing is 7 ft in the row and 10 ft between rows; low bilateral cordon training with pruning to 17 to 18, 2-node spurs spaced roughly 4 to 5 in. apart per vine (or 8 to 9 spurs per cordon). Canopy management practices consisted of shoot positioning, thinning, and selective leaf removal on the north side. All varieties are on 3309C rootstock.
[2] Heat accumulated during the 30 days prior to harvest , using a GDD base of 22 C (71.6 F), were 126 units in 2003, 32 units in 2004, and 210 units in 2005.
[3] Titratable Acidity as % tartaric acid.

Table 4.4. Recommended pH, Titratable Acidity, and Brix for Grape Harvest[1]

Grape Type	pH	TA	Brix
White	3.1 to 3.3	0.70 to 0.90	19 to 20
Red	3.2 to 3.4	0.65 to 0.80	21 to 23

[1] Adapted from information from North Carolina Viticulture & Enology Information Packet, assembled by Tania Dautlick, Executive Director, The NC Grape Council, Inc. Summer/Fall 2003 (after the article, *Making Consistently Good Wine,* Donald E. Gauntner, American Wine Society Journal, Winter Issue, 1997, pp 131-134).

reduction in quality), with the important exception of Tannat (Teubes and Wiese, 2003).

Thus, there may be some advantage to locating vineyards where mean summer temperatures are relatively cool. In North Carolina, sites having cooler daytime temperatures are generally located at higher elevations (Table 4.1). Air temperature is reduced approximately 3°F for every 1,000-foot increase in altitude. Other factors being equal, a vineyard located 1,500 feet above sea level will have slightly cooler average daytime air temperatures than a vineyard located at 500 feet. There is a limit to the benefit achieved with increased altitude, however. Vineyards located above 2,000 feet are more subject to low-temperature injury during the winter.

Slope

The *slope* of a site refers to the degree of inclination of the land. A slight to moderate slope can be beneficial because it accelerates cold air drainage. Generally, the steeper the slope, the faster cold air moves downhill, assuming there are no barriers to air movement (Figure 4.1). Steep slopes, however, can create problems. Machinery is difficult if not dangerous to operate on steep slopes, and the potential for soil erosion is increased. Make every attempt to minimize soil loss, and avoid slopes greater than approximately 15 percent (a 15-foot drop in elevation for each 100-foot horizontal displacement). Consult the local Soil Conservation Service office for advice on erosion control measures.

Aspect

The *aspect* of a slope refers to the compass direction toward which the slope faces (north, south, east, or west). Eastern, northern, and northeastern slopes are probably superior to other aspects. Often, however, other factors such as the presence of woods, steep slopes, and exposed rocks dictate that another aspect must be used. The preference for eastern and northern aspects relates to heat load differences between various slopes. Southern and western exposures are hotter than eastern and northern exposures. Southern exposures warm earlier in the spring and can slightly advance budbreak compared to northern slopes. The consequence of advanced budbreak is increased potential for frost damage. Southern aspects can also lead to more extensive vine warming on sunny winter days than on northern slopes. The consequences could be reduced cold resistance and subsequent cold injury. Bark splitting and trunk injury to the southwest sides of fruit trees is occasionally observed and is related to trunk warming on sunny winter days with subsequent, rapid cooling. Southern and western aspects can also be expected to be hotter during the summer than northern and eastern aspects. Eastern aspects also have an advantage over western aspects because the eastern slopes are exposed to the sun first. Vines on an eastern slope will dry (from dew or rain) sooner than those on a western slope, potentially reducing disease problems. The basic effects of slope orientation on vine performance are summarized in Table 4.5.

Precipitation

Precipitation rates are not generally considered in site selection, but they greatly affect grape production. The water requirements of grapevines vary with their age, the presence or absence of competition from weeds, and the evaporative conditions to which the vines are exposed. Mature vines can use the equivalent of 24 to 30 inches of rainfall per year. Precipitation records indicate that most North Carolina locations average between 40 and 50 inches of precipitation per year. Unfortunately, average records can be misleading because they do not provide a measure of rainfall frequency. Even monthly precipitation averages can be misleading because much of the summer precipitation occurs during thunderstorms. Thunderstorms often affect only a

Table 4.5 Relative Effects of Compass Direction of Site (Aspect) on Various Climatological and Vine Developmental (Phenological) Parameters

Climatological or Phenological Parameter	Aspect			
	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	—	—	Rapid	Slow
Radiant heating of fruit in summer	Less	Greater	Less	Greater
Radiant heating of vines in winter	Less	Greater	Less	Greater

restricted area. Because of their intensity, less of the moisture is absorbed by the soil than when equal amounts of precipitation fall over longer periods. Avoid sites that chronically experience water shortages during the growing season, or consider supplementing natural precipitation with irrigation.

Soil

The soil supplies vines with most of their essential nutrients and water. Grapevines tolerate a wide range of soil types. Furthermore, vines can be grafted to pest-resistant rootstocks that can extend the margins of soil suitability to some extent. However, the soil must meet certain minimum qualifications. Chief among soil requirements are adequate depth and internal drainage. Potential vineyard sites should have a minimum of 30 to 40 inches of permeable soil. Soils that have a shallow hardpan restrict root development and limit the vines' ability to obtain water during extended dry periods.

Roots also require good aeration. The growth of roots and the welfare of the vine are reduced when soils are waterlogged during the growing season. Well-drained soils are essential for vineyards. The color of the subsoil gives some indication of its internal drainage: well-drained soils generally appear uniformly brown or grade into yellow-orange clay at 15 to 20 inches. The subsoil of poorly drained soils may appear mottled or uniformly gray. Soil drainage can be improved by installing drainage tiles, but the process is expensive. Consult Soil Conservation Service soil survey maps to help determine the suitability of your soil for crop use. County soil survey reports are available through most Cooperative Extension Centers or Soil Conservation Service offices.

Vineyard soils ideally should be of moderate fertility. Experience suggests that very fertile soils can complicate vine management because they promote excessive vegetative growth. Conversely, impoverished soils are liabilities if large quantities of nutrients must be routinely applied to support adequate vine growth. Collect soil samples before planting vines to determine soil pH and macro-nutrient levels. (See chapter 9.) Soil test guidelines are available through county Cooperative Extension Centers.

Despite popular opinion, we are largely ignorant about how different soil types affect wine quality. It seems reasonable to assume, however, that the major effect of soil type is indirect; that is, the effect of soil can be gauged by the impact the soil has on above-ground growth of the vine (for example, excessive versus optimal vegetative growth, balanced nutrition versus nutrient deprivation, or adequate water versus drought). However, one recently published book, *Soils for Fine Wines,* does provide additional information on the importance of vineyard soil conditioner (White, 2003).

Proximity to Vineyard Pests

In addition to the physical features of a potential site, consider the proximity of wildlife and other pests that can pose a threat to grapes. Chief among those pests are deer and various species of birds. Deer will browse the young, green shoots of the vines and eat the fruit as it matures. Deer are most destructive when vineyards are located close to woods or other deer habitat. If the potential for severe deer depredation exists, some deer protection measures should be used. Commercial chemical repellents, bars of soap, human hair, tankage, and shooting by permit all offer a temporary remedy to deer damage. Experience, however, suggests that electrified deer exclusion fencing is the only means of providing secure, long-term protection of vineyards.

Birds, particularly flocking species such as starlings, can cause serious crop loss by consuming fruit. Unfortunately, there are no cheap, legal, effective means to combat birds. Sites that are situated near heavy woods in otherwise open country appear to suffer the most damage. Several bird-scaring devices are commercially available, including recorded distress call emitters, propane cannons, Mylar ribbon, and bird-eye scare balloons. Again, experience suggests that those scare tactics offer only temporary crop protection. Bird netting is cumbersome to apply and remove but offers near-perfect exclusion. The overhead netting of entire vineyard sections is more convenient than is the netting of individual rows.

Sites that are, or were in recent years, wooded or planted to fruit trees should be cleared, cultivated, and planted to a grass sod or cereal grain for one or more years before grapes are established. During that period, rid the site of old roots, rocks, and broad-leaved weeds. Certain broad-leaved weeds and some fruit trees are alternative hosts for nematodes that can also attack grapevines. Nematodes are microscopic, wormlike parasites of which several genera, notably *Xiphinema*, can transmit viruses to grapevines. Soil assays for the presence of these nematodes can be arranged through your local Extension center. Soils that contain *Xiphinema* species can be fumigated, but the efficacy and economics of fumigation are uncertain and not recommended. As an alternative, infested soils should be maintained in a non-host grass or cereal grain for several years before vines are planted.

Coastal areas of North Carolina are not recommended for bunch grape production because of the occurrence of Pierce's disease. This bacterial disease is transmitted to grapevines by leafhoppers and severely limits grape production in regions where winter temperatures are warmer. The only practical control method is to avoid bunch grape production in regions where the bacteria is endemic. (See chapter 8.)

Consideration must be given to existing neighbors when contemplating a commercial vineyard. Equipment such as air-blast pesticide sprayers and bird-scare cannons are noisy and can generate complaints from neighbors. Also consider the possibility of pesticide drift from your vineyard onto neighboring property and vice versa. Pasture owners frequently use 2,4-D herbicides for thistle and other broadleaf weed control. Grapevines are very sensitive to 2,4-D injury. You must inform your neighbors of your intentions to grow grapes and diplomatically request that they avoid using 2,4-D or that they use only low-volatile 2,4-D formulations, preferably before grape budbreak.

Avoiding Spring Frost Damage

The best way to avoid frost hazard is to do a good job with site selection. It has been said, "The more effectively site selection rules are obeyed, the less need remains to consider additional frost measures" (Martsolf and Peart, 2003). Since the initial publication of the *Mid-Atlantic Winegrape Grower's Guide* in 1995, winegrape growers in both North Carolina and Virginia have been encouraged to rely primarily on *passive control* of frost by selecting sites that are elevated above a valley floor in hilly and mountainous terrain.

A new methodology introduced in this chapter assesses the *frost risk* of potential vineyard sites by using *predicted phenology* and *long-term temperature records.* It is recommended that you follow this approach, or another appropriate method, to gain a fuller understanding of the risk of spring frost associated with sites you are considering for commercial grape production. Having a complete understanding of the frost hazard associated with a potential vineyard site *before you plant* may help you to:

- ❑ Reject sites that that are highly frost-prone. Sometimes the *best* decision is to pull up and walk away rather than attempt to grow grapes on sites that are subject to repeated spring frosts. (These are sites that typically have chronic problems with winter injury as well.)
- ❑ Purchase and develop frost-free sites even though you can expect to pay extra for such sites. The extra cost for the land may be offset when you don't have to install frost control systems (e.g., heaters, overvine sprinklers and ponds, or wind machines) and pay to operate these systems (fuel for heaters is now prohibitive).
- ❑ Purchase and develop sites with a relatively low risk of frost damage (probability of frost in 1 or 2 years out of 10); especially if you:
    1. Plant *vinifera* varieties with later budbreak characteristics and avoid early budburst varieties like Chardonnay.
    2. Plant interspecific hybrids like Chambourcin, which can produce a good crop even if primary shoots are killed.
    3. Use cultural practices to reduce the likelihood of frost damage (e.g., delayed and double pruning, and/or removing impediments to cold air drainage, such as dense shrubbery and windbreaks).
- ❑ Assess the potential profitability of a site that will require a mechanical system for frost control. Several commercial vineyards in North Carolina have used wind machines over the last decade and can attest to their value on sites with chronic radiational frost problems. Wind machines use the inversion that develops under radiational cooling conditions. A wind machine may be able to raise the temperature 1 to 3°F over 7 to 10 acres of flat or rolling vineyard. On sites where there is a 20 percent or higher probability of spring frost during early stages of new shoot growth, it may prove profitable to invest in a wind machine.

Types of Cold Weather Events in Late Winter and Spring

There are three general types of cold events that can occur in North Carolina vineyards during the late winter and spring. The most common cold event is a *frost,* which is technically termed a *radiational frost*. Radiational frosts occur during calm weather when skies are clear and temperatures near the surface are below freezing. Selecting vineyard sites that have a reduced risk of spring radiation frosts is the primary focus of the rest of this chapter.

The second type of cold event that can occur is a *freeze.* Technically, *freezes* are termed *advective* or *windborne freezes. Freezes* are associated with the passage of large frontal systems of very cold air over an entire region, or state. It is virtually impossible to find sites that are unaffected by windborne freeze events. When the National Weather Service (NWS) issues a warning for a *freeze,* this means that there is potential for a very dangerous weather event with subfreezing temperatures and winds exceeding 10 miles per hour. Fortunately, *advective* or *windborne freezes* occur only rarely in the period following budbreak, as this type of cold event can devastate a vineyard.

While people use the terms *frost* and *freeze* interchangeably, the terms refer to cold weather events with very different characteristics and properties.

There is a third type of cold event called a *frost/freeze*, which combines the characteristics of both a *radiational frost* and a *freeze. Frost/freezes* are only briefly mentioned in this section, but they are discussed more fully in chapter 11 (*Spring Frost Control).* As defined by the NWS, a *frost/freeze* warning indicates the potential for a cold event with winds of less than 10 miles per hour and temperatures lower than 32°F. Although the NWS does not set an official lower limit for the wind speeds associated with a *frost/freeze,* it might be inferred that the winds associated with a *frost/freeze* are in the range of 5 to 10 miles per hour, as Perry (1998) has defined a *radiation frost* event as having winds of less than 5 miles per hour. *Frost/freeze* events are more likely to occur before spring budbreak, but if you are planning to grow *vinifera* grapes in the mountains, especially early budbreak varieties like Chardonnay, it may be prudent to also evaluate the potential for spring *frost/freeze* events in addition to spring *radiation frosts*.

The information presented in this section on *Avoiding Damage from Spring Frosts* focuses on assessing potential vineyard sites for the risk of more common radiation frost events (winds of less than 5 miles per hour and temperatures of 32°F, or colder) in the early weeks following budbreak. We generally recommend planting grapes in relatively warm thermal zones, which are belts that develop upslope where cold air can drain away from the vineyard to avoid damage from radiation frosts. Plants growing in the valley floor zone are frosted if the air is cold enough to freeze susceptible tissues.

Whether the cold event is a radiation frost, frost/freeze, or freeze, vine injury can occur if susceptible tissues (for example, green shoots) are cooled below a temperature critical for their survival. The critical temperatures for tissue freezing are discussed in detail in the following section on *Understanding Critical Temperatures.*

SLOPES DRAIN COLD AIR. Radiational frosts occur as the earth loses heat to the sky during the night. As the ground cools, it also cools the air immediately next to the ground. Cold air is heavier than warm air and will flow down the slope, much like a liquid. *The sinking, cold air displaces warmer air, which rises to higher elevations producing thermal inversions and thermal belts that provide a measure of protection from the coldest air in the valley floor sites* , as is illustrated in Figure 4.1 The rise in temperature with increase in elevation is referred to as a temperature or radiation inversion. Above the warm air layer of radiation inversion, air temperatures decrease with increased altitude.

The relative elevation of a proposed vineyard will have a major impact on the frequency of frost damage. Vineyards located in low frost pockets will be affected by frequent frosts; vineyards located at higher elevations, relative to surrounding topography, will be affected by fewer spring or early fall frosts. Most of us have experienced the ponding of cold air in low areas by strolling, at dusk, from a high hill to an adjacent creek-bottom or gully. The decrease in air temperature as we move downhill is most dramatic on calm, clear evenings. The relationship between relative elevation and air temperature is illustrated in Figure 4.1. The figure also illustrates how barriers to cold air drainage can create localized cold spots in a vineyard. Where possible, vegetation or other impediments to cold air drainage should be removed below the proposed vineyard site. We strongly recommend locating vineyards only on sites affording good cold air drainage.

More strongly sloping ground tends to give stronger inversions. A strong inversion is one in which temperatures above flat ground are at least 7 to 10 degrees warmer than temperatures at the surface, or in the case of a vineyard located on sloping ground, temperatures midway up the slope may be 10 degrees warmer than in the valley below (Figure 4.1).

One of the most remarkable characteristics of the topography in western North Carolina where the piedmont plateau transitions into the Blue Ridge Mountains, is the great variations in elevation that generate strong inversions. For many years "thermal belt" has been used to describe certain sections of North Carolina that "enjoy a more equitable climate" (Hurt, 1923). These thermal areas favoring apple, peach, and grape production have been enjoyed by many generations of fruit growers in North Carolina. In Virginia, historical weather data and grower experience in the piedmont and Blue Ridge Mountain areas have revealed a greater frequency of damaging spring radiational frosts below elevations of 800 feet than at heights of 800 to 1,800 feet, assuming that the higher sites have good relative elevation (Wolf and Poling, 1995).

In assessing vineyard sites in the higher altitudes of western North Carolina, it is very important to consider a site's absolute elevation above sea level. On average, temperature changes 1.1°F per 330 feet of elevation (Jones and Hellman, 2000), and *at some point the benefits of higher absolute elevation are lost.* More recently, Wolf and Boyer (2003) have found that the upper limit of a thermal belt can range from 1,500 feet above sea level in northern Virginia to approximately 2,200 feet in southern Virginia.

Similar guidelines have not been determined for the northern, central, and southern latitudes of western North Carolina, but you may wish to check the North Carolina Wine and Grape Council Web site (www.ncwine.org) for *Vineyard Suitability Maps*. Using a software program and database created by John Boyer, a Virginia Polytechnic Institute and State University geographer, former NCSU viticultural Extension associate Andy Allen generated these maps for potential sites in the mountains, foothills, and piedmont of North Carolina. The program utilizes a series of physical, digitized databases to assess the potential for spring frost on a proposed vineyard site. The validation of maps is ongoing, and refinements will, no doubt, occur.

One limitation of this program that pertains to piedmont counties (Allen—personal communi-

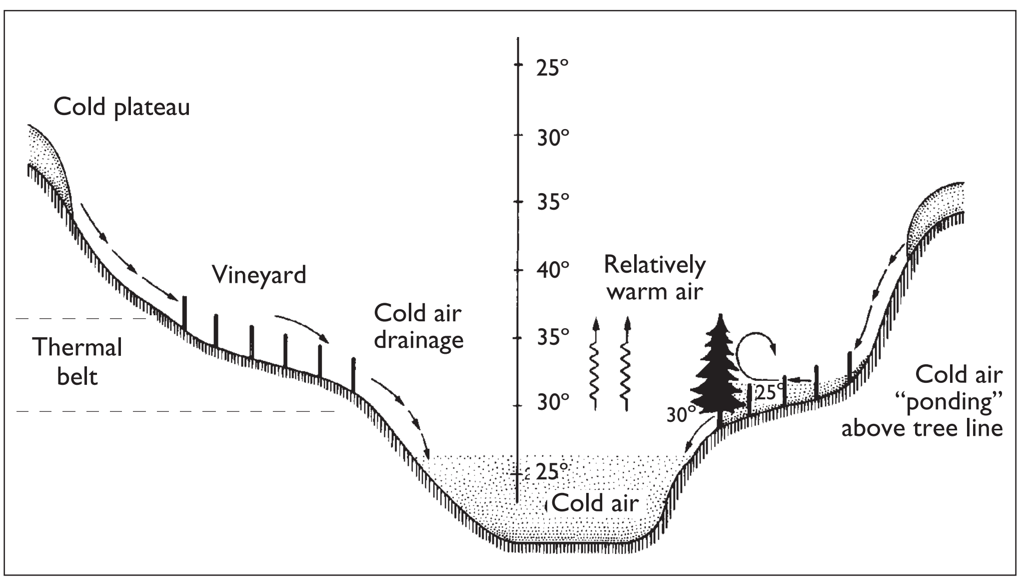


Figure 4.1 Effect of vineyard site topography on air temperature stratification during a radiational cooling period characterized by calm winds and clear skies.

cation). The program assigns its best vineyard ratings to those sites found at the highest absolute elevations in the county. Sites located at lower absolute elevations in the county, despite outstanding local relief features, are not rated as highly. However, Allen has observed that 100 feet in hight can generate highly beneficial thermal zones for relatively frost-free grape production in most seasons in the North Carolina piedmont, provided there is a broad enough valley floor below the vineyard for cold air to collect. The site also must not have any downslope natural or manmade impediments that would block cold air drainage, like dense shrubbery, windbreaks, and buildings at the bottom of a slope (see Figure 4.1).

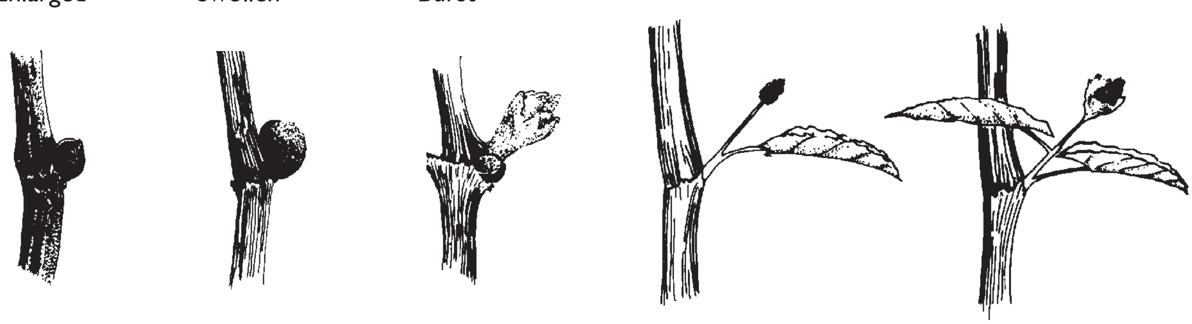
Understanding Critical Temperatures

As grapes develop from budburst to the various shoot development stages, the plant tissues become more susceptible to cold injury. Figure 4.2 shows the chances that Pinot noir buds and shoots will be killed at various temperatures.

Although Pinot noir is poorly adapted to growing conditions in North Carolina, you may use this variety's information on critical temperatures for similar popular *vinifera* varieties like Chardonnay, Merlot, and Cabernet Sauvignon (Evans, 2000).

However, ambient temperatures and humidity may interact to influence *actual* freezing points of newly expanding grape shoots. For example, under very dry atmospheric conditions in the vineyard, Wolf and Boyer (2003) report that injury to grape shoots may not occur until air temperatures reach 25 to 26°F, which is several degrees colder than the critical temperature points reported for young shoots in Figure 4.2. When the humidity is low and cooling is gradual, newly developing grape shoots have the ability to supercool (drop below their normal freezing

Figure 4.2 Critical temperatures of Pinot noir buds and shoots at six stages of development in spring.[a]



STAGES	Dormant Enlarged	Dormant Swollen	Shoot Burst	First[b]	Second
	CRITICAL TEMPERATURES FOR BUDS AND SHOOTS				
50% Killed	–14.0°C 6.8°F	–3.4°C 25.9°F	–2.2°C 28.0°F	–2.0°C 28.4°F	–1.7°C 28.9°F
None killed	— —	— —	–1.0°C 30.2°F	–1.0°C 30.2°F	–1.0°C 30.2°F

[a]Source: Gardea, A.A. "Freeze damage of 'Pinot noir' (*Vitis vinifera L.*) as affected by bud development, INA bacteria, and bacterial inhibitor" Oregon State University, Corvallis.
[b]Shoot stages defined by the number of flat leaves, those that had expanded enough to have an orientation nearly perpendicular to the ground.

points) and not freeze. However, it is very difficult to determine whether grape shoots will supercool during a given freeze event.

The temperature at which grape plant tissues freeze can also be affected by the presence of moisture on the plant surface. Essentially, dry plant tissue freezes at lower temperatures than wet plant tissues. Johnson and Howell (1981) have shown how the presence of hoar (white) frost, dew, ice, or water from precipitation or irrigation will elevate the critical temperatures of developing buds of Concord grapevines by more than 5°F at budburst stage (Table 4.6). Similar data is not reported for early shoot development stages by these authors, but it is very possible that in the presence of moisture the critical temperature of a second flat leaf stage could be closer to 31°F, and not 28.9°F, as shown in Figure 4.2 for Pinot noir.

Another area of some confusion has to do with the time interval required to damage a swollen bud or newly developing grape shoot. Authorities in Oregon (Sugar et. al, 2000), note that "beyond budbreak, damage may occur when developing shoots experience temperatures of 31°F or lower for *one-half hour or longer.*" However, Evans cautions "…that whenever ice forms in the plant tissue, there will be damage regardless of how long it took to reach that point" (2000).

Given the uncertainties and complications associated with pinpointing critical temperatures and durations required for cold injury in grape tissues, it may be safest simply to adopt the *higher end* critical temperature reported for budburst of 28°F by Perry in North Carolina for 50 percent kill (1998a). For early shoot stages, a critical tissue temperature of just below 32°F may be most appropriate, especially under hoar (white) frost conditions.

Table 4.6 Critical Temperatures (°F) for Developing Buds of Concord Grapevines[1]

Stage of Development	Influence of Surface Moisture[2]	
	Wet	Dry
Scale crack	22.1	14.9
First swell	23.9	17.6
Full swell	25.7	19.4
Burst	26.6	21.2

[1] Values are T_{50}; 50 percent of buds will be lost.
[2] Indicates presence of hoar frost, dew, ice, or water from precipitation or irrigation.

New Approach for Assessing Potential Vineyard Sites for Spring Frost Risk

In this publication, we have adapted a method used in New Zealand (Trought et al, 1999) that is based on the *predicted phenology* [1] (i.e., budbreak) of the vine and *estimates of frost probabilities* to assess the frost risk potential of a vineyard site. The *estimates of frost probabilities* are derived from *long-term temperature records*, such as the climate data[2] that can be provided by the State Climate Office of North Carolina. The State Climate Office (SCO) has long-term temperature records (30+ years) for more than 90 weather sites across North Carolina (almost one for each county). This source is felt to be the first choice for quality controlled climate data by many experts in the meteorology field. You may check the Web site at www.nc-climate.ncsu.edu/econet to obtain contact information for the SCO or call 1-877-718-5544 (toll free) to speak with a state climatologist. The actual procedure for generating frost probability estimates from minimum temperature observations for specific locations and periods is not automated, and it is going to be important for you, or your Extension agent, to

[1] Phenology is a branch of science dealing with the relations between climatic and periodic biological phenomena. And from the standpoint of understanding critical temperatures, it is important to know that the temperatures that grape buds and shoots will endure without injury changes with each developmental stage. Grape phenological stages are also very important in the timing of vineyard pest control sprays.

[2] The terms *climate* and *weather* are frequently used interchangeably, but it should be understood that *weather* refers to the current state of the atmosphere, such as temperatures or wind speeds, but *climate* refers to the average or normal weather of a particular location for a specified period of time, usually 30 years (Perry, 1999).

contact this office directly to obtain this information.

Our modification of the New Zealand model for assessing the frost risk of potential vineyard sites involves three steps:

1. Predicting *bud phenology* (i.e., forecasting budbreak for the varieties you wish to grow).
2. Making *probability estimates* for spring frosts from *long-term temperature records* based on information you receive from SCO. Alternatively, where a risk analysis of a new site is required, a limited temperature data set can be used by relating the new site to a nearby SCO station with long-term temperature data. See *Short-term Temperature Records* to learn how to do a direct temperature survey for a minimum of one season (and preferably two).
3. Doing an *investment analysis* to determine whether active frost protection may be economically justified.

To show how the New Zealand approach works, we have utilized phenology information for Chardonnay cl. 96 from an existing research vineyard location (Upper Piedmont Research Station, Reidsville) and SCO climate data from a weather station that is a quarter mile from the vineyard. Even though this vineyard in Reidsville has *so far* been frost-free (2001 through 2005), we can gain considerable insight about the longer-term frost risk of this particular site (shown in Figure 4.3) by analyzing historical temperature records.[1]

Step 1. Collect Data for Stages of Growth in Your Area

At the Upper Piedmont Research Station in Reidsville, Chardonnay cl. 96 passes through the phenological stages of *budbreak, 1- to 2-inch shoot,* and *10-inch shoot* in an approximate 3-week period (mid-April through first week of May). Chardonnay normally reaches budbreak stage in mid-April in Reidsville (Table 4.7), and in just one more week it reaches the 1- to 2-inch shoot stage.

[1] From 1901 to 1999, two Reidsville gages were provided by the National Weather Service and monitored each day by volunteers; today the gage is on the Agricultural Research Station, and temperatures are reported every day by staff. An automated gage on the research station provides hourly data and many other measurements, but it has only been in operation since May 1999.

Figure 4.3. This Reidsville site has not experienced any damaging radiational frosts or frost/freezes in five years of observation. The vineyard has excellent local relief and unimpeded downslope cold air flow patterns. It has a gentle slope and lies approximately 100 feet above a frosty creek bottom at an elevation of 870 feet (top of vineyard). On still nights in April that favor heavy white frost formation on crops growing near the creek bottom (such as strawberries), the vines in this vineyard have been unaffected. (Photo taken March 14, 2005, by Joe French, Superintendent, UPRS).

Table 4.7 Dates for Key Growth Stages in Chardonnay for Frost Occurrence and Pest Management Considerations at the Upper Piedmont Research Station, Reidsville, NC*

Budbreak**	April 15
1 to 2-inch Shoots	April 22
10-inch Shoots	May 5
Prebloom	May 15

*Weather shelter elevation is 890 feet, 36° 23' N. latitude; 79° 42' W. longitude, and is a quarter mile from the vineyard location (elevation: 870 feet)
**Budbreak is defined as the time when the dormant buds open and newly formed leaves are seen (Wolf and Boyd, 2003)

Based on the critical temperature data in Figure 4.2, the threshold temperature for frost damage (50 percent kill) will increase from 28°F (budburst) to 28.9°F (second flat leaf), in approximately one week's time. At a later stage (fourth flat leaf), Chardonnay shoots can potentially be damaged at 31°F. However, for reasons previously given, it may be safest simply to adopt the *higher end* critical temperature reported for early shoot stages of just below 32°F (Trought et al., 1999), and this is the assumption we have made in characterizing the frost sensitivity of young

Short-term Temperature Records

Even if you have longer-term climatic records for a site, we encourage you to assess the potential for frost on possible vineyard sites by doing a direct temperature survey for one season and preferably two. Frost events during critical growth periods in the early spring *are more strongly influenced by a site's local topography and possible barriers to air drainage* than by regional climatic factors.

The effect of local topography on air stratification during radiational cooling can be demonstrated by positioning thermometers that record maximum and minimum temperatures in shelters at various elevations on the proposed vineyard site. It is not unusual to find temperature differences of 3 to 5°F over a 50-foot difference in elevation. Two or three recording thermometers can provide considerable data on temperature variations at the site. High quality maximum/minimum recording thermometers are recommended; avoid inexpensive U-shaped maximum/minimum thermometers because instrument errors are large (Jones and Hellman, 2000). Mount the thermometers 5 feet above the ground and shield them from the sky with a roof painted white. If you plan to use low cordon training (the most popular training method for *vinifera* in North Carolina), it may be more advisable to position your temperature sensing device at a 3-foot level, and not 5 feet (standard weather shelter height). It is helpful to remember that swollen buds and shoots that are 3 feet from the ground will be colder (and more subject to injury) on a typical night of radiational cooling than shoots trained to a height of 5 feet.

Alternatively, an on-site weather station that records spring temperature minimums as well as wind speeds, relative humidity, and precipitation can be a valuable tool for making a more complete assessment of the actual radiational frost and advective freeze hazard of any site you are considering for grape production. Weather stations can range from simple devices to complex multi-instrument stations, but some authorities recommend a housed temperature sensor (thermister), which is calibrated and positioned mid-slope (Jones and Hellman, 2000). Your Cooperative Extension center can furnish you with current information on the many types of instrumentation available for evaluating a site's temperature characteristics. Recently, portable Mini Weather Stations costing less than $600 have become available. They are designed for use in harsh outdoor environments, and can store daily high and low temperature readings and temperature readings at 30-minute intervals for up to 180 days. These Mini Weather Stations also have an LCD display, which allows you to check current temperatures without connecting to a computer.

When doing your direct temperature survey, it is especially important that you record the dates when temperatures are 32°F, or lower. Also evaluate the height, frequency of occurrence, and strength of the inversion layer of each particular site. As discussed later, it is the warmer air above the vineyard that is used by wind machines (and/or helicopters) to warm the air around the vines.

Chardonnay grape shoots from April 22 (1- to 2-inch shoots) through early May (10-inch shoots).

Information regarding the range in budbreaks for winegrape varieties in North Carolina is quite limited,[1] but your Extension agent and/or local growers may already know and be able to tell you the approximate budbreak dates for popular varieties like Chardonnay, Merlot, or Cabernet Sauvignon. Just knowing when Chardonnay normally breaks bud in your area will help you predict budbreak for other varieties. Cabernet Sauvignon, for example, is usually two weeks later in budburst and development than Chardonnay. In the next step, *Estimate Probability of Spring Frost Events*, we will compare the average date of budbreak of Chardonnay to the dates of significant frost events at the Reidsville research vineyard using long-term temperature records.

Step 2. Estimate Probability of Spring Frost Events

Past observations are an essential ingredient to predicting future conditions for your vineyard. The frost probability estimates you receive from long-term temperature observations from the North Carolina State Climate Office can help you assess the statistical probability that a spring frost will damage the varieties you plan to grow. With the assistance of a qualified state climatologist, you can investigate the so-called *frost climatology* of the vineyard sites you are evaluating for commercial production. You should expect to pay a modest fee for these services, especially in situations requiring extensive analysis to generate useful frost probabilities.[2]

As discussed earlier, at the Reidsville research station, Chardonnay buds typically pass from dormant to budbreak stage in mid-April, and by around April 22, the stage of 1- to 2-inch shoots

[1] Models that can be used to predict budbreak have been developed by Moncur et al. (1989) and have been used in New Zealand (Trought et al., 1999).

[2] The commercial company SkyBit (www.skybit.com) can also provide historical probability analysis of the frequency of specified temperature(s) at a site based on the site's location and elevation (Wolf and Boyer, 2003).

Table 4.8. Percentage of Chardonnay Vines at Various Stages by Date and Weekly Frost Probabilities for Reidsville Site in April and Early May*

Temperature Threshold	Percent Dormant Buds Swollen April 8-14	Percent Budburst, or Shoot Burst April 15-21	Percent at 1- to 2-inch Shoot Stage April 22-29	Percent Shoots Elongated to 10 Inches April 30-May 5
32°F	53.4	21.0	5.7	2.6
31°F	34.0	16.1	3.4	0
30°F	23.1	12.5	2.1	0
29°F	17.1	10.6	1.6	0
28°F	9.9	5.2	0	0

* The daily probabilities of frost occurrence in the months of April and May were first calculated using Reidsville temperature records from 1902 through 2005. Then this data was then "smoothed," using a 5-day moving average. The smoothed daily probabilities of frost occurrence (at set temperatures of 28, 29, 30, 31, and 32°F) were then summed to generate the weekly frost probability estimate shown. Daily smoothed frost probability estimates provided courtesy of North Carolina State Climate Office.

has been reached (Table 4.7). Now let's review frost probabilities during this critical period.

LAST SPRING FROST DATE for Reidsville. Traditionally, 32°F is used in assessing the frost potential of a site, and Perry (1998b) notes that the average date of the last spring air temperature of 32°F (50 percent probability of frost later than this date) for this location is *April 7*. More recent calculations of the average date of the last spring frost (also called the *last spring frost date*) by Ryan Boyles, state climatologist, for 1962 through 2005 showed a 50 percent probability that the temperature would be as cold or colder than 32°F on *April 7*. But, with Chardonnay budburst coming a full week after the so-called *last spring frost date,* we are naturally more concerned about the probability of damaging frost during the second half of April.

EVALUATING FROST PROBABILITY LEVELS after budbreak. What is the probability of temperatures of 28°F or colder occurring *after budbreak* (at budburst we are assuming a critical tissue temperature of 28°F). We found from analyzing temperature records for the 103-year period of 1902 to 2005 that there is only a 5.2 percent probability of observing a temperature this cold, or colder, in the week of April 15 through 21 (Table 4.8). Essentially, this means is that a temperature of 28°F or colder during this particular week occurs about once every 20 years (Perry, 1998b).

In the next week, April 22 through 29, the probabilities of observing an air temperature as cold, or colder than 32°F, is only 5.7 percent (Table 4.8). If you assume a critical temperature for the 1- to 2-inch stage that is lower than 32°F, you will note that the probability of temperature as cold, or colder, than 31°F is 3.4 percent; for 30°F, the probability is 2.1 percent.

In assessing the frost climatology of a site, you may also investigate some *worse-case* scenarios. One such scenario involves atmospheric conditions that favor rapid radiation heat losses at night in newly developing grape shoots. Under low humidity and calm wind conditions, plant tissues can become 3 to 5°F *colder* than the surrounding air. Explained another way, plants cool themselves (by radiating their heat) to the point that they can cause their own damage (Evans, 2000). Thus, when a weather shelter sensor 5 feet above the ground records an air temperature of 34°F, the actual temperature of a young grape shoot at 5 feet could already be below 31°F (or possibly colder), which is potentially injurious.

Thus, given the potential divergence of air temperatures and grape tissue temperatures, with plant tissues potentially being 3 to 5 degrees colder than the air, you can examine frost probability estimates associated with a slightly higher air temperature of 34°F (for comparison to the standard 32°F threshold). This technique may keep you from underestimating the real threat of frost damage to the vineyard under radiation frost conditions with low atmospheric humidity.

In our sample case, we evaluated climate data for Reidsville for 1962 through 2005 using an air temperature threshold of 34°F and found a 30 percent chance of an air temperature of 34°F, or colder, occurring after April 21 (Table 4.9). In contrast, if we use a standard 32°F air temperature threshold, there is only a 10 percent probability of a temperature this cold, or colder, after April 21. *The first scenario predicts damaging frost once every three years; the second, once every ten years*. But, an air temperature observation of 32°F at the weather shelter height (5 feet) under radiational cooling conditions may be related to grape tissue temperatures of less than 29°F (at 5 feet), which could be very damaging to primary shoots of Chardonnay.

Without more data on atmospheric conditions associated with minimum temperature observations at Reidsville for 1962 through 2005 (especially relative humidity and dew points), we cannot really be certain of whether the risk of damaging frosts will occur with a frequency of three times in 10 years (30 percent probability), or only once per decade (10 percent). However, the vineyard uses vertical shoot positioning (VSP) canopies with a cordon height 3 feet, which makes frost damage more likely than if another system were used, so the level of frost risk would be greater than 10 percent for this location. Under radiation frost conditions, the height of the bud or newly developing shoot alters the potential frost hazard (Dethier and Shaulis, 1964). Researchers in New Zealand, for example, have reported that buds on a high cordon training system (Geneva Double Curtain) at 6.5 feet can be approximately 7°F warmer than those on a standard 3-foot VSP cordon, and 13°F warmer than the temperature at ground level (Trought et al, 1999).

Thus, it is worth remembering that any frost climatology data from official state weather stations that you use to estimate frost probabilities for a specific location are based on air temperature measurements made at 5 feet above the ground, and that bud and shoot temperatures at 3 feet for VSP training will be colder under radiational cooling conditions. Furthermore, it may be prudent to use a 34°F threshold to take into account the phenomenon that grape tissues may be 3 to 5 degrees lower than air temperatures on chilly nights with low relative humidity and little air movement (Trought et al., 1999).

Let's summarize our findings about the budbreak and early shoot development of Chardonnay at this central piedmont location, as well as the information we generated on spring frost probabilities:

1. *Predicted phenology.* At the Reidsville research vineyard, Chardonnay cl. 96 breaks bud

Table 4.9. Probability of Daily Lows at Reidsville Weather Station Based on Data Collected 1962 Through 2005

Temperature (°F)	Probability of Later Date in Spring Than Indicated										
	99%	**90%**	**80%**	**70%**	**60%**	**50%**	**40%**	**30%**	**20%**	**10%**	**1%**
36	3/31	4/6	4/11	4/15	4/18	4/21	4/24	4/28	5/2	5/7	5/10
34	3/23	3/30	4/5	4/08	4/11	4/14	4/16	**4/21**	4/24	4/30	5/7
32	3/16	3/23	3/28	4/1	4/4	4/7	4/9	4/13	4/16	**4/21**	5/4
28	3/7	3/12	3/16	3/20	3/22	3/25	3/27	3/30	4/2	4/7	4/20

in mid-April and reaches the 1- to 2-inch shoot stage around April 22. Thus, the potential for frost damage in most spring seasons will be highest in the second half of April.

2. *Making probability estimates from long-term temperature records.* Historical temperature records (1902 to 2005) collected at a meteorological station near the Reidsville vineyard were analyzed using an air temperature threshold of 28°F (or colder). It was found that the probability of a damaging frost in the week following budbreak (second week of April) was only 5.2 percent. Using an air temperature threshold of 32°F for the 1- to 2-inch shoot stage, the data show only a 5.7 percent risk of cold injury in third week of April. A 5 percent risk can be interpreted as a vineyard that would have a significant frost in 1 out of 20 years.

However, these risk levels may present an overly optimistic a picture of the actual frost hazard at this location. To take into account the phenomenon that grape tissues may be several degrees lower than air temperatures on still nights of radiational cooling and low relative humidity, we examined an air temperature threshold of 34°F. In evaluating climate data for Reidsville for the period 1962 through 2005, it was found that there is a 30 percent chance of an air temperatures of 34°F or colder occurring after April 21. In contrast, if we use a standard 32°F air temperature threshold, there is only a 10 percent probability of temperatures this cold or colder after April 21. In the end, a **20 percent risk of frost injury** may be an appropriate compromise as the canopy is just 3 feet high, and bud and shoot temperatures at 3 feet above ground level can be significantly colder under springtime radiational cooling conditions than for higher cordon training systems of 5 feet or higher.

From the information gathered about the potential risk of frost damage to Chardonnay at the Reidsville location, we can now undertake an investment analysis that will address the question of whether an active frost protection system may be economically warranted.

As you will see in the following section, once you determine from long-term temperature records that a site has frost risk greater than 20 percent (2 out of 10 years), it can become economical to consider an investment in a wind machine. Over-vine sprinkling systems offer a higher degree of frost protection than wind machines, but their fixed-rate design delivers more protection than generally necessary in most vineyards. (See chapter 11 for a more complete consideration of various active frost protection methods and their relative advantages and disadvantages.)

Step 3. Decide if a Frost Protection System Makes Economic Sense

While frost protection methods can be expensive, an active protection system, or combination of systems, may allow the grower using a frost-prone site to have more consistent crops and improved cash flow in years with potentially damaging frost events. An informed decision on whether an investment in a wind machine (or any other type of mechanical protection system or combination of systems) can be profitable requires economic analysis.

CROP LOSSES. First we need to consider potential crop losses in Chardonnay. If the primary shoots of *vinifera* varieties are killed by spring frost, secondary and tertiary shoots will grow, but the resulting clusters are fewer in number and are delayed in ripening past the normal harvest season. In a frost-free season, Chardonnay has a potential yield of 4-plus tons per acre, but a spring frost destroying the primary shoots of this variety could reduce yield by 50 percent or more. At Reidsville, we determined that in 2 out of 10 years we may experience damaging frost events in this early budbreak variety.

Economic impact of 50 percent crop loss at Reidsville. Even with a price per ton of $1,400 for Chardonnay grapes, a yield of 2 tons per acre will generate only $2,800, which is barely enough revenue to cover annual vineyard operating expenses of $2,675.[1] However, operating costs vary, and actual total costs of production on this site were estimated to be $4,103 per acre in 2006.[2]

Economic Benefits of a Wind Machine

Wind machines have proven valuable in combating radiational frosts at several commercial vineyards in North Carolina over the last decade (Figure 4.4). Table 4.10 shows the estimated cost of installation of a 125 HP gasoline-powered wind machine 35 feet tall with a 19-foot fan.

Figure 4.4. This Orchard-Rite wind machine stands 35 feet above the vineyard floor and has a 125 HP gas-powered engine that turns the 19-foot fan. It protects a 7-acre vineyard in Davidson County. (Photo taken by Barclay Poling, December 18, 2005)

To analyze the long-term consequence of frost events in a vineyard with and without a wind machine, Table 4.11, which shows the effect of the reduced crops due to frost events in the 10-year average returns of the vineyard. The average returns are calculated for different probabilities of having frost damage. For example, the Reidsville vineyard had a 20 percent probability of frost damage, which would cause two 50 percent yield losses every 10 years.

A wind machine adds $180 per acre. From Table 4.11 you will note that if no frost occurs in the 10-year period, the average net return in the vineyard without the wind machine is $294 per acre higher than the average net return in the vineyard with the wind machine. But, if there is a 20 percent risk of frost, as in the Chardonnay vineyard in Reidsville, the average net returns of the vineyard with the wind machine will be $180 per acre higher than the vineyard with no active frost protection. On a vineyard prone to spring frost in only one out of ten seasons (10 percent probability of frost damage), the wind machine would not produce a positive net return (-$56 per acre). Thus, on sites where temperature records indicate that there is a 20 percent or higher probability of spring frost during critical early stages of budbreak and new shoot growth, the investment in a wind machine may result in higher average net returns, better cash flows, and potentially improved vine health and management (Evans, 2000).

Over-vine Sprinkler Irrigation Systems

Relatively few of these systems have been installed in North Carolina, and you are advised to choose this method only if you have determined that your vineyard site is highly prone to frost and frost/freezes and that you have enough water to provide three consecutive frost/freeze nights of protection (about 155,000 gallons of water per acre).

Heaters

For years the principal method of frost protection in fruit crops was burning fuel to create heat. But burning diesel or propane as the sole means of frost protection has become prohibitively expensive. At $2.50 per gallon for

[1] This represents variable costs without harvesting costs.

[2] Total costs except harvesting are $4,103, and this is made up of variable costs of production without harvesting ($3,075) + fixed costs of production ($1,428). Note that annual fixed costs of production include mainly the establishment costs ($1,273) and also machinery depreciation and other items that are incurred regardless of the level of production of the operation.

Table 4.10. Estimated Costs of Installation and Use of a Wind Machine in a 10-acre Vineyard

Item/description	Cost ($)
Initial cost of equipment	28,000
Annual total ownership (fixed) cost*	294/acre
Operating costs/hour**	2.17/acre
Labor costs***	10.50/hr

* Includes depreciation, interest, taxes, and insurance costs. It assumes 20 years of life of the equipment and a salvage value of zero.
** Includes fuel and repair costs. Repair costs equal 50 percent of the initial costs during the 20 years of use (this implies average annual costs of $700). Fuel and lubricants calculated at $380 per year.
*** Annual hours of labor = 1/3 of the machinery annual hours.

diesel, the cost of burning 40 heaters per acre would be $100 per hour. You must also figure in the cost for labor to light the heaters, put them out in the vineyard, and refill them for the next night of frost protection. *However, they remain an effective method of adding extra heat during nights when temperatures may fall below the capacity of wind machine protection* (Perry, 1998d).

Helicopters

Helicopters are an expensive method of frost protection, and their use is often limited to special cases and emergencies. Typically, these include times when a cold event is forecasted that will require significantly more protection **than a wind machine can provide** (not usually reliable for more than 1 to 3°F protection), and the potential for crop loss is high enough to justify it. Hourly costs ranging from $825 to $1,600, depending on the size of the helicopter, and availability. Usually, the grower is asked to guarantee at least 3 hours of work.

Table 4.11 Average Net Returns of Vineyards With Different Probabilities of Frost Damage (assumes 40 hours of wind machine use in years with frost)

	10-year Average Net Returns($/acre)		Difference in Average Net Returns	
Probability of Frost Damage (%)	Vineyard with Wind Machine	Vineyard Without Wind Machine	$/acre	$/10-acre Vineyard
0	803.00	1,097.00	-294.00	-2,940.00
10	780.32	837.00	-56.68	-566.80
20	757.64	577.00	**180.64**	1,806.40
30	734.96	317.00	417.96	4,179.60
40	712.28	57.00	655.28	6,552.80
50	689.60	-203.00	892.60	8,926.00
60	666.92	-463.00	1,129.92	11,299.20
70	644.24	-723.00	1,367.24	13,672.40
80	621.56	-983.00	1,604.56	16,045.60
90	598.88	-1,243.00	1,841.88	18,418.80
100	576.20	-1,503.00	2,079.20	20,792.00

Passive Methods for Managing Spring Frost Risk

Short of an investment in an active frost control method (wind machine, irrigation system, heaters, and helicopters) for sites determined to be prone to spring frosts, you may wish to consider three methods of passive frost protection:

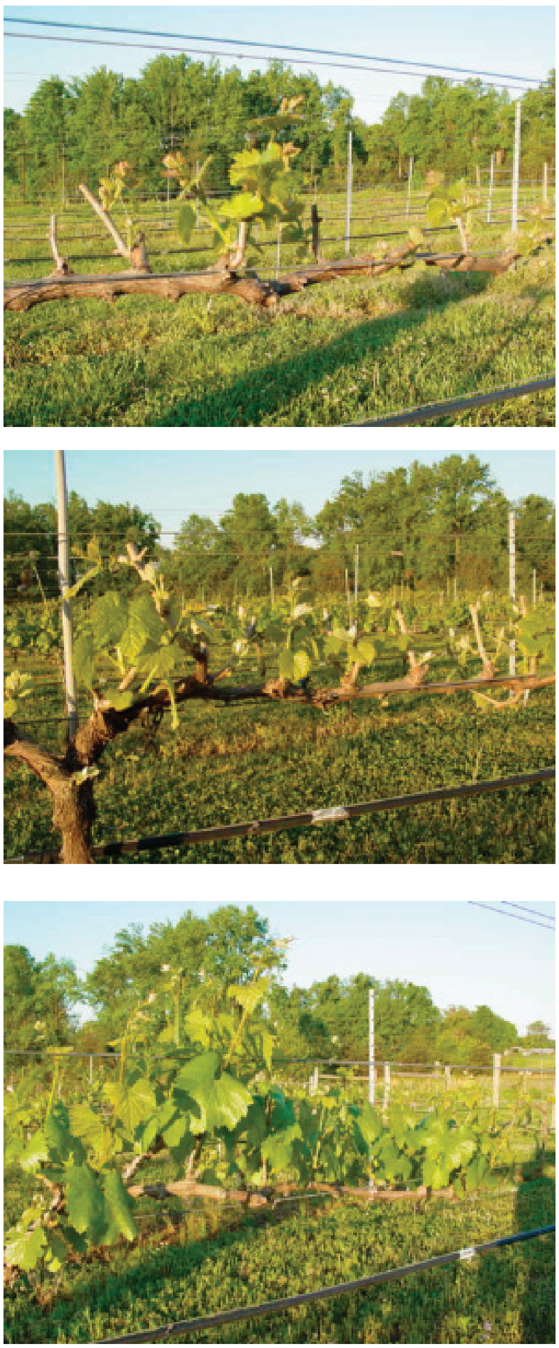


Figure 4.5. Variety makes a difference. Compare the 3-inch shoots in Verdejo (top) with the 5-inch shoots in Traminette (center) and the 8-inch shoots in Chardonnay (bottom). All three photos were taken April 28, 2005, at the research station in Reidsville. (Photos by Ashley Johnson, research technician, UPRS, Reidsville.)

- ❑ Select varieties with later budburst and shoot development.
- ❑ Select a hybrid with very fruitful secondary buds (not a *vinifera*).
- ❑ Use cultural techniques that minimize frost damage.

VARIETY SELECTION. Chardonnay clones are the first to break bud at the Reidsville research vineyard location, and by the end of April you can see a considerable range in average shoot development among varieties. Chardonay cl. 96 is an early budbreak variety, compared to two later breaking *vinifera* varieties (Figure 4.5). Chose a variety with a later budbreak, and you may be able to escape frost damage and use a frost-prone site. From a frost-control perspective, grape varieties that are 1 or 2 weeks later in budbreak would be better matches for the Reidsville vineyard location than Chardonnay. Given the frost climatology of any site, it would be best to identify varieties that do not break bud until the probability of damaging frosts is significantly reduced in the final week of April. There is currently little information on possible differences in frost resistance of *vinifera* varieties at the same stage of development.

SELECTING TYPES OF GRAPES OTHER THAN *VINIFERA*. Another strategy for sites particularly prone to frost may be to consider *interspecific hybrids,* which produce more fruitful secondary buds than *vinifera* varieties after primary shoots are injured by cold. At the Reidsville vineyard site, Chambourcin, an interspecific red hybrid (see chapter 3), breaks bud a week later than Chardonnay. Its later budburst reduces the chance of damage from spring frosts, and it also has fruitful secondary shoots should a frost damage the vine. With the risk of a late April or early May frost, an interspecific hybrid like Chambourcin may be a better match for locations with frost risk characteristics similar to the Reidsville research vineyard.

While much of the current discussion in this chapter concerns susceptibility to spring frosts, grape varieties like Cabernet Sauvignon, which mature their fruit and wood relatively late in the season, should be avoided in areas that are subject to early fall frosts.

CULTURAL TECHNIQUES. In addition to making sure that a site does not have either natural or manmade down-slope impediments to cold air drainage (e.g., dense shrubbery, windbreaks, and buildings), use these cultural strategies to minimize frost damage:

- ❑ Select a northern or eastern aspect for early budbreak varieties. The same varieties on a southern aspect can break bud up to 7 days earlier (Wolf and Boyd, 2003).
- ❑ Cleanly cultivated vineyards are usually 1 to 2°F warmer than vineyards covered by sod or ground cover. Vegetation reduces the amount of heat absorbed by the ground during the day and inhibits release of heat at night (Sugar et al., 2000). However, do not cultivate the soil just before a frost or freeze because it loosens and dries the soil.
- ❑ Maintain a moist, compact soil that is able to store more heat during the day than a loose, dry soil. Moist, compact soil has more heat to transfer to the crop at night.
- ❑ Mow sod closely in spring. It has been found in Oregon that sod mowed close to the ground with a flail mower is nearly equivalent to a clean-cultivated vineyard floor (Sugar et al., 2000).
- ❑ Train varieties with a procumbent (trailing) growth habit to a high cordon to lessen the frost hazard, as the closer buds are positioned to the ground, the greater the frost hazard (see Table 3.2).
- ❑ Prune vines in the dormant season, but leave those canes that are ultimately to become bearing spurs at their unpruned length; return to prune them to the desired number of buds when the terminal buds have sprouted 2 to 4 inches (Sugar et al., 2000).

Summary

The first three chapters in this guide have considered a large number of factors that are important to the success of the grape-growing enterprise, including economic and market considerations as well as careful variety selection. Consistent production of high yields of quality fruit will be more easily attained if you plant your vineyard on a good site. The information in this chapter gives you a solid starting point to work from in evaluating the suitability of potential grape sites. Once vines are in the ground, it is prohibitively expensive to relocate them. Mistakes made in site selection can be very costly. Weigh the many factors in selecting a site; focusing on one feature to the exclusion of others is a serious mistake.

Compromises must inevitably be made because few sites are ideal in all regards. However, you should not compromise on good soil depth and internal drainage, and on having good local relief. We have observed that even 100 feet in local relief can generate highly beneficial thermal zones for relatively frost-free grape production in most seasons, provided there is a broad enough valley floor below the vineyard for cold air to collect. This chapter provides considerable information on the important first step of *how to* evaluate the probability of damaging frost events for potential vineyard sites. We encourage you to take advantage of climate information available from the North Carolina State Climate Office , where experts can provide historical probability analysis of the frequency of temperature events below 32°F (or, 34°F, if you wish to identify the potential for cold injury under low atmospheric humidity conditions) for a number of locations across the piedmont, foothills, and mountains. Your county Extension agent can assist you in this initial phase of site evaluation and may also be able to furnish you with information regarding the range of budbreak dates in your area for winegrape varieties you are interested in growing.

While it is still possible to identify slopes and hillsides that have a lower risk of spring frost, it is also important to recognize that the hazards of a late spring frost, or frost-freeze, cannot be entirely avoided. Rather than adopt a view that all forms of active frost protection are too costly, a more practical approach may be to first pinpoint the frost hazard may be associated with a particular site, and then to consider the most economical methods for reducing these potential losses.

Short of investing in an active frost protection system, consider passive protection approaches for a site that may be too frost-prone for an early budbreak variety like Chardonnay. For example, at the Reidsville test vineyard site, we identified a *vinifera* variety that breaks bud later than Chardonnay, and by growing this variety, we would significantly reduce the need for active frost protection. If substitution of varieties or types of grapes is not an option, it is very important that you evaluate different types of active frost protection. In using an economic investment analysis, we demonstrated that for vineyard sites with a probability of radiational frost in 2 years out of 10, a wind machine could be a profitable risk management tool.

Realizing that many potential grape growers do not have the financial flexibility to purchase prime vineyard sites with minimal frost hazard, chapter 11, *Spring Frost Control,* provides further information on each of the major methods of active frost protection. Several commercial vineyards in North Carolina's piedmont have used wind machines over the last decade and can attest to their cost-effectiveness on relatively frost-prone sites.

References

Amerine, M. A., H.W. Berg, R. E. Kunkee, C. S. Ough, V. L. Singleton, and A. D. Webb. 1980. The Technology of Winemaking. 4th edition. AVI Publishing Co. Inc. Westport, CT.

Dethier, B.E. and N. Shaulis. 1964. Minimizing the hazard of cold in New York vineyards. Cornell Extension Bulletin 1127. 8pp.

Evans, R. G. 2000. The art of protecting grapevines from low temperature injury. Proceedings of ASEV 50th Anniversary Annual Meeting, Seattle WA, June 19-23, pp 60-72.

Gardea, A. A. 1987. Freeze damage of 'Pinot noir' (*Vitis vinifera* L.) as affected by bud development, INA bacteria, and bacterial inhibitor. M.S. Thesis, Oregon State University, Corvallis.

Gladstones, J. 1992. *Viticulture and Environment.* Winetitles, Adelaide, Australia. 310 pp.

Hurt, W. N. 1923. Thermal belts and fruit growing in North Carolina. U.S. Department of Agriculture's Monthly Weather Review Supplement, No. 19.

Jackson, David, and Danny Schuster. 1987. The Production of Grapes & Wine In Cool Climates. Butterworths of New Zealand (Ltd), Wellington, New Zealand, p. 5.

Jones, G. V., and E. Hellman. 2000. In: Oregon Viticulture, Site assessment, ed., E.W. Hellman, Oregon State University, pp 44-50.

Johnson, D. E., and G. S. Howell. 1981. Factors influencing critical temperature for spring freeze damage to developing primary shoots of Concord grapevines. American Journal of Enology Viticulture. 32. 144-149.

Martsolf, J. David, and Robert M. Peart. 2003. Frost control rules. Proceedings of the Florida State Horticultural Society. FAES J. Series No. N-02253, 115.

Moncur, M. W., K. Rattigan, D. H. McKenzie and G. N. McIntyre. 1989. Base temperatures for budbreak and leaf appearance of grapevines. American Journal of Enology Viticulture. 40:21-26.

Perry K. B. 1998. Basics of Frost and Freeze Protection for Horticultural Grapes. Hort Technology. 8(1) 10-15.

Perry, K. B. 1998a. Guide to deciding when to start and stop irrigation for frost protection of fruit crops. Horticultural Information Leaflet 713, North Carolina Cooperative Extension Service, NC State University, Raleigh, NC.

Perry, K. B. 1998b. Average Last Spring Frost Dates for Selected North Carolina Locations. Horticultural Information Leaflet 707, North Carolina Cooperative Extension Service, NC State University, Raleigh, NC.

Perry, K. B. 1998c. Average Growing Season for Selected North Carolina Locations. Horticultural Information Leaflet 709, North Carolina Cooperative Extension Service, NC State University, Raleigh, NC.

Perry, K. B. 1998d. Basics of frost and freeze protection for horticultural crops. *HortTechnology* 8:10-15.

Perry, K. B. 1999. Weather and climate information for North Carolina. Horticultural Information Leaflet 706, North Carolina Cooperative Extension Service, NC State University, Raleigh, NC.

Smart, R. E., and P. R. Dry. 1980. A climatic classification for Australian viticultural regions. Australian Grapegrower and Winemaker 17: 8-16. Ryan Publications Pty Ltd., Ashford, Australia.

Sugar, D., R. Gold, P. Lombard, and A. Gardea, 2003. In: Oregon Viticulture, Strategies for frost protection, ed., E.W. Hellman, Oregon State University, pp.213-217.

Teubes, Andrew and Johan Wiese. 2003 (Nov). Practical Viticultural Experience of Certain "New" Cultivars: Viognier, Petit Verdot, Tannat, Mourvédre Part 4. Wynboer – A Technical Guide for Wine Producers, Suider-Paarl, South Africa http://www.wynboer.co.za/recentarticles/1103cultivar.php3.

Trought, M.C. T, G. S. Howell and N. Cherry. 1999. Practical considerations for reducing frost damage in vineyards, Lincoln University, New Zealand, 43 pp.

White, R. E. 2003. Soils for Fine Wines, Oxford University Press, New York, NY.

Winkler, A. J., J. A. Cook, W. M. Kliewer, and L. A. Lider. 1974. General Viticulture. University of California Press, Berkeley, CA.

Wolf, T. K., and J. D. Boyer. 2003. Vineyard Site Selection. Publication Number 463-020, Virginia Polytechnic Institute and State University, Blacksburg, VA. http://www.ext.vt.edu/pubs/viticulture/463-020/463-020.html.

Wolf, T. K., and E. B. Poling. 1995. The Mid-Atlantic Winegrape Grower's Guide. North Carolina Cooperative Extension Service, NC State University, Raleigh, NC.