Understanding and Preventing Freeze Damage in Vineyards
~ Workshop Proceedings ~

December 5-6, 2007
University of Missouri-Columbia

Workshop Sponsors
Institute for Continental Climate Viticulture and Enology, University of Missouri-Columbia
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Memorial Union ~ Mark Twain Ballroom

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Organizing Committee Members

Dr. R. Keith Striegler
Mr. Andy Allen
Mr. Eli Bergmeier
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Cover photo: One freeze-injured shoot and one surviving shoot in central Missouri shortly after the April 4, 2007, freeze. Photo courtesy of Andy Allen.

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Workshop Agenda

Wednesday, Dec. 5, 2007

8 a.m.	**Registration opens**
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9:15 a.m.	**The Easter Freeze of 2007 — What Happened?** *Dr. Patrick Guinan; Assistant Professor and State Climatologist, University of Missouri-Columbia*
9:45 a.m.	**Freezing and Survival Mechanisms of Grapevines** *Dr. Imed Dami; Assistant Professor and Extension State Viticulturist, Ohio State University*
10:30 a.m.	**Break**
10:45 a.m.	**Grapevine Cold Injury and Recovery After Tissue Damage and Using Cane Burial to Avoid Winter Injury** *Dr. Martin Goffinet; Senior Research Associate, Cornell University*
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1:45 p.m.	**Overview of Active Frost, Frost/Freeze and Freeze Protection Methods** *Dr. E. Barclay Poling; Professor and Extension Small Fruit Specialist, North Carolina State University*
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	Dr. David Zoldoske; Director, Center for Irrigation Technology, California State University-Fresno
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	Dr. Imed Dami; Assistant Professor and Extension State Viticulturist, Ohio State University
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	Dr. E. Barclay Poling; Professor and Extension Small Fruit Specialist, North Carolina State University
9:45 a.m.	**What We Learned From the Easter Freeze in Missouri**
	Mr. Andy Allen; Extension Viticulturist, Institute for Continental Climate Viticulture and Enology, University of Missouri-Columbia
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	USDA-Farm Service Agency Representative
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	Mr. Lynn Gay; Hindsville Farms
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1 p.m.	**Adjourn**

The Easter Freeze of 2007 — What Happened?

Patrick Guinan

Missouri State Climatologist
MU Extension Commercial Agriculture Program

An unusually warm and persistent weather pattern established itself across the contiguous United States in March of 2007 and led to an early start to the growing season for a large part of the nation. At the same time Alaska was witnessing one of their coldest Marches on record with bitterly cold temperatures affecting much of the region for most of the month. As seen in Figures 1 and 2, and reminiscent of a Dickens classic, it was a tale of two cities. While most of the nation was basking, Fairbanks, Alaska, had witnessed its second coldest March in the past 104 years. Daily temperatures were running 10 to 30 degrees below normal and only one day reported an above normal average temperature. Alternatively, Columbia, Mo., reported its fourth warmest March in the past 118 years. Daily temperatures were averaging 5 to 20°F above normal, and there were only six days with below-normal temperatures.

Overall, March 2007 was the second warmest March on record for the lower 48 states and the warmest March since 1910. Temperatures over the lower 48 states averaged more than 6°F above normal. Alaska had recorded its third coldest March since 1918, averaging more than 12°F below normal for the month.

The meteorological condition that led to this anomalous and persistent warm weather pattern was a blocking ridge of high pressure in the upper atmosphere that developed during March and encompassed a large part of the contiguous U.S. This weather pattern remained entrenched for the entire month of March and first few days of April and prevented any cold air invasions from Canada.

Toward the end of March, long-range computer models were indicating a major weather pattern change to affect a large part of the United States. The ridge of high pressure was forecast to break down and allow bitterly cold air that had been trapped in Alaska and northern Canada to spill southeastward into the nation east of the Rocky Mountains. As anticipated, on April 3, 2007, a major weather pattern shift in the form of an arctic cold front dived southeastward through the northern Plains and sent temperatures tumbling to record low levels for many locations, especially over Easter weekend (April 7-8).

The record cold spell that affected the eastern half of the United States from April 4-10, 2007, was nothing short of incredible and disastrous. According to the National Climatic Data Center, the average temperature for the 7-day period was 10 to 20°F below normal across a large part of the impacted region and more than 1,500 temperature records were either tied or broken.

During Easter weekend temperatures across much of the region plummeted to the teens and lower 20s, shattering previous records (Figure 3). Various communities in eight states broke all-time record low temperatures for the month and other locations experienced their latest spring date where the mercury dipped below 20°F. For example, on Easter morning Joplin, Mo., dropped to 19°F and tied their all-time record low for the month of April. Figure 4 shows the minimum temperatures that occurred during this cold wave across Missouri. Figure 5 shows the number of hours Columbia, Mo., was below freezing throughout the event.

What made the situation especially troubling was the unusual warm spell prior to the cold wave. Using Columbia, Mo., as a midpoint for the state, Figure 6 shows the unprecedented nature of this event when the third warmest March 21 through April 3 period on record abruptly transitioned to the coldest April 4 through April 9 period on record. The average temperatures during the two week period of March 21 through April 3 were 14 to 16 degrees above normal across Missouri and it was during this time vegetative growth rapidly responded.

Because of this unusually long-lived and mild period, winter wheat and forage crop growth was ahead of schedule across the central Plains and Midwest and many fruit crops were blooming across portions of the Midwest and southern U.S. Much of the corn crop had been planted and had emerged across the south as well. Numerous tree and plant species were also in more advanced stages of growth than usual. This set the stage for a major disaster to sensitive vegetation as record cold temperatures dived southward and encompassed the eastern half of the United States. According to Dr. Michele Warmund, a University of Missouri professor of horticulture who specializes in fruit crops, the only other freeze that had a greater impact on Missouri was the Armistice Day Freeze of 1940 when whole fruit trees were lost due to the rapid drop in temperatures in autumn. The temperature anomalies in March and April were so unusual that statewide average monthly temperatures in Kansas, Arkansas, Oklahoma, Tennessee and Mississippi were colder in April than in March.

Another harsh ingredient of the freeze event was the wind associated with it. Strong winds persisted throughout the coldest period and prevented any successful effort of mitigating freeze effects. For 39 consecutive hours, beginning 5 a.m. April 6 through 7 p.m. April 7, the average 10-foot hourly wind speeds at Columbia ranged from 10 to 16 mph with gusts approaching 30 mph. During this time, the temperature remained at or below 32°F for 34 hours.

Unfortunately, the impacts for Missouri and other states were widespread, and it was an economic burden for agricultural producers and commercial interests not to mention the freeze damage homeowners experienced in their yards and gardens. According to a preliminary assessment compiled by various state and federal agencies and others, the April freeze event exceeded 1 billion dollars in losses across the affected area. This estimate does not include supplementary losses experienced by small nurseries, retail garden centers, farmers markets, homeowners, etc. The Easter Freeze of 2007 will go down as an historical and memorable event for many with lingering effects that will last indefinitely.

Figure 1.

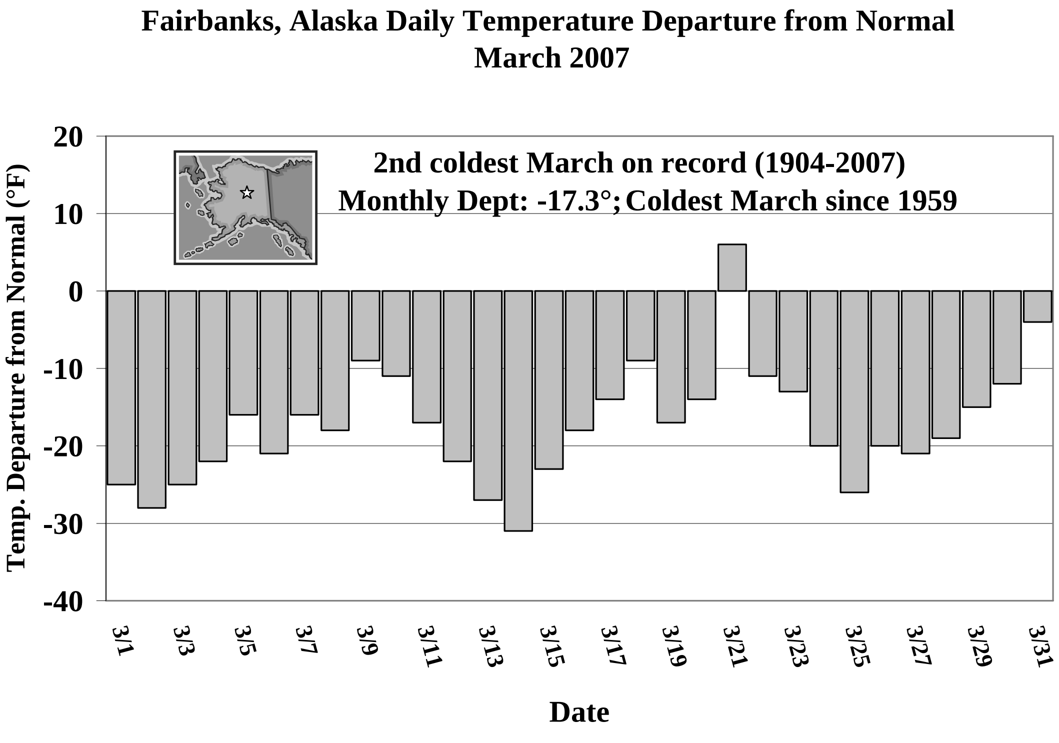


Figure 2.

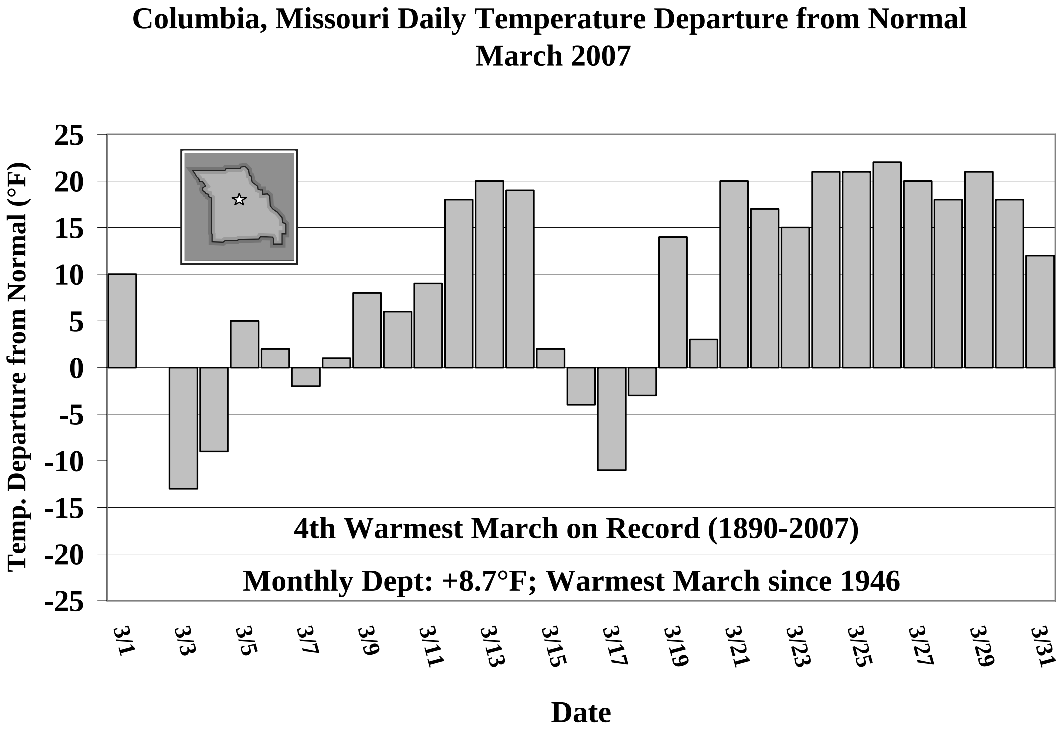

Columbia, Missouri Daily Temperature Departure from Normal
March 2007

Figure 3. Minimum temperatures (°F); April 4-10, 2007.

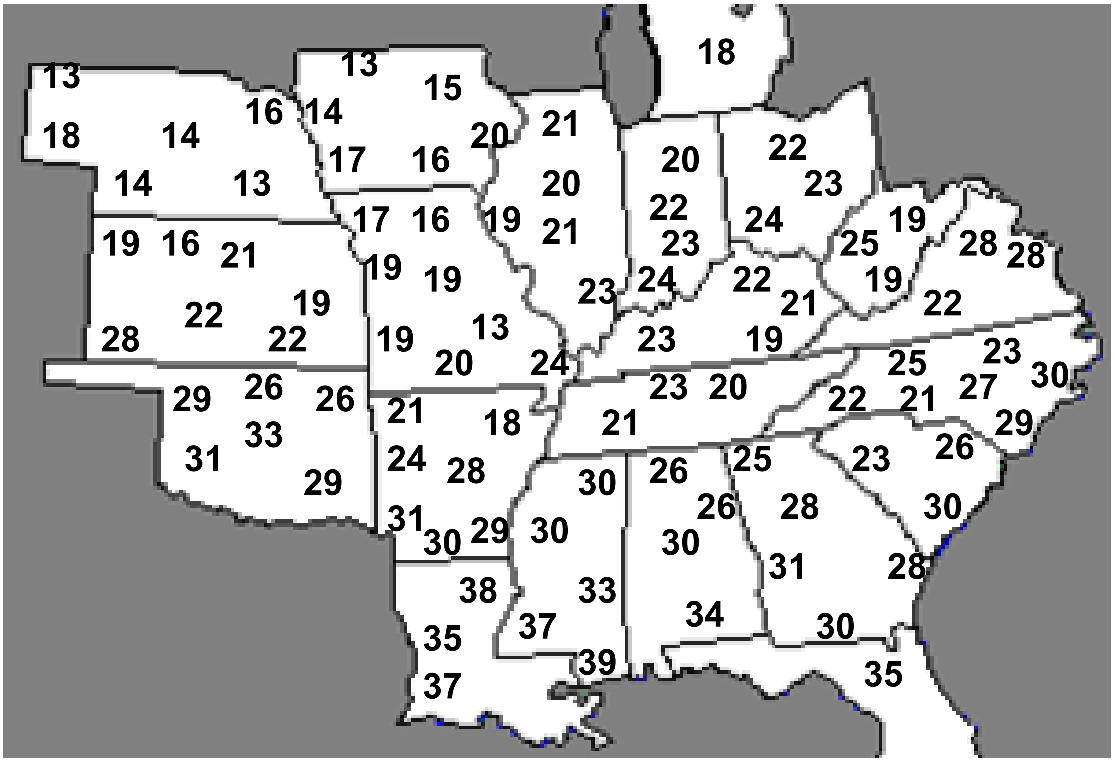
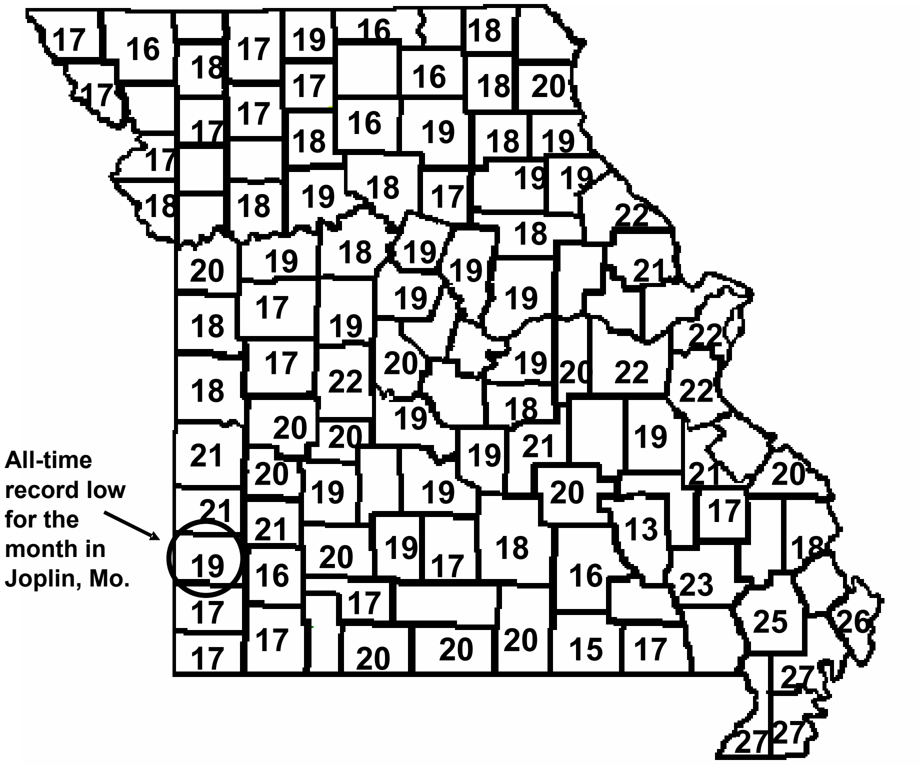


Figure 4. Minimum temperatures (°F) in Missouri April 4-10, 2007.



All-time record low for the month in Joplin, Mo.

Figure 5.

Average Hourly Temperature at Columbia, MO (April 4-9, 2007)

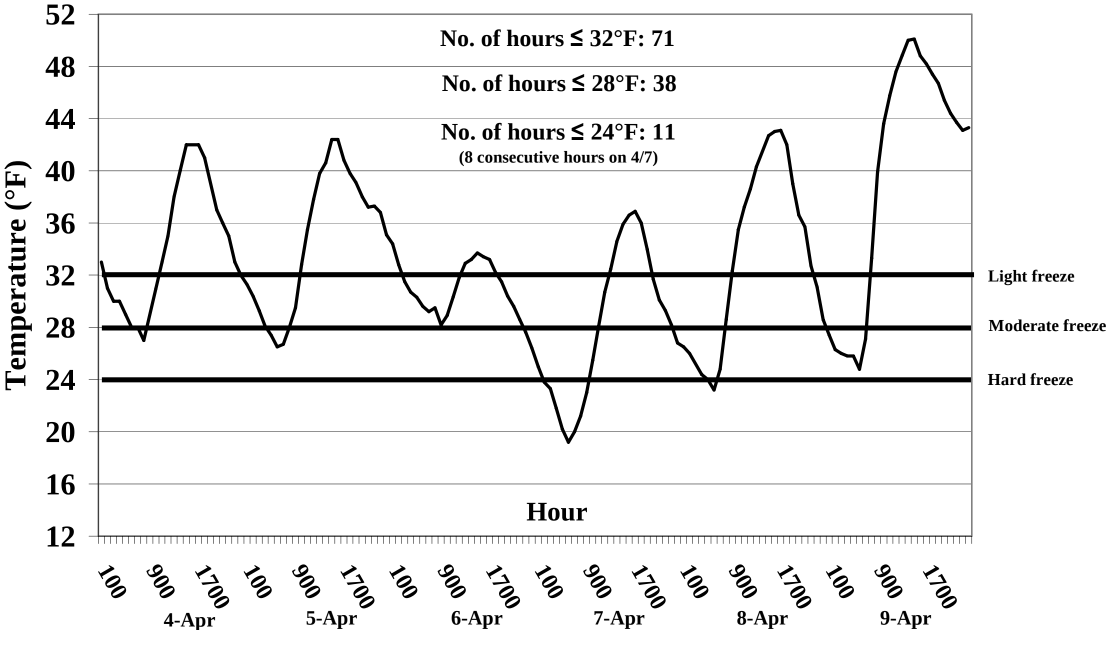
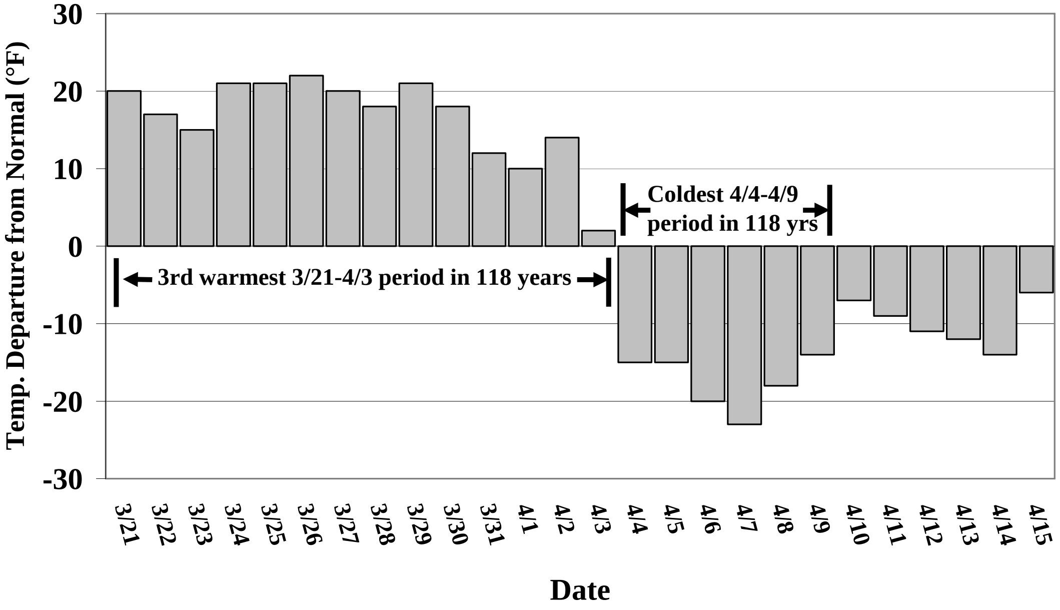


Figure 6.

Columbia, Missouri Daily Temperature Departure from Normal
March 21-April 15, 2007



Freezing and Survival Mechanisms of Grapevines

Imed Dami

Horticulture and Crop Science
The Ohio State University

Cold Hardiness and Survival Mechanisms of Grapevines

Cold hardiness is the ability of dormant grapevine tissues to survive freezing temperature stress during autumn and winter. During the dormant season, grapevines withstand freezing temperatures through two mechanisms. First, cane and trunk tissues tolerate ice outside living cells, which results in desiccation of the cytoplasm inside the cells. Second, buds avoid freezing injury by supercooling. Supercooling is the ability of the contents of a cell to remain liquid at subfreezing temperatures. When ice forms inside the cells it ruptures cell membranes and leads to leakage of cell content and ultimately cell death.

Site of Injury at the Cellular Level

Living cells of all grapevine tissues are composed mostly of water. Their subcellular organelles are adapted to function in a highly aqueous environment. These organelles are bound within membranes that allow selective, regulatory movement of materials in or out of the organelles. Therefore, membrane integrity is essential for cells to do their job and to exchange materials between cells within tissues. Freezing and intracellular ice formation destroy these structures and cause cell cytoplasm and vacuole contents to leak out, resulting in cell death. If enough cells die, that portion of the affected vine dies. With extensive freeze injury, the vine suffers significant structural and functional injury to all aboveground organs.

Measuring Freeze Injury

Severe winter injury events do not occur in major viticultural regions every year. Therefore, to study the mechanisms of cold hardiness and winter injury, laboratory methods have been developed to simulate freeze episodes using temperature-controlled chambers. Cold hardiness of grapevines is often measured by the temperature that kills 50 percent of the primary bud population in midwinter, termed “lethal temperature 50” (LT_{50}). Two methods are described in this section. Other methods are fully described in the book *Winter Injury to Grapevines and Methods of Protection* (Zabadal et al. 2007).

Oxidative browning

This most common and relatively inexpensive method of measuring tissue viability is based on color change of bud or cane tissues that occurs after freezing and thawing. Healthy tissue maintains its green color; an injured tissue leaks its cell contents (phenolic compounds) and turns brown. This is similar to the reaction that occurs when you peel a potato — a few minutes later, it turns brown. In a controlled freezing test, cane or bud samples are retrieved along a series of decreasing set temperatures. They are placed at room temperature to thaw and to allow the oxidative browning reaction to take place. Samples are visually examined 48 to 72 hours later. The LT_{50} is estimated with a statistical analysis method. Although oxidative browning is a subjective observation, LT_{50} values derived from this method often correlate well with the actual killing temperature. This method is used extensively by grape growers and researchers to assess bud mortality prior to pruning.

Thermal analysis

Supercooled water can be detected using thermal analysis (TA). Thermocouples (or thermoelectric modules) are used to detect the latent heat released (called an exotherm) by water in the bud tissue as it freezes. During a controlled freezing test of a grape bud, TA detects two exotherms. A high-temperature exotherm (HTE) indicates the freezing of bulk or free water outside bud cells (i.e., ice forming between bud scales). This freezing event often occurs at temperatures between 23 and 14°F and does not cause bud injury. A low-temperature exotherm (LTE) often follows an HTE and indicates the freezing of supercooled water inside bud cells. An LTE typically occurs between 14 and -40°F and always results in bud death. TA is the only method that actually measures the killing temperature, rather than estimating it. This method has been used effectively for various grape genotypes and provides accurate and consistent results that correspond to field observations. TA, however, requires the use of specialized and expensive equipment and is currently conducted only at research institutions.

The Dynamic Cycle of Cold Hardiness

Cold hardiness is a complex, genetically regulated process that involves several genes that work in concert to cause the physiological, biochemical, and molecular transformations of a grapevine. These changes include the formation of new compounds (e.g., sugars, proteins, and amino acids) and changes in composition (e.g., lipids). The ultimate goal is plant survival. Grapevine survival and adaptation in cold climates depend on seasonal changes that result in a transition from a cold-tender to a cold-hardy state, a process known as cold acclimation. The response of grapevines to short days and low temperatures is different from that of other woody plants (e.g., apples) in that shoots of vines do not set terminal buds as an indication of growth cessation and initiation of cold acclimation. There are two basic stages of cold acclimation in grapevines. The first stage is induced primarily by low but above-freezing temperatures (above 32°F) and occurs in late summer to early fall before any freeze events. In general, Native American species such as *Vitis labrusca* and *Vitis riparia* begin to cold acclimate in response to short days first. *Vitis vinifera* grapevines cold acclimate in response to both short days and low temperatures. During the first stage of cold acclimation, buds of grapevines do not reach their maximum cold hardiness, but they can survive temperatures below freezing (LT_{50} ~ 5 to 20°F). The second stage of cold acclimation is exclusively induced by temperatures below freezing and usually coincides with the first killing fall freeze in mid-October to mid-November. At this stage, cold hardiness increases dramatically, and vine tissues become hardier as daily temperatures continue to decrease or remain below freezing. Grapevines reach maximum hardiness in midwinter, when the coldest temperatures occur. Bud cold hardiness is usually at its maximum in December, January and February, with LT_{50} values ranging from -5 to -35°F.

Cold hardiness is also increased when the temperature drops below freezing and remains below freezing through midwinter. Periderm formation; mobilization of carbohydrate reserves to canes, trunks and roots; and isolation of dormant buds from the vascular tissues in canes and trunks are complete shortly after leaf fall. However, cold hardiness continues to increase as a result of redistribution of water within bud tissues and desiccation. This process is strongly influenced by winter temperatures. For this reason, the absolute temperature at which cold injures grapevines will vary among regions. Temperature fluctuations during midwinter (January thaw) are not desirable because grapevines can deacclimate quickly under those conditions. After chilling requirements are met, fluctuating temperatures above and below freezing may allow winter injury to occur at above-normal critical temperatures. This phenomenon has often been observed in the lower Midwest such as in Missouri.

As spring approaches and temperatures increase, the vines begin to lose hardiness through a process called “deacclimation.” This is the transition from a cold-hardy to a cold-tender state, or the reverse of cold acclimation. Deacclimation occurs more rapidly than fall acclimation and is dependent primarily on increasing air temperature. Cultivars respond at different rates to temperature cues. Concord acquires and loses winter hardiness much more rapidly than Cabernet Sauvignon, and Riesling is intermediate. Some wild grapevines, such as *V. riparia* when growing in Canada or *V. amurensis* when growing in Russia, are adapted to very cold winters and short growing seasons. However, these species may rapidly deacclimate during brief midwinter rises in temperature. They may also be highly susceptible to spring freeze injury because their buds deacclimate too quickly. By the time of bud break and subsequent shoot growth temperatures, only a few degrees below 32°F may be lethal to grapevine tissues. Because the grapevine buds go through a U-shaped cycle of cold acclimation and deacclimation each year, it is important to note that cold hardiness is dynamic rather than constant throughout the dormant season.

Seasonal Changes in Vine Anatomy Related to Cold Hardiness

Shoot acclimation

Vineyardists talk of “wood maturity” and its importance to cold hardiness and to next year’s cropping. Growers have a keen sense that the woody parts of the vine, especially the current season’s stems, must develop certain physical and physiological characteristics if they are to survive winter. What are these changes? A key change signaling stem acclimation to cold is the progression of stem browning from shoot base to tip. As autumn progresses, grapevine shoots change color from green to tan or brown, and leaves turn yellow and/or red and fall. After leaves fall off the shoot, the remaining woody stem is called a cane. This browning results as a new tissue composed of cork cells arises in the stem’s outermost (oldest) phloem. These new cork cells secrete a waxy substance in the cell wall. Together with the cells that created them, the band of cork cells is known as periderm. Cork cells die after they reach full-size, after which they are then nearly impervious to water. When fully formed, the periderm seals off the inner dehydrating cells from the once green outer cortex, which then dies and turns brown. The periderm thus prevents the rehydration of acclimated cells by external water. Browning of internodes progresses along the stem from stem base to stem tip. The stem’s protected living cells interior to the periderm continue to dehydrate through the fall and become filled with cryoprotectant (freeze-resistant) compounds (sugars, amino acids, and proteins). The vascular cambium is no longer active at this point, so no new cold-tender cells are produced. An early, well-developed periderm is a sign of vine preparation for winter.

Cultural practices that result in overcropping, heavily shaded canopies, inadequate nutrient uptake, high levels of pests and disease, and any other stress may delay or reduce periderm formation. Such practices may also affect production and storage of carbohydrates and nitrogen-based compounds needed for both winter protection and optimal vine growth and flowering next season.

Bud acclimation

The dormant buds on canes during winter pruning contain several complex, miniature branching systems within their bud scales. The whole bud is referred to as a compound bud, complex bud, or eye. This compound bud begins as a simple, small, green lateral appendage at the base of a small shoot growing in the angle formed between the green stem and a leaf. No matter their size, all buds of a grapevine arise in the angle (i.e., axil) between a leaf's petiole and the shoot or between a bud scale and the bud's central cylinder. The compound bud is actually an axillary bud at the base of a small shoot, the summer lateral shoot, which grows out at most nodes of a green shoot. Although the summer lateral may produce many leaves and become woody, small summer laterals usually turn yellow and fall off later in summer or fall. The compound bud persists as the overwintering bud.

By winter, the compound bud contains many embryonic leaves, some primordial inflorescences (clusters), and also some accessory buds in the axils of the bud scales and embryonic leaves. A careful cut across the compound bud or a vertical cut through the center of the bud will show at least three major buds inside the bud scales. Knowledge of this structure and of their differential susceptibility to subfreezing temperatures is important to growers. The size of next year's crop depends on which of the interior buds develops in the spring.

The central bud is the largest of the three major buds that make up the compound bud. The central bud is termed the primary bud because of its position relative to the summer lateral and because of its size, dominance, and potential for cropping. Because the primary bud produces the main flowering shoot, its destruction by freezing severely limits fruiting potential. The secondary bud is smaller and less fruitful than the primary bud and usually remains dormant when the primary bud elongates in spring. However, the secondary may break along with the primary and produce one or two clusters of its own. The third bud, situated on the side facing away from last year's leaf scar, is called the tertiary bud. It is smaller than the secondary bud and usually is not fruitful. Nonetheless, if the primary and secondary buds do not emerge, whatever the reason, the tertiary may at least produce some leaf area for vine survival. Growth of the strong primary bud usually inhibits the emergence of the secondary and tertiary buds. Over the seasons, assuming they are not removed as a result of pruning, secondary and tertiary buds become embedded in the stem as new growth rings surround them. These hidden buds may remain dormant for many seasons and may never emerge. Shoots that emerge as suckers come from such buds that are released from their dormant state. They also often emerge near the base of the vine after winter injury occurs to the trunk and upper parts of the vine.

The compound bud's acclimation to cold begins much like that of stem tissue by gradual dehydration of cells, changes in membrane composition, and the development of freeze-resistant compounds. The vascular system that connects the bud to the cane is only weakly developed before winter. This helps to isolate the bud tissues and limits the potential for rehydration of bud tissues by any water that may remain in the cane during vine acclimation. After leaf fall, there is no transpiration stream to move water upward in the vine. The hard, almost varnish-like surface of the outer bud scales is nearly impervious to exterior wetting, as are the dense, woolly hairs found on the outer surface of all the interior bud scales and largest leaves in the bud. All of these factors combine to keep the bud tissues dry over the winter.

Buds on a cane acclimate to different levels of cold hardiness. The primary bud is the least hardy of the three buds typically found within the compound bud. This may be related to the degree of tissue maturation or degree of development. The primary bud typically has larger organs with more differentiated and specialized cells. The smaller, denser, less differentiated cells and tissues of secondary and tertiary buds may allow these buds a better opportunity to supercool.

Cell acclimation

In late summer and fall, cellular acclimation involves slow cell dehydration — that is, the gradual elimination of as much unbound (free) water as possible. Simultaneously, cellular membranes are stabilized, the cell's solute concentration rises, and the concentration of cryoprotectant compounds increases. These cryoprotectants include certain sugars and protein complexes. They help to dehydrate the cell, stabilize its membranes, and bind water. Free water that is not bound up with other compounds will form ice as it freezes and destroy the cell's regulatory membranes. Therefore, all free water must be either bound or eliminated from the cell during the acclimation period so that it can freeze harmlessly in intercellular spaces of the tissue.

Variation in Cold Hardiness Among Grape Genotypes

Genotype determines a vine's maximum cold hardiness potential. Environment (soil, weather, topography, and pests) and grower management determine how much of that potential is realized. We don't completely understand why some varieties are hardier than others, but we know that cold hardiness does indeed vary among grape species. The most to least cold-hardy species are: *V. riparia* (North American species), *V. amurensis* (Asian species), *V. labruscana*, interspecific hybrids, *V. vinifera* and *V. rotundifolia.* Cold hardiness of grapevines is often measured by LT_{50}. Field and laboratory testing have identified distinct groups of vine hardiness (Table 1).

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Table 1. Relative cold hardiness of various grape genotypes.

Cold hardiness class	Range of critical temperatures*	Species	Example of varieties
Very tender	5 to -5°F	Most *Vitis rotundifolia*	Carlos, Cowart, Scuppernong, Supreme
		Most *Vitis vinifera*	Chenin blanc, Merlot, Semillon, Syrah (Shiraz), Sauvignon blanc, Zinfandel
Tender	0 to -8°F	Most *Vitis vinifera*	Chardonnay, Cabernet Sauvignon, Gewurztraminer, Pinot gris, Pinot noir, Sangiovese, Viognier
Moderately tender	-5 to -10°F	Some *Vitis vinifera* Some hybrids	White Riesling, Cabernet franc, Lemberger, Gamay noir, Chambourcin
Moderately hardy	-10 to -15°F	Most hybrids	Cayuga White, Chardonel, Traminette, Norton, Seyval blanc, Vignoles
Hardy	-15 to -20°F	Most *Vitis labrusca*	Catawba, Concord, Delaware, Niagara
Very hardy	-20 to -30°F	Some hybrids	Frontenac, Foch, LaCrescent

*Temperature that will kill 50 percent of primary bud tissues, or LT_{50}. It is expressed as a range because it varies with varieties, season, environment, and cultural practices. Also, note that LT_{50} of some varieties may overlap between hardiness classes.

Grapevine Cold Injury and Recovery After Tissue Damage and Using Cane Burial to Avoid Winter Injury

Martin C. Goffinet

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New York State Agricultural Experiment Station

Abstract

Significant winter injury to aerial parts of the vine includes injury to the vascular system and to the buds. No matter the stage of vine acclimation or deacclimation to cold, freeze injury of canes, cordons, and trunks begins in the outermost living cells of the phloem, just below the periderm layer. Severe cold events can kill all the conductive phloem right down to the cambial zone or even further, into xylem tissue. Once the cambium itself is injured, tissue recovery becomes very difficult or even impossible. Recovery will begin only after bud break. Tissue repair depends on a high level of cell division and differentiation that will later replace the conductive function of the dead tissue. This process depends, in turn, on the use of stored reserves and on the perfusion of growth regulators that move through healthy vascular tissue up or down the vine. Emergent leaves and maturing leaves are major producers of these stimulants to vascular differentiation. Assuming there is still some vascular continuity between shoots and roots in a stem or trunk with freeze injury, the relatively undifferentiated cells of the cambium and vascular rays nearest the injury are stimulated to divide and to form callus tissue. In time, the callus tissue generates an organized cambium and new, vertically oriented vascular cells that once again are efficient at water, nutrient, and carbohydrate movement.

As the stem tissues become acclimated, so do the nearby buds that will over winter. Buds typically are more cold hardy than cane tissues entering winter, but in late winter buds begin to deacclimate sooner than canes. There are major varietal differences in bud cold hardiness before, during, and after winter. After shoot emergence, zones of dead buds create management problems, because pruning decisions may have already been made. The repair of freeze-injured canes, cordons, and trunks depends on the stimulus of emerging shoots and leaves. The greater the number of buds breaking and the less injured the vascular system in older wood, the faster and more efficient the repair becomes. When not enough buds are present in the canopy area to allow adequate repair of badly injured wood down below, the vine may need either replacement or retraining with suckers.

Cane burial has been examined in New York through research efforts with cooperating growers of tender *Vitis vinifera* varieties. Although the burial each fall of hardened sucker canes does avoid deep freezing injury suffered by the aerial canes of the vines, buds of buried canes also show problems the next growing season. These problems have appeared in our experimental vineyard blocks in our late winter and early April excavations of cane samples. Although not frozen, the primary buds of these samples display significant "water-soaking" and dark discoloration. When buried canes are brought up and laid out on the trellis to

> produce a crop, they often show more “blind nodes” and more delayed bud and shoot emergence than do canes not buried. Previously buried canes also have significantly fewer clusters per useful cane than do unburied canes. This may result for the above reasons, but also because buds and shoots lying below the wire on previously buried canes will be rubbed or cut off before bloom. Growers can expect about half the cluster counts per cane on previously buried canes compared to unburied canes. In normal or warm years, this is an issue, but in vine-killing years, buried canes allow a “half crop” and no dead vines. Typical extra costs per acre for cane burial in the Finger Lakes Region is about $400 to $500. This includes labor needs for laying out ground wire, wrapping them with suckers, hilling, and buried cane extraction, pruning, and tying in spring.

Introduction

In temperate North America our commercial grapevine varieties, especially those of *Vitis vinifera*, are often severely injured by cold. This may take the form of early winter injury before vines are fully acclimated to deep-winter cold. It may entail severe freeze events in mid-winter that kill even normally acclimated tissue. An additional concern is spring freeze injury due to heavy frost after initiation of bud and shoot growth. This presentation will cover tissue injury and vine repair processes after cold injury in the winter. Following this, I will present some recent research in New York State on winter burial of grapevine canes to avoid potential killing freezes, a practice that is becoming an important part of the annual viticulture practices of growers in New York and other cold growing regions.

Vine Tissues and Cold Injury

My intent herein is to show specific tissue injury and repair in light of the severity of cold injury. In another article in these proceedings, Dr. Imed Dami covers the theory of cold acclimation processes in vines and how ice forms in their tissues. To understand the processes involved in the mechanism of vine repair, we need to review the basic anatomy and tissue organization in grapevines. The cellular destruction through freezing and the resultant type and extent of tissue injury will dictate to the vine and to the grower the likelihood of recovery and vineyard productivity.

A critical concept is that the vine is integrated throughout its length — root tip to shoot tip — by the vascular system. This system is composed of three tissues organized as concentric cylinders in all stems and roots: phloem on the outer side, xylem on the inner side, and the vascular cambium between these (Figure 1). The phloem carries organic materials, such as sugars made in leaves, primarily downward throughout the vine. The xylem functions to convey water and mineral nutrients primarily upward into shoots and into leaves. Xylem also becomes lignified and offers enlarging stems and roots rigid structural support. Green shoots have a simple ring of vascular tissues surrounding a central pith. To the outside of the vascular ring there is a soft green tissue known as the cortex just under the epidermis. All these tissues consist of living cells and therefore can be seriously injured if a cold event exceeds the depth to which they have acclimated to cold.

In late summer and fall, as leaves begin to yellow from shoot base to tip, the browning of the shoot progresses in the same direction (Figure 2). This occurs because the cortex tissues are sealed off from the vascular tissues by the formation of a waterproof band tissue in the outer phloem. This band, known as periderm, signals to growers that the vine is acclimating to winter cold and to the desiccating effects of wind during a season that lacks available soil moisture. The entire vascular system of all aerial parts of the vine dry down and develop both physical and physiological protective barriers to freezing temperatures. Buds at the nodes of the naked canes also develop protective barriers, including physiological cold acclimation, physical isolation from the cane, bud scales, and dense hairs within the buds that aid in keeping buds dry through the winter.

Given enough years, the internodes of a green shoot will grow into a thickened stem if not pruned away. Each season in woody stems and roots the vascular cambium becomes active under the influence of newly emerging leaves and undergoes cell divisions to create new layers of phloem and xylem. By the end of each year, the previous year’s ring of phloem in stems is isolated by a new underlying layer of periderm, which kills the older outer ring. The stringy bark tissue seen on older stems and trunks is the product of several years of phloem and periderm layer formation and removal. This means, of course, that no matter how old a vine part is, it will only have a very thin layer of active phloem to conduct all organic materials in the vine. Xylem, on the other hand, will build up ring by ring, year by year, because xylem (wood) is produced to the inside of the cambium and thus is left behind each season.

The final segment of this discourse on cane structure is that there must be an annual renewal of xylem and phloem production in canes, spurs, cordons, and trunks if the new leaves are to be fully integrated with the root system. As we will see, cold injury can seriously impact this shoot-root connection. In spring, as water moves into stems and as shoots put on new leaves, the cane vascular system “wakes up,” that is, it once again activates the cambium tissue to begin cell divisions that produce more xylem and phloem (Figure 3). In the cane, new vessels and fibers can be seen first in the outer xylem beneath the cambium, and later there are new phloem cells produced next to the outer side of the cambium. Of course, if freezing kills buds, there will be no stimulus of new leaves for cambium activity in that part of the cane.

Regardless of the tissues or cells that might be killed by freezing, the result is that the membranes surrounding small sub-cellular organelles are destroyed, so organelle function (thus cell function) is lost. The outer cell membrane also is destroyed; so cellular materials leak out into the surrounding tissue and create a “water-soaked” appearance in freeze-injured vine organs. The spilled contents of cells also become oxidized and the browning of phenolic materials may appear. Often, in once-green tissues such as cane internodes or in fruitful buds, these tissues take on a “cooked asparagus” appearance (Figure 4). These symptoms of cold injury often will not appear in the vineyard if growers cut such organs to see problems. Rather, the vines must be sampled and brought into a warm room for two to three days, so that thawing, cellular leakage, and oxidation can occur. Living (thus unfrozen) vine parts will remain green or cream-colored, while frozen parts will then be obvious.

In all stems — canes down to the lower trunk — phloem tissue has a higher freezing point than xylem at all times of the year. Slices of freeze-injured canes and trunks demonstrate the differential susceptibility of these two vascular tissues (Figure 5). Phloem, being located just beneath the bark surface is also more readily affected by fluctuations in air temperature. This can especially be a problem when trunks are warmed above 32°F by sunlight on the south and west sides in winter, followed by a night of very cold temperatures. This thawing may deacclimate phloem over several days, further raising the freezing point.

Repair of Cold-Injured Organs

Cells injured by deep winter freeze events usually die and cannot be repaired. However, it is usual that many cells in and near the affected tissue will escape this fate. Many of these “escapes” are very simple, non-specialized cells that retain the capacity for cell division. Such cells include cambial cells and unspecialized cells of the nearby xylem or phloem tissue. In spring, when temperatures increase and begin to drive metabolic activity, these living cells begin division and form a loose aggregation of non-specialized cells call callus. Callus tissue begins to fill in and displace the nearby dead tissue and, in time, new functional xylem and phloem cells begin to develop in the callus as the callus spreads (Figure 6A). Depending on how much of the entire area of a stem was injured, the repair of the damage may take place quickly or it may be prolonged or even impossible. Small, injured sectors of cambium soon heal over and produce new xylem and phloem, although the new tissues may be poorly differentiated (Figure 6B). Much depends on whether buds are also killed, because, without new shoots there will be no stimulus for cambium development and new vascular cells in the affected area of callus (Figure 6C).

The greater issue for vine survival and vine management is whether winter injury has occurred throughout so many regions of the vine that the vascular integrity between the root system and any new shoots is inadequate for growth and cropping. When the whole vine is debilitated or destroyed by cold, vine replacement becomes the only option. Partial killing of canes, buds, or killing of one trunk of a double-trunked vine may allow retraining of a vine. The strategy of keeping several suckers available for such restructuring each year is a part of normal practice in cold-prone regions. Included in the grower's toolbox for winter vine survival are methods of physically protecting cold-susceptible varieties, including hilling up over graft unions and burying some sucker canes under the soil during the winter to assure at least some crop the next year and to be in a position to train up new trunks should the need arise.

New York Experiences With Winter Cane Burial

Our research into the effects of burying sucker canes to avoid severe winter freezes started after the extreme years suffered in the winters of 2003-04 and 2004-05. After the first such winter, several Finger Lakes growers decided to bury sucker canes to see if winter cold could be avoided and to test the costs and labor issues of doing burial. For winter 2004-05, which also killed or debilitated whole vineyard blocks, these growers had buried a range of varieties. In spring of 2005, after buried canes were tied to the trellis, one grower surveyed bud survival and growth for buried and unburied canes (Table 1). Clearly, canes left up in the canopy over winter suffered severe killing compared to the buried canes on the same vines. This gave a marketable crop for these vines. However, it became obvious to this grower and several others that buds of buried canes had a significant problem with bud emergence and survival, even though they did not experience extreme cold.

We developed a grant proposal to look at several issues of the cane burial practices of cooperating growers. The first was to avoid anecdotal information by setting up controlled replications that would test the survival and subsequent growth and productivity of buried vs. unburied canes on the same vine. The second was to test cane burial of several vinifera varieties that were either more cold tolerant (Cabernet franc) or less tolerant (Pinot gris, Gewurztraminer, Pinot noir). In doing this, we looked at the cold hardiness levels of buds in mid-winter and early spring for buried and unburied canes, we visually rated tissue injury of buds and cane internodes, and we made counts of bud and shoot performance in spring to gauge cropping potential. We also wanted to know the grower's cost per acre for burying vines here in New York.

Experimental Setup

Vines in the experimental blocks were each selected for good sucker canes that would be buried beneath a deep hill of soil (Figure 7). Canes were laid out on ground wires, tied, and then buried. Three temperature sensors (Thermochron iButton, Dallas Semiconductor, Dallas, Texas) were placed in each vineyard site on insulated backers on the north side of a central vineyard post. Figure 7A shows the relative position of the buttons, at the level of the buried wire, another placed at the level of the trellis wires having the aerial canes, and a third to be positioned just above the level of the hilled soil. We pre-selected two dozen similar vines for each variety and flagged them for follow-up. At several times over the winter, up to the week before the grower took up the buried canes, we collected the buried canes and also two representative aerial canes from each of five vines in each variety studied. After canes were unburied, we used all remaining flagged vines to study the differences in shoot emergence and subsequent productivity between any tied-up buried canes and their aerial counterparts. This included counts of total nodes, number of "blind" nodes, dead buds, or nodes having delayed shoot growth. Near bloom, we counted cluster numbers along the parts of the canes actually tied in the trellis for cropping.

Results and Discussion

The temperatures recorded hourly by the sensors showed that no bud-killing temperatures were experienced either in winter 2005-06 (Figure 8) or in winter 2006-07. Sensors in the aerial environment fluctuated daily between daytime highs and nighttime lows, while the buried sensors remained buffered from both the lowest and highest temperatures. Buried canes never experienced temperatures lower than about 26 to 24°F in either of the two winters. Actual bud-killing temperatures for three varieties in late-winter 2006 are plotted as circles in Figure 8. Both of our test winters were relatively mild, so all bud samples showed little to no cold injury.

Regardless of the mild winters, our examination showed much more tissue damage in buried buds than in buds of aerial canes on the same vines from January to time of cane digging in April (Figure 9). In the case of Pinot gris, burial caused considerable damage to buried buds, so bud cross-sections revealed a "water soaked" or "cooked asparagus" discoloration. Although this injury looked similar to that of cold-injured buds seen in winter-killed aerial buds, the buried buds did not experience freezing. Our view is that the subterranean environment is decreasing the viability of buried buds. We do not yet know whether this is because of high soil water content, anoxia due to waterlogging of tissue, invasion by microorganisms into tissues from the soil, or by slow respiration and depletion of stored carbohydrate. We still have bud samples from our two study years in the freezer awaiting carbohydrate analysis to determine if respiration under the soil might be part of the problem.

After canes were extracted from the soil in our study plots, the growers typically trained up at least one previously buried cane as either a potential trunk renewal or as a fruiting cane for crop production. A dozen or more of our flagged vines had this procedure done to them, so we looked at "return bloom" and cane productivity on these canes. For each vine examined, we compared the usable "buried" cane with one of the "aerial" canes tied up on the vine. We counted total nodes along each cane type, node number actually on the wire (the productive section of the cane); number of nodes and percentage with missing buds, buds delayed in emergence, and the numbers and percentage of clusters per new shoot.

In both years there was an obvious difference in the two cane types early after bud break (Figure 10). Buried canes had more "blind nodes" (Table 2) and delay of shoot emergence compared to aerial canes. This was the case, whether one counted the entire cane from base to tip or just the nodes actually tied onto a trellis wire for crop production. In fact, aerial canes averaged almost half the percent blind nodes compared to the percentage for buried canes. This could be expected, based on the above assessment of the poorer quality of the buds when extracted from the soil. Thus, the winter bud ratings carried through into the spring growing season.

The most critical issue for the grower is whether cane burial will provide enough "insurance crop" to make it all worthwhile, should buried canes have to be used to provide a crop after severe freezes wipe out aerial cane productivity. Our counts of clusters along the entire canes were slightly lower for buried canes than for aerial canes, but the real difference showed up when counts were made only for the cane ends tied to the trellis for a crop (Table 3). Buried canes had half the clusters of aerial canes on the wire portion. Also, the percentage of all the clusters that lay on the wire of buried canes was only a little more than half that of the percentage for aerial canes (42 percent vs. 76 percent).

Looked at another way, we found that aerial canes retained about twice as many clusters per node than did buried canes, whether for the entire length of cane or only for that part tied to the trellis (Table 4). The upshot of all this is that growers can expect about half their "normal" crop if they have to train up buried canes to replace dead or severely winter-injured buds of aerial canes. Perhaps after a severe winter, this percentage might increase, as there is some evidence that buds buried in severely cold winters do better than those buried in milder winters.

Economics of Burial in New York Vineyards

Cane burial is not a cheap operation. A grower must make the determination as to whether burial costs can be borne each year. This decision will rest on likelihood of vine-killing freezes, the varieties to be protected, the vineyard site, other annual expenses and income, and past experiences with killing freezes in the region. Our cooperating growers have tried several burial methods, including the typical soil mounding/removal and also the use of baled straw. We also have contacted a grower using large round bales of straw as a winter cover. Costs for these methods here in New York are summarized in Tables 5 through 8.

One of our cooperators decided to bury entire vines of Pinot gris in the 2005-06 winter after losing his crop the previous two cold winters. Vines were cut to near the ground, leaving four or more long canes from retained suckers. These were wrapped on ground wires and covered with soil. In spring these were tied up into the trellis as fruiting wood or as renewal trunks. His crop was about half that of a good crop year before the freeze years hit. His net cost per acre for doing whole-vine burial was $573 over any other per acre cost he would normally have (Table 5).

Another cooperating grower in western New York compared soil burial to straw burial, using 40-lb. straw bales. If one extrapolates the cost of covering his experimental 50-vine row with this straw to the cost per acre, assuming $3 per bale, his cost would be $800 to $1,000 per acre (Table 6). This estimation was also based on costs experienced by Dr. Tom Zabadal in Michigan a few years ago.

In correspondence with a grower on a cold hilly site in the Finger Lakes, I was told that he cut straw cost by using large round straw bales and spooling it out on the vineyard floor between, and then into, the rows. This cut some cost, with the result that he had a net additional management cost of $600 per acre per year (Table 7). A concern of this grower is that he has a high-vigor site, so vines grow very fast and very large, and the addition of so much organic material to the vineyard seems to be exacerbating this problem.

Our major cooperator the last two winters has given us the best estimate of costs and benefits of covering canes with soil (Table 8). If his vinifera vines give him $1,600 per ton (which was typical this fall) at 3 tons per acre, and if he loses half his vines to freezing once every 10 years, he would have a return of about $37,000.00 per acre after replant and recovery costs are considered. If he buries suckers every year for 10 years, it will cost him about $4,000.00, whether he had a killing freeze or not. One killing freeze in that 10 years gives a return of $44,000.00.

This grower will continue to bury canes on an annual basis because:

1. There is less money to finance ($7,100 less per acre reestablishment cost over 10 years), assuming there will be at least one bad year in 10.
2. There are fewer replants to buy, plant, and establish, and this rate is predictable.
3. The grower retains production after severe freezes.
4. The winery has no loss of a vintage and has a product to sell annually.
5. The cost of buying in grapes in a bad year would be very high, area-wide.
6. The grower accepts this $400/acre cost as a planned crop insurance premium.

Summary of Cane Burial Studies

On the research side, the following points can be made:

1. Cane burial indeed can save vines, although in mild winters the grower sees no gain in revenue, and actually sees a loss.
2. Buried canes are less productive than are aerial canes in good years, but likely improve their quality and productivity in deadly cold years.
3. We have found buried buds to actually be slightly less cold hardy in our freezer studies (perhaps there is some deacclimation in the warmer environment).
4. Buried buds appear to suffer injury unrelated to freezing.
5. Buried canes have more sporadic, delayed, weakened and dead buds than do aerial canes after normal or warm winters.

From the grower and economic sides, growers *can* save about half the usual crop by burying canes in severe winters, but more important, they can save a vintage and have wine to provide their customers. They also save in that they will not have to buy-in higher-priced grapes after vines are killed or set back, nor buy, replant, and retrain whole vineyard blocks. That, too, will save the two to three years it takes for vines to payback growers with a crop. The overall strategy of growers who bury canes is to have the advantage of consistent, less risky crop production for their most cold-sensitive varieties.

Acknowledgements

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Table 1. Bud survival rates of several varieties assessed in a Finger Lakes vineyard the third week of April 2005, for canes buried or not buried.

Variety	Notes	Not buried	Buried
Cabernet franc		45%	90%
Merlot	Older vines	4%	51%
	Younger vines	3%	39%
Gewurztraminer		29%	37%
Cabernet Sauvignon	Older vines (3 March)	23%	44%
	Younger vines	16%	43%
Pinot noir	Young vines		51%
Pinot noir	Mariafeld		38%
Pinot gris			53%
NY Muscat hybrid			65%

Table 2. Percentage of blind nodes on aerial vs. buried canes trained on the trellis wires at a Finger Lakes test site in spring 2007.

	Entire cane		On wire only	
Variety	Aerial canes	Buried canes	Aerial canes	Buried canes
Pinot noir	21%	42%	19%	45%
Pinot gris	17%	41%	14%	39%
Gewurztraminer	18%	28%	19%	17%
Cabernet franc	17%	28%	14%	18%
Overall mean =	18%	35%	16%	30%

Table 3. Clusters counted on aerial vs. buried canes and percentage of their clusters retained for a crop on the trellis at a Finger Lakes test site in spring 2007.

	Entire cane		On wire only		Percentage on wire	
Variety	**Aerial**	**Buried**	**Aerial**	**Buried**	**Aerial**	**Buried**
Pinot noir	15	11	11	4	74%	30%
Pinot gris	17	9	12	4	73%	39%
Gewurztraminer	20	18	16	8	77%	46%
Cabernet franc	18	14	13	6	81%	42%
Overall mean =	18	14	13	6	76%	42%

Table 4. Clusters per node on aerial vs. buried canes trained on the trellis wires at a Finger Lakes test site in spring 2007.

	Entire cane		On wire only	
Variety	**Aerial**	**Buried**	**Aerial**	**Buried**
Pinot noir	1.2	0.6	1.2	0.5
Pinot gris	1.4	0.5	1.4	0.5
Gewurztraminer	1.4	0.8	1.4	1.0
Cabernet franc	1.5	1.0	1.7	1.4
Overall mean =	1.4	0.7	1.4	0.8

Table 5. Example of whole-vine burial cost per acre of Pinot gris for a Finger Lakes grower in winter 2005-06.

Item	Cost per acre
70 hours/acre pruning, brush removal, wrapping, clipping:	$795
0.5 hours/acre brush chopping:	$8
2.7 hours/acre hilling up soil:	$42
Material — wire lips @ $0.08 each:	$9
5 lbs. No. 8D coated nails:	$4
Established costs (pruning, brush pulling/chopping):	-$285
Net additional costs per acre:	$573

Table 6. Example of costs per acre for tying sucker canes to ground wires and covering with 40-lb. straw bales.

Item	Cost per acre
Tractor operation	$70
Mulching equipment	$20
Labor installing, removing canes & wires, extra pruning	$500
135 bales of straw x $3 per bale	$400
Extra wire	$10
Net additional costs per acre:	$1,000

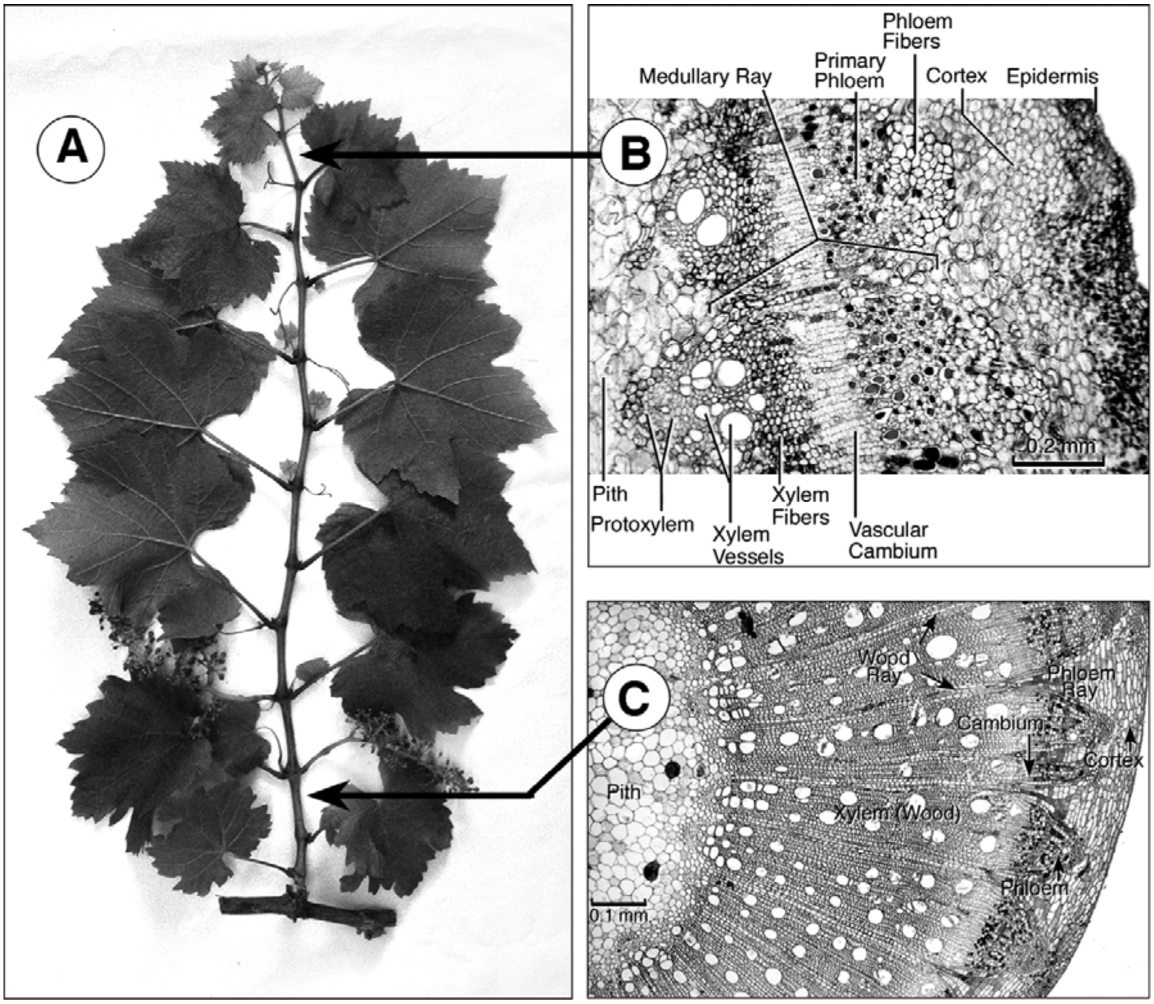
Table 7. Example of costs per acre for cane burial with large round straw bales.

Item	Cost per acre
Tractor operation, maintenance, spooling, disking, etc.	$100
Labor installing, removing	$300
20 bales of straw x $10 per bale	$200
Net additional costs per acre:	$600

Table 8. Example of sucker cane burial costs per acre for a Finger Lakes cooperator compared to costs associated with one vine-killing freeze to half his vines in a 10-year period.

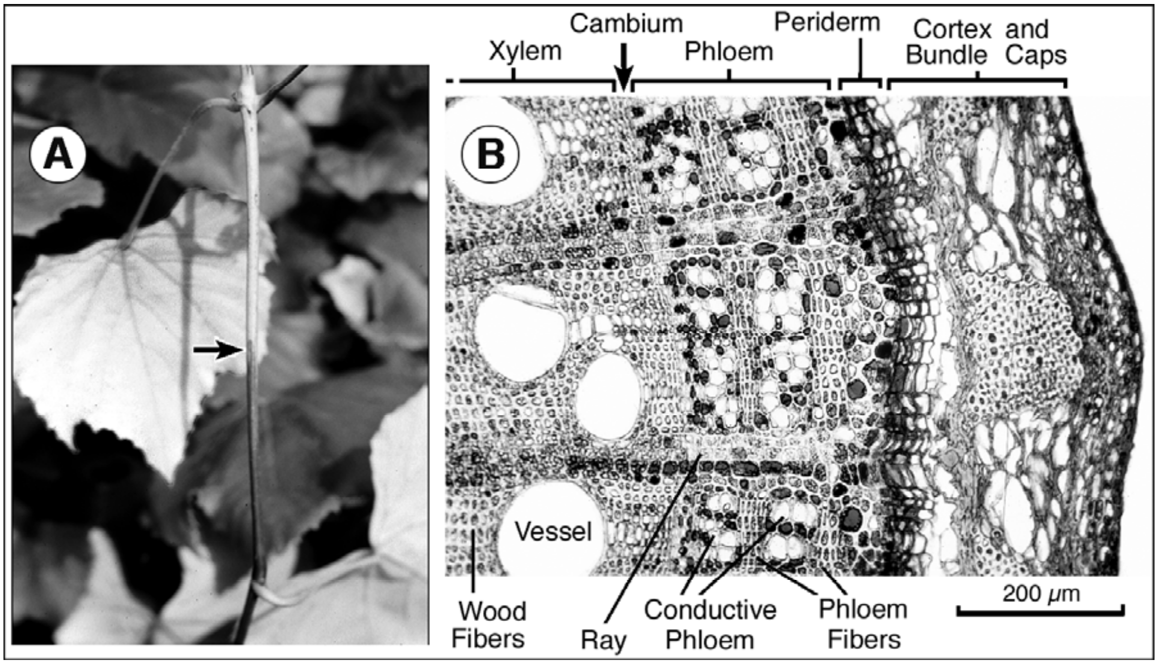
Item	Value
Crop value annually — Assume $1,600 per ton at 3 tons/acre	$4,800
Value of crop per acre over 10 years	$48,000
<u>After single freeze (no burial) with 50% vine loss (10 year return):</u>	
Assume 2 years to recover production after freeze loss	
(50% x $4,800 x 2)	–$4,800
Partial replant cost per acre (one-time cost)	–$6,300
Revised per-acre value over 10 years ($48,000 – $11,100)	$36,900
<u>After cane burial in hilled soil over 10 years:</u>	
Added cost per acre of cane placement, wiring, tying, burial	
and extraction (10 x $400 per year)	–$4,000
Revised per-acre value over 10 years ($48,000 – $4,000)	$44,000

Figure 1.



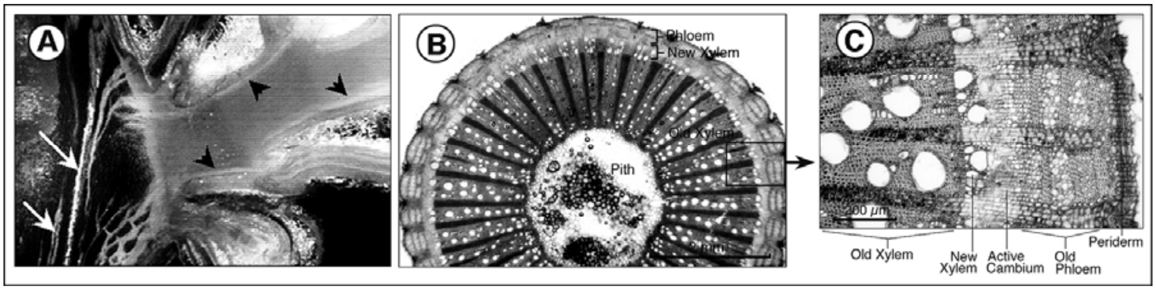
Summer shoot of Chardonnay grapevine showing external (A) and internal (B, C) development. Position B is a region of green flexible internodes, while position C is a region having green but stiff woody internodes. B. Cross-section of a young green internode. The “bundles” of vascular tissues contain xylem on the inner side, phloem on the outer, and a young vascular cambium between. Bundles are separated laterally by ray tissue. Note the central pith tissue of the internode and the cortex tissue outside the vascular bundles. Phloem conducts sugars and other organic materials. Xylem conducts water and inorganic nutrients via the large open vessels. C. Cross-section of a thickened, woody, green internode. Note the production of a widened xylem band to the inside of the vascular cambium but only a very thin increment of phloem.

Figure 2.



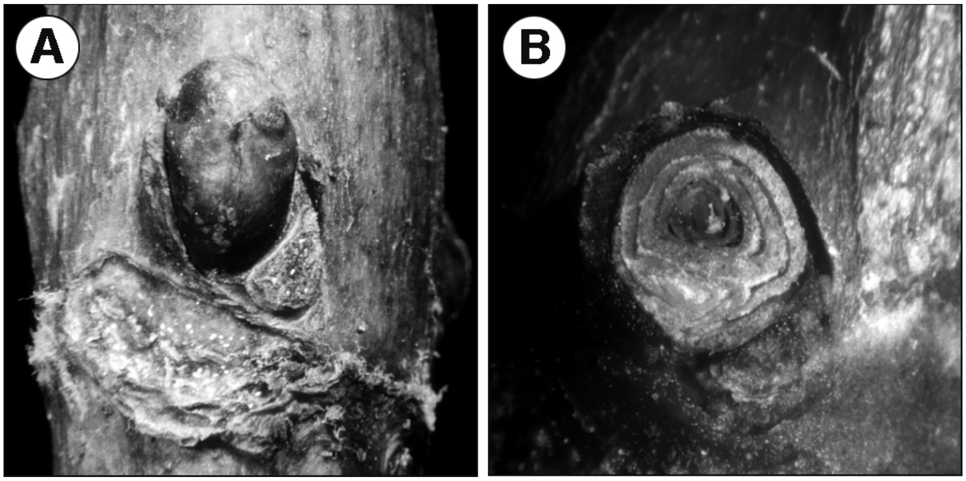
A. Cane “maturation” occurs as internode-browning progresses toward the shoot tip in late summer and fall. B. Cross-section of an internode recently browned. Browning results because periderm tissue seals off all tissues on its outer side and that tissue dies. Conversely, all tissues to the inside of periderm are sealed against outside moisture and they must remain dry all winter in their cold-acclimated state. Note absence of an active vascular cambium between xylem and phloem is the norm between fall and spring.

Figure 3.



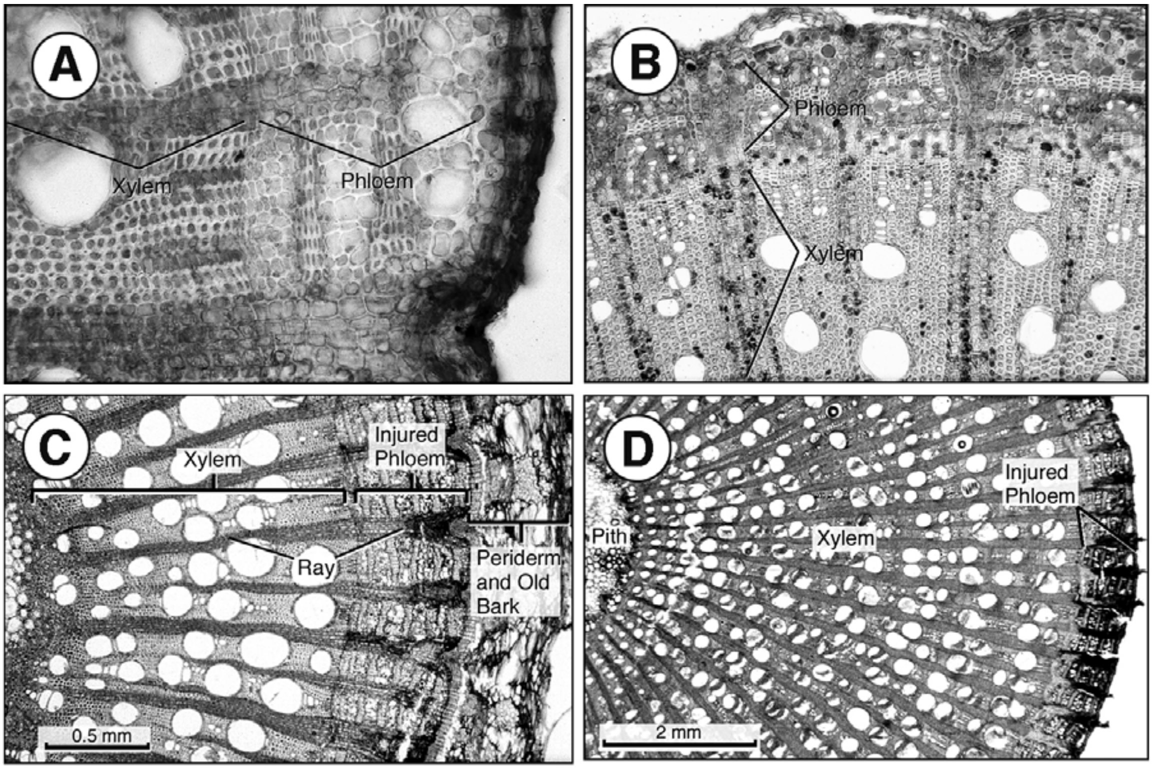
Normal development of a new ring of vascular tissue in canes in spring. A. Vertical slice through an emergent primary shoot at the cane node. Vascular strands (arrowheads) have developed during shoot emergence, and expanding leaves stimulate the cane into renewing vascular development (arrows). B. Cane internode cross-section showing production of new xylem outside the older woody xylem. C. Magnified view showing new water-conducting xylem elements by the now-active vascular cambium. New phloem has not yet been formed by the cambium; so older phloem has to serve the new shoots until new phloem will form on the outer flank of the cambium.

Figure 4.



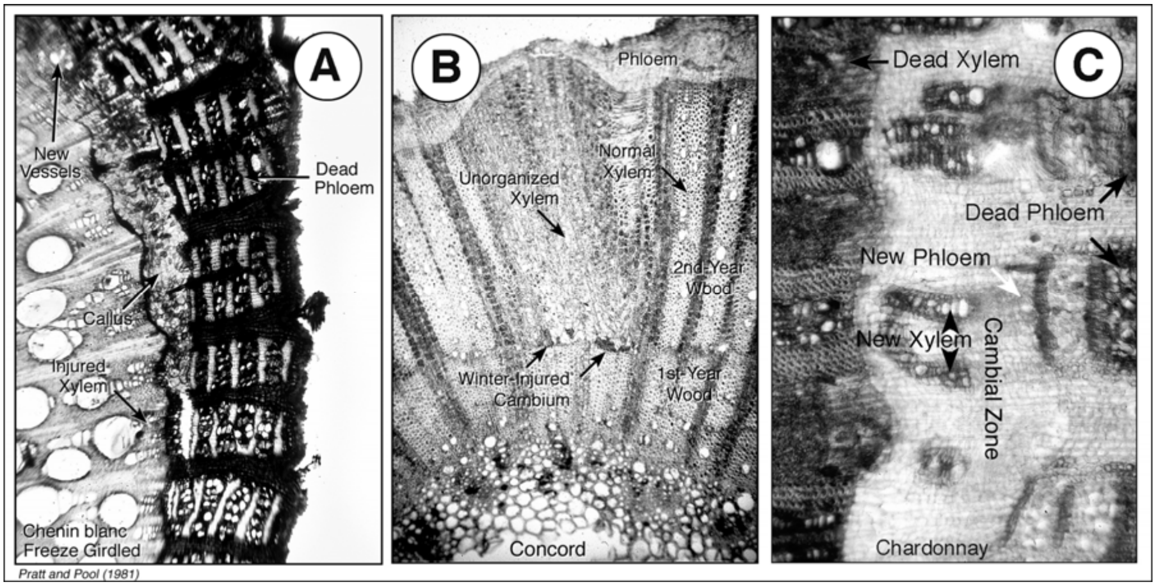
A. Face view of a dormant bud at the node of a grapevine cane in winter. B. Cross-section of a winter bud whose central (primary) bud component has been freeze-injured, showing a dark, water-soaked appearance (“cooked asparagus”).

Figure 5.



Cane and trunk cross-sections showing winter injury. A. Normal, unfrozen cane section of Concord in the region of the outer xylem and phloem. All tissues are healthy. B. Similar region in a cane internode that suffered mid-winter freeze injury. Note darkened phloem, with xylem still functional. C. Winter-injured Niagara cane showing severe phloem injury below old bark and periderm tissues. D. A young Niagara trunk cross-section, showing completely injured phloem from a late-winter freeze event. Xylem tissues remain good. Vine recovery above trunk is “iffy.”

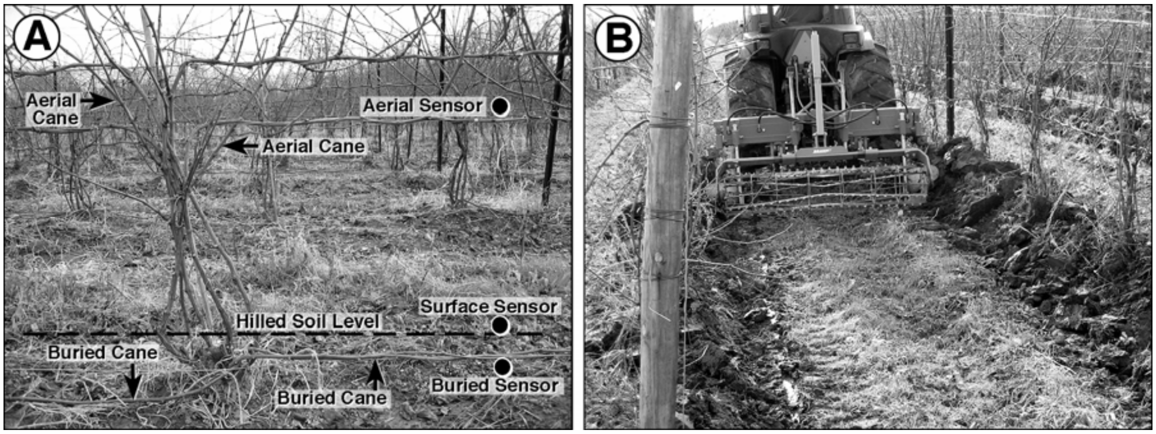
Figure 6.



Pratt and Pool (1981)

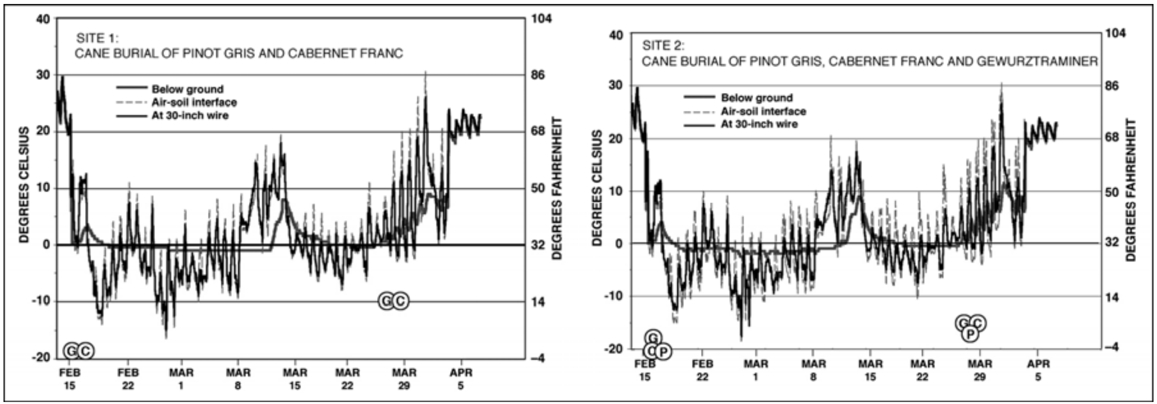
Cross-sections showing repair of frozen cane and trunk tissues. A. Chenin blanc cane in late spring after severe freeze injury with liquid nitrogen. Cells still alive in the cambial region have proliferated a wedge of callus tissue between dead phloem and injured xylem. Some weak, new xylem vessels have appeared in the callus. B. Late summer two-year Concord cane showing repaired sector that had frozen the previous winter. Note that the entire second year's layer of new xylem has not produced normal, large vessels and the outer rind of phloem is thinner than in nearby sectors. C. Cambial zone of a Chardonnay trunk in spring after February cold injury. Note severely injured older xylem and phloem, with the reactivated cambium only producing very small new xylem vessels and the new phloem not well organized. Bud break and leaf development on this vine was very weak and much delayed.

Figure 7.



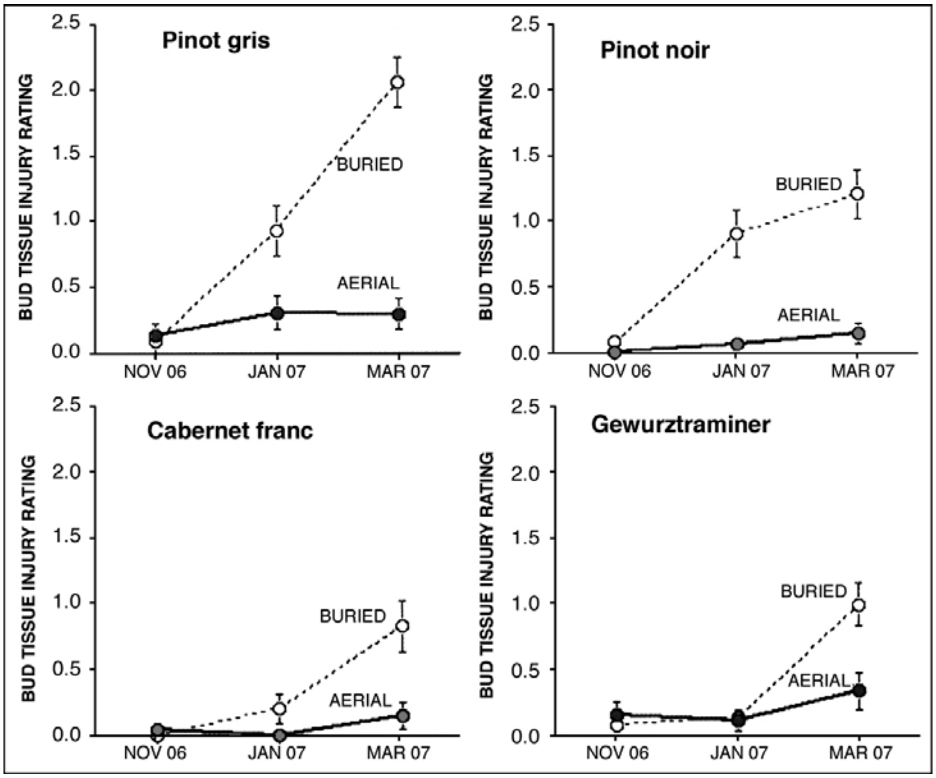
Vine preparation for cane burial. A. Vine showing sucker canes tied to a ground wire. These were later compared to canes left "unburied," up in the trellis (aerial canes). The hatched line is the intended level after soil mounding. Black circles represent levels at which temperature-sensing "buttons" were placed for hourly temperature readings through winter. B. Burial of trunk bases and tied-down canes in early November.

Figure 8.



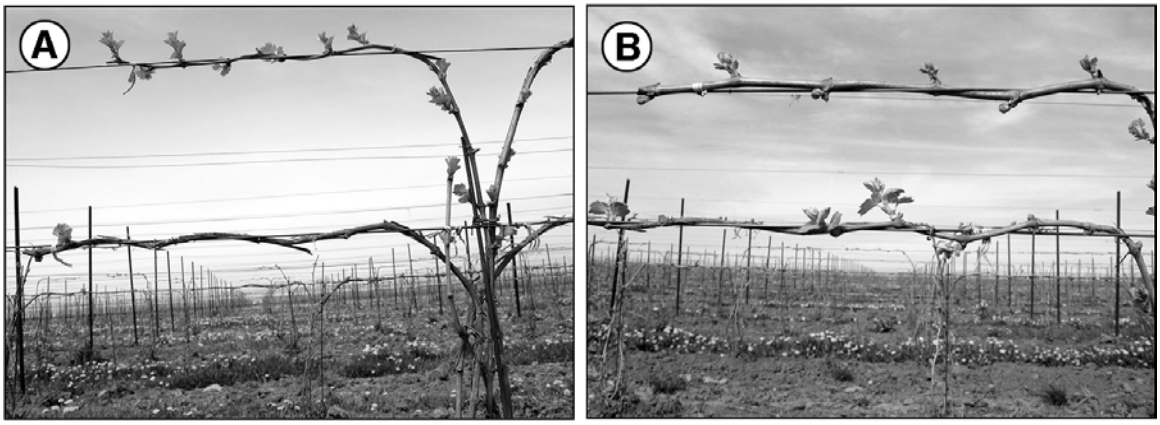
Late-winter temperatures in two Finger Lakes vineyard sites in February to April 2006, as recorded by temperature sensors positioned below the hilled soil, just above the air-soil interface, and at the height of the aerial canes. Site 1 (left) had Pinot gris (P) and Gewurztraminer (G), while site 2 (right) had those as well as Cabernet franc (C). The actual bud-killing temperatures of these varieties are circled on the graphs for mid-February and late March. Killing temperatures were not experienced. Note the great fluctuation of the daily high and low temperatures at the level of the ground and the trellis wires, but the steady, “comfortable” temperatures experienced by the buried canes. The soil is a huge temperature buffer and insulator.

Figure 9.



Visual ratings of primary bud injury in four varieties November 2006 (date of burial) to March 2007 for canes left exposed to air or buried in soil over winter in a Finger Lakes vineyard. Buried canes had buds significantly more injured, especially by time of unburial. Bud ratings were: 0 = no injury; 1 = moderate injury; 2 = “water soaked” or “cooked asparagus” color; 3 = brown or necrotic, in whole or in part.

Figure 10.



Comparison of shoot emergence from buried canes trained up as fruiting canes vs. typical aerial canes on Cabernet franc (A) and Gewurztraminer (B) vines, May 9, 2006. A. Buried cane is on the lower wire. B. Buried cane is on the upper wire.

Passive Freeze Prevention Methods

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Abstract

Low temperature damage is a significant problem in many grape-growing regions. Cold injury to grapevines may result from the winter minimum temperature; spring temperatures below -0.6°C (31°F), which may damage developing buds and shoots; or fall temperatures below -0.6°C (31°F), which may injure maturing canes and berries.

Efforts to minimize damage from spring freeze events can be divided into passive and active methods. Passive methods involve site selection, cultivar selection, and cultural practices, while active methods involve modification of the vineyard climate. The effectiveness of frost protection methods is dependent on the characteristics of the freezing event. This article will focus on passive methods of frost protection and management practices for vine recovery following frost damage.

Types of Freeze Events

The types of freezing events encountered in vineyards are radiation and advection freezes. These types of freezing events differ greatly in their frequency of occurrence and the meteorological conditions associated with them. Widespread cooling occurs as a result of the advection (horizontal movement of an air mass over land) of cold air into a region or from loss of heat due to radiation. An advection freeze occurs when cooling by advection predominates, and a radiation freeze occurs when radiational heat loss is the predominant form of cooling.

Radiation freezes occur mostly on clear, calm nights after cold air has moved into the region. The primary mechanism is loss of heat into space during the night. The rate of heat loss by radiation into space is partially determined by the amount of moisture present in the atmosphere. If the air is dry (low dew point) heat loss will be greater than when the air is moist. During radiation freezes, layers of cold air are formed with the coldest air normally found near the radiating surface. Normally, temperature decreases as height in the atmosphere increases. Thus, this meteorological condition is known as a temperature inversion (warm air layers over cool air layers).

An advection freeze occurs when a large mass of Arctic air invades and covers the region resulting in low day and night temperatures. Conditions can be clear or cloudy with strong winds which continue into the night. Due to the wind there is considerable mixing of the lower layers of the atmosphere.

Spring freeze events in Midwestern vineyards can be either radiation or advective freezes. Most of the passive frost protection methods that are addressed in this paper are more effective during radiation freezes than advective freezes. Unfortunately, it is very difficult to protect vineyards from damage during a severe advection freeze. Other papers in these Workshop Proceedings will discuss methods to combat advective freeze conditions.

Passive Protection Methods

Passive protection methods are used to avoid or minimize spring freeze damage. Site selection, cultivar selection, and cultural practices comprise passive protection methods. These methods can provide several degrees of protection, but generally do not offer as much protection as active methods. However, 0.6 to 1.2°C (1 to 2°F) of protection can often mean the difference between having a crop and crop loss. Also, passive protection methods do not cause significant increases in establishment costs for most vineyards.

Passive protection methods can be divided into those which are done prior to vineyard establishment and those which are done after vineyard establishment. Pre-planting practices are site and cultivar selection while post-planting frost protection efforts involve cultural practices such as soil management, row middle management, pruning, and applications of frost-protectant materials.

Site and cultivar selection are of great importance in reducing spring frost damage in vineyards. Site characteristics which influence air temperature are slope, exposure to the sun or aspect, and elevation. Sloping ground and elevation are important because they provide good air drainage (see Figure 1). Cold air is more dense than warm air and flows downhill in a similar manner as water. Vines growing in low areas where cold air accumulates are more likely to be damaged by frost. In addition, sites which have impediments to cold air drainage — such as raised road beds, buildings or vegetation (forests, overgrown fence rows, etc.) — should be avoided. Sides of hills facing toward the sun (SE or SW slope) will be warmer than hillsides facing away from the sun. In the spring, warm temperatures can result in early bud development. Planting on a north slope instead of a south slope may delay bud burst and reduce the probability of frost damage.

Another site characteristic which is important in certain vineyard districts is distance from large bodies of water. Large bodies of water, such as the Great Lakes, substantially moderate the climate of land areas on the leeward side of these bodies of water. The modifying effect is sometimes one of cooling the air while at other times it is one of warming the air, depending on the season and the prevailing weather conditions. In early spring warm air moving over the lakes is cooled, which can delay bud burst beyond the period of time when frost damage is most likely. Later, after bud/shoot development has begun, cold air masses moving into the area are warmed by the lakes and late spring freeze damage is avoided. The beneficial effects of large bodies of water are greatest for sites which are as close to the leeward side of the body of water as possible. As distance increases, temperature modification due to large bodies of water decreases.

Cultivar selection can influence the incidence and severity of spring frost damage. Differences in frost susceptibility among varieties are often related to bud phenology. In general, as bud development proceeds in the spring, the critical temperature (temperature at which buds will endure for 30 minutes or less without injury) increases or becomes warmer. Therefore, cultivars which have early bud burst and development are usually more susceptible to spring frost damage than varieties with late bud burst and development. For example, bud burst of Chardonel vines is often two weeks earlier than bud burst of Vidal blanc or Norton vines when grown in adjacent blocks. Planting Chardonel in frost prone sites without some active method of frost protection is inviting disaster. On the other hand, Vidal blanc or Norton might be planted on this site and grown successfully.

Cultivar differences in frost tolerance may also be related to factors other than bud phenology. Johnson and Howell (1981) detected small but consistent differences in cold resistance of buds from three cultivars at the same stage of development.

After the vineyard has been established, other passive protection methods can be used to reduce the chance of frost damage. Some examples are soil management, row middle management, pruning, and application of frost protectant materials.

Soil and row management can influence the minimum temperature in vineyards. The minimum temperature is affected by soil texture and soil water content. In general, peat and sandy soils do not store or conduct heat as well as loam or clay soils. Also, darker colored soils may absorb more solar radiation and store more heat than lighter colored soils. Consequently, if all other factors are the same, sandy soil would pose a greater hazard of frost damage than clay or loam soil. However, soil texture effects are probably not too important during most freeze events. Other factors usually have a greater impact than soil texture.

Soil conductivity and heat storage are also affected by the soil texture and soil water content. This is due to the unique properties of water which allow it to store considerable heat. In addition, moist soil will conduct heat better than dry soil. Frost hazard is lower for moist soil as compared to dry soil. Growers with drip irrigation can provide some protection for their vines by applying water before predicted freeze events. There would be no benefit from this action if the soil is already moist.

Row middle management can have an important impact on the susceptibility of vines to spring freeze damage. Until recently, recommendations for row middle management to avoid frost damage were to have moist, firm, bare soil in the row middles. The basis for these recommendations was that the conditions described favored absorption of solar radiation and subsequent transfer of the absorbed heat to vines during a freeze. These recommendations are still valid and should be followed in most situations. However, recent research results and grower observations indicate that in some situations the current recommendations need to be re-examined. Donaldson et al. (1993) found that vines where early season vegetation between rows was killed by spraying with herbicide had slightly warmer minimum temperatures than vines where row middle vegetation was controlled by mowing or discing. This occurred on most nights during the spring freeze season and was not influenced by vineyard canopy development. Also, some growers have observed that the presence of a cover crop (mowed close to the soil surface) has not caused increased risk of frost damage. Furthermore, the risk of frost damage with higher cover crops needs to be reevaluated in different viticultural districts due to the positive benefits that have been documented from cover crop use.

Pruning practices can be effective in reducing frost hazard, particularly on sites which are frost prone. The most obvious pruning practice to avoid frost damage is delayed pruning or late pruning. This is an effective strategy for small acreages, varieties with early bud burst, or as mentioned above, sites which frequently have frost. Delayed pruning is not the answer when the grower has a large acreage which must be pruned, unless mechanical pruning is used. Another practice which can be implemented is long-cane pruning. Buds on a cane begin to develop at the apex of the cane. This can be used to provide protection for buds at the base of the canes which are retained for fruiting during standard pruning. Vines are pruned to retain long canes and then, after the frost period has passed, canes are cut back to the proper length. Long-cane pruning is effective for frost protection, but the cost-effectiveness for most vineyards needs to be determined.

The application of frost protectant materials and subsequent reduction of frost injury has been a goal of viticulture researchers for quite some time. The use of ice nucleation bacteria inhibitors to change the freezing point of grapevine tissues has had little or no success. Conversely, the application of oils such as soybean oil appears to have great potential to reduce spring frost injury and this topic will be covered in detail in another paper in these Proceedings. In addition, the application of hydrophobic particle film just prior to a freezing event holds promise for reducing frost damage to grapevines.

Vine Recovery From Frost Damage

If protective measures fail and the critical temperature is reached, injury will occur. The grower faced with this situation must manage his/her vineyard to maximize yield for the current season and vegetative growth so that yield is unaffected for the following season. Freeze injury usually does not result in complete crop loss. The grapevine node has three growing points or buds (the primary, secondary, and tertiary buds). Primary buds usually develop first and have the greatest crop potential. Due to their early development, primary buds are also more susceptible to frost damage than are secondary and tertiary buds. Certain varieties, such as Catawba or Concord bear almost their entire crop from primary buds. Other varieties will bear a partial crop from secondary, tertiary, and latent buds. For some wine grape varieties, the amount of crop from growing points other than the primary bud can be significant.

Proebsting and Brummund evaluated the response of Concord grapevines to spring freezing injury. All shoots were lost on frozen vines (complete primary bud kill), while control vines (protected by sprinklers) displayed no shoot injury. Freezing injury delayed bloom which appeared to be beneficial since conditions were generally unfavorable during the normal bloom period. As a result, vines which were injured had more berries/ cluster than non-injured vines. Frost damage reduced yields significantly, and the reduction was due to a reduction in the number of clusters per vine. Berries from injured vines were less mature than berries from non-injured vines.

Removal of injured shoots was investigated by Kasimatis and Kissler to find a method of increasing the yield of vines exposed to frost. Treatments consisted of removal of all primary shoots, removal of frost-damaged shoots only, and control. None of the shoot removal treatments significantly improved yield. Shoot removal had little effect on fruit maturation. For most situations, it appears that removal of frozen shoots would not be beneficial.

Growers should also evaluate their cultural practices following a spring freeze event which injures vines. If crop loss is severe, pest and disease control measures may be reduced somewhat without influencing the crop potential for the following season. Other cultural practices, such as cultivation, irrigation, etc., should be done in a normal manner to allow for good vegetative growth.

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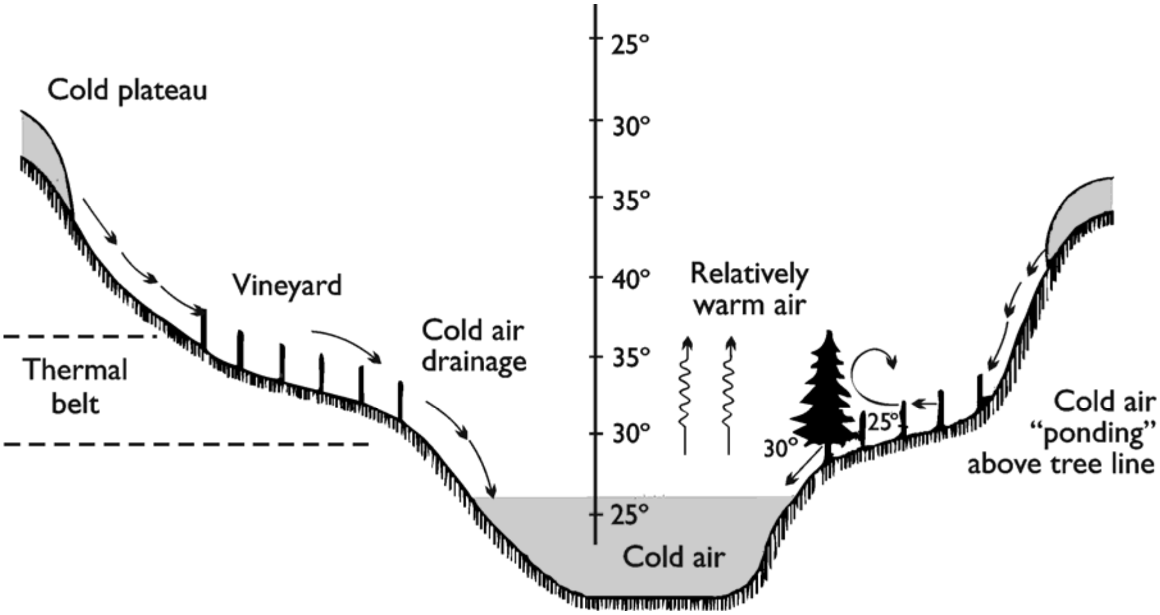
Figure 1. Effect of topography and obstructions on cold air drainage. Image courtesy of Barclay Poling, North Carolina State University.



Source: Figure 4.1 from *The North Carolina Winegrape Grower's Guide*, 2006, E. Barclay Poling (editor).

Overview of Active Frost, Frost/Freeze and Freeze Protection Methods

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Abstract

Your first and best defense against damaging spring frost is to avoid sites that are subject to repeated spring frosts (Wolf and Boyer, 2003). In North Carolina, we have adapted a method used in New Zealand (Trought et al., 1999) for assessing potential vineyard sites for spring frost risk that is based on the *predicted phenology* (i.e., bud burst) 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*, and finally an *investment analysis* is conducted to determine whether active frost protection may be economically justified. While cold protection methods can be expensive, an active protection system, or combination of systems, may allow the grower farming 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. Our research in North Carolina has shown that a wind machine could be a profitable risk management tool for a site that is prone to radiational frost events following bud burst in two or more seasons out of 10 years (20 percent probability, or higher, of frost damage). On a vineyard prone to spring frost in only one out of ten seasons (10 percent probability of frost damage), the wind machine may not produce a positive net return. Wind machines do not provide more than 1 to 3 degrees of warming, and in aftermath of the arctic cold front in early April 2007 that caused extensive damage to grape vineyards in the Midwest and Southeast (following the nation's second warmest March on record), grape growers are now being challenged to reevaluate whether this type of freeze event in the post-bud burst period is explained by "climatic variability" or is perhaps representative of a significant, unexpected shift in climate (i.e., "climate change"). Regardless of how you wish to interpret the Easter freeze of 2007 (an anomaly, or indicator of what's to come), this historic event should prompt us to critically evaluate current and potential strategies for preventing injury to grapes in post-bud burst stages at sub-freezing temperatures (that are beyond the limits of wind machine protection). This paper explores how plasticulture growers in North Carolina have learned to cope with severe weather events during the critical strawberry blossom stage. Some consideration in the oral presentation will be given to a new strategy that would use over-vine sprinkling in late winter/early spring to delay bud burst with evaporative cooling.

Introduction to Active Frost Control

Active frost control differs from passive control strategies and methods in several important ways:

1. **Energy Use.** Active control *methods* include energy intensive practices (vineyard heating with fuel, over-vine sprinkling with water, etc.) that are used during the cold event to replace natural energy, or heat losses from the vine (Snyder, 2001).
2. **Direct vs. Indirect Method.** Active control *strategies* rely on *direct* frost protection methods (e.g., wind machines, heaters, and over-vine sprinkling), and involve active control against a cold event (Westwood, 1978). Passive control or protection involves *indirect* practices (e.g., site selection, variety selection, and cultural practices like double pruning) that cause the plant to be less susceptible to cold injury, or decrease the probability or severity of radiation frosts (Evans, 2000).
3. **Time of Implementation.** Active control strategies and methods must be implemented *just prior to and/or during* the cold event to counteract an immediate threat of a radiation frost or frost/freeze. Passive protection includes strategies and practices that are generally done well ahead of cold events. However, it is very important to note that the installation of an active control system such as a wind machine or over-vine sprinkling system requires considerable advance planning, and some components of an over-vine sprinkling system will need to be installed before the vineyard is planted.

Choosing a Frost Protection System

While people use the terms frost and freeze interchangeably, you need to learn the key differences between a freeze, a frost/freeze, and two types of frost. You must match your frost protection system to the prevailing types of cold events that occur in your vineyard following bud burst. This basic information will help you select the most effective type of active protection system for your vineyard and will be the key to operating that system effectively. Some forms of active frost protection that are highly effective in certain types of frost can actually damage the vines when used in other types of frost.

Remember, there is no perfect method of active frost control that will be able to counter all of the different types of cold events that may be encountered, especially a freeze when the winds are greater than 10 miles per hour.

***Freeze** (also called advective or wind-borne freeze)*

1. Temperature below freezing.
2. Wind usually greater than 10 miles per hour.
3. Little if any stratification of air temperature occurs with changes in elevation.
4. More common in late winter (February or early March) in North Carolina, well before new shoots have emerged.

*All mechanical methods of conventional spring cold protection discussed in this paper (wind machines, heaters, over-vine sprinklers and helicopters) are of very limited value, or no value, under true freeze conditions. Do not use active methods for frost control when winds are greater than 10 miles per hour; you can damage the vines (Trought et al., 1999). See the end of this paper for a potential use of over-vine sprinkling in late winter/early spring to delay bud burst with **evaporative cooling**.*

Even good site selection, the basic method of frost protection, can work against a vineyardist in a freeze. Lower lying river-bottom-type areas that are protected from the winds would be the best choice in a freeze, but these areas are not recommended for vineyards because they are highly subject to radiational frost events. Fortunately, freezes are rare after bud burst.

Wind machines and over-vine sprinkler irrigation systems must **not** be used in a freeze. The winds can damage equipment and the vines. Sprinkler irrigation is also risky due to a phenomenon known as *evaporative cooling* under freezes. Perry (2001) has indicated that heaters may provide some protection under wind-borne freeze conditions due to radiant energy, which is not affected by wind and will reach any solid object not blocked by another solid object. However, the cost of fuel presently rules out the use of heaters.

Frost/Freeze

1. Temperature below freezing.
2. Persistent winds in the range of 5 to 10 miles per hour will prevent the formation of an inversion, so wind machines and helicopters will not provide sufficient protection.
3. A well-designed over-vine sprinkling system can be effective, but you risk extensive crop losses if sprinkling is inadequate, or if the irrigation system fails during the night.
4. Vineyard heaters provide some protection, but the cost of fuel may make their use cost prohibitive.

The National Weather Service may issue a “Frost Warning” for temperatures *above* 32°F, but this is simply a *warning* of a possible frost event. It does not mean that a radiation frost event has temperatures above 32°F. In fact, Perry (2001) defines a *radiation frost* as having temperatures near the surface *below freezing* (32°F). See Table 1 for descriptions of conditions that prompt the National Weather Service to issue frost and/or freeze warnings.

Radiational Frost

1. Caused by rapid radiational loss of heat.
2. North Carolina has two types of radiational frosts: hoar frost and black frost. *Hoar frost* results when atmospheric water vapor freezes in small crystals on solid surfaces, and is also called a white frost. *Black frost* has few or no ice crystals because the air in the lower atmosphere is too dry; sometimes called a dry freeze even though it is not technically a freeze.
3. Either type of radiational frost may occur after grapevines have broken bud and commenced spring shoot growth.
4. A black frost is always going to be a killing frost; a hoar frost may or may not damage the crop.
5. Active frost protection can protect the crop under certain conditions, as explained below.

Types of Active Frost Protection

Use Table 2 to help you assess the potential effectiveness of different methods of active cold protection under hoar frost, black frost and frost/freeze conditions. As the first column in Table 2 shows, wind machines, heaters, over-vine sprinklers, and helicopters *all* may protect against hoar (white) frost conditions. However, as you can see, the method of active frost protection you select matters a great deal when it comes to either a black frost or frost/freeze condition. For example, in a black frost condition (second column) with temperature minimums below 28°F, a wind machine may require supplemental heaters, or possibly even a helicopter (which can adjust to the height of the inversion) to add extra heat to the vineyard when minimum temperatures are going to be too low for a wind machine. Generally, wind machines are not found to be practical when you need to raise the temperature more than 1 to 3°F. Keep in mind that wind machines require an inversion to be effective. Also, they are not effective if winds are greater than 5 miles per hour. Wind machines are not an appropriate choice for sites subject to frost/freeze conditions following bud burst. Wind machines will provide no protection under freeze conditions, and their use may increase injury to vines and damage the equipment as well.

For vineyards subject to black frosts and/or frost/freeze conditions, over-vine sprinkling can be very effective. Over-vine sprinkling can be designed to provide enough heating capacity to protect vines in cold events with minimums in the low 20s. But, you must be aware of the greater complexity of operation of sprinkler irrigation, especially under winds in the 8 to 10 mile per hour range.

Ultimately, the proper choice of protection equipment will depend on many factors. A detailed economic analysis of each frost protection system is beyond the scope of this paper, as is a full consideration of the environmental impacts of the various protection systems. Here are some general points regarding the general utility, relative cost effectiveness, and environmental impacts of these systems outside the area being treated.

Wind machines may prove profitable on sites where there is a 20 percent or higher probability of spring frost during early stages of new shoot growth. Wind machines use the inversion that develops in a radiation frost. Seven to 10 acres is the minimum size vineyard for a wind machine. The experiences of several commercial vineyards in North Carolina over the last decade have affirmed the value of wind machines on Piedmont sites with chronic radiational frost problems. In some instances, the sites that benefit are near valley floors or creek bottoms that are very prone to frost. Although wind machines do not provide more than 1 to 3°F of warming, they are particularly well suited for managing the dominant kinds of cold weather events that occur in North Carolina vineyards after bud burst — radiational frosts.

Although hourly operating costs are higher than for over-vine sprinkling, these costs are still substantially below operating costs for return-stack oil heaters and standard propane heaters. In 2005, the initial cost of a fully installed wind machine was approximately $2,800 per acre in North Carolina.

Other benefits not widely reported have to do with using them for moisture control during harvest in August and September, when heavy dews in lower lying areas can cause significant delays in harvest and increase fruit rot pressure. Wind machines started at 6 a.m. can have the grape canopy dry and ready for harvest as early as 9 a.m.

Wind machines may also be appropriate for use to protect a grape crop from fall frosts in higher elevation areas with shorter growing seasons, and they may also be useful for protecting the vineyard canopy from frost damage shortly after harvest. Leaf damage from fall frost may delay cane hardening and render the vines more susceptible to winter damage (Sugar et al., 2003).

Wind machines produce a very loud noise, and you should be aware that nearby neighbors may strongly object to their use!

Heaters may be the sole source of protection for radiation frosts, but the rising cost of fuel may make the use of 40 to 50 heaters per acre prohibitively expensive. No heaters are being used in North Carolina vineyards at this time, but a limited number of heaters arrayed near the perimeter of the vineyard and in portions of the vineyard farthest from the wind machines may merit consideration under colder radiational frost conditions. Air pollution by smoke can be a significant problem, and the use of oil-fired heaters is banned in many areas.

Over-vine sprinkling for frost and frost/freeze protection has been very successful in North Carolina for years on low-growing crops like strawberries, but it has not been very popular with vineyard operators in the state for a number of reasons, including:

1. the cost of materials, installation, and development (usually including a pond);
2. not having enough water resources to safely provide three consecutive frost/freeze nights of protection (about 150,000 gallons of water for each acre of vineyard);
3. complexity of operation and high risk of vine damage if the system fails in the middle of the night; and
4. even though sprinkler irrigation offers the highest level of protection of any single frost control system, their fixed-rate design delivers more protection than generally necessary (Perry, 1998). They can only be turned on or off, so you can’t vary the irrigation rate. This contributes to over-watering, which can waterlog soils, leach fertilizers, and may increase disease pressures.

If your vineyard is highly prone to frosts and frost/freezes, one of the real advantages of over-vine sprinkling is its very reasonable cost of operation. Evans (2000) has reported that the hourly cost of over-vine sprinkling was about 12 percent of the cost per hour of wind machines (requiring fuel), and only about 4 percent of the hourly cost to operate a return-stack oil heater system (40 per acre). If you decide to invest in over-vine sprinklers for frost/freeze control in the vineyard, it is much more convenient to install the system before the vineyard is planted than it is to add it to an existing vineyard.

Helicopters are another option that may be economically justified under special circumstances, despite the fact that charges started at $825 an hour in 2006. Currently, helicopter services are used in Virginia vineyards, but not in North Carolina.

Foggers can be utilized when the dew point temperature is close to the air temperature. The fog that is formed can act as a barrier to radiative heat losses from plants at night. Fog lines that use high pressure lines and nozzles to make fog droplets have been reported to provide excellent protection under calm conditions. Little water is deposited, minimizing the potential for ice-load damage (a concern with over-vine sprinkling). However, containing and/or controlling the drift of fogs and potential safety/liability problems (if fogs cross a road), are factors that may seriously limit the usefulness of fogging systems (Evans, 2000).

Ice nucleation bacterial inhibitors, such as special foliar nutrient sprays, are being utilized by a few vineyards in North Carolina to change the freezing point of the plant tissue, but more research on this technique is needed. In trials conducted in Oregon (Sugar et al., 2003), little or no frost protection was obtained from treating vines with substances that are supposed to depress the freezing point or inhibit bacteria that can serve as nucleators for ice formation.

Operating Frost Protection Systems

This section provides in-depth information on the actual operation of conventional frost control systems (wind machines and heaters), and also explores scenarios where combination approaches may be a better choice, such as the use of both wind machines and heaters. Information is also provided on helicopters, which are another option that may be economically justified under special circumstances despite their high hourly charges (starting at $825 per hour). The operation of an over-vine sprinkler system is discussed in a separate paper in these proceedings.

Wind Machines

Choose this method for your vineyard when:

1. most spring cold events during grape bud burst and early shoot development are likely to be radiational;
2. there is a 20 percent probability, or higher, that you will lose 50 percent of your yield an average of twice every 10 years; and

3. the frequency and strength of low-level inversions during the bud burst and early shoot development will make over-vine wind machines effective.

Installation

Typically, an 18-ton crane is required for installation, but a 14-ton truck crane can often suffice as long as the boom-out is at least 60 feet. The heaviest part of the wind machine is the steel tower, which weighs about 4,000 pounds. Also, the ground-mounted unit requires a concrete pad (about 7.5 yards of concrete gravel mix with no fly ash). There are well-qualified wind machine vendors serving North Carolina and other parts of the U.S. Your county Extension agent can also provide you with contact information. Wind machine suppliers typically have a great deal of field experience, and they will be able to assist you with appropriate placement of the wind machines in your vineyard.

Principles of Operation

Ground-mounted wind machines with heavy-duty industrial engines, combined with high-strength 18-foot fan blades mounted approximately 30 feet from the ground, can move large volumes of air through the vineyard. *These machines rely on the principle that a large, slow moving cone of air can produce the greatest temperature modification around the vines by mixing warmer air above the vineyard with cooler air around the vines.* The propeller revolves at approximately 590 revolutions per minute and rotates 360 degrees about its vertical axis every four and one-half minutes. The motor should be strong enough to drive the air turbulence into the vineyard 300 to 400 feet under windless conditions. Due to natural patterns of air movement (“drift”) in the vineyard during frosty nights, an oval pattern of protection is provided by wind machines. The wind machine pushes air approximately 300 to 350 feet perpendicular to the vector of drift, 250 to 300 feet against the drift, and 500 to 600 feet with the drift, giving the overall distribution of air an oval shape.

The effectiveness of a wind machine depends on a temperature inversion so that there is a source of warm air for mixing (Sugar et al., 2003). A vineyard in Davidson County, NC, where a wind machine has been recently installed, quite commonly experiences inversions of 7°F from ground level to 50 feet in elevation. (This would be considered a strong inversion with 1.4°F per 10 feet). The general rule is that with a typical inversion layer at 40 to 50 feet, wind machines can be expected to increase the temperature around the vines by one-fourth to one-half of the difference in temperatures between air around the vines and the warmest air within range of the wind machine.

Operation

1. A reliable **weather prediction system** will allow you to decide in advance of the cold event if frost protection with a wind machine will be adequate. Start checking weather forecasts at least 48 to 72 hours in advance of the event. Once you know what type of cold event is coming, you can start making plans to use your wind machine or to add a backup system if supplemental heating may be needed. On the night of the cold event, make sure your frost alarm is correctly set (usually at 37°F).

2. **Calculate the strength of the inversion.** Wind machines work well under hoar frost (white frost) conditions, but you may need to use an additional method in *black frost* conditions when more than 2 or 3°F is needed to keep developing shoots above their critical temperature. Remember that wind machines bring in warmer air from the thermal inversion, but these machines are not very effective when the inversion strength is small. Calculate the strength of the inversion by multiplying the difference in air temperature at 50 feet and the vine level by a factor of one-fourth to one-half (e.g., if the difference in temperature is 4°F, then the inversion will only provide about 1 to 2°F of warming of the air around the vines). Advance information about the probable strength of the inversion may be obtained from your weather forecast service.

3. **The critical temperature** will vary with the stage of plant tissue development and environmental conditions. Generally speaking, an air temperature of 31°F or lower for 30 minutes or longer may be considered critical beyond bud burst (Sugar et al., 2003) for frost and frost/freeze protection.

4. **Air temperature measurement.** By definition, the critical temperature of 31°F is the *air temperature* as read on a properly sheltered, correctly calibrated vineyard thermometer. A well-managed frost protection system depends on accurate temperature readings and also on having thermometers properly distributed. At least one is needed in the coldest location in the vineyard, and the number of other thermometers required will be a function of vineyard size. The thermometers must be sheltered and not exposed to the sun during the day or sky during the night.

5. **Know your dew point temperature!** When your frost alarm clock has awakened you, begin checking temperatures in the vineyard. Many growers will automatically turn on the wind machines at about 32°F (based on the temperature of the thermometer in the coldest vineyard location), but this may or may not be a good decision. A better strategy takes into account both air temperature *and* dew point temperature. Dew point is

predictable from the difference between the wet- and dry-bulb thermometer readings. Grape growers who do not have a weather forecast service that provides hourly dew points may find it to their advantage to determine their own dew points with a sling psychrometer. Your Extension agent can tell you where you can purchase a sling psychrometer and obtain a copy of psychrometric tables for obtaining the dew point. When the dew point is low, temperature can drop very rapidly, and it is not unusual to see the air temperature drop more than several degrees in the first hour. The U.S. Weather Service reports that dew points of 30°F are considered **high** and those of less than 20°F are considered **low** (Ballard, 1981). Evans (2000) recommends that if the weather forecast is for subfreezing temperatures accompanied by low dew points (less than 20°F), you should turn on the wind machine(s) at 35 to 37°F to start moving the warmer air through the vineyard, even if the inversion is weak. This will at least partially replace radiative heat losses and strip cold air layers away from the buds and shoots. If the dew point is in the low- to mid-20s and air temperatures are dropping at an average of 2 degrees per hour, turn on the wind machine when the temperature is around 34°F. If the dew point is in the upper 20s, 32 to 33°F should be a satisfactory threshold.

6. If the dew point is near or above the critical temperature for grape tissue (around 31°F), it is important to be aware that the heat released at the dew point may provide sufficient heat to avoid reaching damaging temperatures, or at least may delay the temperature fall and postpone the need to turn the wind machine on (Sugar et al., 2003). *However,* as soon as you detect any frost forming on exposed grape plant tissues, *turn the wind machine on*! By stirring up the air, wind machines can interfere with ice crystal formation. As discussed in *Principles of Cold Protection*, the formation of ice crystals on succulent grape shoots can be very damaging.

7. **Heaters** may be lit to supplement the wind machines on nights when temperatures are expected to go below 27 to 28°F. See the section on *Heaters* for additional information.

8. **Using a helicopter service as back-up.** Under colder radiational frost conditions, some Virginia vineyards will use wind machines and also have helicopters on standby if it appears possible that temperatures may fall below the capacity of wind machines. This can be relatively expensive, but growers faced with devastating black frost losses find them very effective. Information about helicopters is provided in a later section of this paper.

9. **Shutdown of wind machine.** Monitor air temperatures after sunrise, and continue to run the wind machine until the temperature is above 32°F in the lowest area of the vineyard. Technically, you could safely turn off the wind machine before an air temperature of 32°F is reached, as the air temperatures will warm more slowly in the morning than the grape shoot tissues. If you own a device for monitoring actual tissue temperatures (e.g., digital thermometer with thermocouple inserted in grape shoot tissue), you will see that as the crop tissues receive direct rays from the sun in the morning they will warm up more rapidly than the surrounding air. You would need an instrument for monitoring this, and since few grape growers own these devices, it is recommended that you continue to run the wind machine until the air temperature is safely above 32°F in the lowest area of the vineyard.

Heaters as a Supplement to Wind

For years, the principal method of frost protection in fruit crops was by burning fuel to release heat. Today, burning these fuels (e.g., diesel, propane) as the sole means of frost protection is prohibitively expensive. Burning 40 heaters per acre with a diesel price of $2.50 per gallon would cost $100 per hour. There are the additional costs of labor to place the heaters in the vineyard and light them, as well as to refill them with oil for the next night of frost protection. *However, in North Carolina, heaters can be considered an effective method of adding extra heat during nights when temperatures may fall below the capacity of wind machines to provide adequate protection*.

Principles of Operation

The hot gases emitted from the top of the heater initiate convective mixing in the crop area, tapping the important warm air source above in the inversion. About 75 percent of a heater’s energy is released as hot gases. The remaining 25 percent of the total energy radiates from the hot metal stack. Radiated heat is not affected by wind and will reach any solid object not blocked by another solid object. *Heaters may thus provide some protection under wind-borne freeze conditions.* A relatively insignificant amount of heat is also conducted from the heater to the soil.

Operation With Wind Machines

Using heaters with wind machines is more energy efficient than relying on heaters alone. The number of heaters is reduced by at least 50 percent by dispersing them into the peripheral areas of the wind machine’s protection area (Evans, 2000). In Oregon vineyards, when heaters are the sole source of protection, 40 to 50 heaters burning at the rate of 0.5 gallons per hour per acre is recommended (Sugar et al., 2003). There do not seem to be any absolute formulas to follow on this, but by lighting 20 to 25 heaters per acre you may expect approximately 3°F protection (Sugar et al., 2003). The lightest heater concentration should be nearest the wind machine tower to minimize vertical current interference with the fan blast (Ballard, 1981). Grower testimony in North Carolina has further revealed that heaters are not usually necessary within a 150- to 200-foot radius from the base of the wind machine. Heaters give you the option of delaying protection measures if the temperature unexpectedly levels off or drops more slowly than predicted. There is no added risk to the crop if the burn rate is inadequate; whatever heat is provided will be beneficial (Perry, 2001).

Helicopters

Because of the great expense, helicopter use for frost protection is limited to special cases and emergencies, such as when a black frost in the mid-20s is forecasted at a critical growth stage and only a wind machine is available for protection, which is not likely to be adequate under such conditions (wind machines usually provide 1 to 3°F protection; in this scenario at least 5°F or 6°F protection is required). Helicopters are generally hired for particular events, and will remain on standby either in the vineyard or close by. This is a relatively expensive operation, with hourly costs ranging from $825 to $1,600 per hour (dependent upon the size of the helicopter and availability). Additionally, the grower is often asked to guarantee at least three hours of work.

Principles of Operation

Helicopters are an expensive variation of wind machines (Evans, 2000), but they can be considerably more effective than a wind machine since they can adjust to the height of an inversion. A single large helicopter can protect more than 50 acres under the right conditions (Evans, 2000).

Operation

Contact the helicopter service(s) well in advance of any serious frost/freeze events to make appropriate arrangements – these services may already have commitments to other vineyards or industries in your region. A list of helicopter services operating in North Carolina can be found in the Resources section near the end of this paper. Since frost/freeze protection on some nights will be required for six hours or more, it is usually necessary for the company to dispatch a jet fuel truck to the vineyard for refueling. Typically, you will also be given a two-way radio so that you can communicate with the helicopter operator. You and your workers must walk the vineyard during the cold event, checking vineyard thermometers with flashlights so you can give the helicopter operator information on cold spots in the vineyard. A rapid response thermometer in the helicopter helps the pilot adjust the flying height for the best heating effect (Evans, 2000).

Summary

The cost effectiveness of active frost control depends on how prone a particular vineyard site is to radiation frosts (and possibly frost/freezes) in the spring from bud burst through early shoot development. Good site selection is still the best method of passive cold protection, but as more winegrape vineyards are planted in frost-prone areas of North Carolina and other states and regions with continental climates, growers need to consider active methods of frost control. A number of growers in the Piedmont and mountains of North Carolina are now using wind machines to control radiation frost events in their vineyards. Radiation frosts occur on clear nights with calm winds (less than 5 miles per hour) and temperatures near the surface below freezing. When either a hoar frost or black frost threatens, they turn on the wind machines to break up the temperature inversion (warm air above the cold air close to the ground) and increase vine tissue temperatures by mixing warmer air with cold air.

Once ice forms in the plant tissue, there will be damage. Growers are advised to be proactive in their use of wind machines or any other frost protection method (over-vine sprinklers, heaters, and helicopters) in preventing ice crystal formation associated with a *hoar (white) frost.* In a *black frost* few or no ice crystals form because the air in the lower atmosphere is too dry, and the grower cannot wait for “evidence” of ice crystals to activate frost protection measures under these conditions.

Advance weather forecasts from a subscription service can provide information on *dew-point temperatures* (DP), which can help the grower assess whether he or she may be dealing with a *hoar frost* (DP in the upper 20s and low 30s), or *black frost* (DP in the mid 20s or lower). When the dew point (DP) is below the critical temperature of 31°F, expect that plant tissue temperatures will fall more rapidly than the surrounding air temperature, and the amount of *upward adjustment* in the start-up air temperature is going to be related to the dryness of the lower atmosphere, as indicated by dew point temperature. In dry atmospheric radiation frost conditions, be conscious of the need to monitor *both* vineyard air temperature and humidity (*using dew point temperature*).

For example, if the DP is in the low to mid-20s, turn on the wind machines when the air temperature is around 34°F.

On a *frost/freeze* night, the best strategy may be to take no action at all. Five to 10 mile per hour winds will prevent the formation of an inversion, so wind machines and helicopters will not be effective. Over-vine sprinkling can be designed to provide enough heating capacity to protect vines exposed to *frost/freeze* conditions. The system must be carefully engineered specifically for use under windy conditions that promote evaporative cooling. If the grower has any doubt about the capacity of the irrigation system to provide adequate heating in *frost/freeze* conditions, the best strategy may be to take no action at all as an ice-covered vine will cool below the temperature of a comparable dry vine if freezing stops and evaporation begins.

Use the details for operating several conventional frost control systems (wind machines, over-vine irrigation, and heaters), and the discussion of some cold event scenarios to help you determine which system(s) might be best for your vineyard. Regardless of the system(s) you use, remember that successful cold protection must be approached with a sound understanding of many things. These include frost and frost/freeze management principles, a good knowledge of your vineyard site's microclimate, weather conditions that are favorable for the operation of your cold protection system, and careful attention to the details contained in specialized weather forecasts on air temperature minimums, dew point temperatures, wind speeds, cloud cover, and inversion strength.

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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

Resources

Climate Information

1. Jan Curtis, Applied Climatologist, NRCS — National Water & Climate Center, 1201 NE Lloyd Blvd, Suite 802, Portland, OR 97232-1274; E-mail: jan.curtis@por.usda.gov; Phone: 503-414-3017; Cell phone: 503- 956-4609; Fax: 503-414-3101; Web site: http://www.wcc.nrcs.usda.gov/

Heaters (HY-LO Return Stack Heater and similar heaters)

1. Plummer Supply, Agricultural Irrigation & Orchard Supply Co., 2875 Plummer Park Place, Bradley, MI 49311; Phones: 269-792-2215, 800-632-7731; Web site: http://www.accn.org/~plummer

Helicopter Frost Control Service (NC, VA)

1. HeloAir, Inc., 5733 Huntsman Road, Richmond International Airport, VA 23250; Phones: 804-226-3400, 888-FLY-HELO; Web site: www.heloair.com

Over-vine Irrigation System Suppliers

1. B.B. Hobbs, PO Box 437, Darlington, SC 29540; Phone: 843-395-2120; E-mail: sales@bbhobbs.com; Web site: http://www.bbhobbs.com
2. Berry Hill Irrigation, 3744 Hwy 58, Buffalo Junction, VA 24529; Phones: 434-374-5555, 800-345-3747; E-mail: sales@berryhilldrip.com; Web site: http://www.berryhilldrip.com
3. Gra-Mac Irrigation, 2310 NC Hwy 801 N., Mocksville, NC 27028; Phones: 336-998-3232, 800-422-35600; E-mail: gramacirr@yadtel.net
4. Johnsons & Company, PO Box 122, Advance, NC 27006; Phones: 800-222-2691, 336-998-5621; E-mail: henry.johnson@johnsonandcompanyirrigation.com; Web site: http://www.johnsonandcompanyirrigation.com
5. Mid-Atlantic Irrigation Co., PO Box L, Farmville, VA 23901; Phone: 434-392-3141; E-mail: mairrigation@cstone.net; Web site: http://www.irrigationparts.com
6. W.P. Law Co., 303 Riverchase Way, Lexington SC 29072; Sales Representatives: Brad Scease, Tom Plumlee; Phone: 803-461-0599; Fax: 803-461-0598; Web site: http://www.wplawinc.com/

Weather Forecasting Services

1. AccuWeather.Com, Online subscription weather forecasting service, State College, PA; Web site: http://www.accuweather.com/
2. AWIS Inc, Agricultural Weather Information Service Inc., PO Box 3267, Auburn, AL 36831; Phones: 888-798-9955, Ext. 1 or 334-826-2149; E-mail: info@awis.com; Web site: http://www.awis.com
3. SkyBit, Inc., 369 Rolling Ridge Drive, Bellefont, PA 16823 ; Phone: 800-454-2266; E-mail: info@skybit.com; Web site: http://www.skybit.com

Weather Instruments (thermometers, sling psychrometers, frost alarms, digital thermometers, portable weather stations)

1. B.B. Hobbs, PO Box 437, Darlington, SC 29540; Phone: 843-395-2120; E-mail: sales@bbhobbs.com; Web site: http://www.bbhobbs.com
2. Berry Hill Irrigation, 3744 Hwy 58, Buffalo Junction, VA 24529; Phones: 434-374-5555, 800-345-3747; E-mail: sales@berryhilldrip.com; Web site: http://www.berryhilldrip.com
3. Forestry Suppliers (http://www.forestrysuppliers.com/)
4. Gempler's, PO Box 44993, Madison, WI; Phone: 800-382-8473; Web site: http://www.gemplers.com/
5. Omega Engineering, PO Box 4047, Stamford, CT 06907; Phones: 800-848-4286, 203-359-1660; E-mail: sales@omega.com; Web site: http://www.omega.com
6. Spectrum Technologies, Inc., 12360 South Industrial Dr., East Plainfield, IL 60585; Phones: 800-248-8873, 813-436-4440; E-mail: info@specmeters.com; Web site: http://www.specmeters.com

Wind Machine Suppliers

1. Orchard-Rite Ltd., PO Box 9308, Yakima, WA 98909; Contact: Rod Robert; Phone: 509-457-9196; Fax: 509-457-9186; E-mail: sales@orchard-rite.com
2. Plummer Supply (distributor for Orchard-Rite Ltd.), PO Box 117, 2875 Plummer Park Lane, Bradley, MI 49311; Sales: Lee Deleeuw; Phone: 800-632-7731; Fax: 269-792-6637; E-mail: plummer@accn.org
3. W.P. Law Co. (distributor for Orchard-Rite Ltd.), 303 Riverchase Way, Lexington, SC 29072; Sales: Brad Scease, Tom Plumlee; Phone: 803-461-0599; Fax: 803-461-0598

Note: The mention of commercial products, services, or publications is for the reader's convenience and does not constitute endorsement by the North Carolina Cooperative Extension Service or the North Carolina Grape Council, nor does it imply discrimination against other products, service, or publication not mentioned.

Table 1. Definition of frost/freeze warnings issued by National Weather Service.

Frost event	Wind speed (mph)	Air temperature (°F)
Frost	Below 10	Above 32
Frost/freeze	Below 10	Below 32
Freeze	Above 10	Below 32

Table 2. Relative effectiveness of passive, active frost, and active frost/freeze protection methods under different cold event scenarios.

Method	Radiational hoar frost; temperature 28 to 36°F	Radiational black frost and/or weak inversion; temperature below 28°F	Frost/freeze and temperature below 28°F (winds 5 to 10 mph)	Comments
Good site selection (passive)	Highly effective	Effective	Limited effectiveness	Locations with good air drainage; visualize air flow and evaluate frost climatology.
Wind machine	Highly effective	Limited effectiveness	Ineffective, potentially damaging	**Do not use** if winds are greater than 5 miles per hour.
Wind machine plus heaters	Not applicable	Effective	Limited effectiveness	Can be effective in black frost, weak inversion, or frost/freeze; merits further attention. Not needed in a hoar frost.
Wind machine plus helicopter	Not applicable	Highly effective	Ineffective	Useful when inversion ceiling is high. Not needed in a hoar frost.
Over-vine sprinkling	Highly effective	Highly effective	Highly effective	Incorrect use can cause greater damage.
Helicopter	Highly effective	Effective	Ineffective, potentially damaging	Very high costs per hour, greater than $825 in 2006.
Heaters	Highly effective	Effective	Effective	Very limited use in North Carolina vineyards due to high cost of fuel.

Overhead Sprinkler Systems for Frost and Frost/Freeze Protection

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Abstract

Sprinkling for frost and frost/freeze protection has been very successful in North Carolina for years on low-growing crops like strawberries, but it has not been very popular with vineyard operators in the state for a number of reasons, including: 1) the high installation cost; 2) not having enough water resources; 3) complexity of operation and high risk of vine damage if the system fails, and 4) their fixed-rate design delivers more protection than generally necessary (Perry, 1998). The fact that they can only be turned on or off (you can't vary the irrigation rate) may contribute to over-watering, leaching of fertilizers, and may increase disease pressures. However, if your vineyard is highly prone to frosts and frost/freezes, one of the real advantages of over-vine sprinkling is its very reasonable cost for operating. Evans (2000) has reported that over-vine sprinkling was about 12 percent of the cost per hour of wind machines (requiring fuel), and only about 4 percent of the hourly cost to operate a return-stack oil heater system (40 per acre).

Introduction

In North Carolina we have limited experience with sprinkler irrigation for cold protection in grapes, but this form of active protection is well established in strawberries and blueberries. In 2007, overhead irrigation systems were used during an Easter weekend freeze by North Carolina strawberry growers to achieve an 80-percent crop (Poling, 2007); and blueberry growers saved approximately 50 to 60 percent of their crop using overhead sprinkling (personal communication, Bill Cline, Research and Extension Specialist, NC State). In contrast to the positive experiences of strawberry and blueberry growers who relied upon overhead sprinkling during this freeze, Wolf (2007) reports that "all active frost control measures (heating, wind machines or helicopters and overhead irrigation)," in Virginia, "were of limited or no value due to the duration of the cold temperatures associated with the (2007) Easter freeze, the wind speed, or the absolute degree of cold attained."

Nonetheless, sprinkling in grape vineyards for frost control is used in other regions and parts of the world to minimize cold injury (Jackson, 2000). Overhead sprinkling is complicated, but a well-designed and correctly operated sprinkling system has superior cold protection capabilities compared to other methods of active protection such as wind machines (Table 1). I harbor a personal view that one of the main reasons that overhead irrigation has not caught on with grape growers in North Carolina is related to the greater complexity of operating these systems relative to wind machines. Thus, I would like to start out this presentation on “Overhead Sprinkler Systems for Frost and Frost/Freeze Protection” by familiarizing you with the key principles of frost protection, and also share some important management strategies that our strawberry and blueberry growers use to get this most out of this very *versatile* method of modifying a crop’s microclimate.

As an important footnote to this discussion, I think grape growers in the Midwest and Southeast should be aware of how overhead irrigation can be used for *both cold and heat protection*. I know that hindsight is 20:20, but I cannot stop myself from thinking that if our vineyard operators in North Carolina had access to over-vine sprinkling technology in 2007, Tarheel farmers might have harvested full crops of grapes this past fall instead of half crops (from vines that also suffered severe wood injury). By using evaporative cooling during those warm days and weeks of March to “cool down” trunks, cordons and vineyard floors, we might have “bought” a very precious week of delay in bud burst. We can’t go back in time to try this, but I am very excited about examining this potential for evaporative cooling in a new muscadine vineyard block we have just planted in Clinton, NC, where we will be experimenting with using a low gallonage in-row sprinkling system in warm weeks of March to cool down vines of the ‘Carlos’ cultivar. This cultivar has a problem with early bud burst similar to ‘Chardonnay’ in our western Piedmont and mountains (Poling, 2007; Spayd, 2007). The downside of this lower volume irrigation system is that while it should be useful for in-row evaporative cooling and radiation frost protection, it will not likely be reliable for frost/freeze events (subfreezing temperatures and winds in excess of 5 miles per hour).

Key Principles

This method of freeze protection is based upon 3 principle factors:

1. When the water freezes, its latent heat is released. This latent heat keeps the temperature of the plant from dropping below freezing point.
2. A mixture of ice and water exposed to temperatures below freezing remains at 32ºF until all the water is frozen.
3. Most plants do not suffer frost damage until the temperature drops slightly below 31ºF, because the freezing point of the plant tissue liquid is below that of water.

The amount of heat generated when water freezes is 1,200 British thermal units (Btu) per gallon or 80 calories per gram of water frozen. This heat keeps plant temperatures safely at 31.5 to 32°F (Sugar et al., 2003) when air temperatures are colder. Evans (2000) indicates that the ice and water mixture is at about 30.9°F. The main thing to understand is that as long as an *adequate layer of* ***freezing water*** covers the buds and shoots, the temperature will stay above the critical damaging temperature. Thus, for this method of protection to be successful, over-vine sprinkling must be continued until the temperature of the surrounding air has risen above 32°F and all ice formations on the plants have melted.

Other Key Considerations

Successful protection of crops from frost damage using sprinklers also depends on these crucial factors:

1. **Sprinkler rotation speed.** Research has shown that a more consistent plant temperature is maintained with a faster rotating sprinkler. To be considered fast enough, a sprinkler should complete one full revolution in less than 60 seconds. Thirty to 40 seconds is ideal.
2. **Water application rate.** The water volume in relation to area application rate has been found to be one of the most important considerations when designing for frost protection. The application rate is calculated after considering factors such as air temperature, wind speed and humidity levels. This is so because wind affects evaporation rates as well as application uniformity (discussed in next section). Windy conditions result in the need for a higher water application rate to provide the same degree of protection as when wind is absent. The presence of wind while sprinkling over the vines can lead to extensive crop loss if sprinkling rates do not offset evaporative cooling heat losses. Since the heat taken up by evaporation at 32°F is about 7.5 times greater than the heat released by freezing, at least 7.5 times as much water must freeze as is evaporated. Thus, relatively high sprinkling rates are required under windy compared to calm wind conditions (Table 2), and this is needed to both supply heat to warm the vineyard as well as to satisfy heat losses through evaporation. Keep in mind that under cold conditions, evaporation from the liquid and frozen water is occurring continuously, and if the system should fail at any time during the night, it goes immediately from a heating system to a very good refrigeration system. If this occurs, damage can be much worse than if no protection had been used at all (Evans, 2000).

3. **Uniformity**. Effective frost protection also depends on how uniformly the sprinkler distributes the water. Extreme care should be exercised in evaluating sprinkler spacing, operating pressures and wind conditions.

Start-Up Temperatures for Sprinkler Irrigation in Dry Atmospheric Conditions

Grape shoot freeze injury may occur in the absence of ice crystals forming on the plant surface under low humidity atmospheric conditions. Keep in mind that plant tissue temperatures may be several degrees colder than air temperature under dry atmospheric conditions. Thus, under dry atmospheric conditions, *start watering before the wet-bulb temperature reaches the critical grape shoot temperature of 31°F*.

Wet bulb. The wet bulb temperature determines when you turn the irrigation system on and off, not the ambient air temperature ("regular air temperature"). Except when the air is saturated with moisture, the wet-bulb temperature is normally lower than the air temperature but higher than the dew-point temperature. Wet bulb temperature is a measurement of the evaporative cooling power of the air and can be measured using a sling psychrometer, an instrument comprised of two thermometers. By waiting to turn on the irrigation system until the wet-bulb temperature is below 31°F, you are running some risk of plant tissue injury due to the "cold jolt" phenomenon. The wet bulb temperature has a gauze wick attached to the bulb end. To measure wet bulb temperature, the gauze wick is immersed in water, and the instrument is swung in a circular motion for a few minutes.

Dry bulb. In the absence of wet bulb temperatures, grape growers can make use of dew point (DP) temperatures to determine the time to begin sprinkling (but it is always better to rely on wet bulb temperatures for starting up sprinkling). The start-up air temperature for cold protection will depend on the dryness of the lower atmosphere, as indicated by dew point temperature. If the DP is in the:

1. 10s, start frost equipment when the air temperature is around 35 to 37°F.
2. low- to mid-20s, start frost protection equipment when the air temperature is around 34°F.
3. upper 20s, start frost equipment when the air temperature is around 32 to 33°F.

If you do not use wet bulb and/or dew point temperatures, you are simply guessing at when to start cold protection on radiational frost nights with low atmospheric humidity.

Start-Up Temperatures for Sprinkler Irrigation in Moist Atmospheric Conditions

Dew point temperature is an excellent indicator of whether the lower atmosphere is moist enough for ice crystals to form on plants. Essentially, a forecast for DP temperatures near or above the freezing point (in the upper 20s and low 30s), indicates that the lower atmosphere is relatively moist and there is a good possibility of a hoar frost. Under low wind speeds (less than 2 miles per hour) and/or no winds, along with relatively high dew points *start frost protection procedures at the first sign of ice crystals forming on the plant surfaces under hoar frost conditions.*

When the dew point is near or above the critical temperature for grape tissue (around 31°F), it is important to be aware that the heat released at the dew point may provide sufficient heat to avoid reaching damaging temperatures, or at least may delay the temperature fall and postpone the need to turn on the irrigation system. *However,* as soon as you detect any frost forming on exposed grape plant tissues, *turn the irrigation on*! The formation of ice crystals on succulent grape shoots can be very damaging. Frost formation may trigger ice nucleation and possibly plant freezing.

Natural factors that will help keep ice crystals from forming include winds greater than 5 miles per hour, cloud cover, and potentially drier soil conditions. Thus, in cloudy, breezy weather, frost will not occur and observed low temperatures will likely be very close to forecast values. But under clear calm conditions with DP temperatures in the upper 20s to lower 30s, there is potential for heavy frost.

Once Sprinkling Starts

Once sprinkling starts and an ice coat has built up, the system must operate continuously through the night until the vines are free of ice the next morning, or at least until the wet-bulb temperature of 32ºF, or above, has been reached. Be especially cautious about stopping the application of water during the night if the temperature rises because of a light breeze or a few clouds. Once the breeze falls or the clouds disappear, the temperature will probably drop rapidly again. With sprinkler irrigation for frost protection in vineyards, the system must be designed for worst-case conditions. There are several excellent irrigation suppliers in North Carolina who can design a vineyard sprinkler system to provide protection down to a target temperature of 20 to 22°F. In Oregon, it is reported that an application rate of 0.19 inch per hour can protect grape buds and shoots down to 22°F (Sugar et al., 2003). However, it should be noted that under relatively high wind conditions and temperatures approaching 22°F, you may need to apply more than 0.19 inch per hour (Table 2). In North Carolina it would be better to design a vineyard sprinkler irrigation system that can deliver precipitation rates of up to 0.25 inch per hour to take into account evaporative cooling heat losses when winds are in excess of 5 miles per hour at an air temperature of 22°F. Less water is required for protection to 26°F, and in Oregon it is recommended that an application rate of 0.12 inch per hour will be sufficient at this temperature (Sugar et al., 2003). Water should slowly but continuously drip from the vine when the sprinkling system is working properly (Evans, 2000). The application rate is not sufficient if the ice has a milky color (from occlusion); ice should be clear at all times.

Irrigation Water Usage

Large amounts of water are required for over-vine irrigation, so you should size your pond(s) to provide three continuous nights of protection at 10 hours per night. You would need 5.7 acre-inches of water (27,152 gallons equal 1 acre-inch) for sprinkling at the rate of 0.19 inch per hour (for control down to 22°F), for 10 continuous hours each night over three nights. Or, 1.9 inch per night (10 hours x 0.19 inch) x 3 nights = 5.7 acre-inches. An irrigation pond would need to hold about 155,000 gallons of water for each acre of vineyard production under these conditions (5.7 inch x 27,152 gal per acre inch = 154,766 gallons).

Shutdown of Irrigation System

Operate continuously after sun-up until you can see free water running between the ice and the grape buds and shoots, or until ice falls easily from the vine structures (spurs, cordons). It is not necessary to run until all the ice has melted after the warm sunlight “takes over” (Ballard, 1971). However, if the morning should turn cloudy after sunrise and/or if there are chilly winds, *continue to run the irrigation system until the wet bulb temperature is above 32°F in the coldest portion of the vineyard.*

Supercooling Potential

When the humidity is low and cooling is gradual, newly developing grape shoots have the ability to supercool (drop below their normal freezing 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 bud burst stage. It is very possible that in the presence of moisture the critical temperature of a second flat leaf stage, for example, could be closer to 31°F, and not 28.9°F as reported by Gardea (1987). USDA researcher Michael Wisniewski (2007) has also provided further information about the importance of free moisture as an extrinsic ice nucleator in herbaceous plants at the ASHS Easter Freeze Symposium in Scottsdale, Arizona.

The factors that determine when and to what extent a plant will freeze are complex, but the author wishes to emphasize that in using overhead irrigation for cold protection of sensitive critical tissues, *growers should use a critical grape shoot temperature of 31ºF.* Lower critical temperatures may apply under conditions which favor supercooling, but keep in mind that this phenomenon occurs in the absence of free moisture on the plant surface. Growers are advised to be proactive in their use of over-vine sprinklers in preventing ice crystal formation associated with a *hoar (white) frost.* A critical tissue temperature of just below 32°F may be appropriate in early grape shoot stages under hoar white frost conditions. Once ice forms in the plant tissue, there will be damage.

Frost/Freeze Nights

On a *frost/freeze* night, the best strategy may be to take no action at all. Five to 10 mile per hour winds will prevent the formation of an inversion, so wind machines and helicopters will not be effective. Over-vine sprinkling can be designed to provide enough heating capacity to protect vines exposed to *frost/freeze* conditions. The system must be carefully engineered specifically for use under windy conditions that promote evaporative cooling. If the grower has any doubt about the capacity of the irrigation system to provide adequate heating in *frost/freeze* conditions, the best strategy may be to take no action at all as an ice-covered vine will cool below the temperature of a comparable dry vine if freezing stops and evaporation begins.

Freeze Conditions

All mechanical methods of conventional spring cold protection (wind machines, heaters, over-vine sprinklers and helicopters) are of very limited value, or no value, under true *freeze* conditions. Do not use active methods for frost control when winds are greater than 10 miles per hour; you can damage the vines (Trought et al., 1999). Sprinkler irrigation under freeze conditions is very risky due to a phenomenon known as *evaporative cooling*.

Summary

Successful cold protection must be approached with a sound understanding of frost and frost/freeze management principles, a good knowledge of your vineyard site's microclimate, weather conditions that are favorable for the operation of your cold protection system, and careful attention to the details contained in specialized weather forecasts on air temperature minimums, dew point temperatures, and wind speeds. Growers are advised to be proactive in their use of over-vine sprinklers in preventing ice crystal formation associated with a *hoar (white) frost.* In a *black frost* few or no ice crystals form because the air in the lower atmosphere is too dry, and the grower cannot wait for “evidence” of ice crystals to start up frost protection measures in these conditions. Dewpoint temperatures can help the grower assess whether he or she may be dealing with a *hoar frost* (DP in the upper 20s and low 30s), or *black frost* (DP in the mid 20s or lower). If the DP is low, indicating dryness of the lower atmosphere, *start watering before the wet-bulb temperature reaches the critical grape shoot temperature of 31ºF*. The wet bulb temperature should determine when you turn the irrigation system on and off — do not rely on ambient temperature readings in dry atmospheric conditions to decide when to start irrigating. Over-vine sprinkling cannot be engineered to provide enough heating capacity to protect vines exposed to *windborne freeze* conditions. Over-vine sprinkling can be designed to provide enough heating capacity to protect vines exposed to *frost/freeze* conditions, but the system must be carefully engineered specifically for use under windy conditions that promote evaporative cooling.

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Table 1. Relative effectiveness of wind machines and sprinkler irrigation methods under different cold-event scenarios.

Method	**Radiational hoar frost; temperature 28 to 36°F**	**Radiational black frost; temperature below 28°F**	**Frost/freeze (winds 5 to 10 mph)**	**Freeze (winds in excess of 10 mph)**
Wind machine	Highly effective	Effective	Potentially damaging	Potentially damaging
Wind machine plus heaters[1]	Not applicable	Effective	Limited effectiveness	Potentially damaging
Sprinkler irrigation	Highly effective	Highly effective	Effective	Potentially damaging

[1] Can be effective in black frost and/or weak inversion if heaters are arrayed near perimeter of vineyard and in portions of the vineyard farthest from the wind machines.

Table 2. Required irrigation rates (inches per hour) in fruit crops to maintain a temperature of 28°F and relative humidity of 70 percent. (This table is intended to illustrate the affect of wind speed on precipitation rates in fruit crops; it is not specific to grapes.)

	Wind speed			
Minimum temperature (°F)	**0 to 1 mph, apply**	**2 to 4 mph, apply**	**5 to 8 mph, apply**	**9 to 14 mph, apply**
7	0.10	0.11	0.14	0.16
26	0.10	0.13	0.16	0.17
25	0.10	0.14	0.18	0.21
22	0.10	0.18	0.24	0.29
20	0.11	0.21	0.28	0.34
18	0.12	0.23	0.31	0.38
16	0.13	0.26	0.35	0.43

Source: Perry, Katherine (February, 1998). Guide to deciding when to start and stop irrigation frost protection of fruit crops, *Hort. Information Leaflet 713, North Carolina State University*.

Ontario's Experience With Wind Machines for Winter Injury Protection of Grapevines and Tender Fruit

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Introduction

Protecting grapevines from adverse winter temperatures has been an ongoing challenge. The grape and tender fruit industries in Ontario have experienced a significant impact due to winter injury sporadically for many years. The repetitive episodes from 2003 to 2005, however, have pushed growers to look more aggressively at protecting their livelihoods. From just a few wind machines present in vineyards in 2001, there are now over 450 machines operating in Niagara and other grape-growing regions of Ontario.

The following information presents an overview of a 3-year project (fall 2005 to spring 2008) to investigate the effectiveness of wind machines under Ontario conditions to reduce the risk of spring and fall frosts as well as winter injury to grapes and tender fruit. The project was established to help growers use wind machines more effectively. Ontario is one of the few places in the world using wind machines to reduce the risk of winter cold injury because strong temperature inversions are common under very low (-15°C and lower) temperature conditions.

CanAdvance, through the Agricultural Adaptation Council of Agriculture and AgriFood Canada and CRESTech, part of the Ontario Centres for Excellence are the major funding agencies. The Grape Growers of Ontario (GGO) and the Wine Council of Ontario (WCO) are the major sponsors of the project. Other funding partners include: KCMS Applied Research and

Consulting; Stephane Bosc, supplier of Orchard Rite Wind Machines; Roger Vail, supplier of Chinook Wind Machines; Agricorp (the crop insurance agency in Ontario); the Ontario Tender Fruit Producers' Marketing Board; and the Niagara Peninsula Fruit and Vegetable Growers' Association. In-kind contributions supporting the project are recognized from the Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA); the Cool Climate Oenology and Viticulture Institute (CCOVI) at Brock University; the University of Guelph; KCMS; GGO; and Agricorp.

Major objectives of the project are:

1. to study and evaluate vine and tender fruit winter hardiness throughout the dormant season,
2. to study the behavior of air thermal inversions below and above the Niagara Escarpment,
3. to study wind machine noise and its effects off-site,
4. to establish Best Environmental Management Practices for wind machines in consultation with industry and government partners, and
5. to develop an advanced warning system to advise growers on the best use of wind machines.

Evaluation of Plant Hardiness

Bud sampling for the project started on Dec. 20, 2005, and continued every two weeks until April 6, 2006. In 2006, bud sampling commenced on Nov. 20 and continued throughout the winter and spring until April 2007. Bud sampling will continue through the 2007-08 winter/spring period with the first samples being collected during the week of Nov. 19, 2007.

There are 28 cooperating vineyards in five growing zones within the Niagara region. At these locations, 14 cultivars are evaluated in blocks with and without wind machines. Canes are taken and individual buds examined to determine if they are alive (primary bud intact) or dead (primary bud injured) to determine if the use of wind machines has an impact on bud survival. Bud survival rates are posted on the Brock University website (www.brocku.ca/ccovi) for immediate grower access and published in the Ontario Ministry of Agriculture Food and Rural Affairs periodic newsletter, "The Tender Fruit Grape Vine" (www.omafra.gov.on.ca/english/crops/hort/news/news_grapevine.html).

In 2005, a small-scale programmable freezer was built to assess grapevine bud hardiness levels. This unit has the capacity to measure exotherms (freeze points) during controlled declines in temperatures, but only for a limited number of buds. Preliminary results have been encouraging and it continues to be tested for reliability. Two Brock University students, as a part of their formal studies under the supervision of Dr. Helen Fisher, also investigated vine hardiness levels using this equipment. A second, larger-scale unit (freezer unit by Tenney Corporation) has been constructed and is currently being operated to allow for larger samples of buds to be tested. The objective is to establish general parameters of bud hardiness for most locally grown cultivars to assist growers in decision making for use or non-use of wind machines and other temperature-modifying systems in vineyards. Once this data has been reviewed for accuracy, the information will be posted on the Brock University website and recorded as LTE_{50} (temperature where 50 percent of the buds will die).

Measuring Temperatures and Inversions

Temperatures are being measured at vine level and above the vineyard at two commercial vineyards — one above the Niagara Escarpment, and a second below the Escarpment mid-way between the base of the Escarpment and Lake Ontario. The vineyard below the Escarpment has a tall tower located within the influence of a wind machine with real-time air temperature sensors located at 2 feet, 4 feet, 8 feet, 32 feet and 66 feet above ground. Five real-time and 13 downloadable temperature sensors are located at vine level around the vineyard both within and outside the area impacted by the wind machine to measure the area influenced by it. The vineyard above the Escarpment also has a tall tower with five real-time temperature sensors at similar heights, but there is no wind machine present. The measurements in this vineyard are being taken and studied to determine if thermal inversions are also present above the Escarpment. Wind speed and direction are also monitored at the 32-foot height on each tower. Plant health and yields are monitored over the three-year duration of the study.

Noise Issue

The noise from the operation of wind machines has affected some neighbors in the grape growing areas of the Niagara Peninsula because there are many homes built within rural areas. Sound consultants were hired to record the source of the sound near wind machines and inside a few residential dwellings. Most sound is produced from the rotation of the wind machine blades, which create a helicopter-like sound. Blade noise is affected by speed, diameter, shape, and the number of blades, as well as tower design, airflow, and any wind that may be present even from adjacent machines. The engine produces very little sound in comparison. The sound is generally aggravated in homes with large rooms, square shape rooms and in corners, rooms with large windows, hard surfaces such as hardwood floors, light wall construction and less insulation.

Data collection is ongoing and results are preliminary. Since the inception of the program we have not had severe low winter temperature episodes but have experienced some spring frosts where the machines were used. The winter of 2005-06 produced average daily air temperatures of about 9ºF higher than the 85 year average at Vineland Station, Ontario. On the evening of Dec. 13, 2005, one test site reached 1ºF at 2 feet above ground level (vine height) and was about 18ºF warmer at 66 feet above the vineyard. Temperature inversions appear to occur only if wind speeds drop below 9 miles per hour.

We have been observing the effectiveness of wind machines in protecting grapevines and tender fruit for several years but are still searching for answers to many questions. When (at what temperature) should growers turn on the machines based upon the time of year? When should they be turned off? Capital costs of the machine run around $30,000 U.S. (installed), but what are the operating costs and the life span of the machines? The experience we hope to gain over the three years of this project aim to address key issues related to wind machine use and answer many growers' questions.

Sprinkler Systems Used for Frost Protection

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Introduction

Frost protection from sprinklers is a proven method to help protect crops from damages caused by freezing weather. For areas prone to freeze events, installing and operating a sprinkler system designed for frost protection can be the difference between having a crop at harvest time and losing the crop completely. Frost protection from sprinklers is provided in two different forms, one is referred to as overtree or crop, which uses ice encapsulation as the main method for protecting the plant tissue from frost damage. The second is undertree, which relies on high humidity (localized fog) to protect the crop. This paper will discuss the general requirements of both methods.

Water as a Heat Source

The major source of energy (heat) is found as water changes from the liquid state to ice. It is estimated that 144 British Thermal Units (BTU's) per pound of water is released to the atmosphere during the freezing process. There are 8.3 pounds of water in a gallon. This process is referred to as heat of fusion.

An example of the heat released from 0.1 acre inch of water as it cools down from 62°F (which can be typical of groundwater) to 32ºF is 680,000 BTU/hour. This same water will also release an additional 1,630,000 BTU/hour if half the applied water or 0.05 acre inches freezes. The sum total of both heat sources is 2,310,000 BTU/hour (680,000 +1,630,000).

Estimating Your Water Needs

There are a number of critical issues to consider when planning for a frost protection system. The first and most important question to be answered is water supply. How much water is available in terms of gallons per minute, and how many gallons of water are available in total. Flow rate is important to know because many frost protection systems target a water application rate of at least 0.1 inches per hour to help protect the crop. This number can vary depending on available water, expected temperature, and dewpoint.

The application rate of 0.1 inches per hour expressed as flow rate on a per acre basis is approximately 45 gpm. The math becomes simple at this point: Number of irrigated acres requiring frost protection, times 45. Thus if you have a 20-acre block, it would require a flow rate of 900 gallons per minute.

In many areas of the country an overhead sprinkler system may have to operate for at least eight hours during the critical frost event. In some areas like the Napa and Sonoma region of California, frost events may statistically last up to three consecutive days (nights).

Therefore, the total amount of water required for frost protection on the 20-acre block used in the above example would be 1,296,000 gallons of water and is calculated as follows:

45 gpm/acre x 20 acre = 900 gpm

Where 45 gpm per acre is required times the field size of 20 acres equals 900 gpm

900 gpm x 60 minutes x 8 hours = 432,000 gallons of water/day

Where the required flow rate of 900 gpm is multiplied by 8 hours of operation

432,000 gallons/day x 3 days = 1,296,000 gallons of water

Where the daily water requirement is multiplied by a potential three day frost event

Providing for 1,296,000 gallons of water requires the equivalent surface storage of an acre reservoir, filled four feet deep. A reservoir designed for 100 acres of frost protection would require five times as much surface storage or five acres, filled to a depth of four feet, and so on.

In some areas where overhead sprinkler frost protection is not the same system used for the purpose of irrigation, “stand-by” diesel engines can be used to run the pumps. This is done mainly to avoid “demand” charges from the utilities which can be substantial for the relative large flow and pressure requirements of frost protection. However, selecting diesel power plants over electric motors does require due diligence in maintaining the engines so they operate without failure on short notice.

Sprinkler Selection and Spacing for OverTree/Crop Systems

Now that the amount of available water has been determined for frost protection, it is time to select sprinkler type, spacing, and operating pressure. All of these decisions will effect how evenly water will be applied to the crop.

The cultural practices used to establish crop plantings will many times dictate the sprinkler spacing used in the field. For instance, a vineyard might use a row spacing of 12 feet; common sprinkler spacing would be 32 feet down the row and 48 feet between rows (or 4 rows by 12 feet). In row crops, the field spacing may be further apart, perhaps 45 feet by 45 feet or more.

There are several types of impact sprinkler designs commonly found in the field. One is the spoon drive sprinkler which is common in field crops using portable aluminum irrigation pipe. Figure 1 illustrates a typical spoon drive sprinkler.

A second type of sprinkler is the wedge drive, which provides a faster speed of rotation. This type of sprinkler is commonly used for frost protection in California vineyards. Figure 2 illustrates a typical wedge drive sprinkler.

The key to determining which choice is most appropriate is typically driven by economics and performance. In trees and vines, the system must conform to the established spacing. Many of these frost protection systems are referred to as permanent, since mainlines and laterals are buried underground. Other systems like those used in row crops may use portable aluminum or plastic mainlines and laterals. In designing systems, care should be taken to assure that the uniformity of the irrigation system is as high as possible. Under calm winds (3 miles per hour or less) a field audit of the sprinkler system should provide a distribution uniformity approaching 80 percent or greater.

Performance information can be obtained from sprinkler manufacturers before purchase and installation. The following examples show both the performance of a spoon and wedge drive sprinkler. The first sprinkler is a Weather Tec 10-30 spoon drive sprinkler with a 5/32-inch taper bore nozzle. This sprinkler has a 3/4-inch base and was tested at 60 psi. Figure 3 shows the sprinkler profile and a wetted radius to be about 50 feet. Sprinkler profile and wetted radius are key components used to calculate distribution uniformity (DU).

If we project the sprinklers performance over a range of possible field spacings, we can evaluate uniformity against potential system costs. In Figure 4, the 10-30 sprinkler DU (broken line) is shown over a range of possible field spacings. It begins with 36 feet by 36 feet spacing and ends at 60 feet by 60 feet spacing. It should be noted that at the spacing of 45 feet by 45 feet, the sprinkler continues to provide good uniformity. At this spacing, the calculated DU is 86 percent, with an application rate of 0.271 inches per hour. However, as the sprinklers spacing increases beyond this distance (45 feet), uniformity begins to drop-off quickly. DU's are also negatively impacted by wind, and this can be more pronounced in "stretched" spacings. The Coefficient of Uniformity (CU) and Scheduling Coefficient (SC) are also shown for reference.

The second sprinkler is a Weather Tec 10-10 wedge drive sprinkler with a 1.8 flow control nozzle. The sprinkler has a 1/2-inch base and was tested at 35 psi. Flow control nozzles are designed to provide a constant flow rate over a range of operating pressures. This type of nozzle is most commonly used where large changes in topography exist in the field. Note that with every elevation change of 2.31 feet, the pressure changes by 1 psi (either positively or negatively). Figure 5 shows the sprinkler profile and a wetted radius to be about 40 feet.

Again, if we project the sprinklers performance over a range of possible field spacings, we can evaluate uniformity against potential system costs. Figure 6 shows the 10-10 sprinkler DU over a range of spacings, beginning with 25 feet by 42 feet and ending at 40 feet by 57 feet spacing. It should be noted at a spacing of 32 feet by 48 feet, the sprinkler's calculated DU is 78 percent with an application rate of 0.107 inches per hour. However, as the sprinklers are moved further apart from this distance, uniformity begins to drop-off. Uniformity measurement for CU and SC are again shown for reference.

The performance of sprinklers can be modeled with various nozzle types, flow rates, and operating pressures. This information can be valuable when making the final system design decisions.

It is critical to maintain a temperature of 31 to 32ºF in the ice encased plant tissue. To do this, the plant should be re-wetted every 30 seconds or so. Sprinklers used for frost protection typically have a faster rotation speed than those sprinklers used specifically for irrigation. If the sprinklers being used for frost protection have a slower rate of rotation (e.g., 60 seconds), they may need to apply 10 to 20 percent more water for equivalent protection at similar conditions.

Application rate does determine the level of potential frost protection that can be achieved. For example, a vineyard frost protection system might be designed for 0.12 inches/hour, which has provided protection down to 23ºF with a dewpoint of 25ºF. It is recommended that for each 1 degree dewpoint below 25ºF that an additional 0.01 inches/hour be applied through the system. So to protect down to 23ºF with a dewpoint of 22ºF, an application rate of 0.15 should be used. Please note that higher application rates require more water and energy. Also during prolonged periods of frost, fields can become water logged, making cultural practices impractical until an acceptable level of drying occurs.

Overhead sprinkler application depends on ice encasement to protect the plant from frost damage. It is a generally accepted method for row crops and vineyards. It provides a higher level of protection than undertree, but requires more water per acre. Water must be repeatedly applied during the frost event to ensure the ice-coated vegetation has a film of water. If the sprinkler rotation (and water application) is not sufficient to keep the ice "wet" before the next application of water, significant frost damage is likely. Systems with a poor DU will be more prone to frost damage, particularly in areas of low water application.

Undertree Sprinklers

Undertree sprinkler application is more common in deciduous or citrus trees and in areas where the threat of low dewpoint is rare. Undertree systems work by saturating the air with water vapor, thus causing the trees to be engulfed in a fog. These systems tend to operate better with a larger number of sprinklers per acre (but less flow per sprinkler) and with relative high pressures which produce smaller water droplets. Plastic rotating and micro sprinklers are commonly used in undertree applications. Design of these products differs in that many times each tree has one or sometime two sprinklers located around the base of the tree. Flow rates are typically measured in gallons per hour (e.g., 10 to 60 gph), rather than per minute volumes. Caution should be taken when operating micro sprinklers as water in the small diameter distribution hoses commonly used will freeze quickly if the system is not started early enough, rendering the system useless.

Advantages of the micro sprinkler system are that they can be operated both for irrigation and frost protection, so the cost and maintenance of a redundant system are eliminated. These systems also require significantly less water to operate. Therefore, where the water supply is an issue, this system may be an acceptable alternative for overtree/crop sprinkling. However, the system is limited in its ability to provide adequate protection during a severe freeze event.

Research on Florida citrus has indicated a minimum of 33 gallons per acre to provide some level of protection. Undertree systems may only provide partial protection of 2 to 3ºF up to a height of 4 feet. Protection above these heights is reduced or negligible. Obviously, levels of protection are influenced by local freeze conditions. Low dewpoint conditions should be noted, as increased water rates are required to meet the evaporative demand required to maintain temperatures. Failure to provide enough water may exasperate freeze damage to the crop.

Finally, significant work was done in California exploring micro sprinklers which are designed to apply water in a “strip” over vines. The main advantage of this approach was reduced water requirements because the row centers do not receive water. Only the plant tissue is wetted. Research has shown that this system can be operated successfully under proper conditions. However, these systems have not been widely accepted by growers as the risks of failure or problems are seen as significantly higher than those found with conventional overhead sprinklers.

System Operation and Start-Up

One common mistake made by growers is starting the sprinkler system too late. When the system is first turned on, there is an immediate “supercooling” or drop in temperature due to evaporation. Under certain conditions, this may damage the crop more than if the system was not used. It is critical that both temperature and dewpoint be monitored so that the system is started before supercooling will negatively affect crop health. Figure 7 can be used as a reference guide to system start-up. Local conditions may vary.

In the absence of dewpoint information, wet bulb temperature may be used to start the system. The system should be turned on at 32ºF wet bulb temperature. It should not be turned off until the wet bulb temperature is at least 34ºF, and higher if there is a wind blowing to cause evaporation.

Drier air will have a lower dewpoint. Temperatures can fall quickly until the dewpoint is reached. Therefore, on nights when low dewpoints are anticipated the irrigation system must be started at higher air temperatures than on nights when the dewpoint is significantly higher.

The sprinkler system should continue to be operated until temperatures rise to a safe level. Shutting the system off too soon will cause the plant tissue to freeze if temperatures have not risen to a level where ice has quit forming.

Conclusions

Planning for a sprinkler frost protection system should include an experienced irrigation designer. Special consideration should be given to Certified Irrigation Designer (CID) or Professional Engineer (PE) that have demonstrated competency in this area. A list of CIDs can be found on the Irrigation Association website (irrigation.org).

A properly designed, installed, maintained, and operated sprinkler system will provide growers with an expected level of frost protection. Accepting anything less will put the crop at risk and potentially provide less than satisfactory results.

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Figure 1. Spoon drive sprinkler.

Figure 2. Wedge drive sprinkler.

Figure 3. Weather Tec 10-30 sprinkler profile.

Sprinkler Name	WEATHER TEC	Base Pressure (PSI)	60.0
Sprinkler Model	10-30	Riser Height (IN)	24.0
Nozzle Size	5/32"	Set Screw Setting	
Flow Rate (GPM)	5.70	Degree of Arc	360
Date/Time of Test	11/14/07 11:10	Mins./Revolution	0.86
Testing Facility	C. I. T.	Record Number	
Comment	Sprinkler provided by: CIT		

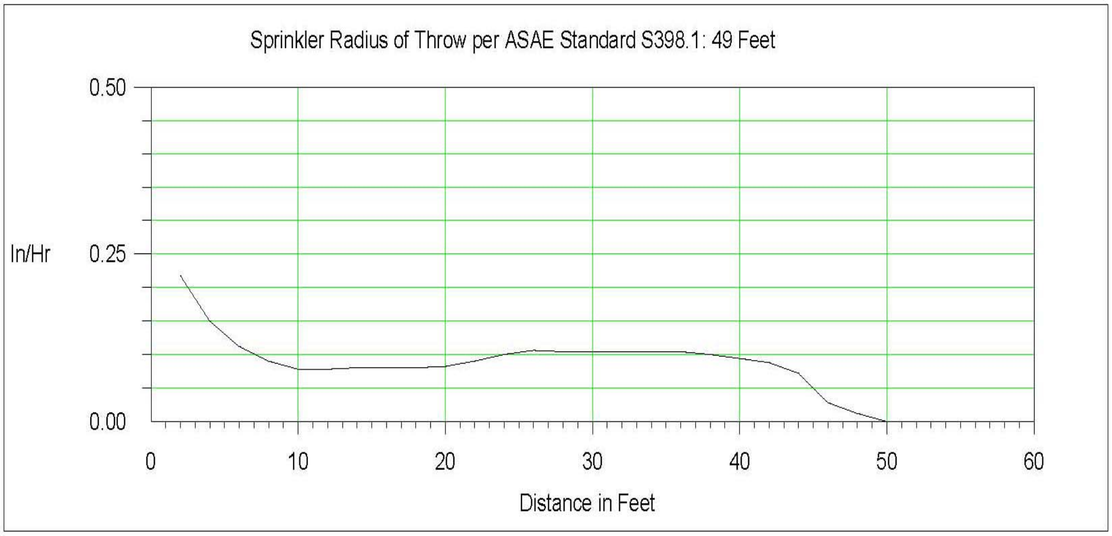


Figure 4. Effect of spacing on distribution uniformity.

Sprinkler Name	WEATHER TEC	Base Pressure (PSI)	60.0
Sprinkler Model	10-30	Riser Height (IN)	24.0
Nozzle Size	5/32"	Set Screw Setting	
Flow Rate (GPM)	5.70	Degree of Arc	360
Date/Time of Test	11/14/07 11:10	Mins./Revolution	0.86
Testing Facility	C. I. T.	Record Number	
Comment	Sprinkler provided by: CIT		

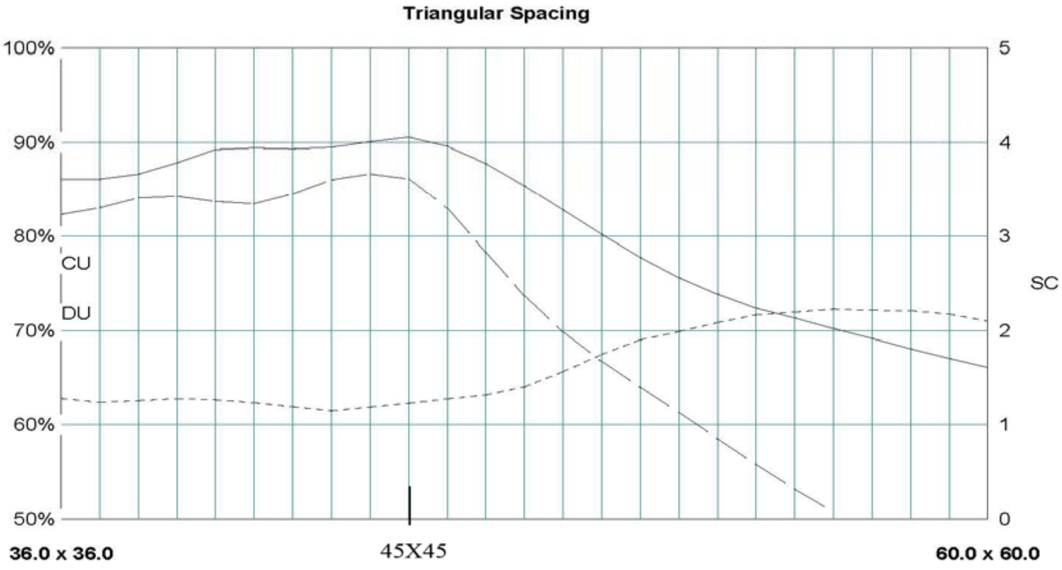
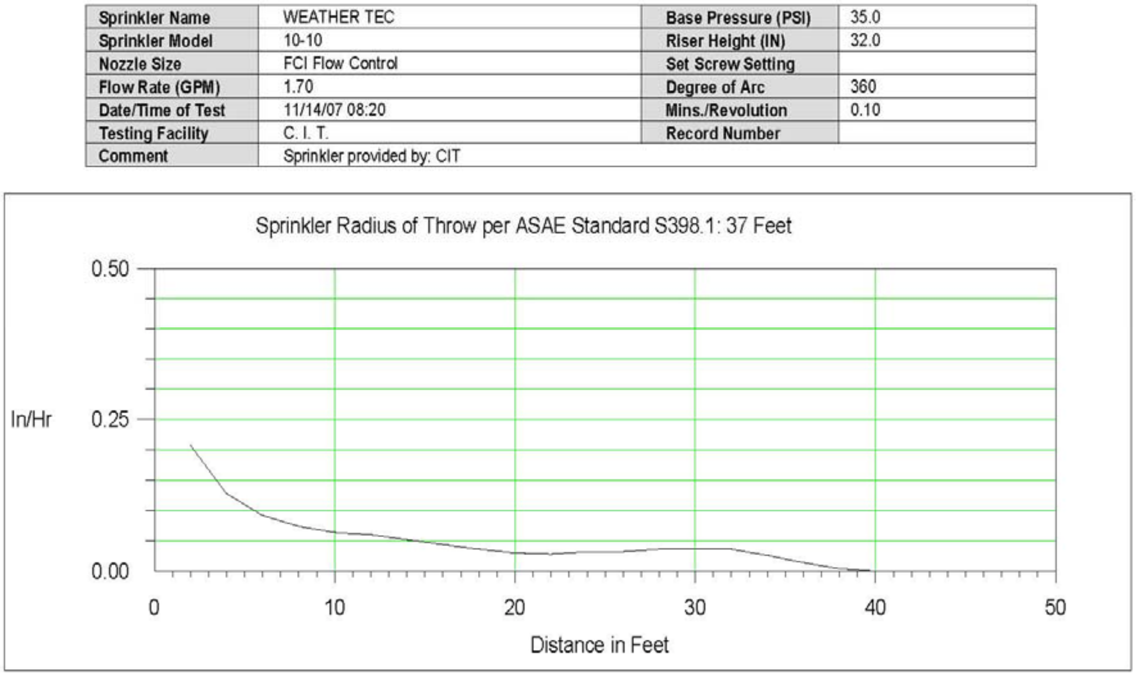
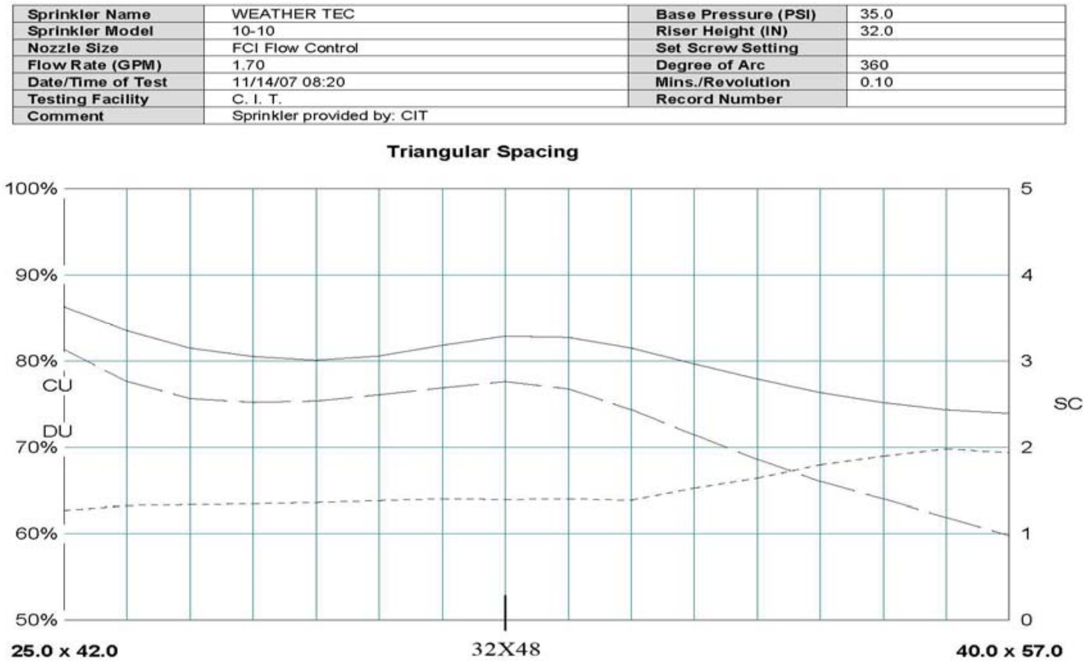


Figure 5. Weather Tec 10-10 sprinkler profile.



Sprinkler Name	WEATHER TEC	Base Pressure (PSI)	35.0
Sprinkler Model	10-10	Riser Height (IN)	32.0
Nozzle Size	FCI Flow Control	Set Screw Setting	
Flow Rate (GPM)	1.70	Degree of Arc	360
Date/Time of Test	11/14/07 08:20	Mins./Revolution	0.10
Testing Facility	C. I. T.	Record Number	
Comment	Sprinkler provided by: CIT		

Figure 6. Effect of spacing on distribution uniformity.



Sprinkler Name	WEATHER TEC	Base Pressure (PSI)	35.0
Sprinkler Model	10-10	Riser Height (IN)	32.0
Nozzle Size	FCI Flow Control	Set Screw Setting	
Flow Rate (GPM)	1.70	Degree of Arc	360
Date/Time of Test	11/14/07 08:20	Mins./Revolution	0.10
Testing Facility	C. I. T.	Record Number	
Comment	Sprinkler provided by: CIT		

Figure 7. Irrigation system start-up temperatures and dewpoints.

Dewpoint temperature (°F)	Air temperature (°F) at which sprinklers should be started (0- to 500-foot elevation)
15º	39º
16º	39º
17º	38º
18º	38º
19º	37º
20º	37º
21º	37º
22º	36º
23º	36º
24º	35º
25º	35º
26º	34º
27º	34º
28º	33º

Delaying Grapevine Bud Burst With Oils

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Introduction

Mid-winter freeze and spring frost are two of the major climatic threats of commercial grape production under continental climate conditions. Due to low cost and ease of application, spray chemicals have long been used to protect plants from low temperature injury. Several chemical products such as growth regulators, anti-transpirants, dormant oils, and cryoprotectants have been used in order to enhance cold hardiness and/or delay bud break of horticultural crops. However, their effectiveness has been inconsistent and varied according to the product, rate, plant species, site, and time of application. Dormant oils have been used for decades primarily for insect control in fruit trees. However, researchers found that oils also cause a retardation of bloom and foliage development of apple and peach trees. The goal of this research study was to delay bud break of grapevines using oils, thus minimizing the likelihood of spring frost injury.

Materials and Methods

The effects of dormant oil applications on bud phytotoxicity, bud cold hardiness, bud break, yield components, and fruit composition of grapevines were investigated. The study was initially conducted in Virginia and continued in Illinois and Ohio with the following wine grape varieties: Cabernet franc, Cabernet Sauvignon, Chambourcin, Chancellor, Chardonel, Chardonnay, Concord, Lemberger, Pinot gris, Norton, Seyval, and Vignoles. Throughout the course of this study, several oils were applied: mineral-based oils such as JMS stylet oil and soybean-based oils, including crude soybean oil, and adjuvants such as Amigo, Prime Oil, and Soydex. Oils were applied on canes during the dormant season and after leaf fall. Time of application and rates from 0 percent to 20 percent (volume of oil/volume of water) were also investigated. Control vines were untreated.

Results and Discussion

Phytotoxic rates of oils. Rates above 10 percent (v/v) of all oils were phytotoxic to almost all varieties. Therefore, lower rates were subsequently used. Stylet oil appears to be phytotoxic at the lowest rate used, i.e., 2.5 percent for Cabernet franc. Furthermore, at the same rate, stylet oil is more phytotoxic than soybean oil. It is concluded that oil phytotoxicity depends on oil type, rate, time of application, and variety treated. It is suggested that rates of stylet oil and soybean oil should be below 2.5 percent, and 10 percent, respectively. Optimum soybean oil rate was determined at 8 percent (v/v) mixed with an emulsifier or spreader sticker such as Latron B-1956 at 1 percent (v/v) and water. Thorough coverage of canes is critical and volume sprayed can be as high as 200 or more gallons per acre.

Bud cold hardiness. Oils did not affect mid-winter bud cold hardiness. In other words, dormant oils did not enhance nor reduce bud hardiness in mid-winter. However, during deacclimation, oil-treated buds maintained higher levels of hardiness than untreated buds. Therefore, vines treated with oils have a slower rate of deacclimation than controls. This is a desirable outcome since vines could tolerate lower temperatures without injury in early spring.

Bud break. Dormant oils applied at non-toxic rates delayed bud break of several cultivars (Figure 1). Bud break was delayed between two and 19 days dependent upon the variety. However, it is noted that bud break delay beyond 10 days has deleterious effects on shoot and fruit growth. These observations were made especially with stylet oil even at the lowest rate used of 2.5 percent. We demonstrated that bud break delay of Chardonel was also associated with a 30 percent reduction in respiratory activities of oil-treated buds as compared to untreated buds. It is suggested that oils may have caused a slow resumption of growth in the spring due to low respiratory activities.

Conclusions

1. Cultivars respond differently to dormant oils. At the same rate, stylet oil is more phytotoxic than soybean oil. Rate of soybean oil should be 8 percent (v/v). Rate of Stylet oil should be below 2.5 percent to minimize phytotoxicity.
2. Mid-winter bud hardiness of several cultivars was not affected by dormant oils.
3. Deacclimation of oil-treated buds is delayed and results in higher bud survival than that of untreated buds during a frost event.
4. Soybean and stylet oils delayed bud break by two to 19 days. However, delay beyond 10 days is not desirable and could be deleterious to vine growth and fruit ripening.
5. Higher rates caused a reduction in yield components. Therefore, only non-phytotoxic rates of oils should be used to avoid crop reduction or loss.
6. Dormant oil application did not affect fruit maturation and did not cause uneven ripening. Fruit composition is not affected except when bud break is extensively delayed.

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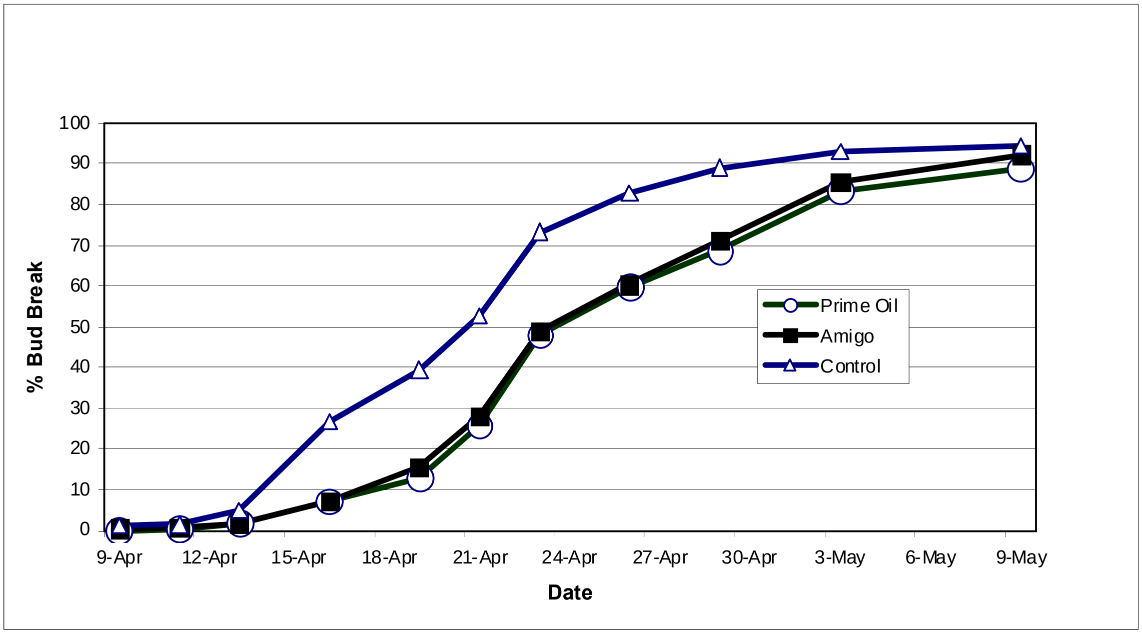
Figure 1. Effect of soybean-based oils on bud break and development of Chambourcin.



What We Learned From the Easter Freeze in the Mid-Atlantic Region

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Abstract

All Eastern and Midwestern fruit industries learned valuable lessons from this freeze. Strawberry and blueberry growers in North Carolina discovered how *unreliable* forecasts for wind speeds are, and these industries are now making a concerted effort to work with our State Climate Office in Raleigh to improve the accuracy of wind speed forecasts as well as to provide farmers with real time information on dry bulb, wet bulb and dew point temperatures. Not that many years ago, before most of us knew much about global warming and climate change, the strawberry plasticulture industry in North Carolina, Virginia, Tennessee and South Carolina was clobbered with an *Easter Freeze-like event*, and that was our wake up call! We had to make a decision to adapt or face extinction. We went to work on developing new approaches to managing the brutal combination of high winds and subfreezing temperatures, and came up with the "ice blanket" method where we apply floating row covers to the crop prior to the freeze, and then run sprinkler irrigation on top of the covers to form a blanket of ice that provides excellent blossom protection against the strawberry grower's worst adversary — the windborne freeze. In fruit industries that have little experience with active cold protection techniques, I have observed a tendency by these growers to view the Easter Freeze of 2007 as an anomalous event, something that happens say once in 50 years. I don't know whether this was an anomalous event or not? Frankly, the key findings in a report just issued on Nov. 17, 2007, by the United Nations Intergovernmental Panel on Climate Change was anything but encouraging, especially the statement that "Extreme weather events will be more common in the future." Remember, the historic freeze on April 7 and 8, 2007, occurred from the central and southern Plains into the Midwest and Southeast, following the nation's *second warmest March on record.* One dimension of overhead sprinkling that Missouri grape growers may not be aware of is how this technology may be adapted to *heat protection*. Time will tell, but perhaps we will discover that one of the greatest benefits associated with over-vine sprinkling for grape growing in continental climates like Missouri is related to the potential of this technology to beneficially *delay bud burst* by using sprinklers for *evaporative cooling*. Time will also tell as to what the Missouri grape industry's response will be to the *April freeze of 2007.* This presentation is designed to challenge the Missouri grape industry to re-think their position on active cold protection, and especially over-vine sprinkling.

What We Learned From the Easter Freeze in Missouri

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Abstract

After an unusually early and extended warm period in March, a severe advective freeze moved across the region around the Easter weekend in early April 2007. Most vines had deacclimated and commenced shoot development from most of their buds, especially in the southern areas of the region. Injury of primary buds and shoots was almost total, with severe injury of secondary buds in some cultivars. Surveys were conducted post-freeze in commercial vineyards around the region to assess the amount of bud injury in the more important winegrape cultivars, and again at harvest to determine the relative contribution of clusters from count and non-count shoots to the total crop. Cluster counts and weights and berry samples according to count or non-count shoots were taken from cultivars and selections from the Winegrape Cultivar Evaluation Trial at the State Fruit Experiment Station in Mountain Grove, Mo. Results from both the harvest survey of commercial vineyards and the cultivar evaluation trial indicated that basal shoots contributed the majority of the crop for most cultivars and that the variation in fruit maturity at harvest was insignificant for most cultivars, with pH and titratable acidity being the most variable indices of maturity. Additionally, clusters from count shoots tended to be slightly more advanced in maturity than clusters from non-count shoots.

Introduction

The Easter freeze of 2007 was an historic event without precedent in the modern Missouri wine industry. The unusually warm weather in March preceding the freeze event had led to the early deacclimation and budburst of all major winegrape cultivars in all growing areas around the state. Even late-opening cultivars such as Norton and Vignoles had begun opening buds and commencing shoot development throughout the region. Early-opening cultivars such as Chardonel and St. Vincent had opened all or nearly all buds and in some areas had already developed several inches of shoot growth. All of these shoots and opened buds were killed by the ensuing freezing weather that lasted for several days and reached record low temperatures. In the aftermath of the Easter freeze the questions to be answered were “what is the extent of the damage” and “what are the crop expectations for this season.” To answer the first question would simply require visiting vineyards and assessing bud and possible wood injury of the more important winegrape cultivars. The answer to the second question would be more difficult to ascertain since the necessary information was unavailable.

The Missouri wine industry is based upon native and hybrid cultivars. Native cultivars such as the *Vitis labrusca*-based Concord and Catawba are known to have very poor fruitfulness on shoots from non-primary buds, while other native cultivars such as the *V. aestivalis*-based Norton/Cynthiana have a low to moderate level of fruitfulness on those shoots. While many hybrid cultivars such as Seyval blanc are known to have fruitful secondary and sometimes tertiary buds, the level of fruitfulness and potential cluster size of the lesser buds of many of the more important cultivars is not well established. In addition, many newer hybrid cultivars have increased in importance to the Missouri wine industry in recent years. Knowledge and experience with these cultivars is limited, particularly with regard to their response to severe freeze events once in a completely deacclimated condition. Newer cultivars such as Chardonel and Traminette from Cornell University and Frontenac from the University of Minnesota, as well as the older French-American hybrid cultivar Chambourcin, have experienced an increase in acreage due to increased demand by wineries and the wine-consuming public. Fruitfulness from secondary, tertiary, and basal buds is not well-known for these cultivars. Also of concern was the difference in ripening and maturity at harvest of clusters from shoots of differing origins. If clusters from shoots developing from the differing buds were harvested at the same time, what would be the range in maturity of the fruit and what would be the resulting quality of the wine? The viticulture team at the Institute of Continental Climate Viticulture and Enology (ICCVE) at the University of Missouri-Columbia initiated activities to answer these questions.

Materials and Methods

A few days after the freeze event was over, the ICCVE viticulture team began evaluating bud injury of several cultivars in the major winegrowing regions of Missouri and Northwest Arkansas. Representative vineyards in each area were visited by one of the viticulture team members who estimated the percent survival of primary, secondary, and tertiary buds of cultivars important to the wine industry. The results were then compiled to determine the potential crop loss for the season. At the State Fruit Experiment Station in Mountain Grove, Mo., cultivars and selections in the Winegrape Cultivar Evaluation Trial were examined after shoot re-growth had commenced to determine the level of bud and vine injury and which buds were contributing to canopy development and potential crop as a result of the freeze.

During the 2007 harvest season, a second survey was conducted in commercial vineyards to determine the source and size of clusters making up the 2007 winegrape crop in Missouri. At or just before harvest of several important cultivars, a member of the ICCVE team visited a representative vineyard and counted clusters on 15 to 20 vines per cultivar according to whether they were borne on shoots from count or non-count bud positions. (A count position is a node on a fruiting cane or spur that is intentionally retained as part of a formula during balanced pruning of the vine; non-count buds are basal or latent buds.) One cluster per vine from both count (when available) and non-count shoot were collected and brought back to the lab where they were individually weighed to determine whether cluster size varied according to the bud from which the shoot developed. During harvest of the cultivars and selections in the Winegrape Cultivar Evaluation Trial, berry samples were collected separately from each replicate from count and non-count clusters for fruit composition analysis and clusters were harvested and counted separately from each vine according to whether they came from a count or non-count shoot. The data were then analyzed to determine the relative contribution of count and non-count shoots to yield and difference in composition as affected by the source of the cluster.

Results and Discussion

The survey of bud injury revealed a devastating loss of primary buds/shoots in all cultivars and serious losses of secondary buds in many of them (Table 1). Observations showed that the level of injury was affected by site, cultivar, and cultural practices. In more southern areas of Missouri and in Arkansas, where temperatures had been warmer, vines were in a more advanced stage of development and therefore more susceptible to the freezing conditions that blanketed the entire region. While the freeze was advective in nature with associated strong winds, ICCVE personnel noted that in some vineyards where the same variety was planted in both a high and low site, lower plantings appeared to have greater injury than their higher-located counterparts. Time of budburst and level of bud or shoot development as affected by cultivar played a role in bud injury or survival. In several vineyards no live count buds could be found on Chardonel and extensive phloem injury was observed on many Chardonel vines. Other varieties with all buds either opened or swollen suffered 95- to 100-percent primary bud loss. Cultivars with a late budburst such as Norton and Vignoles suffered the least injury since they had many buds in lower node positions on the canes that still had not begun development. Where long-cane (5 to 8 nodes) pruning was utilized, primary bud survival tended to be higher since the development of lower-node positions' buds was delayed, particularly with cultivars such as Norton and Vignoles.

Examination of cultivars and selections from the Winegrape Cultivar Evaluation Trial revealed similar data (Table 2). All vines experienced near complete loss of primary, secondary, and tertiary buds, with Norton and Vignoles having the highest rates of count bud survival. Other cultivars in the trial with count bud survival included Traminette, GR-7, and the newly released cultivars from Cornell University, Valvin Muscat and Corot noir. Several of the cultivars and selections in the trial have a very early budburst period and were much more susceptible to cold injury when the freeze event occurred. These vines suffered complete loss of count buds, and in many cases, of basal and latent buds as well. Due to serious damage to cordons and/or trunks, most of these vines were later cut back and are in the process of having new cordons and/or trunks retrained from suckers. As a result, these vines were not harvested in 2007 (Table 3). In vines where the permanent woody structure survived, the canopy was mainly composed of shoots from basal and latent buds (Table 2). This was similar to what was observed in commercial vineyards around the region. With the inhibitory effect of count buds reduced or removed, numerous basal and latent buds developed and were the source of both canopy and crop. One positive effect of this phenomenon was that in many blocks of older vines where fruiting positions along the cordon had been lost, the development of shoots from latent buds that had lain dormant will allow these fruiting positions to be reestablished. Thus, growers will be able to develop new fruiting canes or spurs from the canes that now fill these positions.

The harvest period survey of cluster origins and sizes for the major cultivars revealed that for many, if not most cultivars and vineyards, clusters from non-count shoots provided the majority of the 2007 crop (Table 4). Some important cultivars were not included in the survey. Concord, Catawba, and Chardonel were excluded due to the lack of count bud survival in these cultivars. For the rest of those surveyed, except in the case of the Norton vineyard sampled, non-count clusters made up 50 to 99 percent of the crop and reflected the stage of bud development at the time of the freeze event. Crops from cultivars that were earlier to open buds such as Cayuga White, St. Vincent, Vidal blanc, and Chardonel (not sampled) were composed almost entirely of clusters from non-count shoots. The Norton vineyard, located in central Missouri, had nearly two-thirds of its crop come from count shoots. Of particular interest in the results presented in Table 4 are the two Chambourcin vineyards. The one labeled as ‘Chambourcin SCBC’ (single-curtain, bilateral cordon) was from a vineyard in Northwest Arkansas, where the vines were fully deacclimated and suffered severe bud injury. Many of these vines suffered significant trunk injury as well. The other, ‘Chambourcin GDC,’ (Geneva Double Curtain) was located in west central Missouri and still had unopened buds in the first and sometimes second node positions on the fruiting spurs. During the initial bud injury assessment survey, these vines were estimated to have 5 to 10 percent primary bud survival. Average cluster size of the two groups showed mixed results, with most cultivars having similar cluster sizes for count and non-count shoots. For some cultivars showing larger differences between the two cluster groups, such as Cayuga White and St. Vincent, there were far fewer clusters in the count cluster sample taken back to the lab, reflecting the relative lack of count clusters in the crop, which may have affected the results. Looking at the range of cluster sizes for each cultivar (data not shown) showed a very large amount of variability in cluster size in both groups.

Analysis of the yield data from the vines in the Winegrape Cultivar Evaluation Trial reveals similar information as the commercial vineyard cluster survey. Cluster counts per vine according to the origins of the bearing shoots shows that non-count shoots were the main source of crop for the 2007 harvest season (Table 5). In most cases the ratio of non-count:count shoot clusters range from 2:1 to 4:1. Only in the older replicates of Norton (IV) were the two sources nearly the same. Cluster weights were not very different between count and non-count shoots. Only in the cases of Traminette, Corot noir, and the younger replicates of Norton (V) were the differences statistically significant, although in almost all cases count clusters were numerically larger than non-count clusters, some by more than a tenth of a pound. The lack of statistically significant difference may be due to the fact that the count clusters were almost exclusively from secondary and tertiary buds, which may not differ as much in fruitfulness from basal buds as primary buds do. Also, the very low crop loads experienced as a result of the freeze meant that there was very little cluster-to-cluster competition for carbohydrates and other resources from the vine, which may have allowed the differences between clusters to dissipate somewhat. Most cultivars yielded around a ton per acre or less, while the best performing cultivars (Corot noir, Norton, Valvin Muscat, Vignoles, and the Cornell selection NY 84.101.4) yielded approximately 2 tons per acre (Table 5).

Analysis of the fruit composition data showed that as a group clusters from non-count shoots did not significantly lag behind clusters from count shoots in most cases (Table 6). Individual berry weights did not significantly differ between the two types of clusters except in a few cases and in most of these the differences were less than a tenth of a gram. Nor was there a consistent pattern, with berries from count clusters being larger in one half of the cultivars and berries from non-count clusters being larger in the other half. Soluble solids of the two cluster groups showed the least difference, with only two of the Cornell breeding program selections having significantly different levels. In most cases, the soluble solids were nearly identical for both cluster groups within each cultivar. The pH values showed somewhat more variation than the soluble solids, but only in four cases were the differences significant and differences were only large in two of those cases, NY 81.315.19 and the younger replicates of Norton. The largest amount of variation in maturity was found in the titratable acidity (T.A.) of the various cultivars. Ten of the fourteen cultivar sample comparisons showed significantly different T.A. values.

However, as with the pH values, even when differences were significant they were not large, except in the case of NY 81.315.19, where the non-count clusters had 2.4 g/L lower T.A. than count clusters. Even though the overall differences were not large, count clusters as a group tended to be slightly more advanced in maturity than non-count clusters. As with the lack of large differences in cluster sizes, the lack of large differences in maturity indices of the two cluster groups may be due to the lack of more advanced primary clusters and to the much reduced crop load. The reduction in crop load led to an increase in canopy size as shoot growth was not hindered by significant competition from the crop for nutrient resources. The abundant leaf area per gram of fruit would have been more than enough to ripen the crop adequately and may have helped to reduce the differences in maturity level of the two cluster groups. According to this data, for the 2007 harvest, having crops from two different shoot sources on the same vine should not have been a source of large variation in fruit, and possibly wine, quality.

Conclusions

The Easter Freeze of 2007 provided an opportunity to learn valuable information about the performance of several important winegrape cultivars after a post-deacclimation severe freeze. With the lack of reliable information on vine performance in the aftermath of such an event, many concerns were based on speculation as to how the vines and grape crop would respond. There were concerns that lesser buds, particularly basal and latent buds, would not have good fruitfulness. Another concern was that if crops from different types of buds were all retained on the same vines, the high degree of variability from one cluster group to another would lead to highly variable fruit maturity at harvest, requiring either multiple hand harvests or harvesting a single crop of much lesser quality.

While fruitfulness of secondary and basal buds was not high for most cultivars, in some such as Chambourcin, Chardonel, and Vidal blanc, it resulted in crop levels approaching 60 percent of normal or higher in some vineyards. These results are all the more impressive in that these cultivars had been classified as only moderately hardy (Chardonel, Vidal blanc) or cold tender (Chambourcin) in a previous survey of winter bud injury (Brusky-Odneal, 1983). In this instance, the vines had experienced January freezes of -25º C (-13º F) and -27º C (-16º F). In the present situation the vines experienced much less severe temperatures, but were almost fully deacclimated with developing shoots. Other cultivars surveyed that have been rated as only moderately winter hardy include Traminette (Reisch, 1997), Cayuga White (Einset and Robinson, 1972), Noiret, Corot noir, and Valvin Muscat (Anon., 2006).

Fruit maturity from the different cluster groups appeared quite different around veraison, with clusters from non-count shoots appearing to be about 1 to 2 weeks behind those from count shoots. But by harvest, those clusters lagging behind had nearly caught up with the rest, reducing the differences in maturity to non-significant levels. As stated earlier, however, this is probably due to the fact there were almost no clusters from surviving primary shoots, which could reasonably have been expected to be much more advanced in maturity. It may also be due to the fact that in most cultivars, the crop loads were very small, resulting in more than adequate leaf area available to fully ripen all clusters. Had crop loads been closer to normal, more cluster to cluster competition for nutrients and photosynthates may have resulted in the variation in maturity remaining higher at harvest.

Finally, while the vines in most blocks around the region appear to have recovered and are expected to deliver nearly full crops in 2008, many blocks are requiring extensive vine retraining as a result of severe freeze injury in cordons and/or trunks. Still others are expressing the final symptom of severe winter injury — crown gall. Many vines will require replacement or retraining as current structures are removed and new trunks trained in place of those lost as a result of the Easter freeze.

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Table 1. Composite estimates of bud injury of several important winegrape cultivars in commercial vineyards in Missouri as a result of a severe freeze event in 2007.

Cultivar	Primary bud injury (%)	Secondary bud injury (%)
Catawba	100	No estimate
Cayuga White	100	No estimate
Chambourcin	95	25-50
Chardonel	100	75
Concord	100	No estimate
Norton	70	No estimate
Seyval blanc	100	>50
St. Vincent	95	25-50
Vidal blanc	95	50
Vignoles	85	No estimate
Vivant	100	No estimate
Rougeon	95	No estimate
Traminette	95	No estimate
Frontenac	95	10

Table 2. Origin of live shoots of several cultivars and selections in the Winegrape Cultivar Evaluation Trial at the State Fruit Experiment Station at Mountain Grove, Mo., after a severe freeze event in 2007.

Cultivar	Primary buds[x]	Secondary/ tertiary buds	Basal buds	Latent buds
Corot noir	3.8 abcd[y]	1.5 b	13.4 cde	14.8 bcd
GM 318	0.1 ef	0.1 b	3.3 fg	4.6 efgh
GM 322	1.2 cdef	0.9 b	4.0 fg	1.2 gh
GR 7	1.7 bcdef	1.8 b	18.3 abcd	20.8 b
LaCrescent	0.8 cdef	0.5 b	11.3 def	7.5 defgh
M36-12/110	0.0 f	0.0 b	0.0 g	0.0 h
M36-12/114	0.5 def	0.0 b	1.4 g	0.3 h
M36-13/38	0.0 f	0.0 b	0.0 g	0.0 h
M36-13/41	0.0 f	0.0 b	0.0 g	2.1 gh
M36-13/9	0.0 f	0.0 b	0.0 g	0.0 h
NY 76.844.24	1.0 cdef	0.8 b	19.0 abcd	14.3 bcde
NY 81.315.17	0.1 ef	0.3 b	9.8 ef	5.4 defgh
NY 81.315.19	0.6 def	0.1 b	4.9 fg	6.3 defgh
NY 84.101.4	2.5 abcdef	2.9 b	19.0 abcd	10.6 cdefg
Norton IV	5.4 a	6.5 a	22.3 ab	22.8 b
Norton V	4.7 ab	2.8 b	19.9 abc	19.2 bc
Otilia	0.8 cdef	0.4 b	4.8 fg	3.4 fgh
Rubin T	0.3 ef	0.5 b	7.9 efg	2.6 fgh
Traminette	2.0 bcdef	1.8 b	15.5 bcde	21.3 b
Valvin Muscat	3.7 abcde	2.3 b	24.8 a	36.7 a
Vignoles IV	4.1 abc	3.4 ab	20.5 abc	14.8 bcd
Vignoles V	4.6 abc	6.8 a	14.3 bcde	13.6 bcdef

[x] Means followed by a different letter are significantly different at the p>0.05 level.

[y] Means separation calculated by Tukey’s HSD test.

Table 3. Winegrape cultivars and selections in the Winegrape Cultivar Evaluation Trial at the State Fruit Experiment Station at Mountain Grove, Mo., not harvested due to extensive injury resulting from a severe freeze event in 2007.

GM 318
M36-12/110
M36-12/114
M36-13/38
M36-13/41
M36-13/9
Otilia
LaCrescent — not harvested due to crop loss from bird damage

Table 4. Count and non-count cluster data collected from cultivars at harvest in several commercial vineyards in 2007.

Cultivar	Count cluster number	Non-count cluster number	Count cluster weight (g)	Non-count cluster weight (g)	Total cluster number	Percent count clusters	Percent non-count clusters	Estimated vine yield (lbs.)
Cayuga White	0.3	26.9	295.0	207.2	27.2	1.0	99.0	11.7
Chambourcin (SCBC)	4.2	17.6	182.2	281.4	21.8	17.2	82.8	12.6
Chambourcin (GDC)	34.2	38.6	295.9	263.2	72.8	46.3	53.7	44.3
Corot noir	15.2	16.9	228.2	149.8	32.2	43.2	56.8	12.7
Frontenac	20.3	38.4	199.7	149.8	58.7	32.8	67.2	20.7
Noiret	17.8	24.2	192.3	192.2	42.0	42.3	57.7	17.8
Norton	28.5	17.4	131.8	114.3	45.8	62.1	37.9	12.8
St. Vincent	1.4	31.4	270.0	135.2	32.8	4.3	95.7	9.7
Vidal blanc	4.6	27.9	266.0	289.4	32.5	14.0	86.0	20.6

Table 5. Yield of several cultivars and selections according to the origin of the shoot (count versus non-count bud) from the Winegrape Cultivar Evaluation Trial at the State Fruit Experiment Station at Mountain Grove, Mo., after a severe freeze event in 2007.

Cultivar	Shoot origin	Cluster number[x]	Cluster weight (lbs.)	Yield per vine (lbs.)	Yield per acre (tons)
Corot noir	Count	11	0.32 a	4.44	1.21
	Non-count	26	0.23 b	5.68	1.54
GM 322	Count	4 b[y]	0.32	1.22	0.33
	Non-count	8 a	0.25	1.73	0.47
GR 7	Count	7 b	0.16	1.19 b	0.32 b
	Non-count	29 a	0.12	4.11 a	1.12 a
NY 76.844.24	Count	5 b	0.22	0.90 b	0.24 b
	Non-count	21 a	0.18	3.31 a	0.90 a
NY 81.315.17	Count	2 b	0.24	0.53 b	0.14 b
	Non-count	17 a	0.18	2.67 a	0.72 a
NY 81.315.19	Count	2 b	0.25	0.56 b	0.15 b
	Non-count	8 a	0.15	1.10 a	0.30 a
NY 84.101.4	Count	11 b	0.20	2.61 b	0.71 b
	Non-count	24 a	0.20	4.72 a	1.28 a
Norton (IV)	Count	22	0.16	3.77	1.03
	Non-count	28	0.15	4.02	1.09
Norton (V)	Count	14	0.16 a	2.24	0.61
	Non-count	22	0.12 b	2.83	0.77
Rubin T	Count	3	0.36	0.98	0.27
	Non-count	10	0.23	2.31	0.63
Traminette	Count	6 b	0.27 a	1.61	0.44
	Non-count	21 a	0.15 b	3.36	0.91
Valvin Muscat	Count	12 b	0.19	2.04	0.55
	Non-count	48 a	0.12	6.14	1.67
Vignoles (IV)	Count	12 b	0.17	1.74 b	0.47 b
	Non-count	33 a	0.14	3.27 a	0.89 a
Vignoles (V)	Count	16 b	0.15	2.77 b	0.75 b
	Non-count	30 a	0.18	4.43 a	1.20 a

[x] Means followed by a different letter are significantly different at the p>0.05 level.

[y] Means separation calculated by Tukey’s HSD test.

Table 6. Fruit composition of several cultivars and selections according to the origin of the shoot (count versus non-count bud) from the Winegrape Cultivar Evaluation Trial at the State Fruit Experiment Station at Mountain Grove, Mo., after a severe freeze event in 2007.

Cultivar	Shoot origin	Berry weight (g) [x]	Soluble solids (%)	pH	Titratable acidity (g/L)
Corot noir	Count	2.18	17.9	3.54 a	6.3 b
	Non-count	2.17	16.9	3.44 b	7.1 a
GM 322	Count	1.84	21.4	3.55	5.4 b
	Non-count	1.82	21.5	3.50	5.8 a
GR 7	Count	1.34 b[y]	22.4	3.61	6.0 b
	Non-count	1.47 a	22.2	3.61	6.2 a
NY 76.844.24	Count	1.46	21.0	3.48	7.4 b
	Non-count	1.63	20.7	3.46	7.9 a
NY 81.315.17	Count	1.72	22.2	3.57	6.3
	Non-count	1.66	22.4	3.54	6.5
NY 81.315.19	Count	2.13	23.0 b	3.35 b	10.4 a
	Non-count	2.21	23.8 a	3.65 a	8.0 b
NY 84.101.4	Count	2.20	21.9 a	3.67 a	5.9 b
	Non-count	2.07	21.2 b	3.54 b	7.1 a
Norton (IV)	Count	1.25 a	21.1	3.56	8.6
	Non-count	1.20 b	20.8	3.51	8.5
Norton (V)	Count	1.18	20.6	3.65 a	8.3 b
	Non-count	1.10	20.7	3.47 b	9.0 a
Rubin T	Count	1.53 b	25.4	3.70	7.7
	Non-count	1.62 a	25.5	3.68	7.9
Traminette	Count	1.94 a	18.9	3.43	5.4 b
	Non-count	1.83 b	19.0	3.44	5.7 a
Valvin Muscat	Count	2.45 b	18.8	3.68	5.4 b
	Non-count	2.69 a	19.0	3.72	5.6 a
Vignoles (IV)	Count	1.41	23.7	3.30	9.9
	Non-count	1.43	23.7	3.30	10.0
Vignoles (V)	Count	1.48	23.7	3.33	10.5 a
	Non-count	1.48	23.5	3.32	10.0 b

[x] Means followed by a different letter are significantly different at the p>0.05 level.

[y] Means separation calculated by Tukey's HSD test.

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