
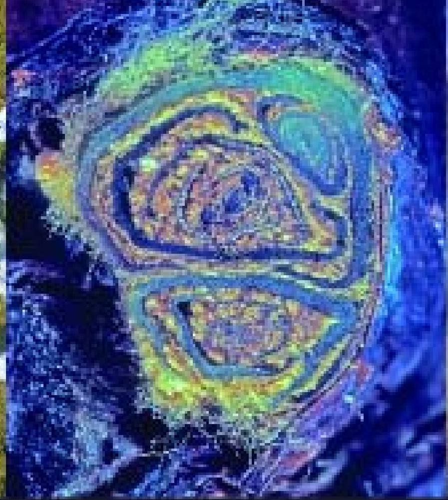

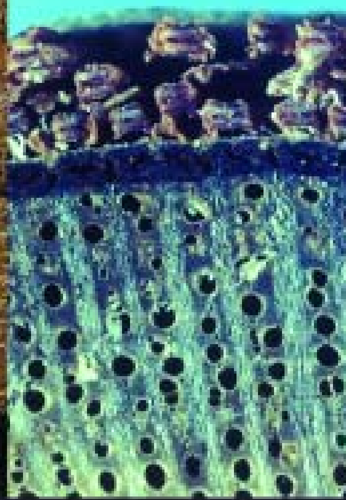

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Winter Injury to Grapevines and Methods of Protection

MICHIGAN STATE UNIVERSITY EXTENSION

Winter Injury to Grapevines and Methods of Protection

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E2759, Fruit Crop Ecology and Management, 108 pages, $16.00

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E2889, A Pocket Guide for Grape IPM Scouting in North Central and Eastern U.S., 122 pages, $14.00

E2930, Winter Injury to Grapevines and Methods of Protection, 106 pages, $15.00.

ACKNOWLEDGMENTS

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Cover photos:
Lower page – A three-disc plow hilling up grafted grapevines to protect grafts from winter injury at the Michigan State University Southwest Michigan Research and Extension Center. *Upper page (left)* – A grapevine in an Ohio vineyard in waterlogged soil showing dead main trunks and live trunk renewal canes. *Upper page (second from left)* – The cross-section of a compound bud of the Dutchess cultivar showing winter-injured, dead primary and secondary buds and a live tertiary bud. *Upper page (second from right)* – The application of straw mulch in late fall to a Merlot vineyard at the Douglas Nitz farm near Baroda, Mich., to insulate vine graft unions. *Upper page (right)* – Cross-section of a grapevine trunk showing the dark, discolored winter-injured phloem tissue below the fibrous bark.

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INTRODUCTION

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.

Winter injury to grapevines has challenged grape growers for centuries. The Romans burned prunings and other wastes to protect vineyards from cold. It is estimated that 5 to 15 percent of the world's grape crop is lost to cold-related damage in any given year. Preventing cold injury to vines is a key viticulture concern in many grape regions (Evans, 2000).

Grapevine tissues are susceptible to injury at temperatures as warm as 28 °F. Yet some grapevines, most notably cold-hardy *Vitis riparia*, can survive temperatures down to -40 °F (Howell, 2000). Winter injury to grapevines, particularly the cold-tender cultivars of *Vitis vinifera*, has many detrimental effects on wine growing in cold regions of the eastern and midwestern United States. As regional wines capture the imagination of consumers, wine production is expanding into areas that are considered high-risk for winter injury. Growers and consumers are especially interested in the classic European cultivars, which generally are susceptible to winter injury.

The effects of winter injury can be extensive, complex and devastating for vineyard businesses. For example, in the Finger Lakes region, almost half of the *Vitis vinifera* crop was lost in 2004 because of a single freeze event in January (Martinson and White, 2004). Winter injury can occur to all species of vines, but, ironically, there is often a direct correlation between the popularity of a grape, as judged by its wine quality, and its susceptibility to winter injury. Winter injury is also the major cause of crown gall disease development in vines. Injured or dead canes, trunks and buds cause crop losses or, worse, the need to replant vines with associated significant production loss and considerable expense. The economics of these losses to winter injury can be devastating to a vineyard business and are even more significant when value-added in wine. The cost of establishing a *Vitis vinifera* vineyard can reach $25,000 per acre, with the vines being the single largest expense. Loss of vines affects a vineyard's profitability for many years.

A shortage of grapes directly affects winery profitability. Wine markets are sensitive to shortages, and customers may be lost if supplies vary from year to year. Finally, there is the emotional cost to the grower, particularly to new grape growers who may be expecting their first crop, only to see vines die before they become productive.

Eastern and midwestern U.S. temperate growing conditions are challenging all year long, from spring freezes to hot, humid, wet summers to hurricanes and freezes in the fall. But it is the total loss of vines and/or crop due to winter injury that is the most difficult for a grower to endure. Fine wine grapes can be grown from Ontario to Georgia and from Michigan to Texas, but without control of winter injury to vines, the wines that are produced from these grapes will be at a severe economic and quality disadvantage to those from milder climates.

Research over the years in cold regions has revealed much about the anatomy and physiology of cold damage to grapevines. Practices such as hilling-up soil over graft unions and using wind machines to mix cold and warm air have been developed to reduce the severity of winter injury to grapevines. Careful site selection may be the most important decision a new grower can make. Cold-hardy cultivars are becoming increasingly available, and plant breeding programs continue to offer new hardy cultivars with good wine character. Although potentially controversial, genetic engineering may someday offer the best hope of a cold-hardy vine.

A grower plants a vineyard with the expectation of growing a quality product and creating a sustainable and successful farm business. Too often, winter injury prevents the achievement of these basic goals. The research and experience related to winter injury to grapevines had never been compiled into an easy-to-reference publication. This bulletin fills this void and places in the hands of grape growers the information to understand winter injury, to prevent it and, if affected by it, to respond to it. This practical guide has the added value of numerous citations to more in-depth discussion of many topics. The authors have more than 100 years of collective experience in cold-climate viticulture. We have relied on scientific evidence and, in some cases, on reports that indicate a recurring documented experience. We identify those areas where further investigation would be helpful. This publication will lead the reader to a better understanding of winter injury to grapevines, will provide strategies for avoiding and dealing with winter injury to grapevines, and will provide a basis for advancing our knowledge of this topic.

ECONOMICS OF WINTER INJURY

1. Economic losses from winter injury

Winter injury results in significant direct losses in grape production and even greater losses in value-added wine production. For example, winter injury from a single event in January 2004 in the Finger Lakes region resulted in direct crop losses of $5.7 million and a value-added estimate of lost wine sales of $41.5 million (Martinson and White, 2004). Additional crop losses in the 2005-08 crop years — 200 to 300 acre-equivalents of dead *V. vinifera* vines — are estimated at 2,300 tons, with a value of $3 million. Replanting costs are estimated at $2.1 million. Over the following 4 years, reduced wine production is estimated at 391,000 gallons of wine with a value of $16.9 million. Total losses to the New York wine industry from this one freeze are estimated at $63.6 million (Martinson and White, 2004).

Per-vine costs of vine replacement. What is the economic loss caused by a missing vine? Table I-1 presents estimates of the per-vine direct and indirect value of crop loss caused by death of the above-ground portions of the vines (trunks injured but suckers present) and total vine death for *V. vinifera* and hybrid cultivars. Assumptions were: (a) vines with suckers present could return to full production in the year following trunk loss; (b) missing vines would be replaced the year following their death and would be in full production by the fourth year following replacement; and (c) average production is 3.5 tons/acre for *V. vinifera* and 5 tons/acre for hybrids. The value of wine was calculated by subtracting the cost of grapes from a 70/30 retail/wholesale split in wine sales from a small winery.

For *V. vinifera* vines, direct crop loss per year was about $6 per vine, with 4-year lost value of production of about $24. Replanting costs were estimated at $7.75 per vine for a total direct loss of about $32 per missing vine. Costs were lower for hybrids -- a $2.48 crop loss per year and a replanting cost of $5.75/vine (ungrafted vines) for a total direct loss of about $16 per vine.

Value-added losses from wine production were higher. A 1-year crop loss resulted in an approximate wine loss of $33 (*V. vinifera*) and $29 (hybrids), assuming a 70/30 split in retail and wholesale value, which is typical of the sales mix of many small wineries. For missing vines, 4-year wine losses are approximately $123 (*V. vinifera*) and $110 (hybrids), respectively.

Thus, under our assumptions, the total cost of a missing vine would be $155 per *V. vinifera* vine or $126 per vine for a hybrid cultivar (Table I-1).

The wine production cost savings resulting from processing less crop were not subtracted, so the wine value-added is overstated. However, wineries generally would have already invested in the tank space needed to process a full crop and likely would turn to alternate purchased fruit or bulk wine to maintain production levels.

2. Risk management

The risk inherent in growing cold-tender cultivars requires growers to consider the impact of crop loss to their businesses and to ask themselves how they can manage that risk. Two ways growers and wineries can reduce risk are to diversify their cultivar mix and to use crop insurance to protect against catastrophic losses.

Crop diversification. For many small wineries, having a diverse cultivar base could make the difference between not having wine to sell (or having to purchase it from others) and merely facing the marketing challenge of offering customers a modified line of products to buy. For growers, some hybrid and high-yielding labrusca grapes offer returns per acre equal to or higher than those of *V. vinifera* cultivars, despite prices in the $200 to $500 range vs. $1,200 to $2,000 per ton. For wineries, higher yields of the vineyards may compensate for lower per-bottle prices for the wines (Table I-1). Even if returns per acre are not as high for some cultivars, the more efficient use of machinery by spreading fixed costs over more

Table I-1. Financial losses per vine for own-rooted hybrid and grafted *V. vinifera* vines, assuming a 1-year crop loss for dead trunks or a 4-year crop loss for dead vines.

Item	*V. vinifera*	Hybrid
Vineyard losses		
Assumptions:		
Vines per acre[1]	806	806
Yield (tons/acre)	3.5	5
Yield per vine (lb)	8.7	12.4
Price/ton	$1,400	$400
Resulting losses:		
Crop value/acre	$4,900	$2,000
Annual crop value/vine	$6.08	$2.48
Value — 4 years' production	$24.32	$9.93
Replanting costs[2]	$6,250	$4,638
Replanting cost/vine	$7.75	$5.75
Vineyard cost per missing vine	$32.07	$15.68
Wine losses		
Assumptions:		
Gal/acre[3]	595	850
Cases/acre	248	354
Bottles/vine	3.7	5.3
Retail price/bottle	$12	$7
Wholesale price/bottle	$7	$3.50
Resulting losses:		
Retail wine value/acre	$35,700	$29,750
Wholesale wine value/acre	$20,825	$14,875
Retail wine value/vine/year	$44.29	$36.91
Wholesale wine value/vine/year	$25.84	$18.46
4-year retail wine value	$177.17	$147.64
4-year wholesale wine value	$103.35	$73.82
Wholesale wine value-added[4] (per killed vine)	$71.28	$58.14
Wholesale wine value-added[4] (1-year crop loss)	$19.76	$15.97
Retail wine value-added[4] (per killed vine)	$145.10	$131.96
Retail wine value-added[4] (1-year crop loss)	$38.21	$34.43
70/30 retail/wholesale split (per killed vine)	$122.95	$109.82
70/30 retail/wholesale split (1-year crop loss)	$32.68	$28.89
Total economic losses (per killed vine)	$155.02	$125.50
Total economic losses (for 1 year of lost production)	$38.76	$31.37

1 Planting density of 9 feet by 6 feet.

2 Cash costs derived from White (2005); costs of site preparation and trellis construction were subtracted; additional fungicide costs in year 2 were added. Full cash cost of vineyard establishment estimated at $9,976 per acre; lower cost for hybrids assumed savings from planting ungrafted vines or layering.

3 Assumes wine yield of 170 gallons per ton of grapes.

4 These values are the value of the wine minus the vineyard replanting costs and crop values.

COLD HARDINESS OF GRAPEVINES

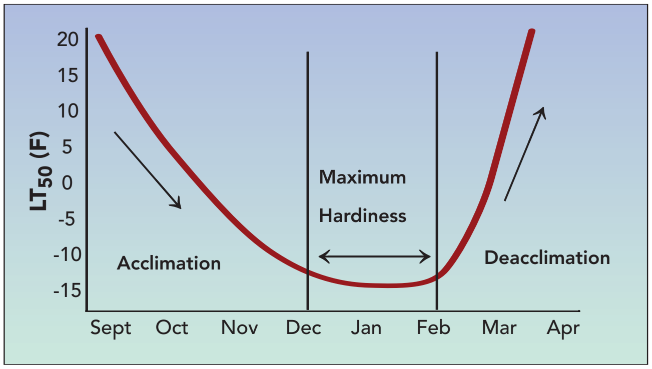
1. Defining cold hardiness

Cold hardiness is the ability of dormant grapevine tissues to survive freezing temperature stress during autumn and winter (Levitt, 1980; Sakai and Larcher, 1987). Grapevines withstand freezing temperatures through two mechanisms. Cane and trunk tissues tolerate ice outside living cells, which results in desiccation of the cytoplasm inside the cells. Buds avoid freezing injury by supercooling. Supercooling is the ability of the contents of a cell to remain liquid at subfreezing temperatures. Cold hardiness of grapevines is typically measured by the highest temperature that kills 50 percent of the primary bud population in midwinter, termed "lethal temperature 50" (or LT_{50}). Vines gain cold hardiness during the dormant season as a result of their exposure to decreasing low temperature. The colder the temperature, the more hardiness that the grapevine gains up to a critical threshold that is determined by the environment, cultural practices and the genetic makeup of the cultivar (see the section below on differences in cold hardiness between cultivars).

2. Seasonal changes in vine physiology related to cold hardiness

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 the 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 (Wolpert and Howell, 1985; Dami, 1997; Fennel, 2004). 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 *V. labrusca* and *V. riparia* begin to cold acclimate in response to short days first (Fennel and Hoover, 1991; Wolpert and Howell, 1986). *V. vinifera* grapevines cold acclimate in response to both short days and low temperatures (Fennel, 2004; Schnabel and Wample, 1987). 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 °F to 20 °F) (Fig. II-1). The second stage of cold acclimation is exclusively induced by temperatures below freezing and usually coincides with the first killing fall freeze (freezing event at which temperature drops below 32 °F to cause a total damage and subsequent fall of leaves) in mid-October to mid-November.

A. Profile of grape bud hardiness



B. Outdoor minimum T° & bud hardiness

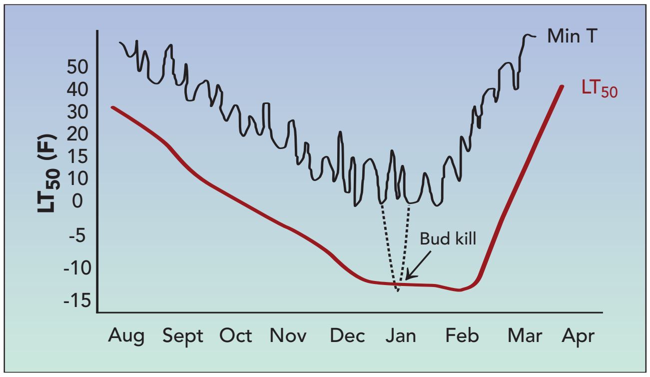


Fig. II-1. **A.** Profile of bud cold hardiness in grapes during the dormant season, showing the acclimation, maximum hardiness and deacclimation stages.
B. Profile of bud cold hardiness in relation to outdoor minimum temperature. Bud kill occurs when a cold event (minimum temperature) coincides with the critical lethal temperature of bud tissue (LT_{50}).

At this stage, cold hardiness increases dramatically, and vine tissues become hardier as daily temperatures continue to decrease or remain below freezing (Hamman et al., 1996; Howell, 2000). Grapevines reach maximum hardiness in midwinter, when the coldest temperatures occur (Fig. II-1). Bud cold hardiness is usually at its maximum in December, January and February, with LT_{50} values ranging from -5 °F to -35 °F (Fig. II-1) (Dami, 1997; Fennel, 2004; Howell, 2000; Wample et al., 2000).

Cold hardiness is also increased when the temperature drops and remains below freezing through midwinter (Wolf and Pool, 1987b; Wolf and Cook, 1994; Wample and Wolf, 1996). 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 (Wolpert and Howell, 1985; Howell, 2000). 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 (Odneal, 1984; Wolf and Cook, 1992).

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 (Fig. II-1). Cultivars respond at different rates to temperature cues. Concord acquires and loses winter hardiness much more rapidly than Cabernet Sauvignon, and Riesling is intermediate (Wolf and Cook, 1992). 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 (Kovacs et al., 2003).

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 an annual U-shaped cycle of cold acclimation and deacclimation, it is important to note that cold hardiness is dynamic rather than constant throughout the dormant season (Figs. II-1 and II-2).

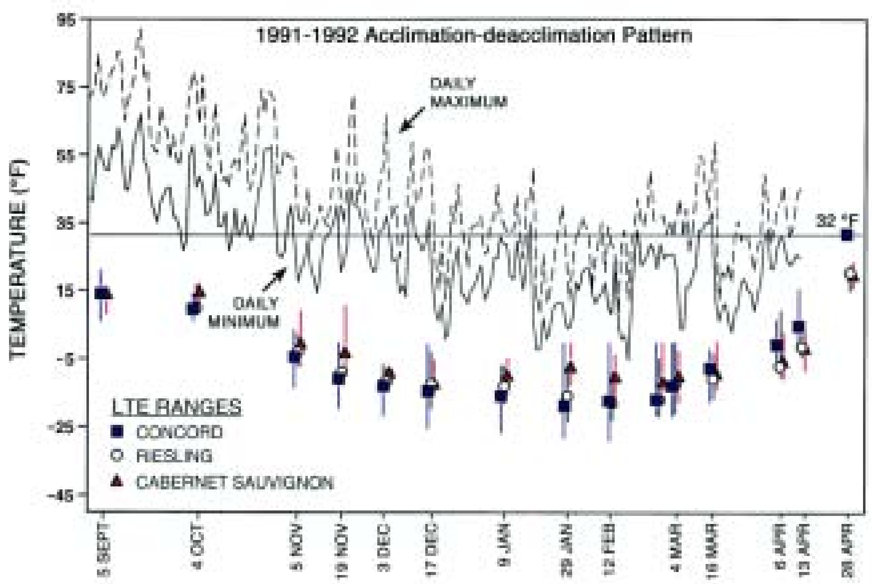


Fig. II-2. Example of the seasonal pattern of bud acclimation assessed by low-temperature exotherm analysis (LTE) for three grape cultivars at Geneva, N.Y., as maximum and minimum temperatures changed from 9/5/91 to 3/28/92. Each symbol is the mean median LTE for all buds frozen each date in a programmable freezer. Vertical bars represent the range of LTEs on each date. Buds freezing at temperatures warmer than 10 °F were not included for the mid-December to mid-March period because even dead buds will show LTEs in that range or warmer in winter.

3. Seasonal changes in vine anatomy related to cold hardiness

Cell structure and acclimation

In the summer, the 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 (Fig. II-3). The cell also contains vacuoles, membrane-bound sacs that regulate or store water and water-soluble products. 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 above-ground organs. In late summer and fall, cellular acclimation involves slow cell dehydration — that is, the gradual elimination of as much unbound (free) water as possible (Wisniewski et al., 1996; Wisniewski et al., 2003). Simultaneously, cellular membranes are stabilized and 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.

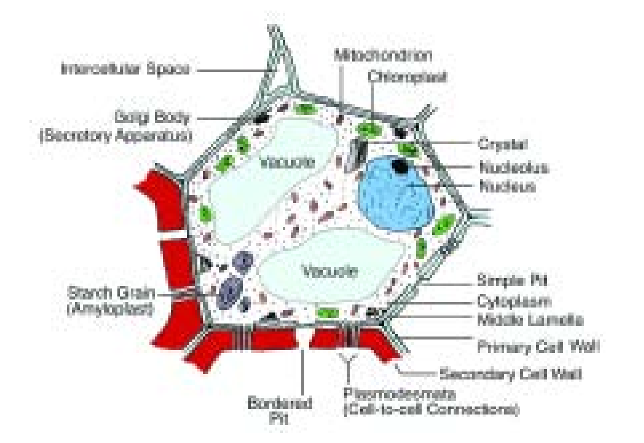


Fig. II-3. A generalized plant cell, showing many of the features to be found within living tissues of grapevines. Cell walls vary in thickness and elasticity, depending on cell function within a tissue. Membrane-bound organelles provide specialized function, with cytoplasmic strands interconnecting cells within tissues. Specialized cells emphasize the function of some organelles over others, but this generalized cell shows organelles for respiration (mitochondria), photosynthesis (chloroplasts), secretion (Golgi bodies), starch storage (amyloplasts), gene regulation of protein synthesis (nucleus), cell-to-cell communication (pits and plasmodesmata), and water and waste regulation (vacuoles). Other active structures are too small to present in this drawing. Freezing destroys membrane integrity and cell function.

Stem construction and tissue acclimation

As autumn progresses, grapevine stems change color from green to tan or brown, and leaves turn yellow and/or red and fall. The oldest tissues and organs of a green shoot are found near the base of the shoot; younger tissues are continually formed near the shoot tip (Fig. II-4). The internodes and leaves mature and acclimate to cold from the shoot base to the shoot tip, as does the vascular system inside the stem. Stem vascular development is important to cold acclimation because, after leaf fall, almost all remaining stem tissue is vascular tissue. Thus, the seasonal development of the vascular system is critical to acclimation, cold hardiness and spring renewal of growth. Young, flexible internodes near the shoot tip in summer (Fig. II-4 A, arrow 1) contain a ring of vascular bundles between the outer green cortex and the pith in the center of the stem (Fig. II-4 B). Bundles in the ring are separated by ray tissue. The inner cells of each bundle make up xylem tissue, whose function is to provide structural support (via fibers) and to conduct water and inorganic nutrients (via large, open vessels). The outer cells of each bundle make up phloem tissue, whose function is to conduct sugars and other organic materials (via specialized sieve tubes). A band of rapidly dividing cells is situated between these conductive xylem and phloem tissues.

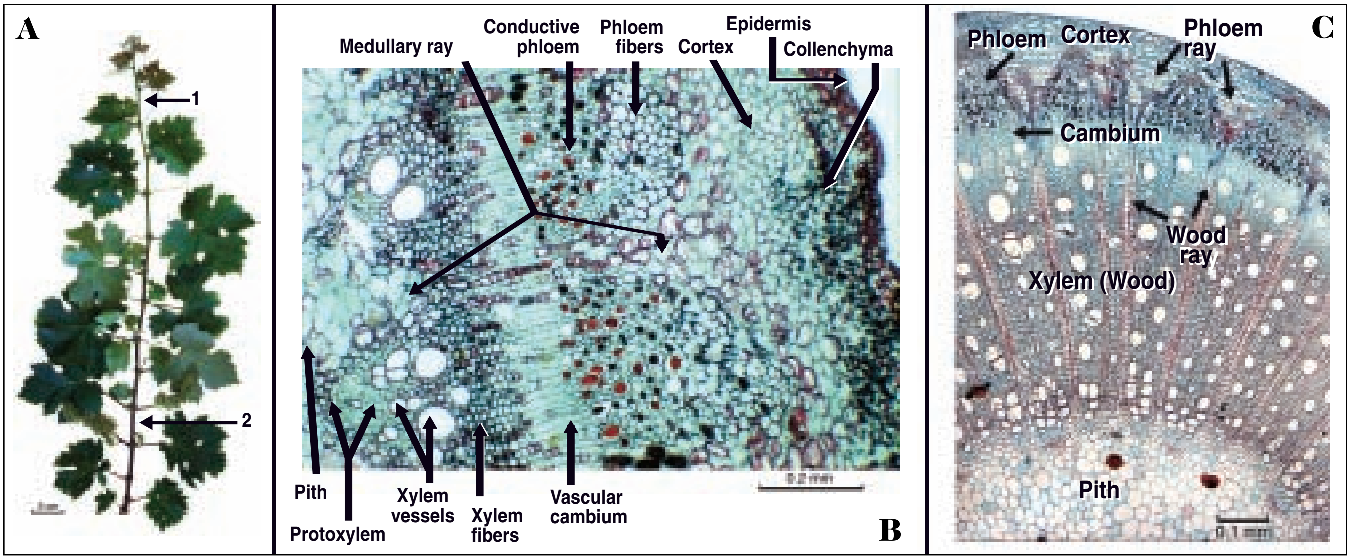


Fig. II-4. Development of grapevine stem tissues in summer. **A.** Early postbloom Cabernet Sauvignon shoot. Level 1 represents a still elongating flexible region; level 2 is woody and no longer elongating. **B.** Cross-section through level 1, showing vascular bundles composed of xylem and phloem separated radially by vascular cambium and tangentially by medullary rays. **C.** Cross-section through level 2, showing how the cambium has moved outward after producing a thick band of woody xylem but only a smaller increment of new phloem. The cell walls of the xylem have become thick and lignified.

These cells are the vascular cambium, which produces all the new xylem and phloem for the life of that part of the vine. Cambium cells divide in such a way that their daughter cells lie mostly in the radial direction. As the daughter cells develop into either new xylem or new phloem cells, stem girth increases. The internode at the base of the shoot (Fig. II-4 A, arrow 2) eventually becomes stiffened by this new growth in girth. A slice across an internode in this region shows a thickened band of new xylem on the cambium's inner side but only a small amount of new phloem on the cambium's outer side (Fig. II-4 C). As internode diameter increases, some cambium cells must divide in a way that adds daughter cells in the tangential direction to maintain ever enlarging increments of xylem and phloem tissue. When shoot growth is in this most active phase, cells and tissues are not yet acclimated to cold because they contain a large amount of free water.

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 (Fig. II-5 A). This browning results as new tissue composed of cork cells arises in the stem's outermost (oldest) phloem (Fig. II-5 B). 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 and become 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. Periderm formation begins at the base of the stem and progresses toward the stem tip. The stem's protected living cells interior to the periderm continue to dehydrate through the fall and become filled with a variety of cryoprotectant (freeze-resistant) solutes. 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. After leaf fall, the remaining woody stem is called a cane.

WEATHER CONDITIONS THAT CAUSE WINTER INJURY TO GRAPEVINES

1. Duration of exposure to a low temperature

It is the temperature experienced by a vine tissue and not the duration of that temperature that determines its susceptibility to winter injury. Nevertheless, under certain conditions, the duration of a vine's exposure to a critical temperature may affect winter injury. For example, a large trunk will take longer to freeze to its center than will a cane, so not all tissues of a vine will experience the same temperature during a low-temperature episode of short duration.

The accumulation of cooling units (temperature below 50 °F) plays a major role in vine acquisition of its maximum genetic cold hardiness (Pool et al., 1992). The colder the region, the closer a vine will get to its maximum genetic cold hardiness (Fig. III-1). For example, a comparison of the cold hardiness of Concord, Cabernet Sauvignon and Riesling grown in Geneva, N.Y., (cooler) and Winchester, Va., (warmer) indicated that more cooling units accumulated in New York than in Virginia. Therefore, the three cultivars were hardier in New York than in Virginia (Pool et al., 1992). This helps to explain the difference in cold hardiness of the same cultivars when grown in northern versus southern viticultural regions.

Warm vs. cold region (same variety)

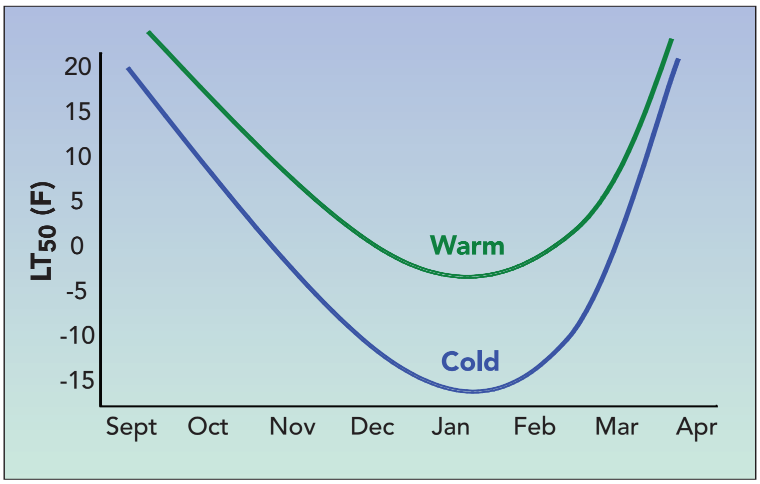


Fig. III-1. Diagram of cold hardiness profile of the same variety grown in a cold (e.g., New York) and a warm (e.g., Virginia) region. Maximum hardiness is reached in the cold region.

For example, buds on the cold-tender cultivars Chardonnay and Riesling in the Finger Lakes are typically 2 to 3 °F hardier than buds on the same cultivars grown in Virginia (Pool et al., 1992). A critical midwinter temperature of -8 °F will produce significant bud mortality in Virginia, but -10 °F is a more typical benchmark for the Finger Lakes (Pool et al., 1992).

2. Rapid temperature drops

Rapid temperature drops during the dormant period can influence the temperature at which some plant tissues are killed (T. Wolf, personal communication). The influence of rapid temperature drops on grapevine tissues is not well-documented, and this area could benefit from additional research. Nevertheless, considerable field experience suggests that grapevines are particularly susceptible to rapid temperature drops during the acclimation and deacclimation periods of grapevine dormancy (Fig. II-1A), but they may also be affected during the midwinter dormancy period (Fig. III-2C). Mechanical trunk injury (splitting) is often associated with water freezing in those tissues during a rapid temperature drop early or late in the dormant season (Paroschy et al., 1980; Meiering et al., 1979).

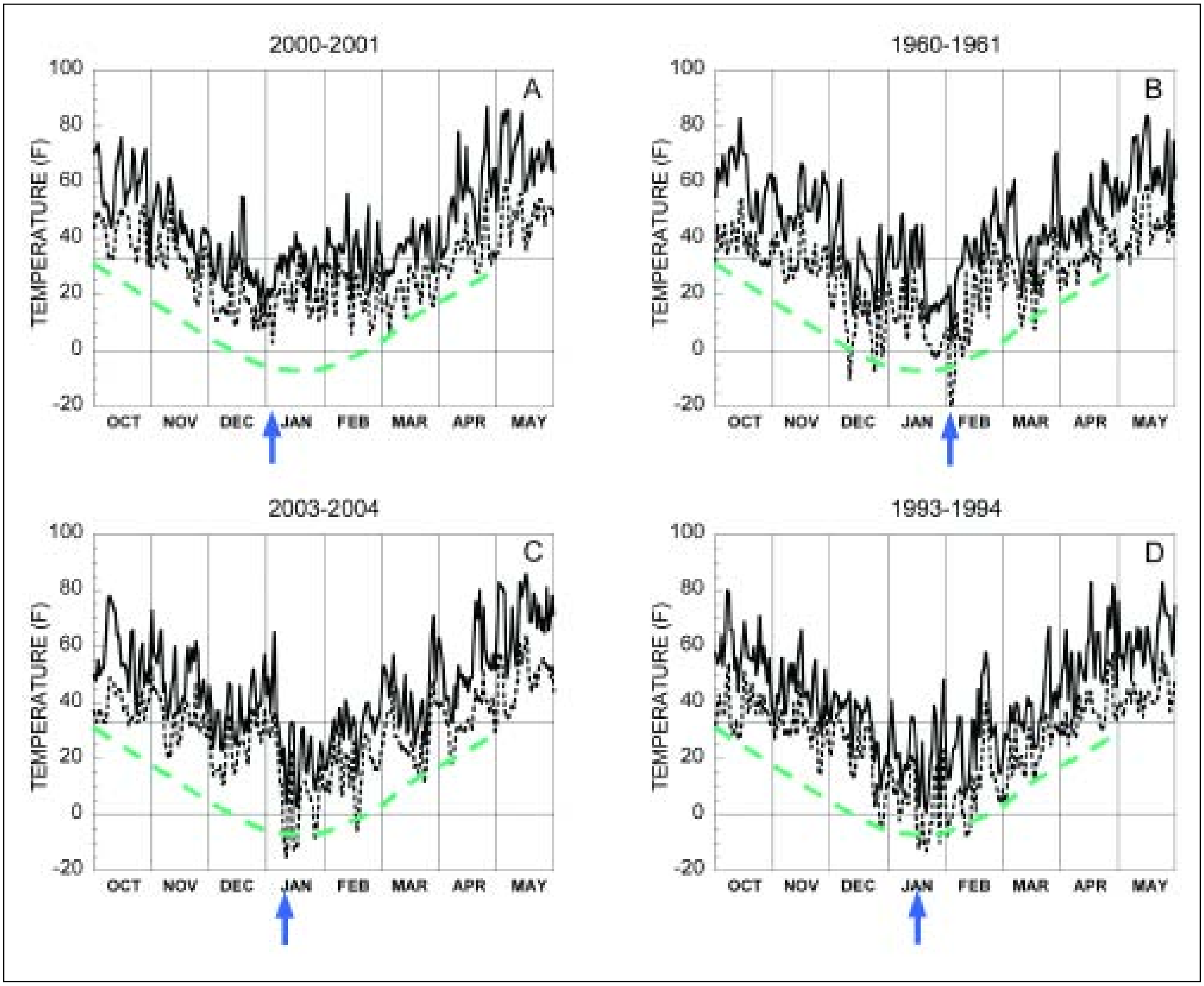


Fig. III-2. Daily maximum/minimum temperatures at Geneva, N.Y., during the winters of 2000-01 **(A)**, 1960-61 **(B)**, 2003-04 **(C)** and 1993-94 **(D)**. Dashed line indicates the estimated bud hardiness at various times of the winter. 1960-61 and 2003-04 winters both produced severe bud and trunk injury. The 1993-94 winter produced moderate to high bud mortality but little trunk injury.

Trunks have thick, woody tissue making up the water-conducting portion of these organs (see Section II-3). The water-transporting cells (vessel elements) are embedded in a matrix of heavy-walled, lignified wood fibers, which are quite resistant to the shearing forces caused by freezing. However, trunks also contain less rigid tissue known as ray cells. They resist freeze damage by supercooling. Vessels in trunks can fill with water when soils are not frozen and temperatures are high enough to result in capillary transport of water from the soil into the trunk tissues. If these tissues fill with water and the temperature drops quickly, ice can form. This expands the trunk tissues and causes the relatively thin-walled ray cells to be killed. Ray cells may also be killed when rapid temperature drops reach the lethal low temperature for those cells even if there is no water in the vessel elements. In either case, the death of ray cells results in radial cracks in the trunk. Once the trunk is split open, the entire trunk and perhaps the entire vine are at risk of being killed.

WINTER INJURY OF GRAPEVINES

1. The anatomy of winter freeze injury to cane and trunk tissues

Throughout a grapevine's dormant period, tissues that survive severe freezes show a light green or creamy-green color when cut. When freeze injury occurs, the membranes surrounding each cell and those enclosing the subcellular organelles are destroyed. This causes a mixing of the cell's compounds and a loss of cell organization and function. When the tissues warm after a damaging freeze, cell contents leak into surrounding regions, so tissues look water-soaked. Oxidative enzymes discolor bright green tissues first to the color of cooked asparagus; then they turn brown. Finally, a blackening necrosis indicates tissue death.

Winter-injured canes also develop the cooked-asparagus color in the affected tissues (Fig. IV-1a). The phloem is the most cold-tender cane tissue, and it is often the first to show these signs. Even when severe phloem injury occurs (Fig. IV-1b), the dormant cambium and the xylem are often not injured or are significantly less injured than the phloem. If the xylem is injured, the cane is likely to recover poorly if at all, whereas the xylem and phloem tissues in normal, non-injured winter canes will be well organized (Fig. IV-1c).

Winter injury to cordons and trunks begins in the phloem tissue and progresses from the outer phloem to the inner phloem (Fig. IV-2). Destruction of phloem cells prevents the critical movement of carbohydrates for bud burst and shoot growth. More severe freezing causes xylem injury, which may proceed from the pith outward or be spread more generally throughout this tissue. Xylem injury often results in scattered or generalized brown streaking, followed later by the filling of vessels with gums or with ballooning of the walls of the cells surrounding the vessels, which blocks water flow.

In spring, as shoots push from the buds, the loss of xylem vascular function becomes apparent when new shoots are stunted or collapse. Leaves may wilt and die because damaged vessels may block the flow of

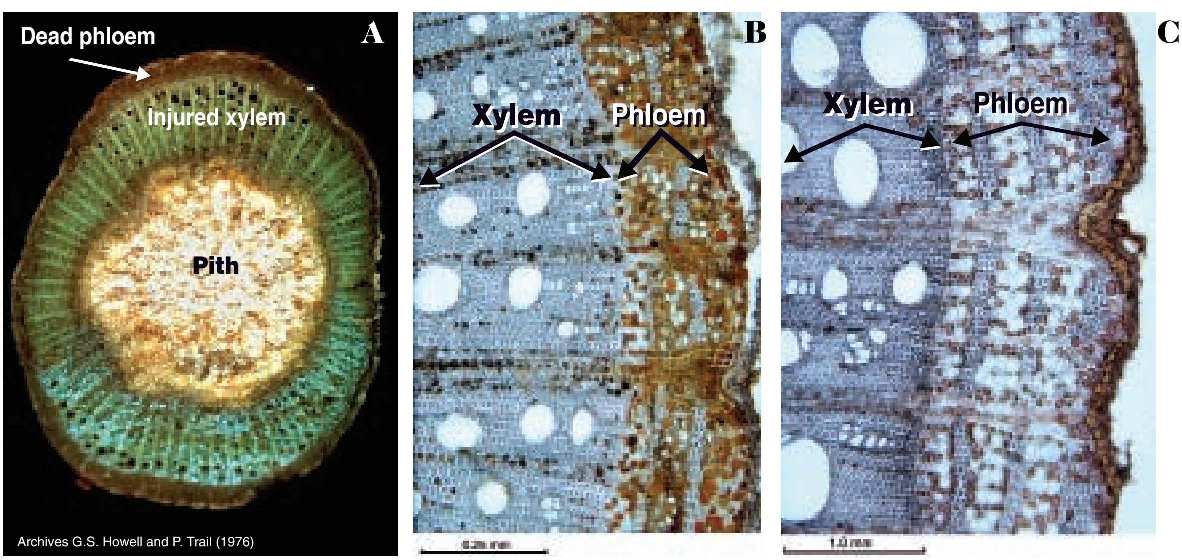


Fig. IV-1. Freeze-injured cane tissue. **A.** Riesling cross-section from a cane naturally frozen in the vineyard in New York state. Note the "cooked asparagus" appearance and also the mushy brown appearance of the phloem. **B.** Section of a Concord cane that was artificially frozen to -28 °C (-19 °F) in mid-November. The phloem is mostly killed and phloem cell contents browned; the xylem is much less affected. Phloem of the early-acclimating, hardy Concord cannot withstand such temperatures in November but often survives them in late December to late February. **C.** Normal dormant Concord cane in mid-November.

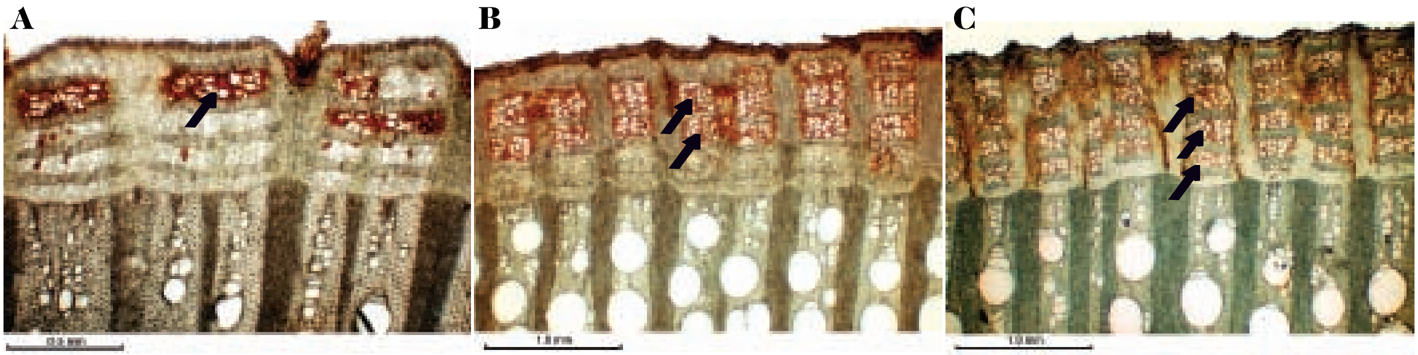


Fig. IV-2. Trunk cross-sections showing increasing levels of freeze injury, from outer phloem (**A**, Chardonnay) into middle phloem (**B**, Seibel) and then into the region just outside the dormant vascular cambium (**C**, Chardonnay). The cambium and xylem appear to have resisted injury in all three photos, but the vine in C may not recover from this injury.

water and nutrients. The collapse of shoots may occur anytime in the growing season (Fig. IV-3). The cambium in a cordon or trunk is often the last tissue to be completely winter-injured. Nevertheless, its survival alone does not allow the vine to function because early shoot growth in spring depends on the conductive capacity of last season's xylem and phloem. The cambium does not produce new xylem and phloem until several weeks after bud break. Also, an extensive winter-injured cambium may produce small, inefficient new cells. (See Section VI-1, "The Cellular Process of Repair of Freeze-injured Canes and Trunks.")

Fig. IV-3. Vine collapse resulting from significant winter injury. **A**. Summer collapse at the time of peak transpiration demand. **B**. Collapse at/after veraison, when demand of crop load also competes with canopy demands.

2. Vine growth responses after winter injury

After vine tissues become frozen, vine growth is compromised in direct proportion to the location, amount and type of tissue or organ injured or killed. The effects of winter injury to vines certainly become apparent during spring and early summer shoot development. In normal years, the primary bud of each compound bud develops into a fruitful shoot. Because the primary bud is the most sensitive to winter injury, its failure to emerge is a major indicator that the vine has been winter-injured. The development of shoots from a large number of secondary buds indicates that there has been significant winter or spring freeze injury. Complete failure of bud break, which produces so-called blind nodes, indicates injury has progressed into the secondary and tertiary buds (Fig. IV-4).

Fig. IV-4. **A**. A cordon with poor bud break on spurs in May. **B**. Vine in early May, following a severe cold spell the previous winter. In both instances, vines have poor bud break and numerous blind nodes.

Large areas of such injury are a problem for vine growth and management for several reasons. First, many of those nodes will have to be retained during pruning to produce a canopy and crop. Second, large gaps in the canopy will make the positioning of shoots for best vine architecture difficult or impossible. Third, severe bud winter injury is often associated with significant injury to the vascular system of canes, cordons or trunks. Therefore, the shoots that do survive and emerge may not be able to draw sufficient water and nutrients to sustain transpirational water loss from the increasing leaf area. The failure of the vascular system to support shoot and crop development may lead to the sudden wilting and death of part or all of a vine's canopy in late spring or summer (Fig. IV-3).

Partial vine kill and localized injury of canes and cordons may be manageable with judicious pruning and retraining, but catastrophic injury to trunks or whole vines generally will not allow vine recovery (Fig. IV-5). After severe winter injury to above-ground parts of the vine, hidden buds at the bases of canes or older woody branches will often break dormancy and push as rapidly growing shoots (Fig. IV-6, A). Similarly, when winter injury kills most or all of the canopy, viable buds at the base of the vine, which have long been dormant, may erupt as very vigorous suckers (Fig. IV-6, B). This vigorous emergence of shoots from

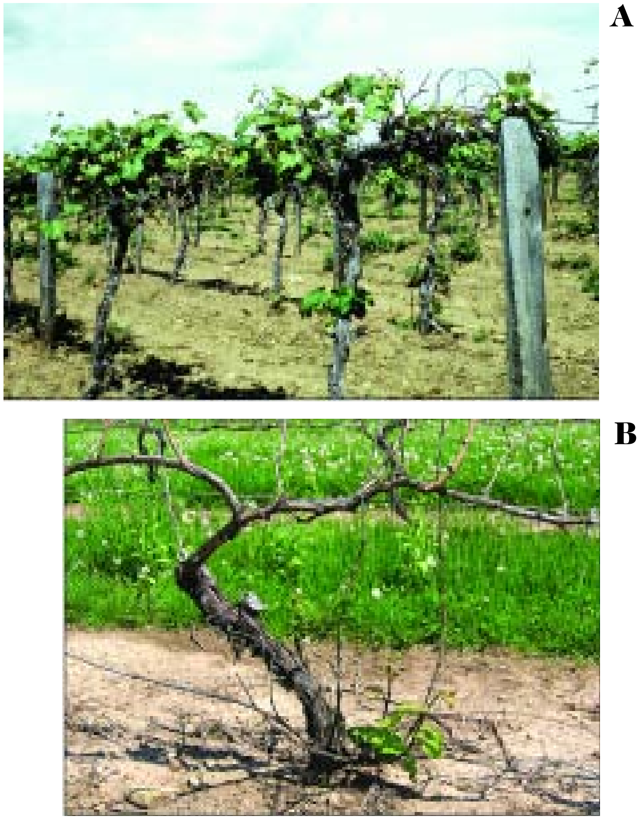


Fig. IV-5. **A**. May canopy fill for Concord vines significantly injured by a winter freeze.
B. May photo of a Cabernet Sauvignon vine after a severe January freeze with a new shoot emerging only from the rootstock.

Fig. IV-6. A. Emergence of a base bud embedded for years at the base of a pruning wound on an arm. **B**. Proliferation of suckers from base buds after winter injury has killed the upper portion of the vine.

long-dormant buds is a sign to the grower of extensive winter injury. The rapid growth rate of such shoots relates to their access to the water and nutrients from a large root system that would normally be used by shoots higher on the vine. The resulting shoots can be used to balance the growth and reestablish the vine.

The amount of winter injury and shoot emergence will guide a grower's decision on whether to retain and retrain a vineyard block or to remove it (with or without a consideration for replanting). (See Section VI, "Managing Winter-injured Vines.")

3. Assessing winter injury to dormant grapevines

As late fall temperatures begin to drop, a grape grower in a cold climate can not predict whether the approaching winter will severely injure vines. Therefore, vines must be managed every year with the assumption that the approaching winter might cause severe vine injury. Weather episodes that cause injury to grapevines may or may not be recognizable. Therefore, whenever pruning begins, there should be a cursory evaluation of vine health to be certain that the vines are indeed as healthy as the grower believes them to be. Primary buds may be killed for reasons other than winter injury. A condition known as bud necrosis has been related to vine conditions that cause vigorous shoot growth and canopy shading. The appearance of bud necrosis may occur from a couple of weeks after bloom to onset of vine dormancy (Perez-Harvey, 1991). Therefore, when bud necrosis is suspected as a cause of primary bud mortality, a bud assessment early in the fall before vines experience low temperature is suggested. Bud necrosis is especially prevalent in the Riesling, Viognier and Syrah cultivars (T. Wolf, personal communication).

Two categories of vine tissues should be evaluated for winter injury. The fruiting bud complex within the nodes on fruiting canes should be evaluated because these tissues determine the fruiting potential and profitability of vines for the approaching growing season. The tissues just below the bark on canes, arms and trunks should also be evaluated because they determine the survival and growth of the vine.

The primary bud, the major source of fruitfulness, extends from the base to about two-thirds of the overall height of the bud (Fig. IV-7). The tissues that will grow into the grape clusters and several of the basal nodes and internodes on the emerging primary shoot are already partially developed in the top half of the primary bud (Fig. IV-7). Primary buds are killed by winter injury from their tip toward their base, and at times they may not be completely killed by win-

MANAGING GRAPEVINES TO PREVENT WINTER INJURY — A holistic view

Stresses affecting grapevines include inadequate or excess light, water, nutrients or temperature, or excess diseases and insect pests. Tolerance and avoidance are the two fundamental strategies for surviving any of these stresses. Tolerance of vine tissues to low winter temperatures has been achieved by the creation of new, hardier cultivars and by the conditioning of vines through the several viticultural practices discussed below. Avoidance of winter injury has economic limitations. Nevertheless, the low-temperature avoidance measures discussed below can be cost-effective in some situations.

The principal goal of commercial grape production is profit, which occurs through a combination of yield and fruit quality. Although minimizing winter injury to vines is not the main goal of a grape grower, it must be given attention because of its huge impact on profitability. It is tempting to say that vine management practices that reduce vine winter injury will increase profit. However, some practices that may reduce winter injury to vines, such as applying extra pesticide sprays or reducing crop level or insulating parts of the vine with mulch, will not always be cost-effective. Therefore, a grower must choose among the vine management practices that combat vine winter injury and select those that will be cost-effective. Practices are interactive in the way they contribute to vine susceptibility to winter injury. The following is a holistic view of the way grapevine management practices interact in regard to vine winter injury.

The French term *terroir* integrates all the variables that contribute to the unique characteristics of a wine. “Vine capacity” is another integrative term, defined as the total of the vegetative and crop (reproductive) growth of the vine. Factors that influence vine capacity can be placed in three categories: biological — choices of cultivar and rootstock; environmental — the many factors of climate and soil; and management — all the cultural practices as they are applied to a vine. The grower’s challenge is to combine all these factors in a way that leads to profitability. Vine balance optimizes the vegetative growth of the vine and crop level to produce the largest sustainable crop with acceptable fruit quality. Optimal values of crop level and fruit quality do vary considerably among growers. Profitability will put primary emphasis on crop level in some situations and on fruit quality in others. Nevertheless, vine balance is important to all growers. Whenever a vine is out of balance — by producing excessive vegetative growth or an excessive crop load (see definition) — the vine will be more vulnerable to winter injury. That translates to reduced profitability.

Vines out of balance with excessive vegetative growth develop dense, shaded canopies that reduce the hardiness of vine tissues (Howell and Shaulis, 1980). Proper management of two components of the ideal grapevine canopy — i.e., shoot density (the number of shoots per linear foot of canopy) and shoot vigor — will maximize vine cold hardiness. Shoot density is managed through choice of a vine training system (Section V-4) and pruning methods (Section V-5). “Shoot vigor” describes the rate of growth of an individual shoot, such as inches of growth per day or feet of growth per growing season, and is influenced by a complex of many factors (Winkler et al., 1974). The characteristics of highly vigorous shoots are rapid growth rate, long overall length, long internodes, large diameter and the development of long lateral shoots emerging from the primary shoot, which often mature into persistent lateral canes after leaf fall (Howell and Shaulis, 1980). It is common to have low-, medium- and high-vigor shoots on the same vine. It is not appropriate to apply the term “vigor” directly to whole vines or vineyards. Nevertheless, when a vine or vineyard consists predominantly of highly vigorous shoots, it is common to refer to a highly vigorous vine or a highly vigorous vineyard. The sum of the growth of individual shoots at the end of the growing season determines vine size, which is defined as a vine's total weight of cane prunings. A large number of highly vigorous shoots on a vine will result in a large vine. Although shoot vigor and vine size are related, they are not identical terms and do not always have a direct relationship. For example, a young vine may have a few highly vigorous shoots but have a small vine size because it has a small number of shoots.

We are concerned about shoot vigor because it influences vine cold hardiness not only through excessive canopy density — that is, by causing heavily shaded portions of the vine — but also more directly. Canes that develop from highly vigorous shoots are often less cold-hardy than canes that develop from less vigorous shoots. Canes of moderate diameter (suggesting moderate vigor) in the area of 6 to 7 mm (Howell and Shaulis, 1980) or those canes with a range of diameters of 9.5 mm or less (Pool and Lerch, 2003) are hardier than very large-diameter canes. Differences in shoot vigor and resulting cane maturity can be very large, with as much as 22 °F difference in the LT_{50} (see glossary) on the same vine (Howell and Shaulis, 1980). Therefore, the avoidance of excess shoot vigor, irrespective of its influence on canopy density, may reduce the incidence and severity of winter injury to vines. Management of shoot vigor involves not only choices of training system and pruning methods but also the interactions of crop control (Section V-6), row-middle management (Section V-16), irrigation (Section V-15), choice of rootstock (Section V-13) and vine nutrition (Section V-11). Lack of vine balance results not only from excessive vegetative growth but also from excessive crop, which can be controlled by adjustment of crop level (Section V-6).

The hardiness of grapevine tissues is genetically limited. The lowest temperature at which a specific grape tissue can survive is called its maximum freezing tolerance (MFT) (Fennel, 2004). The sum of the biological, environmental and management factors that contribute to a vine's performance determines the difference between the actual hardiness of a vine and its potential MFT. A grower must choose cost-effective management that moves the actual lethal temperature of grapevine tissues as close as possible to the MFT while avoiding practices that separate these two values. This section assists the grower in that task by individually discussing the influence of several vine cultural practices on vine winter injury.

1. Vineyard site selection

A. Macroclimate

The management of grapevine winter injury begins with the selection of the vineyard site. Grapevines are temperate-climate plants; the major viticultural regions of the world are concentrated between the latitudes of 30° and 50° (Mullins et al., 1992). The frequency of lethal low temperatures limits the existence of sustainable vineyards at the upper limit of this latitudinal range. Therefore, a site's vulnerability to grapevine winter injury can be rated by the frequency of several low-temperature thresholds. Threshold values of -5 °F, -10 °F and -15 °F have been used, and values are expressed to show how many years out of 10 that these temperatures are likely to occur (Zabadal and Andresen, 1997). To keep the process simple and manageable, neither multiple occurrences of these thresholds in the same winter nor the duration of these thresholds is considered. The rationale for such a rating is that the threshold temperature needs to occur just long enough for the tissue of the vine to come into equilibrium with the air temperature. Latitude, per se, is not an indicator of suitability of a vineyard site. Understandably, the proximity of vineyards to temperature-moderating bodies of water becomes increasingly crucial to sustainable viticulture as latitude increases. For example, several hundred acres of wine grapes involving many *Vitis vinifera* cultivars produce profitable yields in most years in the vicinity of Traverse City, Michigan, which has a latitude of approximately 45° north. These vineyards exist because they are situated on two large peninsulas surrounded by vast areas of Lake Michigan. Much lower winter temperatures immediately adjacent to these peninsulas prohibit commercial viticulture. Such water moderation of winter low temperature becomes less critical but is still highly desirable as latitude decreases.

B. Elevation

Elevation influences the overall acceptability of a region for viticulture. Most of the commercial grape production in California is situated at elevations between sea level and 1,000 feet (Winkler et al., 1974). In the Finger Lakes region of New York, growers generally avoid planting late-ripening and/or tender cultivars at elevations over 1,000 feet. The elevation in the Finger Lakes viticultural region of New York decreases from west to east with an elevation of almost 1,200 feet around Canandaigua Lake to about 400 feet along the shore of Cayuga Lake. Therefore, vineyards at the higher elevations in the western portion of that region are prone to more winter injury than those in the eastern portion. The influence of elevation is also reflected in the distribution of *Vitis vinifera* plantings in the region. Elevation and latitude interact so that with decreasing latitude, higher elevations may be suitable vineyard sites. For example, many suitable vineyard sites exist at elevations above 1,000 feet in Virginia (T. Wolf, personal communication).

Elevation influences vineyard site selection through the phenomenon called adiabatic cooling. As air rises, it expands because of reduced atmospheric pressure. This expansion cools moist air at the rate of 0.2 °F to 0.5 °F per 100 feet of elevation. This reduces the accumulation of heat during the growing season and lowers the minimum temperatures experienced during the winter. If there is enough elevation, undesirable locations for vineyards will exist at the higher elevations for an entire region (Fig. III-3) (Wolf and Boyer, 2000).

C. Topography

Topography has a strong influence on the mesoclimate of a vineyard. Slope influences a vineyard's potential for winter injury by drawing cold air away from the vineyard. The so-called "cold air lake" that forms in the low area of a slope typically occupies about the lowest 25 to 30 percent of the elevational range along a slope (Yoshino, 1984) (Fig. III-3). A "thermal belt" of warm air that has been displaced and pushed upward by the colder, denser air in the cold air lake typically develops on the midslope. This is the portion of a slope that is most suitable for reducing the risk of winter injury.

Aspect is the direction that a slope faces. It has no influence on the air movement described above. Aspect may have little influence on winter minimum temperatures in cloudy, overcast areas and significantly influence winter minimum temperatures in sunny areas with high levels of solar isolation. Aspect can also influence rapid fluctuations in temperatures that can cause vine winter injury. Temperature spikes during the winter are associated with winter injury on the south to southwest sides of vines and tree trunks (Howell, 2000). Amazingly, a vertical surface such as a grapevine trunk growing on a slope with a south aspect at a mid-northern latitude will receive on a clear day at solar noon about twice the radiation at winter solstice (December 21) than at summer solstice (June 21) (Geiger, 1966). This occurs because of the low angle of the sun in the winter versus the high angle of the sun in the summer. Therefore, south and west aspects that promote the warming of vine tissues during the winter increase the risk of winter injury due to temperature fluctuations. A south aspect also warms more rapidly in spring. This warming may be an advantage for advancing the growing season and maturing a crop, but it will also tend to deacclimate vine tissues earlier, increase the risk of late-winter injury to vines and increase the hazard of spring-freeze injury to vines.

D. Soil Drainage

Waterlogged soils are associated with increased water content of vine tissues, which greatly increases the risk of vine winter injury (see Section III-2). Some grape cultivars tolerate waterlogged soils better than others, but such soils are not preferred for any grapevines. Some cultivars, such as the juice grape cultivar Niagara, are notorious for developing trunk winter injury and subsequent crown gall when grown on heavy, waterlogged soils. Therefore, soils with good internal drainage greatly reduce the risk of vine winter injury.

2. Vineyard site preparation

Fig. V-2. The slight depression of this swale was enough to increase winter injury to vines and prevent their normal development.

After a suitable vineyard site has been chosen, it may be possible to modify the site to reduce its potential for vine winter injury. The goals are to raise air temperatures and lower soil moisture. Remove impediments to cold air flow out of the vineyard. Also remove surface (Fig. V-1) or subsurface water from a vineyard site. Tiling, which is the practice of installing pipes in the soil to increase soil internal drainage, has been traditionally performed on heavy clay soils at 25- to 50-foot intervals. In recent years, closer tiling intervals of about 9 feet (every vineyard row) have been used in Ontario, Canada, and Ohio to improve vine health and productivity and reduce winter injury (see sidebar). The impact of waterlogged soils can be very localized. Slight topographical undulations can greatly increase the risk of winter injury to vines (Fig. V-2). Grading the soil surface of the site to reduce localized areas of poor soil water drainage can reduce pockets of winter injury. Another strategy for dealing with heavily waterlogged soil is to create berms or mounds of soil into which the vines will be planted. This elevated volume of soil will drain better than the rest of the soil and, therefore, promote vine growth. The height of graft unions is adjusted to be just above the level of these mounds, which may need to be reestablished periodically.

Crown gall bacteria can reside on dead vine tissues in the soil for at least 2 years and probably for several years (T. Burr, personal communication). Therefore, when replanting a vineyard site, there is a risk of infecting new vines with crown gall and thus increasing the impact of vine winter injury. If newly planted vines are not already infected with crown gall, removing as much old vine tissue as possible from a replant site and fallowing the site for 2 years or more may reduce the risk of crown gall complications from winter injury.

Fig. V-1. A vine with dead trunks and live trunk renewal canes. The waterlogged soil in which this vine is planted is likely the primary cause of the winter injury to these vines.

The Benefits of Tile Drainage

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Most people view tile drainage as a method of dealing with excess soil moisture, but it also has a major impact on vine health, including winter hardiness.

In Ontario, it has been observed for many years that vines that have been stressed in one or several ways are more prone to injury from cold winter temperatures. These stresses include drought, excess soil moisture levels in spring or fall, and saturated soils that restrict root growth.

Many growers install subsurface tile drains down the middle of every row (depending on row spacing, this will be every 8 or 9 feet) in clay loam soils as well as lighter soils. The tiles reduce soil saturation near the root zone in the early spring and allow for greater root development and improved vine establishment. The in-row tiles generally are at a depth of approximately 24 to 30 inches, and they connect to a larger main that spills out into ditches or waterways.

Tiling has promoted greater root development at greater depths, improved soil structure, provided faster equipment accessibility after rain events, and resulted in easier soil hilling in the fall and dehilling in the spring.

Tiled soils promote soil microbial activity, contribute to the root development of both vines and cover crops, and improve water penetration during rain events. The better management of the soil moisture level has resulted in more uniform vine growth and timely implementation of crop management practices such as fertilizer application, pest control, crop load balancing, fruit thinning and canopy management.

A well-balanced vine that grows in a consistent manner with the benefits of tiling will develop the maximum cold hardiness possible for that cultivar.

3. Choice of planting material

The choice of vines to plant should be made not only on the basis of marketing grapes and wine but also on the suitability of the planting stock for a specific vineyard site. Such suitability may be as obvious as not choosing a very cold-tender cultivar such as Merlot for a cold site in northern Michigan. More subtle cultivar/site incompatibilities might involve planting a cold-tender cultivar on the lower and/or more soil-waterlogged portions of a site. For example, a small valley in southwestern Michigan has an elevation range of only 46 feet (717 to 763 feet above sea level) over a horizontal distance of about 1,200 feet. During the winters of both 2004-05 and 2005-06, which were relatively warm for the region, there was a critical 8 °F difference between the winter low temperatures (Fig. V-3) at the top and the bottom of this valley. Merlot vines planted at the top of the hill experienced no winter injury, but many of the vines planted near the bottom of the hill died.

The more vulnerable a site is to vine winter injury, the more restricted should be one's choice of planting stock. On less favorable sites, the use of grafted vines brings additional risk and the extra work of protecting graft unions and renewing trunks. Crown gall has become increasingly prevalent in cold-climate viticul-

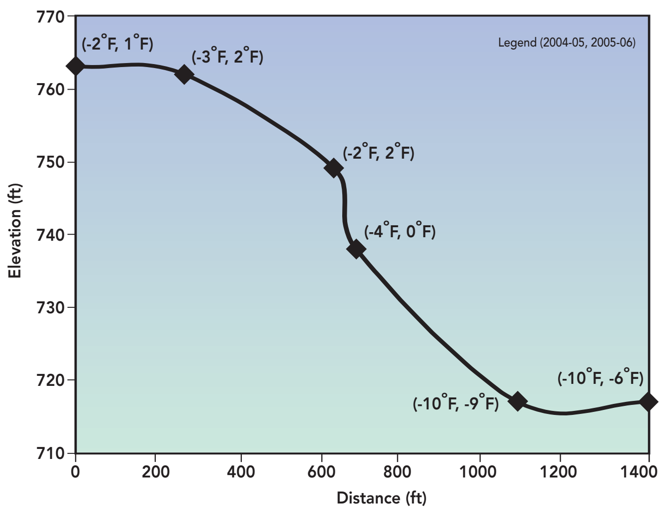


Fig. V-3. The minimum temperature at 60 inches above the ground at six locations along a slope in a small valley in southwestern Michigan in the winters of 2004-05 and 2005-06.

ture because there has been a strong trend to grow cold-tender grape cultivars for the production of premium wines on a broad spectrum of vineyard site conditions. At present, the Northwest Grape Foundation Service (NWGFS) has developed several grape cultivars to be crown gall-free through shoot tip culture. Availability of these vines is limited. Contact the NWGFS at its Web site, http://www.nwgfs.wsu.edu, to obtain information about this program. Increased availability of vines that have been indexed to be free of crown gall (Fig. V-4) is likely in the future. Research in progress will reveal the possible benefits from such planting material (see Section VII).

Matching cultivar and site characteristics. Grape cultivars vary greatly in cold hardiness, the length of growing season required for fruit ripening and the timing of bud break in the spring. Regardless of the hardiness level of a cultivar, a vine's young green tissue after bud break is susceptible to freeze injury when temperatures drop below freezing. Some cold-hardy cultivars may break dormancy early, leaving them susceptible to subsequent freezes. Although some cultivars may acceptably ripen fruit in growing seasons of less than 150 days, most grapes require a growing season length of 165 to more than 180 freeze-free days to ripen. Some cold-hardy, late-budding cultivars, such as Cabernet franc, may be suited to cold-climate (see glossary) sites, but they require a long growing season to ripen. Therefore, they will not adequately ripen when planted on cool-climate (see glossary) sites, which are better suited to a cultivar that is both cold-hardy and early-ripening, such as Marechal Foch. The minimum seasonal growing degree-day (base 50 °F) accumulation sufficient to ripen the earliest cultivars is around 1,800 growing degree-days (GDD) (see glossary) (Jackson, 2000), but in California, any location with fewer than 2,500 GDD is considered a cool-climate area, suitable only for early-ripening cultivars (Winkler et al., 1974). Some cold-tender cultivars can be damaged at temperatures above zero °F; the hardiest grape cultivars can withstand temperatures below -20 °F to -30 °F in midwinter. Planting decisions should be based on a realistic assessment of the site's mesoclimate (see glossary), including winter low temperatures, length of the growing season, the potential for spring and fall freezes, and the accumulation of heat units. Wishful thinking related to cultivar selection for a vineyard site is a recipe for financial disaster due to vine mortality, increased growing costs, and inconsistent fruit and wine quality.

Fig. V-4. Vines in this nursery of Cabernet franc on C3309 rootstock have been developed to be free of crown gall. These vines were planted in several viticultural regions to determine the ability of these crown gall-free vines to reduce the impact of winter injury to vines.

Scott Henry (SH)

Scott Henry training was designed specifically to manage large vines on fertile sites, and its use is justified only in such situations. The basic strategy of SH training is vertical canopy division with shoots being oriented upward (phototropically) and downward (geotropically) (Figs. V-5, B, V-6). Canopy division allows the use of a relatively large number of shoots per vine to achieve vine balance with large vines while reducing the risk of excess canopy density and fruit shading compared with training systems with non-divided canopies, such as MWC. However, the downward orientation of shoots that originate from the lower fruiting wire of the SH training system results in their devigoration (Smart and Robinson, 1991). (See the section on shoot orientation for a full explanation.) This reduces maturity and hardiness of canes derived from those shoots (Pool, 2003). Therefore, a grower needs to weigh the positive attributes of Scott Henry's canopy division against the increased risk of winter injury to the lower portion of the fruit/renewal zone.

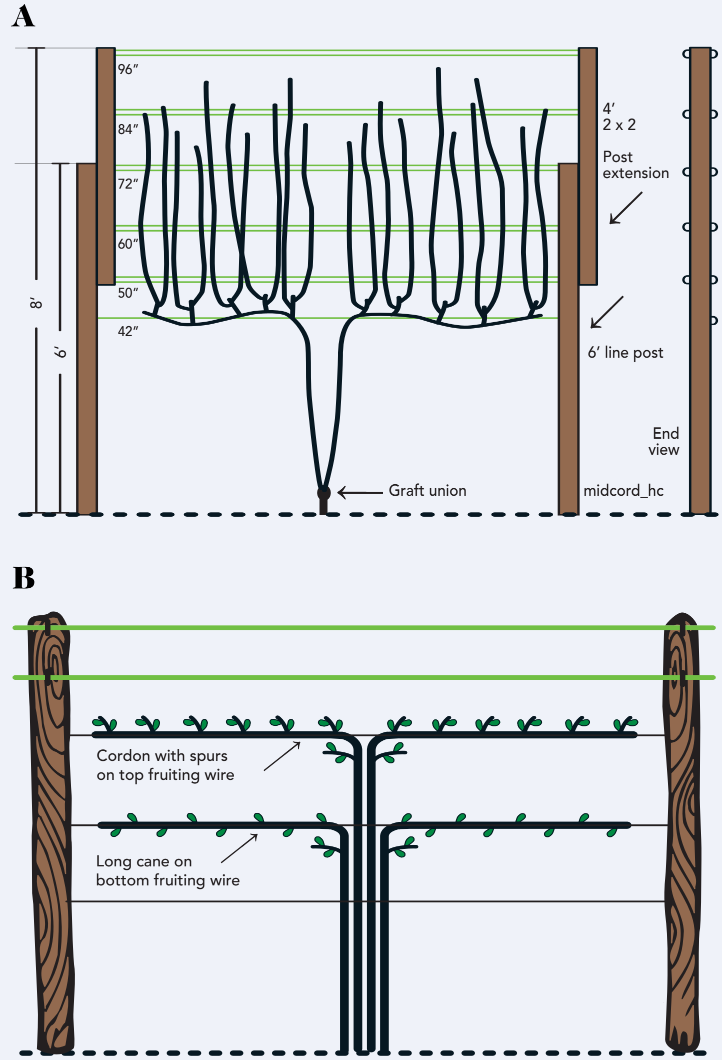


Fig. V-5, A and B. Training systems for grapevines. **A**. Mid-wire cordon, which is also called VSP (vertical shoot position). **B**. Scott Henry with a spur-pruned cordon for the upper fruiting wire and long cane pruning for the lower fruiting wire.

Fig. V-6. Riesling grapevines with Scott Henry training, showing the vertical canopy division and the ability to manage a large number of shoots per vine.

Delayed pruning: The timing of dormant pruning may affect cold hardiness of grapevines. There is evidence that pruned vines occasionally experience greater levels of winter injury than do adjacent unpruned vines. Therefore, fall pruning is not recommended because those vines can suffer more cold injury than unpruned vines (Wolpert and Howell, 1984; Shaulis, 1971). Mid- or late-winter pruning may have no effect on midwinter hardiness or deacclimation (Hamman et al., 1990; Wample, 1994).

Double pruning: This technique involves two stages of pruning. A first pruning in the early to middle portion of the dormant primary season retains two to three times the desired number of nodes on the vine in case winter injury occurs. If no bud winter injury has occurred, a second pruning just before bud break retains the desired number of nodes on the vine. Pruning that utilizes long canes may reduce the risk of spring freeze injury because apical buds on a long cane tend to suppress bud development at the basal nodes. Although this might delay harvest, this is preferable to no harvest. One strategy for double pruning is to perform rough mechanical pruning in the late fall and then delay the follow-up hand pruning until spring.

Cane selection: Prune to select quality canes of appropriate size and color to minimize winter injury. Mature canes that are pencil-sized in diameter with dark periderm have high carbohydrate levels and good cold hardiness. Large-diameter (over 1/2 inch), or “bull” canes, indicate excess vigor. The nodes on those canes will be less hardy than those on smaller diameter canes. Select canes with nodes that were well-exposed to the sun. Depending on the training system, this could be nodes far out on long canes that grow along the top of the trellis. Basal nodes on fruiting spurs along a cordon will be relatively hardy if vines were managed well, with appropriate shoot thinning, crop thinning and shoot positioning during the previous growing season.

Pruning type: Basal nodes on a cane tend to be hardier than apical nodes if they were equally well-exposed to sunlight during development. Therefore, cane-pruned vines may exhibit a higher percentage of bud mortality than spur-pruned vines.

Spare parts: The “spare parts” approach anticipates the frequent loss of parts of the vine from winter injury. Research and field observations indicate that winter injury may vary among trunks of differing age on the same vine (Figs. V-8 and V-9). Thus, the use of

Fig. V-8. A double-trunked vine with one trunk dead from crown gall. The other, younger trunk is healthy and still productive.

Fig. V-9. A vine with three trunks. The oldest trunk is infected with crown gall, but the existence of two younger, healthy trunks will ensure continued productivity.

multiple trunks (two to five) of differing ages is recommended, especially in the most tender cultivars. As the risk of winter injury to vines increases, increase the number of trunks per vine to lessen the impact of having a particular trunk killed. So that new trunks are constantly available, prune to leave renewal spurs near the graft union of grafted vines (Fig. V-10). Retain multiple sucker shoots at the time of suckering to promote a supply of trunk renewal canes (Fig. V-1). The use of multiple trunks also allows replacing those that are affected by *Eutypa* dieback or crown gall (Fig. V-9). Even with the use of multiple trunks, growers may need to replace 1 to 5 percent of vines annually to maintain production.

6. Crop control

Crop level affects cold hardiness of grapevines. Heavily cropped vines experience poor acclimation and a higher potential for winter injury than moderately cropped vines (Wolf, 2004; Dami et al., 2005b, Dami et al., 2006). Some cultivars have a natural propensity to overcrop, such as many hybrids (e.g., Seyval blanc, Chambourcin, DeChaunac) and some *V. vinifera* (Cabernet franc). Overcropped vines may not be able to produce enough carbohydrates to both ripen a large crop and accumulate reserves to develop maximum cold hardiness of vine tissues (Howell, 2000). Lack of periderm formation on shoots at the end of the growing season (Fig. V-11) is a symptom of such overcropping (Shaulis, 1971). Fortunately, growers can control overcropping. Crop control is a powerful tool for developing maximum hardiness (Dami et al., 2005b, Dami et al., 2006). Crop level influences not only the more obvious maturity of the fruit but also the less obvious maturity of the vine itself, which translates to vine cold hardiness (Dami et al., 2005; Dami et al., 2006, Shaulis, 1971; Stergios and Howell, 1977). Accurate crop estimation is essential to maximize fruit quality and minimize vine winter injury. It begins with data collection. This process may at first seem difficult and tedious. The key to successful crop estimation is consistency from year to year. It should be done at the same time of year, with the same methodology and, ideally, by the same person. A multiyear crop estimation database is highly valuable for the long-term management of a vineyard.

Fig. V-10. A grafted vine with a two- to three-bud spur retained near the graft union to create canes for trunk renewal or for burying during the winter.

Fig. V-11. The lack of periderm formation (green instead of brown color) on these shoots at the end of the growing season indicates these tissues will have a low level of cold hardiness.

The three current strategies of crop estimation for wine grapes are presented in Appendix B.

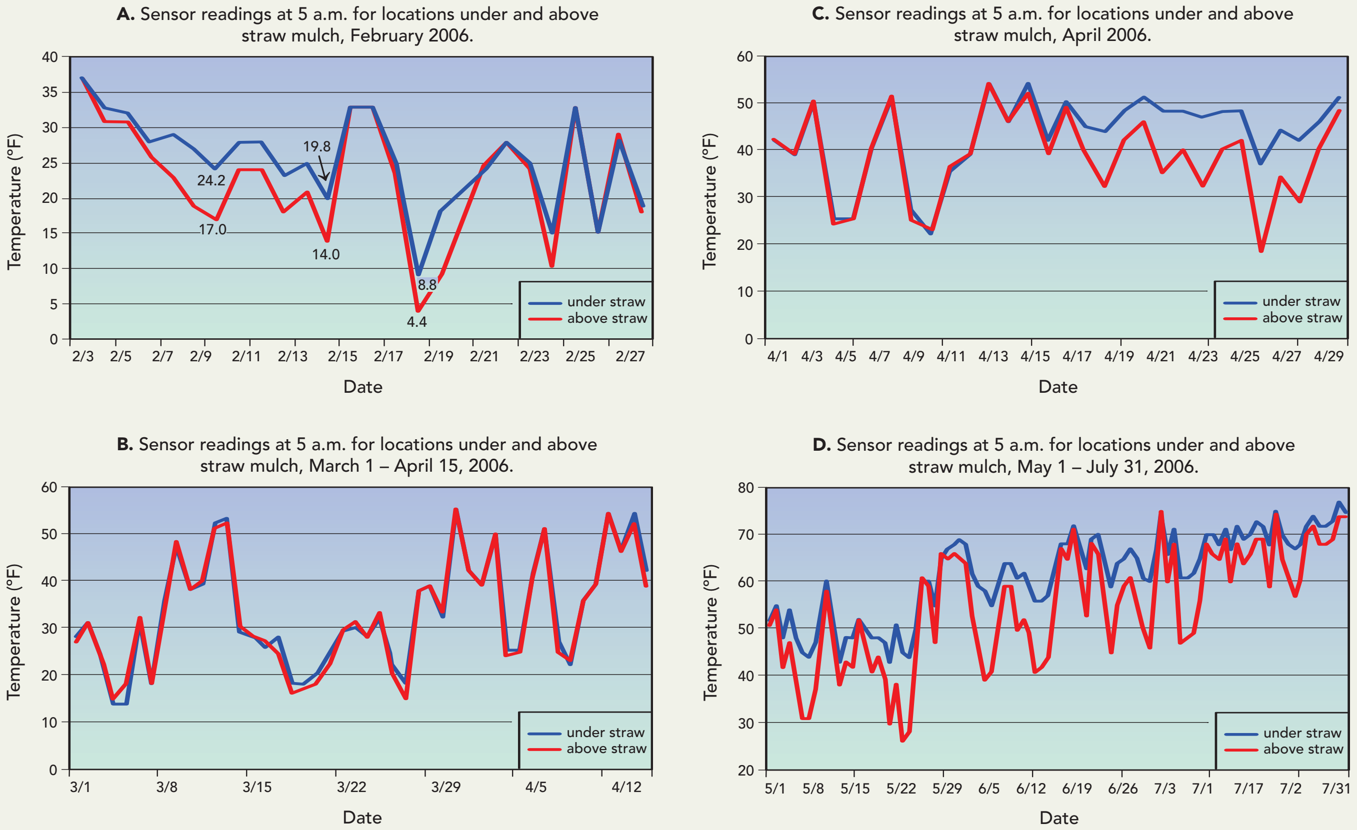


Fig. V-19. A comparison of diurnal equilibrium temperatures at 5 a.m. immediately above and below a straw mulch for the periods (**A**) late winter, (**B**) early spring, (**C**) midspring and (**D**) late spring/early summer.

Fig. V-20. The application of straw at a rate of 3.4 tons/acre in the Doug Nitz vineyard near Baroda, Mich.

Fig. V-25, A. Paddle-wheel implement on a modified Weed Badger unit, custom-designed to remove soil around grapevines.

Fig. V-25, B. Islands of soil remaining around Chardonnay vines after take-out on both sides with the custom take-out implement attached to a Weed Badger in spring 2004 at the MSU Southwest Michigan Research and Extension Center.

Fig. V-25, C. Side one removal of soil around Chardonnay vines with the custom brushing implement attached to a Weed Badger in spring 2004 at the MSU Southwest Michigan Research and Extension Center.

Fig. V-25, D. Side two removal of soil around Chardonnay vines with the custom brushing implement attached to a Weed Badger in spring 2004 at the MSU Southwest Michigan Research and Extension Center.

Fig. V-25, E. A 100 percent mechanical removal of the mound of soil around grafted Chardonnay grapevines involving one pass of the paddle wheel and one pass of brushing on each side of the trellis.

A brushing unit (Fig. V-25, D) can be used to complete that task mechanically (Fig. V-25, E) and avoid laborious hand-hoeing.

Specialized equipment has been developed for hilling of soil (hilling up) under the trellis (Fig. V-23, A-C) and taking out (Fig. V-25, A-E). Plans for constructing some of this equipment are available as SWMREC Special Report #23 at http://www.maes.msu.edu/swmrec under "Publications."

Fig. V-26. Partial removal of soil from around vines with a take-out plow. After this procedure is performed on both sides of the trellis, a third pass with a blade removes the remainder of the soil around vines.

Protecting graft unions

Protecting graft unions against low winter temperatures with soil provides insurance for the long-term survival of a vine (Fig. V-27). Low winter temperatures can cause tissue mortality down to the soil line. If soil is hilled over a graft union so that some of the scion tissues above the graft union are covered, then buried scion tissues will be a source of vine renewal (Fig. V-28) if a low-temperature episode were to kill

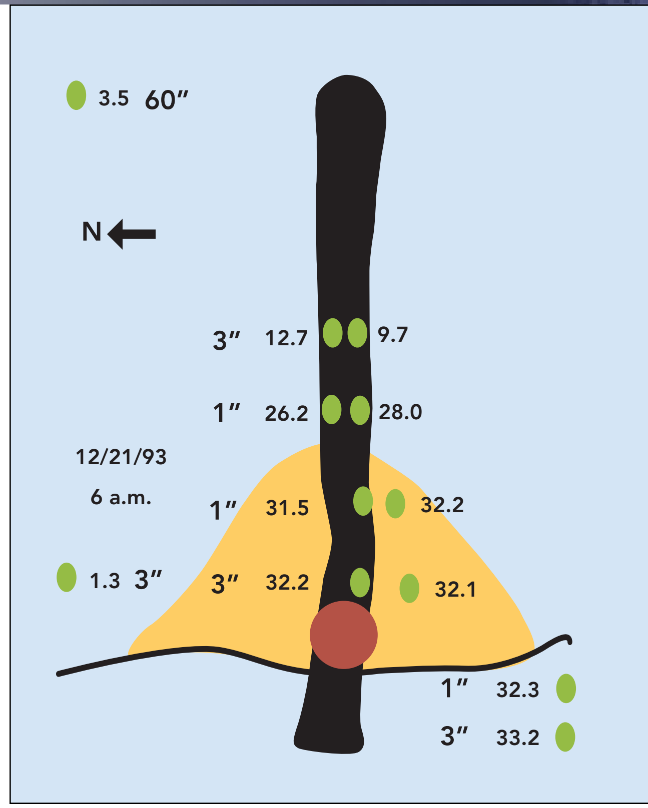
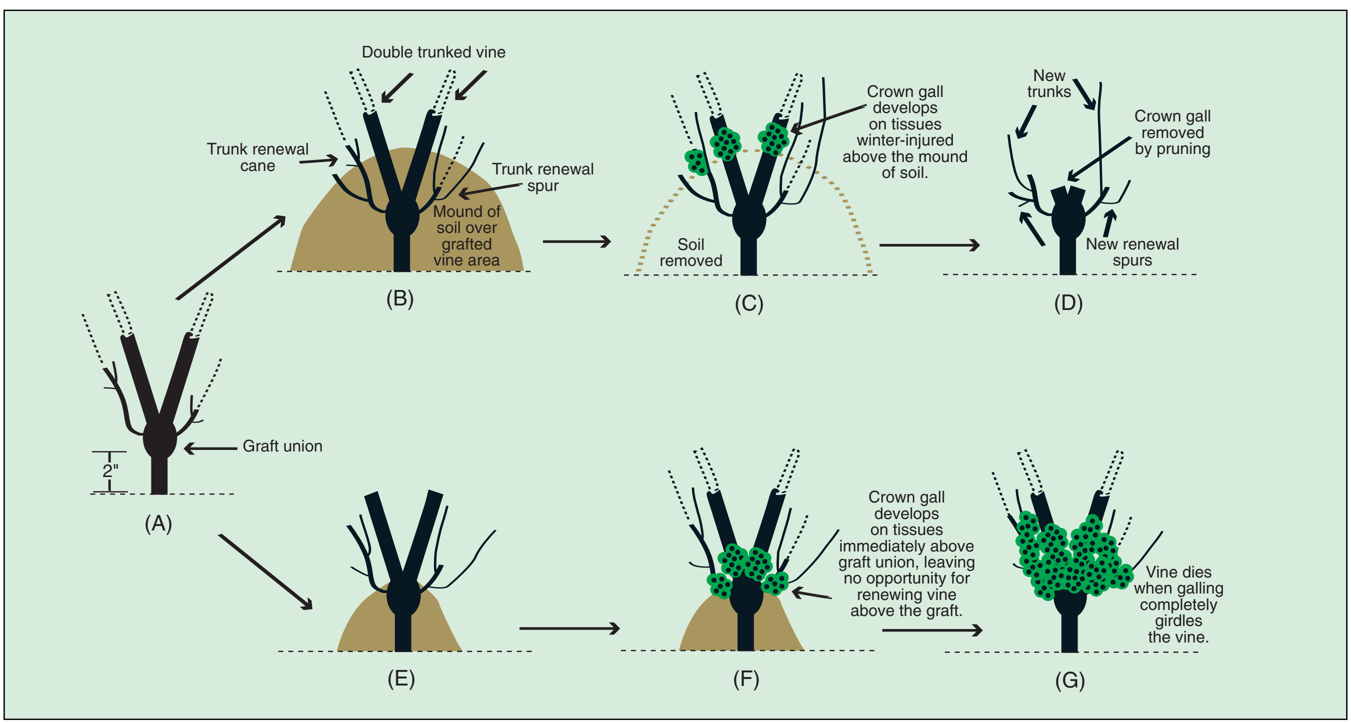


Fig. V-27. Temperature (°F) recorded at various locations relative to the trunk and soil on a cold day in a vineyard near Benton Harbor, Mich.

Fig. V-28. A schematic showing how adequate or inadequate burial of scion tissues above the graft union can result in either the ability to renew trunks and maintain a healthy vine or vine mortality.



all portions of vine exposed to ambient air temperatures. Without such protection, winter injury and the subsequent development of crown gall can kill vines (Figs. IV-16 and V-28). If soil is left hilled up over the graft union, scion rooting readily occurs, especially on young vines (Fig. V-29, A). Scion rooting eventually defeats the purpose of the rootstock (Fig. V-29, B) so that vine size will gradually decline. Therefore, it is necessary to take out soil from around the graft union to prevent scion rooting. As vines mature, some growers find that the intensity of scion rooting declines so that the hilling-up/taking-out procedure can be performed on a two-year or longer cycle.

Fig. V-29. Scion rooting on grafted vines that have had soil hilled up over the graft union for (**A**) one year or (**B**) several years is not desirable.

Hilling up and Taking out Hills Around Vines

Jan Waltz, Waltz Vineyards
Manheim, Pa.

We hill up in October through November before the ground freezes. Soil should be fairly dry for optimum hilling. We use a Braun grape hoe (Fig. V-21) with a side-hilling plow. To attain adequate coverage of the graft area, berms should reach to 3 to 4 inches above graft height. Consider a vineyard's slope when purchasing equipment. A hilling plow with side slope adjustment is helpful for slopes greater than 3 percent.

Taking out should be done in spring after prunings have been chopped or removed. Soil conditions should be fairly dry, which is usually in April or early May. We use a take-out plow on the Braun unit (Fig. V-24) to remove most of the hill and then follow 1 to 2 weeks later with a grape hoe with winged take-out blade to remove the remainder of soil from around the graft union.

Each step in the process of hilling up or taking out takes approximately 1 hour and 15 minutes per acre. Hilling up and taking out also help to control weeds.

MANAGING WINTER-INJURED GRAPEVINES

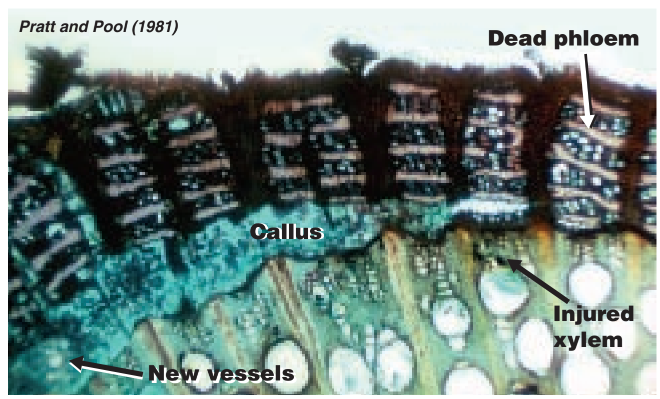
1. The cellular process of repair of freeze-injured canes and trunks

A vine that is not killed outright by low temperatures will attempt to recover. After significant winter injury, the vine's immediate need during the next growing season is functional leaf area. Cropping is of secondary importance. A grower must develop a balance between nurturing the vine's recuperative ability and his/her ultimate goal of vineyard profitability.

At the cellular level, vine recovery from winter injury involves production of new cells that can mature into tissues that replace injured, non-functional tissues. Plant cells, especially those of the cambium, can proliferate into a generalized mass of non-specialized cells known as callus tissue. When cold destroys an area of phloem and/or xylem in canes, cells of the cambium will divide in the spring to produce callus tissue (Fig. VI-1, A). This callus thickens and is influenced by hormones moving downward from new shoots and upward from roots. Small vessel elements begin to develop in the callus (Fig. VI-1, A), and after many weeks or months, normal phloem and xylem cells replace the callus. Often, the second-year growth ring of xylem or phloem doesn't show normal vessels or phloem cells in the previously injured stem sector until near the end of the growing season (Fig. VI-1, B).

Repair of freeze-injured cordons and trunk tissue is similar to that of canes. If only the phloem is injured or killed, the vascular cambium begins production of normal xylem and phloem in springtime (Fig. VI-2, A). The first new xylem vessels may be small because weak shoot growth stimulates only the production of small cells. If injury to both xylem and phloem is severe and bud break is weak or intermittent, the reactivated cambium may produce only small vessels and little phloem, along with much non-conductive vascular tissue (Fig. VI-2, B). Only after an extended period of shoot growth will more efficient vascular tissues be produced. When whole sectors of a cordon or trunk are severely injured, repair comes from the production of callus by the remaining uninjured cells still capable of cell division (Fig. VI-2, C). As in canes, the callus first thickens in the sector with the most viable tissue. The callus then grows and spreads laterally into adjacent dead areas. The cells of the callus "wedge" or "front" are not specialized. Behind the front, however, new xylem and phloem cells eventually develop for longitudinal transport of food and water. Again, unless or until enough new leaf area develops, such conductive cells will not achieve large size.

A



B

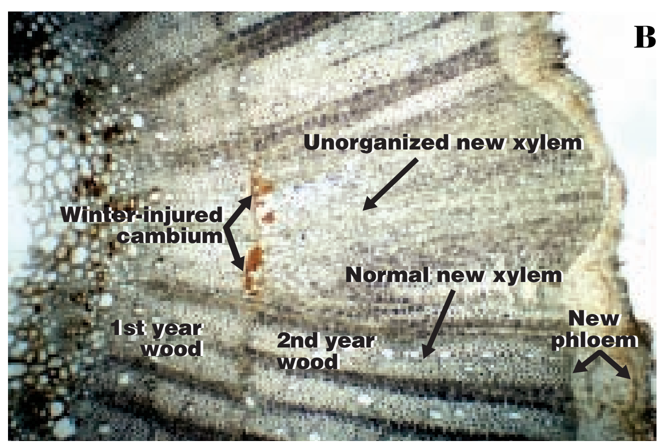


Fig. VI-1. Repair of winter-injured vascular tissues in grapevine canes. **A**. Repair of a sector of a Chenin blanc cane that was frozen with liquid nitrogen. All phloem is dead and black. Even xylem is injured to some extent, but enough cells survived in the cambial zone to initiate callus tissue that has filled the region between xylem and phloem. As callus thickens, new vessels begin to differentiate.
B. Concord cane at the end of its second season, showing evidence that the dormant cambium of the preceding winter had been freeze-injured. Note that the new ring of secondary xylem did not develop normally and that few large vessels can be seen.

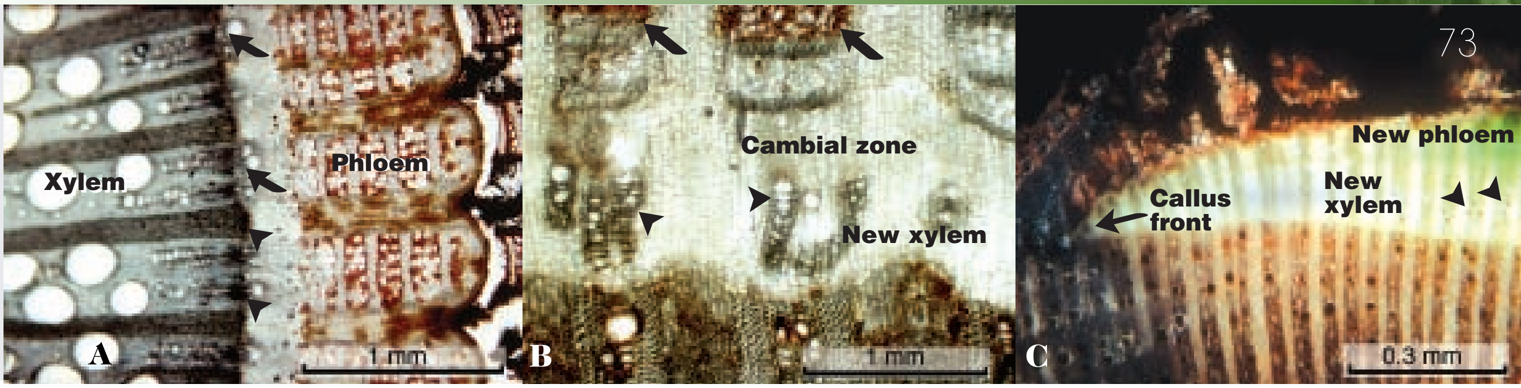


Fig. VI-2. Repair of winter-injured cordons and trunks. **A**. Riesling arm injured in early spring, showing severely injured phloem tissue and some russeting of cells (arrowheads) that were formerly in the vicinity of the vascular cambium. New xylem vessels (arrows) are forming, however, so there is a good chance for recovery. **B**. Chardonnay trunk section at the cambial zone, showing attempted recovery and vascular repair. Note the dead phloem groups (arrows) and also the weak production of new xylem vessels (arrowheads) within a matrix of rather non-differentiated tissue. Lack of xylem fiber production and weak new vessels signify weak canopy growth above this point. **C**. Pinot noir trunk being repaired after winter injury by formation of a crescent-shaped wedge of callus. Note that the callus is spreading laterally (arrow) by rapid cell divisions along the front of the callus formation, while back from this front new xylem and phloem are developing. Note the small vessels (arrowheads) differentiating in the xylem.

The relationship between vascular tissue differentiation in canes and leaf production can be demonstrated by slicing into an emergent bud and its parent cane. As a primary bud develops into a young shoot with leaves and internodes, its vascular tissues begin rapid development, both into the shoot and downward into the cane (Fig. VI-3, A). The dormant vascular cambium of the cane becomes reactivated and gives rise to new xylem vessels under the influence of hormones produced in the new shoots. A wave of cambium activation and production of new vascular tissue spreads from the cane's nodes downward and around the cane (Fig. VI-3, B), then downward into the spurs, cordons and trunk. The new growth ring can be found at the shoot/root crown by about bloom time. Last year's xylem ring thus is covered by a new xylem ring. Winter injury anywhere along the vine's vascular system creates a barrier to that development and to the efficient movement of food, water and inorganic nutrients between shoots and roots. Partial or full vine recovery after winter injury depends on how much tissue is injured and whether there is continuity of the vascular system between emergent leaves and the root system. In humans, we associate

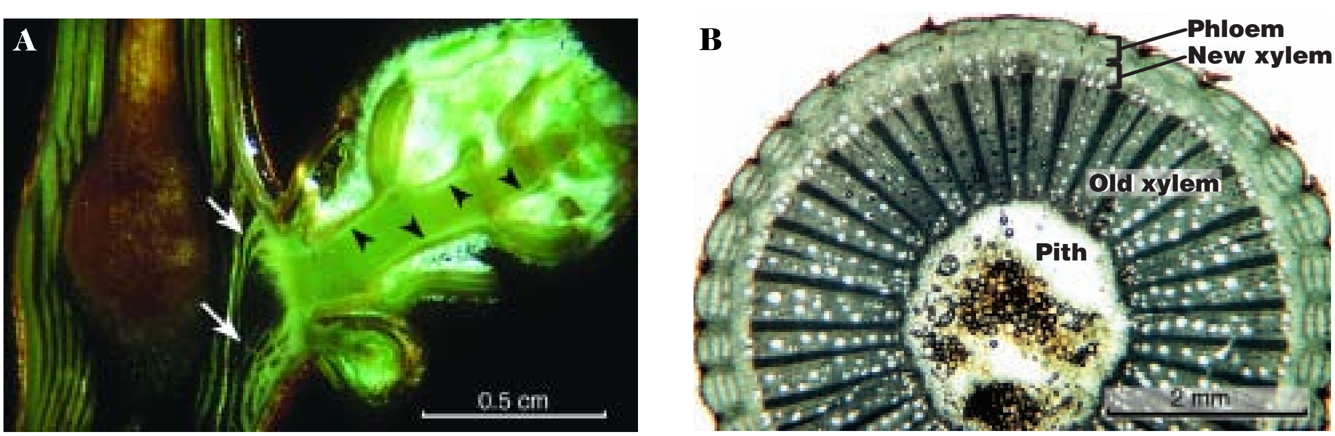


Fig. VI-3. Effects of bud break and new shoot emergence on the annual cycle of vascular tissue activity. **A**. Longitudinal slice through a Concord cane node and emergent primary bud in early May in New York state. As leaves expand, the new shoot's vascular tissues begin rapid development. The once-dormant vascular system of the cane node and its internode below it come under hormonal influence from this shoot to increase the size of their vascular strands (arrows). A wave of cambium reactivation then moves downward in the cane. **B**. Cross-section of a Chardonnay cane 1 cm below an emergent shoot in spring. Note that the vascular cambium produced most new xylem in the sector immediately below the shoot (which would be situated at 12 o'clock above this figure), and this activity spreads both laterally and downward with time.

rest with the process of returning to health after illness. For a grapevine, it is the activity of leaf area, not rest, that is the basis for returning a vine to full health after winter injury.

The following example demonstrates the importance of a viable vertical connection of the vascular system from emergent shoots to the roots if the canopy is to survive to the end of the growing season. Such interconnectivity is no problem for uninjured or only sporadically cold-injured grapevines. It is the vines with very poor postfreeze recovery that demonstrate this important concept. Figure VI-4 shows a poorly recovered spur-pruned Cabernet Sauvignon vine 4 years after it was almost killed in a February freeze in Washington state in 1996. In response to individual shoot growth from the spurs, a segment of live tissue was produced along the cordon (Fig. VI-4, A) and down the trunk (Fig. VI-4, B). This segment of live tissue resulted from viable cambium along the vascular system. This is shown in Fig. VI-4, C, where the entire vine was cut into short cylinders as a cross-sectional series from the spurs on the cordon (upper left) down to the trunk at ground level (lower right). In every slice of the trunk, the seasonal vascular development could be traced apically to live, developing shoots. The reliance of the trunk vascular cambium on a stimulus from shoots is apparent. Continued vascular development on a whole-vine basis depends on at least some vertically connected living tissue between shoots and roots. This interconnectedness of parts of the vine is an important concept when a grower works to reestablish vine health after winter injury. Semipermanent portions of the vine — i.e., trunks and cordons — may survive a winter injury episode but be severely injured. Only when these portions of vines are completely replenished with healthy tissues will the full productive potential of the vine be realized. This strategy is discussed below.

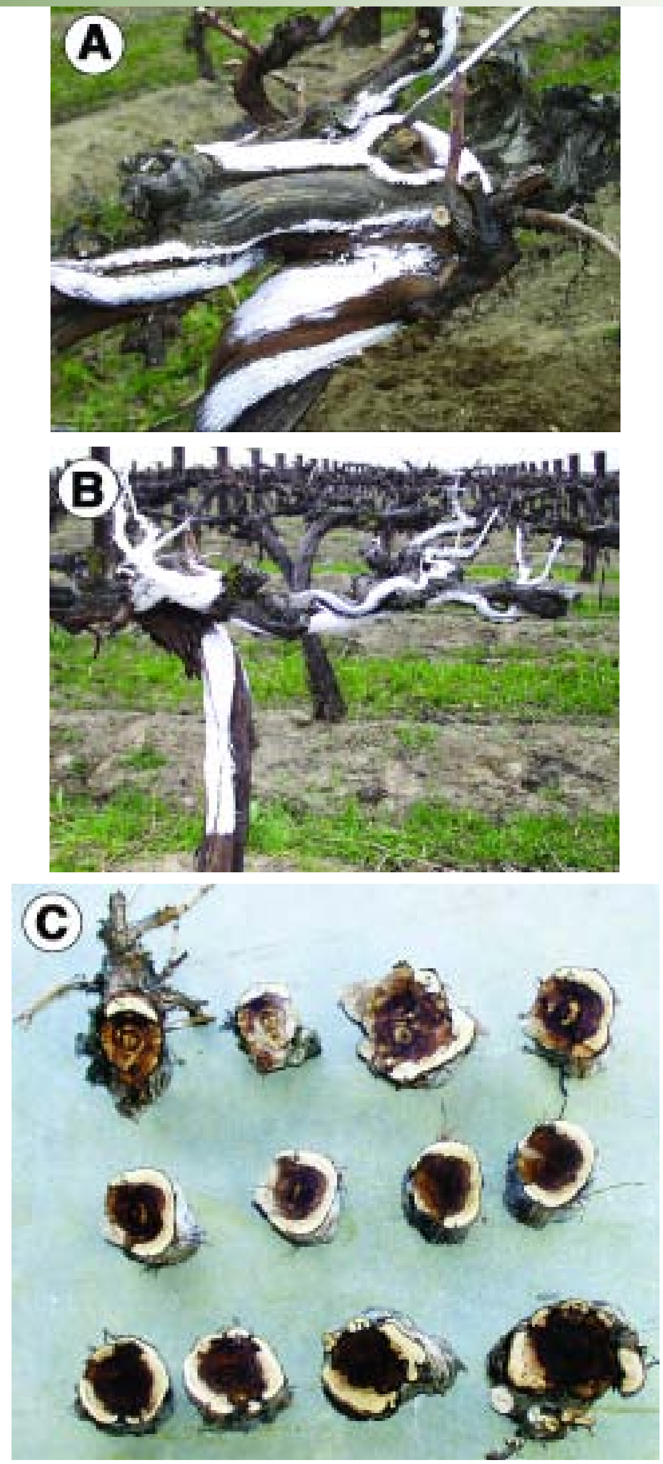


Fig. VI-4. A mature Cabernet Sauvignon vine in Washington state in 2000, four years after a devastating freeze. White paint denotes ribs or flutes of new growth along spurs, cordons and trunk that connect the few viable buds and canes to the root system. **A**. Sectors (flutes) can be followed upward only to regions that produced viable canes and buds. **B**. Flutes can be followed downward, where they expanded only in arm and trunk sectors that retained living cambium tissue after the freeze. **C**. Series of chain-sawn cross-sections tracing a crescent of viable (white) wood beneath viable canes (upper left) downward through viable sectors of one arm to the lower trunk (lower right).

2. Replant decisions

Maintaining vine count is among the most important factors determining profitability of a vineyard. Even in the best years, vineyards with cold-tender cultivars can suffer vine losses of 2 to 4 percent. Because many growing costs are fixed, missing vines directly raise

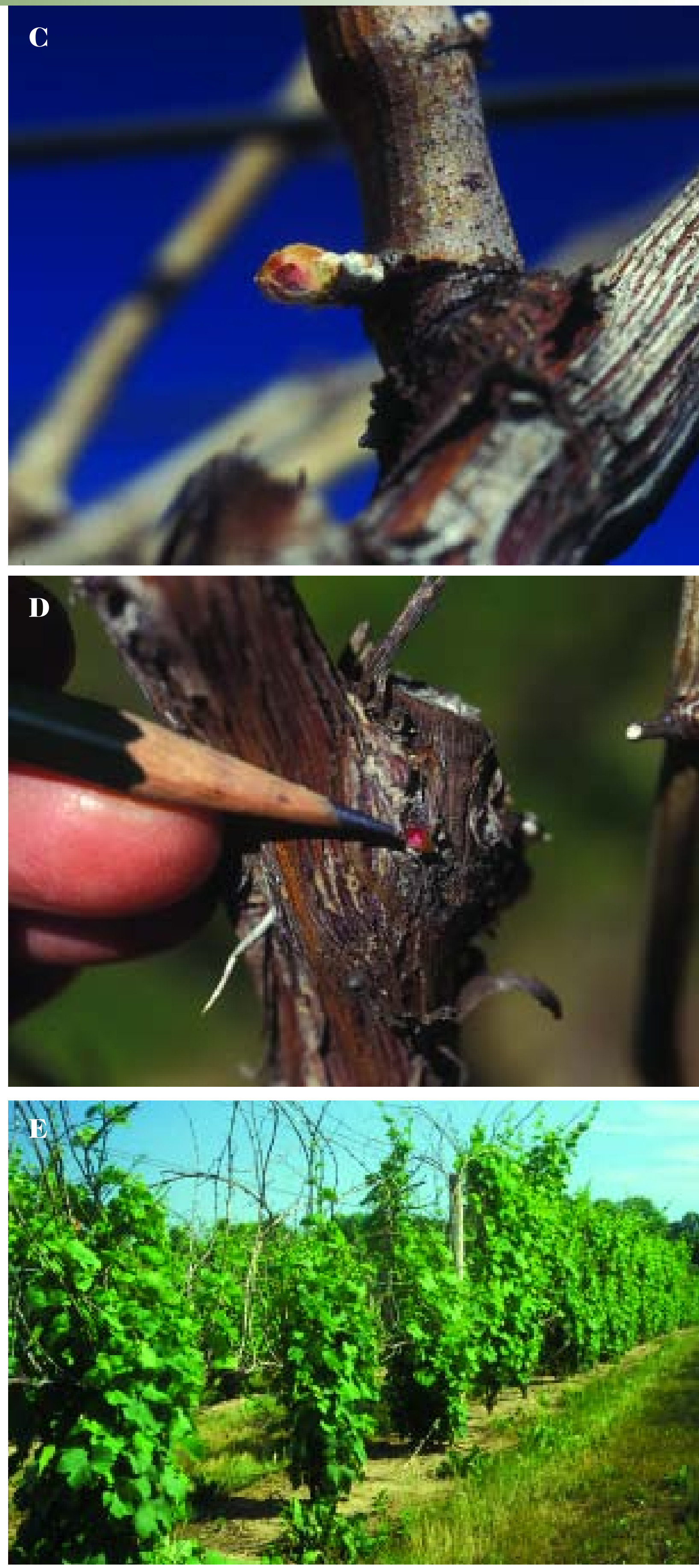


Fig. VI-7. Shoot development of Chardonnay grapevines in a vineyard near Benton Harbor, Mich., under (**A**) normal conditions on 5/20/98 or (**B**) after severe winter injury on 5/23/94. Late-emerging shoots on winter-injured vines from (**C**) basal nodes on canes (5/12/94) or (**D**) base buds (red) by pruning cuts (5/12/94) can grow rapidly to (**E**) fill the trellis with canopy (6/27/94). Vines trained to mid-wire cordon in the foreground and umbrella Kniffin in the background.

TECHNOLOGY OF THE FUTURE

Several approaches have been used to create planting stock free of crown gall disease (*Agrobacterium vitis*). Heat treatment (Wample, 1993) has been used, but it does not completely eliminate *A. vitis* from tissues (Burr et al., 1996). Shoot tip propagation has been used successfully to create scion and rootstock tissues free of *A. vitis* (Burr et al., 1988). Numerous wine grape cultivars and rootstocks have been created in this manner to be free of crown gall disease by the Northwest Grape Foundation Service at Washington State University. Limited numbers of vines are produced by this program. Their primary use is to establish foundation plantings at certified grape nurseries. However, vines are also made available to others. For more information go to the Web site http://nwgfs.wsu.edu. Vines that have been created through tissue culture and then indexed to be free of *A. vitis* (Burr et al., 1998) have been planted in both viticulturally virgin and replant sites. This will determine if and how long they will remain free of this disease and how they will perform. Non-tumerigenic strains of *A. vitis* (Burr and Reid, 1994) have been shown to antagonize the pathogenic strains of *A. vitis*. Therefore, vines inoculated with non-tumorigenic strains of *A. vitis* are also being evaluated as a strategy for reducing the impact of this disease. Were any of these strategies to control crown gall successful, such vines would still be susceptible to winter injury, but the secondary and often lethal effects of crown gall would not occur. It is expected that vines would recover from winter injury more quickly and successfully because there would be no permanent alteration of vine tissues into non-functional gall tissue.

The need for cold-hardy vine materials that make fine wines is increasing. As wine growing spreads into areas traditionally considered too cold for successful viticulture, the potential for these new materials will be discovered through research on many fronts. Grape breeding for cold hardiness has been done for decades and has yielded spectacular results from private breeders as well as from programs at Cornell University and the University of Minnesota. Many of these hybrid cultivars have been successfully commercialized, and work to develop hardier cultivars continues. Cold-hardy cultivars are also being imported from other viticultural regions around the world. A cultivar trial at Southwest Missouri State University is evaluating cold-hardy cultivars from Central Europe that might make high quality wine in the regional climates and soils of Missouri. A USDA project, NE-1020, an effort to merge and coordinate cultivar and clone trials across the United States, has cold hardiness as one of its core objectives.

Genomics is another research area with great potential to increase cold hardiness. Efforts to find the genetic link to cold hardiness in grapevines are well under way at the Grape Genomics Research Unit (GGRU) in Geneva, N.Y. Genetic engineering will offer the ability to make existing commercially successful cultivars genetically hardier. This approach may make it possible, for example, to reliably grow Gewurztraminer and Syrah in regions such as the Finger Lakes. These cultivars have sufficient fruit maturity potential but face a major threat of winter injury. Many social and ethical issues will need to be considered before these types of materials will be made commercially available, but the potential benefits are very clear.

Researchers in Oregon and Washington are investigating methods of protecting vine trunks during winter with various types of insulation including hot water pipe insulation and a sprayable organic cellulose product (C. Kaiser, personal communication). Electrical engineering technology now exists to deliver a small electric current to each vine in a vineyard (Fig. VII-1) so that it can warm a portion of the vine during a low-temperature episode. This ingenious technology has been used to protect the lower portion of vine trunks. Perhaps future applications will also be directed to protect vine fruiting potential. For more information, go to the Web site http://www.theelectricblanket.com/.

The future may hold new technologies that offer protection from winter injury. High-tunnel technology has been tried in vineyards and may eventually be an economically viable option. Wind fans might be used more commonly to protect vines during the winter.

Finally, global warming should not be ignored. How or when will global warming affect winter injury to grapevines within both traditional and non-traditional grape-growing areas?

Fig. VII-1. Vines with trunks wrapped with insulation. Under the insulation of each vine is a thermostatically controlled electric heating unit.

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Internet Resources

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2. Cold hardiness of grapes: A guide for Missouri growers. Marilyn Odneal, Southwest Missouri State University. http://mtngrv.missouristate.edu/Hardiness/Introduction.htm
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6. Grape cold hardiness. Washington State University. http://winegrapes.wsu.edu/frigid.html
7. American Journal of Enology and Viticulture Web site. Use keyword search. http://www.ajevonline.org/

GLOSSARY

Acclimate — To increase the cold hardiness of a tissue.

Acropetal — Growing or developing upward, such as toward the shoot tip.

Adiabatic cooling — The lowering of air temperature as air expands with increasing elevation. This cooling results in no change in the total heat contained in the air.

Advective freeze — A large mass of cold air affecting a large area with windy conditions but without a pronounced vertical gradient of temperature inversion.

Agrobacterium vitis — A species of bacterium that infects grapevine tissues. Some strains of this bacterium can cause the disease known as crown gall.

Ambient temperature — The air temperature recorded at 60 inches above the ground by a shaded sensor.

Apical — At the tip or apex of a vine structure.

Arm — Any 2-year-old or older wood on a grapevine other than the trunk(s).

Aspect — The direction of a slope.

Avoidance — A strategy for surviving a stress by not being exposed to it.

Axillary bud — A bud produced in the upper angle (axil) between a leaf or bud scale and its stem.

Basal — At the bottom or base of a vine structure.

Base bud — A barely visible bud that develops at the base of a grapevine shoot. It may remain dormant for several years.

Base shoot — A shoot emerging from a base bud.

Basipetal — Growing or developing from the tip toward the base, such as from the shoot tip toward the shoot base.

Brix — The percent of soluble solids (mostly sugar) present in grape juice.

Blind node — A node on a cane that does not produce any shoot growth.

Blocking pruning cuts — Large pruning cuts that remove major portions of a vine, such as an entire arm, trunk or cordon.

Bud scale — A cup-shaped modified leaf that covers a dormant bud of a grapevine.

Callus — A non-specialized tissue that develops at the site of a wound. It may or may not differentiate into a specialized tissue.

Cambium — A thin tissue layer in woody stems and roots whose cells divide into new cells. (See *vascular cambium* and *cork cambium*.)

Cane — A leafless, smooth-barked, woody part of the vine that had been a green shoot in the previous growing season.

Canopy — The sum of all green vegetative tissues on a grapevine during the growing season.

Clone — A genetically unique form of a cultivar that can be traced in its propagation to a single mother vine.

Cluster — A stalked group of berries arising at an individual node of a shoot.

Cold air drainage — The local downslope gravity flow of air.

Cold air lake — The accumulation of cold air at the bottom of a slope during a radiation freeze.

Cold climate — Climate conditions during the dormant season. It can be expressed quantitatively by the average daily minimum temperature of the coldest month. (Compare with *cool climate*.)

Cold hardiness — The ability of a dormant vine tissue to survive freezing temperatures.

Cold-hardy — Dormant whole vines or tissues capable of surviving relatively low freezing temperatures (LT_{50} = -15 to -20 °F).

Cold injury — See *winter injury*.

Cold-tender — Dormant whole vines or tissues capable of surviving only relatively high freezing temperatures (LT_{50} = 0 to -8 °F).

Cold tolerance — Cold hardiness.

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