The Art of Protecting Grapevines From Low Temperature Injury

ROBERT G. EVANS*

Frost protection or protecting plants from cold temperatures where they could be damaged must be a consideration in vineyard planning. Cold protection events commonly occur during “radiation” frost conditions when the sky is clear, there is little wind and strong temperature inversions can develop. These conditions can happen during spring, fall or winter when it is necessary to keep canes, buds, flowers, small berries, or foliage above “critical” temperatures. The best frost protection technique is always good site selection. Use of water for frost protection in *V. vinifera* blocks is often not recommended when it is necessary to carefully manage soil water levels. Under-canopy sprinkling systems are usually not an option. Wind machines or “fans” rely totally on the strength of the temperature inversion for their effectiveness in warming the vineyard and may also be helpful in pushing cold air out of a vineyard. The placement of multiple wind machines must be carefully coordinated to maximize the areal extent and net effectiveness. Currently available fossil fuel-fired (oil and propane) heaters can be a big asset in frost protection activities, but are very inefficient and costly to operate. While there is no perfect method for cold temperature protection, quite often combinations of methods are advantageous. Wind machines have been found to work well with properly placed fossil fuel heaters and is probably the most appropriate combination for winter time cold protection in vineyards. A well-maintained and calibrated frost monitoring (thermometers and alarms) network will always be required. Knowledge of the current critical temperatures and the latest weather forecast for air and dew point temperatures are important because they tell the producer if heating may be at any stage of development and how much of a temperature increase should be required to protect the crop.

KEY WORDS: cold temperature injury, frost protection methods, grapevines

Attempts to protect grape vines from cold temperature injury began at least 2000 years ago when Roman growers scattered burning piles of prunings, dead vines and other waste to heat their vineyards during spring frost events [3]. The protection of vines against cold temperature injury is still a crucial element in commercial viticulture in many areas of the world. It is estimated that 5% to 15% of the total world crop production is affected by cold temperature injury every year. However, because of the extreme complexity of the interactions between the physical and biological systems, our current efforts to protect crops against cold temperature injury can be appropriately characterized as more of an art than a science.

The need to protect against cold injury can occur in the spring, fall and/or winter depending on the location and varieties [9]. Frost protection activities on grapes in the spring are to protect new leaves, buds, and shoots (and later the flowers) from cold temperature injury. However, it is often necessary to frost-protect *V. vinifera* vineyards in the fall in areas like the inland Pacific Northwest (PNW) to prevent leaf drop so that sugar will continue to accumulate in the berries. Sometimes protection measures must be initiated during very cold temperature events during the winter periods on *V. vinifera* vines and some perennial tree crops (*i.e.,* peaches, apricots) in colder regions. Winter cold temperatures can injure roots and trunk/cane injuries (splits, wounds, tissue damage). Injuries can also increase the incidence of certain diseases such as crown gall. Usually, only a couple of degrees rise in air temperature is sufficient to minimize cold injury at any time of year.

The terms frost and freeze are often used interchangeably to describe conditions where cold temperature injury to plants result as a consequence of subfreezing temperatures. This discussion will generally refer to frost and to frost protection systems for the wide variety of countermeasures growers may use to prevent cold temperature injury to plant tissues.

Types of frosts. There are basically two dominant types of frost situations which will be encountered. These are radiant frosts and advective freezes. Both types will usually be present in all frost events, but the type of frost is usually characterized by the dominant type.

Radiation frosts: A radiation frost is probably the most common in grape growing areas around the world. It is also the easiest type of frost to protect against and is the main reason that site selection is so important. Almost all frost protection systems/methods available today are designed to protect against radiant-type frost/freezes.

There are two sources of heat loss under radiative conditions: radiative losses and *advection* (wind) that must be counteracted in radiative frost conditions. All objects radiate heat into the environment in proportion to their relative temperature differences. For example, exposed objects will lose heat at a faster rate when exposed to a clear night sky which has an effective temperature around -20°C, but will not lose heat as rapidly to clouds which are relatively much warmer than the sky depending on cloud type and height. With

*Biological Systems Engineering Department, Washington State Univesity, 24106 N. Bunn Road, Prosser, WA 99350, USA [Fax (509)786-9370; e-mail: revans@wsu.edu].

respect to the plant, heat is lost by upward long-wave radiation to the sky, heat is gained from downward emitted long-wave radiation (*e.g.,* absorbed and re-emitted from clouds), air-to-crop (advective) heat transfers, and heat can either be gained or lost soil-to-plant (radiative) heat transfers.

Radiant frosts occur when large amounts of clear, dry air moves into an area and there is almost no cloud cover at night. During these times, the plants, soil, and other objects which are warmer than the very cold night sky will "radiate" their own heat back to space and become progressively colder. In fact, the plants cool (by radiating their heat) themselves to the point that they can cause their own damage. The plant tissues which are directly exposed to the sky become the coldest.

These radiation losses can cause the buds, blossoms, twigs, leaves, etc. to become 1°C to 2°C colder than the surrounding air which radiates very little of its heat. The warmer air then tries to warm the cold plant parts and it also becomes colder. The cold air settles toward the ground and begins slowly flowing toward lower elevations. This heavier, colder air moves slowly ("drifts") down the slope under the influence of gravity (technically called "katabatic wind"), and collects in low areas or "cold pockets." Drift, typically moving 1 to 2 meters per second (m/sec), can carry heat from frost protection activities out of a vineyard and replace it with colder air. It can also carry heat from higher elevation heating activities into a vineyard. The amount of heat lost to wind drift is often at least equal to radiative heat losses that are in the range of 10 to 30 watts per square meter (W/m^2) or more. Consequently, the replacement heat must be greater than the sum of both radiative and advective heat losses during "successful" frost protection activities (*i.e.,* $\geq$ 20 to 60 W/m^2 depending on climatic variables and time of year).

Concurrent with the radiative processes and with very low wind speeds (< 1.5 - 2 m/sec), a *thermal inversion* condition will develop where the temperature several tens of meters above the ground may be as much as 5°C to 8°C warmer than air in the vineyard. Springtime temperature inversions will often have a 1.5°C to 3°C temperature difference (moderate inversion strength) as measured between two and 20-meters above the surface. Many frost protection systems such as wind machines, heaters and under-vine sprinkling rely on this temperature inversion to be effective.

The general rate of temperature decrease due to radiative losses can be fairly rapid until the air approaches the *dew point temperature* when atmospheric water begins to condense on the colder plant tissues (which reach atmospheric dew point temperature first because they are colder). The *latent heat of condensation* (when water condenses from a gas to a liquid, it releases a large amount of heat (2510 KiloJoules per liter at 0°C compared to 335 KJ/L released when water freezes) is directly released at the temperature of condensation, averting further temperature decreases (at least temporarily). Thus, the exposed plant parts will generally equal air temperature when the air reaches its dew point. At the dew point, the heat released from condensation replaces the radiative heat losses. Because the air mass contains a very large amount of water which produces a large amount of heat when it condenses at dew point, further air temperature decreases will be small and occur over much longer time periods. A small fraction of the air will continue to cool below the general dew point temperature and drift down slope.

Thus, having a general dew point near or above critical plant temperatures to govern air temperature drops is important for successful, economical frost protection programs. Economically and practically, most cold temperature modification systems must rely on the heat of condensation from the air. This huge latent heat reservoir in the air can provide great quantities of free heat to a vineyard. Severe plant damage often occurs when dew points are below critical plant temperatures because this large, natural heat input is much too low to do us any good and our other heating sources are unable to compensate. There is little anyone can do to raise dew points of large, local air masses.

Advective freezes: Advective freezes occur with strong, cold (below plant critical temperatures), large-scale winds persisting throughout the night. They may or may not be accompanied by clouds and dew points are frequently low. Advective conditions do not permit inversions to form although radiation losses are still present. The cold damage is caused by the rapid, cold air movement which convects or "steals" away the heat in the plant. There is very little which can be done to protect against advective-type freezes. However, it should be pointed out that winds greater than about 3 m/sec that are above freezing temperatures are beneficial on clear-sky radiative frost nights since they keep the warmer, upper air mixed into the vineyard, destroying the inversion and replacing radiative heat losses.

Critical temperatures: The critical temperature is defined as the temperature at which tissues (cells) will be killed and determines the cold hardiness levels of the plant. Other presentations at this symposium deal with critical temperatures and supercooling; however, this is a poorly understood phenomenon by many growers, and it is surrounded by a substantial body of myths.

Critical temperatures vary with the stage of development and ranges from below -20°C in midwinter to near 0°C in the spring. Shoots, buds, and leaves can be damaged in the spring and fall at ambient temperatures as high as -1°C. Damages in the winter months can occur to dormant buds, canes and trunks and will vary depending on general weather patterns for 7 to 14 days preceding the cold temperature event and physiological stages. Cold hardiness of grapes (and their ability to supercool) can be influenced by site selection, variety, cultural practices, climate, antecedent cold temperature injuries and many other factors [18,19].

Critical temperatures are most commonly reported for the 10%, 50%, and 90% mortality levels, and very often there is less than one degree difference between the values. These are not absolute values, but they give the grower confidence in implementing frost protection activities and can reduce unnecessary expenses. Knowledge of the current critical temperatures and the latest weather forecast for air and dew point temperatures are important because they tell the producer how necessary heating may be at any stage of development and how much of a temperature increase should be required to protect the crop.

It is important to note that critical temperatures determined in a laboratory are done in carefully controlled freezers with slow air movement. The air temperature in the freezer is lowered in small predetermined steps and held there for 20 to 30 minutes or more to allow the buds to come into equilibrium. This practice has given rise to the common misconception that buds have to be at a temperature for 20 to 30 minutes or so before damage will occur. The truth is that whenever ice forms in the plant tissue, there will be damage regardless of how long it took to reach that point. Plant tissues cool at a rate dependent on the temperature difference between it and its environment. Thus, if the air suddenly drops several degrees (as may be the case with "evaporative dip" when over-vine sprinklers are first turned on) the tissues can rapidly cool below critical and cold injury will occur. In addition, mechanical shock from falling water droplets or agitation of the leaves and buds by wind machines can stop supercooling and quickly initiate ice crystal formation resulting in damage even if the tissues are above the laboratory-determined critical temperature values. However, the laboratory values (if available for a site and variety) provide a good ballpark figure as to when and what frost protection measures need to be implemented.

General cold temperature protection strategies: The objective of any crop cold temperature protection program is to keep plant tissues above their critical temperatures. Programs for protection of grape vines from cold temperature injury can be characterized as combinations of many *small measures* to achieve relatively *small increases* in ambient and plant tissue temperatures.

Any crop can be protected against any cold temperature event if economically warranted. The selection of a frost protection system is primarily a question of economics. Fully covering and heating a crop as in a greenhouse are the best and also the most expensive cold protection systems, but they are usually not practical for large areas of vineyards, orchards and many other small fruit and vegetable crops, unless other benefits can also be derived from the installation.

The questions of how, where, and when to protect a crop must be addressed by each grower after considering crop value, expenses, and cultural management practices. These decisions must be based on local crop prices plus the cost of the equipment and increased labor for frost protection activities. They must be balanced against both the annual and longer term costs of lost production (including lost contracts and loss of market share) and possible long-term vine damage.

Avoidance of cold temperature injury to vines can be achieved by passive and/or active methods [29]. Passive methods include site selection, variety selection, and cultural practices. Active methods are necessary when passive measures are not adequate and include wind machines, heaters and sprinklers that may be used individually or in combination. Most successful frost protection programs include both passive and active measures.

Passive frost protection strategies: Passive or indirect frost protection measures are practices that decrease the probability or severity of frosts and freezes or cause the plant to be less susceptible to cold injury. These include site selection, variety selection and cultural practices, all of which influence the type(s) and management of an integrated passive and active frost protection program. Full consideration of several potential passive and active scenarios in the initial planning before planting will make active frost protection programs more effective and/or minimize cost of using active methods while not significantly increasing the cost of vineyard establishment.

Site selection: The best time to protect a crop from frost is before it is planted. The importance of good site selection in the long term sustainability of a vineyard operation cannot be over emphasized [33]. It will influence the overall health and productivity of the vines through: soil depth, texture, fertility and water holding capacities; percent slope, aspect (exposure), subsurface and surface water drainage patterns; microclimates; elevation and latitude; and, disease/pest pressures and sources.

In windy (advective) sites, lower lying areas are protected from the winds and are usually warmer than the hillsides. However, under radiative frost conditions, the lower areas are cooler at night due to the collection of cold air from the higher elevations. Good deep soils with high water holding capacities will minimize winter injury to roots. In short, a good site can minimize the potential extent and severity of cold temperature injury and greatly reduce frost protection expenses and the potential for long term damage to vines.

Good site selection to minimize cold temperature injuries from radiation frost events must include evaluation of the irrigation (and frost protection) water supply, cold air drainage patterns and sources, aspect (exposure), and elevation. Long-term weather records for the area will provide insight to the selection of varieties and future management requirements. Rainfall records will indicate irrigation system and management requirements. Assessment of historic heat unit accumulations and light intensities will help select varieties with appropriate winter cold hardiness characteristics that will mature a high quality crop during the typical growing season. Prevailing wind directions during different seasons will dictate siting of windbreaks, locations of wind machines, sprinkler head selection and spacings, and other cultural activities. Sometimes it is necessary to install the necessary weather stations and collect these data for several years prior to the installation of a vineyard.

Air drainage: The importance of air drainage in defining frost protection strategies is poorly understood by many vineyard planners and is often neglected. This ignorance leads to numerous potentially avoidable frost problems. Cold air movement (drift) into and out of a vineyard during radiative frost events is absolutely critical to the long term success of the operation. Obtaining a good site with good air drainage, especially in a premier grape growing area, can be very expensive, but it is an investment with a high rate of return.

Cold air movement during radiative conditions can often be visualized as similar to molasses flowing down a tilted surface: thick and slow (1 to 2 m/sec). Air can be dammed or diverted like any other fluid flow. Row orientation must be parallel to the slope to minimize any obstruction to cold air as it flows through the vineyard. A relatively steep slope will help minimize the depth of cold air movement and reduce potential cold injury with height.

The major source of cold air movement in a vineyard is usually either up slope or down slope from the site. All the sources of cold air and their flow patterns must be determined early in the planning process. As explained above, the cold air density gradients flow down slope and collect in low areas. Air temperatures in depressions can be 6°C to 8°C cooler than adjacent hill tops [3]. Consequently, a vineyard site at the bottom of a large cold air drainage system may experience severe frost problems. A study of past cropping patterns and discussions with local residents will usually provide insight for defining the coldest areas.

The potential vineyard site must also be evaluated for impediments (natural and man-made) to cold air drainage both within and down-slope of the vineyard that will cause cold air to back up and flood the vineyard. There is little than can be done for most natural impediments, however, the placement of man-made barriers may be either beneficial or extremely harmful. It is possible to minimize cold air flows through a vineyard, reduce heat losses (advective) and heating requirements with proper siting or management of man-made obstructions. Conversely, improper locations of barriers (windbreaks, buildings, roads, tall weeds or cover crops, *etc.*) within as well as below the vineyard can greatly increase frost problems.

Windbreaks are often used for aesthetic purposes, to reduce effects of prevailing winds or to divide blocks with little or no thought about their frost protection consequences. They can be advantageous in advective frost conditions, but they often create problems in radiative frosts. Windbreaks, buildings, stacks of bins, road fills, fences, tall weeds, *etc.* all serve to retard cold air drainage and can cause the cold air to pond in the uphill areas behind them. The size of the potential cold air pond will most likely be four to five times greater than the height of a solid physical obstruction, depending on the effectiveness of the "dam" or diversion. Thus, the proper use and placement of tree windbreaks and other barriers (buildings, roads, tall weeds, cover crops, *etc.*) to air flow in radiative (most common) frost protection schemes is very important.

The basal area of large tree windbreaks at the downstream end of the vineyard/orchard should be pruned (opened) to allow easy passage of the cold air. Windbreaks at the upper end should be designed and maintained, if possible, divert the cold air into other areas or fields that would not be harmed by the cold temperatures.

Aspect: Aspect or exposure is the compass direction that the slope faces. A north facing slope in the northern hemisphere is usually colder than a south facing slope in the same general area (opposite in the southern hemisphere). A northern exposure will tend to have later bloom which can be an advantage in frost protection, but conversely may have fewer heat units during the season and there may be problems maturing the crop with some varieties.

A southern exposure is usually warmer causing earlier bloom and a longer growing period. However, winter injury may be accentuated in southern exposure due to rapidly fluctuating trunk and cane temperatures throughout warm winter days followed by very cold nights. Desiccation of plants due to heat and dry winds may be problematic on south facing slopes depending on the prevailing wind direction. A southwest facing slope will have the highest summer temperatures and may be desirable for varieties that are difficult to mature in some areas.

Elevation and latitude: Air temperature is inversely related to altitude. Temperatures also decrease about 10°C for every kilometer of elevation. Higher elevations and higher latitudes both have a lower thickness of atmosphere above them and have higher nocturnal radiative cooling rates. Due to day length fluctuations throughout the year, higher latitudes will be colder. Thus, both higher elevations and high latitudes generally bloom later and have shorter growing seasons than lower altitudes and lower latitudes. The cooler environment may be offset by a warmer (southern) exposure, however, these factors will have tremendous influence on variety selection and irrigation/soil water management as well as the type and extent of frost protection strategies.

Natural heat sources: Nearby large bodies of water will tend to moderate extremes in temperature throughout the year as well as reducing the frequency and severity of frost events. The "lake effect" is evident in western Michigan which is affected by Lake Michigan as well as the Napa-Sonoma grape growing areas in California which are moderated by "coastal effect" from the cold waters of the Pacific Ocean. Large cliffs, buildings or outcroppings of south facing rock will absorb heat from direct solar radiation in the day and release it at night thereby warming nearby vegetation.

Variety selection: Fitting the best variety to the site is often more a matter of luck than science. It is known that some varieties will perform better under certain exposures, slopes and soils than others in the same area, but this information is lacking for most varieties in most areas [2,14,33]. However, selecting a variety which will consistently produce high yielding and high quality grape is every bit as important as (and dependent on) site selection. Different varieties will behave differently under the same circumstances. It is known that the sensitivity to frost for many deciduous trees is greatly influenced by root stocks, but this has not been demonstrated in the literature on grapes. Johnson and Howell [19] detected small, but consistent, differences in cold resistance from three varieties at the same stages of development.

Considerations will include evaluations of varietal differences in the tendency to break dormancy or deharden too early to avoid the probability of frost injury. The susceptibility of a variety to potential winter damage in the region must be assessed. A variety with a long growing season (high heat unit requirement) may require more frost protection activities in the autumn. Based on the literature, *V. vinifera* appears relatively insensitive to photoperiod with respect to cold hardiness, but some hybrids and other cultivars may have a large response.

Cultural practices: Proper cultural practices are extremely important in minimizing cold injury to vines [12,13,34,37]. Cultural practices generally only provide a 1°C to 1.5°C increase in air temperature. They must be carefully and thoughtfully integrated into a complete package of passive and active frost control measures, and they include: soil fertility, irrigation water management, soil and row middle management (cover crops), pruning and crop load, canopy management, spray programs, and cold temperature monitoring networks.

Fertility: High soil fertility levels by themselves have little effect on cold hardiness of vines. However, when high fertility is combined with high soil water levels late in the season *V. vinifera* vines may fail to harden-off early enough to avoid winter injury. This does not appear to be a problem in Concord and some other American cultivars or French hybrid varieties.

***Irrigation*:** Irrigation has been used for frost protection since the early part of the 20th century [20]. Selecting the proper irrigation system is crucial in frost protection strategies, disease management strategies, and long term production. In arid areas, irrigation management is the largest single controllable factor in the vineyard operation that influences *both* fruit quality and winter hardiness of vines. Additional detail on irrigation system design and management considerations for grapes is presented in Evans [10].

Irrigation management can play a major role in preparing (harden-off) *V. vinifera* vines for cold winter temperatures in some arid, high latitude regions. For example, in the inland arid areas of the PNW, the primary reason that they can successfully and consistently grow high quality *V. vinifera* grapes, as compared to other "high latitude" areas like Michigan and New York, is that they can and do control soil moisture throughout the year. Early season regulated deficit irrigation techniques as well as late season controlled deficit irrigations have both been effective in hardening-off vines in arid areas [10].

Over-vine sprinkler systems have been used for bloom delay (evaporative cooling in the spring) on deciduous fruit trees such as apples and peaches in the spring which ostensibly keeps the buds "hardy" until after the danger of frost has passed. It does delay bloom, however, it has not been successful as a frost control measure on deciduous trees because of water imbibition by the buds which causes them to lose their ability to supercool. This results in critical bud temperatures that are almost the same as those in non-delayed trees. In other words, although bloom is delayed, critical bud temperatures are not and, thus, no frost benefit. However, if the buds are allowed to dry during a cool period when the bloom delay is not needed or after a rain, they can regain some of their cold hardiness. There are no data on this practice in grapes.

After harvest irrigation: In areas with cold winters (*i.e.,* temperatures below -10°C) it is advisable to refill the soil profile to near field capacity after harvest in the fall to increase the heat capacity of the soils so that vine roots are more protected from damage from deep soil freezing and reduce the incidence of crown gall and other diseases through injury sites. This practice also helps inhibit vine desiccation from dry winter and spring winds.

Soil and row middle management (cover crops): Management of the soil cover and row middles in a vineyard can significantly affect vineyard temperatures during a frost event. Weed control can have a significant impact on vineyard temperatures [8]. Cover crops and mulches can offer advantages of lower dust levels, provide habitats for beneficial insects and reduce weed populations. However, historically, it has been recommended that cover crops not be used in frost prone vineyards. The guide was to keep soil surfaces bare, tilled and irrigated to make it darker so as to absorb more heat from the sun during the day and release it at night. Some of this heat is then released during the night into the vineyard and may provide 0.6°C to 1°C of protection only if the grower is not using sprinklers for frost protection (where bare soils may actually be a detriment). But, additional irrigations with cold water (less than the soil temperature) are unlikely to be beneficial.

Current information, however, is that soil with cover crops will still contribute about 0.6°C as long as they are kept mowed fairly short (< 5 cm). Snyder and Connell [31] found that the surface of bare soils was 1°C to 3°C warmer than soils with cover crops (higher than 5 cm) in almonds at the start of a cold period. However, after several days of low solar radiation and/or strong dry winds, the areas with cover crops were warmer. There was no difference in covered soil surface temperatures once the cover crop exceeded 5 cm in height.

Tall cover crops (and weeds) will have a soil heat insulating effect and, more importantly, may hinder cold air drainage and increase the thickness of the cold air layer resulting in more cold temperature injury to the vines. However, taller cover crops will provide a greater freezing surface under sprinkler frost protection systems and additional heat in the vineyard, but should be kept no more than 25 to 30 cm in height during the frost season.

Pruning and crop load: It is well known that pruning too early can accelerate bud break resulting in more frost damage than later pruning [32,43]. Likewise, heavy crop loads may reduce carbohydrate accumulations, weaken the vines and reduce cold hardiness.

There is usually not complete crop loss on grapes from severe frosts. Unlike tree fruit species, grape vines have secondary and tertiary buds that are fruitful and produce a partial crop [22,24,43]. Grape buds include primary buds and secondary buds as well as latent buds from previous seasons. However, secondary and tertiary buds are not as fruitful; their berries take longer to mature than primaries, and mixtures of fruit from both primaries and secondaries will be significant concerns in both harvesting and juice quality. In addition, maturation of berries from secondary and/or tertiary buds may be problematic in areas with short growing seasons. The removal of injured shoots after frost injury is not beneficial in improving yields [22].

Less severe pruning and fruit thinning to desired crop loads resulted in increased cold hardiness of Concord grapevines [32]. Because buds at the end of a cane will open first, another option that delays basal bud break by 7 to 10 days is to delay pruning (if there is time) until the basal buds are at the "fuzzy tip" stage (just starting to open). Thus, a general recommendation for grape vines in a spring frost prone area is to delay pruning as late as possible and to prune lightly. Crop load adjustments can be made later by additional pruning or thinning clusters after the danger of frost is past.

Growers in some warm areas with hot summer nights may not care about loss of primary buds to frost and some managers may actually plan to use secondary buds to delay harvests until cooler fall periods for better juice balance. In these cases, it may be advisable to delay pruning (or even knocking off primary buds) to get desired crop loads and juice character.

Canopy management: Controlling the size and density of a canopy by pruning and soil water management can have substantial benefits on the cold hardiness of the vines during the following winter. Early season regulated deficit irrigation and alternate row irrigation techniques potentially result in reduced vegetative to reproductive growth ratios and better light penetration into the canopy. In addition, canes exposed to direct solar radiation during the growing season were more cold hardy [14].

Spray programs: The use of chemical sprays (*e.g.,* zinc, copper, *etc.*) to improve frost "hardiness" of vines has been found to offer no measurable benefit in limited scientific investigations. Likewise, sprays to eliminate "ice nucleating" bacteria have not been found beneficial because of the great abundance of "natural" ice nucleators in the bark and dust which more than compensate for a lack of bacteria. There is no reported research on grapes using cryoprotectants or antitranspirants for prolonging cold hardiness or delay bud break.

There is very little information on the use of sprays to delay bloom in grapes and thus reduce the potential for frost injury. Some chemical sprays (such as spring-applied AVG, an ethylene inhibitor) have been reported to delay budbreak on some fruit crops with exact timing [6,7]. Fall-applied growth regulators (ethylene releasing compounds: ethephon or ethrel) have also been reported to delay bloom the following spring and increase flower hardiness on *Prunus* tree fruits, but there were some phytotoxic effects on the crop [25,26,28]. Gibberellic acid (GA) was less successful on deciduous fruit trees in delaying bloom [27].

One report [35] found that GA prolonged dormancy in *V. vinifera.* Applications of a growth retardant (paclobutrazol) showed promise in improving hardiness on Concord grapes with applications of 20 000 ppm applied the previous spring and summer. [1].

New research on the use of alginate gel (Colorado on peaches and grapes) and soy oil (Tennessee on peaches) coatings that are sprayed on the plants six to 10 weeks prior to budbreak shows promise in prolonging hardiness and delaying bloom by several days. It is hypothesized that the coatings retard respiration and thus inhibit bud break, providing a frost benefit. However, the coatings need to be reapplied after rain fall events and the economics is unknown.

Frost monitoring systems: Reliable electronic frost alarm systems are available that alert the grower if an unexpected cold front has moved into the area. These systems can ring telephones from remote locations, sound an alarm or even start a wind machine or pump. The sensor(s) should be placed in a regular thermometer shelter and its readings correlated with other "orchard" thermometers that have been placed around the block(s) to set the alarm levels (after considering the critical bud temperatures). It is important to have enough thermometers and/or temperature sensors to monitor what is actually happening across the entire vineyard.

Thermometers and sensors should be placed at the lowest height where protection is desired (*e.g.,* cordon height in grapes). They should be shielded from radiant heat from fossil-fuel fired heaters (a very common problem that gives misleading high readings). Thermometers and alarm systems should be checked and recalibrated each year. Thermometers should be stored upright inside a building during the non-protection seasons.

Active frost protection strategies: Active or direct frost protection systems are efforts to modify vineyard climate or inhibit the formation of ice in plant tissues. They are implemented just prior to and/or during the frost event. Their selection will depend on the dominant character of an expected frost event(s) as well as passive measures used in the vineyard establishment and operation.

Active frost protection technologies will use one or more of three processes: *(1)* addition of heat; *(2)* mixing of warmer air from the inversion (under radiative conditions); and *(3)* conservation of heat. Options for active frost protection systems include covers, fogging systems, various systems for over-crop and under-canopy sprinkling with water, wind machines, and heaters.

In selecting an active system to modify cold air temperatures that may occur across a block, a vineyard manager must consider the prevailing climatic conditions which occur during the cold protection season(s). Temperatures and expected durations, occurrence and strength of inversions, soil conditions and temperatures, wind (drift) directions and changes, cloud covers, dew point temperatures, critical bud temperatures, vine condition and age, land contours, and vineyard cultural practices must all be evaluated. The equipment must be simple, durable, reliable, inexpensive and nonpolluting.

Covering a vineyard (conservation of heat) with a woven fabric for frost protection is very expensive ($20 000 to $30 000 per hectare) and will not be discussed further. Likewise, there are also some soy oil-based, gelatin-based, and starch-based spray-on foams [4] that will not be addressed, but are being investigated as temporary thermal insulators for plants. Thus far these have had limited success in tall crops like vineyards and orchards.

The total calculated radiant heat loss expected from an unprotected vineyard is in the range of 2 to 3 million KJ/ha per hour (60-80 W/m^2). The "heating" or frost protection system must replace this heat *plus* heat lost to evaporation. It is estimated that to raise air temperature 1°C in a 2-meter high vineyard will require that about 25 W/m^2 after all losses (or at 100% efficient). Artificial (active) vineyard and orchard heating systems will supply anywhere from 1.3 to 18.2 million KJ/ha per hour (36 - 510 W/m^2) of heat although it is usually about 7.8 to 13 million KJ/ha per hour (220 to 360 W/m^2). Table 1 presents some relative heat values for oil, propane, and water. These show that a 2.0 mm/hr application of water releases a total of 190 W/m^2 (3.35 million KJ per mm of water per hectare) if it *all* freezes. However, unless this water freezes directly on the plant, very little of this heat is available for heating the air and thereby the plant. By comparison, a system of 100 return stack oil heaters per hectare supplies a total of about 315 W/m^2 (11.3 million KJ/ha/hr) which can potentially raise the temperature as much as 12°C with a strong inversion at 100% efficiency (however, conventional heaters are only 10% to 15% efficient and much of the heat is lost leaving about 30 to 50 W/m^2 which would raise the whole vineyard temperature only about 2°C).

Table 1. Approximate relative heat values of water in KiloJoules (KJ), #2 diesel heating oil and liquid propane (0.2778 KJ = 1 watt-hr; 10 000 m^2 per hectare).

Condensation (latent heat) of water at 0°C releases	2510 KJ/L
Evaporation of water at 0°C absorbs/takes	2510 KJ/L
Freezing or fusion of water (latent heat) to ice releases	335 KJ/L
10°C temperature change of water releases/take	41.4 KJ/L
Oil burning produces	9 302 kilocalories/L or 39 800 KJ/L No. 2 diesel
100 oil heaters/ha @ 2.85 l/hr/heater releases	11 343 000 KJ/hr/ha 3 151 KW/ha
Liquid Propane produces	6 081 kilocalories/L or 25 500 JJ/L LP
160 LP heaters/ha @ 2.85 l/hr/heater releases	11 343 000 KJ/hr/ha 3 151 KW/ha

Over-vine sprinkling: Over-crop or over-vine sprinkler systems (addition of heat) have been successfully used for cold temperature protection by growers since the late 1940s. Many systems were installed in the early 1960s; however, cold temperature protection by over-vine sprinkling requires large amounts of water, large pipelines, and big pumps. It is often not practical because of water availability problems and, consequently, is not as widely used as other systems. Most of these systems are used for both irrigation and cold temperature injury (frost) protection. Traditional "impact" type sprinklers as well as microsprinklers can be used as long as adequate water is uniformly applied.

Over-crop sprinkling is the field system which can provide the highest level of protection of any single available system (except field covers/green houses with heaters), and it does it at a very reasonable cost. However, there are several disadvantages and the risk of damage can be quite high if the system should fail in the middle of the night. It is the only method that does not rely on the inversion strength for the amount of its protection and may even provide some protection in advective frost conditions with proper design and adequate water supplies.

The level of protection with over-vine sprinkling is directly proportional to the amount (mass) of water applied. The general recommendation for over-vine systems in central California calls for about 7 L/sec/ha or 2.8 mm/hr which will protect to about -2.5°C [21]. In colder areas, such as the Pacific Northwest in the USA, adequate levels of protection require that 10 to 11.5 L/sec/ha (3.8 - 4.6 mm/hr) of water (on a total area basis) be available for the duration of the heating period which protects down to about -4°C to -4.4°C as long as the dew point in not less than -6°C. Water application rates should be increased by 0.5 mm/hr for every dew point degree (°C) lower than -6°C.

"Targeting" over-vine applications to only the vine canopy (*e.g.,* one microsprinkler per vine or every other vine) can reduce overall water requirements down to about 5 to 5.7 L/sec/ha in warmer areas to 7 to 8 L/sec/ ha, but the water applied on the vine must still be ≥ 2.8 mm/hr or ≥ 3.8 mm/hr, respectively [16,17]. Protection under advective conditions may require application rates greater than 2.6 L/sec/ha depending on wind speeds and air temperatures. The entire block must be sprinkled at the same time when used for cold temperature protection.

The application of water to the canopy must be much more uniform than required for irrigation so that no area receives less than the designated amount. A uniformity coefficient (UCC) of not less than 80% is usually specified. The systems for frost protection must be engineered for that purpose from the beginning. Mainlines, pumps and motors (7.5 to 12 BHP/ha) must be sized so that the entire vineyard or block can be sprinkled at one time. A smaller pump is often installed for irrigation purposes and the block watered in smaller sets.

Impact sprinkler heads should rotate at least once a minute and should not permit ice to build up on the actuator spring and stop the rotation. Pressures are typically 370 to 400 kPa and should be fairly uniform across the block (*e.g.,* less than 10% variation). Many sprinkler heads will fail to operate correctly at temperatures below -7°C.

Large amounts of water are required for over-vine (and under-vine) sprinkling, so that many vineyard managers in frost prone areas are drilling wells and/or building large holding ponds for supplemental water. There are extra benefits to these practices in that the well water can be warmer than surface waters plus the ponds tend to act as solar collectors and further warm the water. If economically possible, growers should try to size the ponds to protect for as much as 10 hours per night for three or four nights in a row.

When applied water freezes, it releases heat (heat of fusion) keeping the temperature of an ice and water "mixture" at about -0.6°C. If that mixture is not maintained, the temperature of the ice-covered plant tissues may fall to the wet bulb temperature, which could result in severe damage to the vine and buds. The applied water must supply enough heat by freezing to compensate for all the losses due to radiation, convection, and evaporation. Water should slowly but continuously drip from the ice on the vine when the system is working correctly. The ice should not have a milky color, but should be relatively clear.

There may be an "evaporative dip," a 15- to 30-minute drop in the ambient air temperature, due to evaporative cooling of the sprinkler droplets when the sprinkler system is first turned on. This dip can push temperatures below critical temperatures and cause serious cold injury. The use of warm water, if available, can minimize the temperature dip by supplying most of the heat for evaporation. The recovery time and the extent of this dip are dependent on the wet bulb temperature. A low wet bulb temperature (low dew point temperature) requires that the over-crop sprinklers be turned on at higher ambient temperatures. Table 2 presents suggested system turn-on temperatures based on wet bulb temperatures.

Table 2. Suggested starting temperatures for over-vine sprinkling for frost protection based on wet bulb temperatures to reduce the potential for low temperature bud damage from "evaporative dip."

Wet bulb temperature		Starting temperature	
°F	°C	°F	°C
≥ 26	≥ -3.3	34	1.1
24 to 25	-4.4 to -3.9	35	1.6
22 to 23	-5.6 to -5.0	36	2.2
20 to 21	-6.7 to -6.1	37	2.8
17 to 19	-8.3 to -7.2	38	3.3
15 to 16	-9.4 to -8.9	39	3.9

Since the heat taken up by evaporation at 0°C is about 7.5 times as much as the heat released by freezing, at least 7.5 times as much water must freeze as is evaporated. And, even more water must freeze to supply heat to warm the vineyard and to satisfy heat losses to the soil and other plants. Evaporation is happening all the time from the liquid and frozen water. If the sprinkling system should fail for any reason during the night, it goes immediately from a heating system to a very good refrigeration system and the damage can be much, much worse than if no protection had been used at all. Therefore, when turning off the systems, the safest option on sunny, clear mornings is to wait (after sunrise) until the melting water is running freely between the ice and the branches or if ice falls easily when the branches are shaken. If the morning is cloudy or windy, it may be necessary to keep the system on well into the day.

Because of insufficient water quantities, some vineyard managers and orchardists have installed over-crop microsprayer "misting" systems (not to be confused with very high pressure (≥ 1500 kPa) systems that produce thick blankets of very small suspended water droplets that fill a vineyard with "fogs" several feet thick that have other problems) for frost protection. These are not recommended because of the very low application rates (*e.g.,* ≥ 0.8 mm/hr or 2.25 L/sec/ ha). There is absolutely no scientific evidence that these misting systems trap heat, reflect heat or "dam" cold air away from a block. They do not apply adequate water amounts to provide sufficient latent heat for bud/ flower protection that is necessary for over-vine sprinkling conditions and some local irrigation dealers are facing significant legal problems as a result.

Under-vine sprinkling: Below-canopy (under-vine) sprinkling is usually not an option with grapes crops, depending on the trellising system, because of the density of interference from trunks and trellis posts. However, one method that may have some promise is the use of heated water [11,23] applied under the vine canopy (never over-vine) at application rates greater than 1 mm/hr (3 L/sec/ha) at temperatures around 40°C to 45°C.

Fogs: Special "fogging" systems which produce a 6- to 10-meter-thick fog layer that acts as a barrier to radiative losses at night have been developed. However, they have been marginally effective because of the difficulty in attaining adequate fog thickness, containing and/or controlling the drift of the fogs and potential safety/liability problems if the fogs crossed a road.

Fogs or mists which are sometimes observed with both under-crop and over-crop sprinkler systems are a result of water that has evaporated (taking heat) and condenses (releasing heat: no "new" heat is produced) as it rises into cooler, saturated air. As the "fog" rises, into ever colder and unsaturated air, it evaporates again and disappears. The duration of fogs or mists will increase as the ambient temperature approaches the dew point temperature. Thus, the "temporary" fogging is a visual indicator of heat loss that occurs under high dew point conditions and does not represent any heating benefit. It has been shown that the droplet size has to be in the range of a 100-nanometer diameter to be able to affect radiation losses, and the smallest microsprinkler droplets are at least 100 times larger [5].

Heaters: Heating for frost protection (addition of heat) in vineyards has been practiced for centuries with growers using whatever fuels were available. This is still true today in many areas of the world (*i.e.,* Argentina) where oil prices are prohibitive. There are numerous reports of growers using wood, fence rails, rubbish, straw, saw dust, peat, paraffin wax, coal briquets, rubber tires, tar, and naphthalene since the late 1800s. However, these open-fire methods are extremely inefficient because heating the air by convection due to the rising hot exhaust gases is very inefficient with most of the heat rising straight up with little mixing with cooler air in the vineyard. Therefore, current fossil-fueled heater technology which was developed in the early 1900s through the 1920s, was designed to maximize radiant heating by greatly increasing the radiating surface area. Since that time there have been relatively minor refinements and improvements to the return stack, cone and other similar designs. New technologies such as electric radiant heaters have not proved economical.

Heaters were once the mainstay of cold temperature protection activities but fell into disfavor when the price of oil became prohibitive, and other alternatives were adopted. They have made a minor comeback in recent years, particularly in soft fruits and vineyards where winter cold protection may be required, but are plagued by very low heating efficiencies, high labor requirements, and rising fuel costs. In addition, air pollution by smoke is a significant problem and the use of oil-fired heaters have been banned in many areas.

Table 3. Estimated initial costs of installed frost protection systems common to Washington vineyards and orchards.

Method	Estimated cost/hectare
Wind Machine (4-4.5 ha)	$ 3700 - $ 4500
Overvine Sprinkler	$ 2200 - $ 3000
Undervine Sprinkler	$ 2200 - $ 3000
Overvine Covers	$ 20000 - $ 37000
Undervine Microsprinklers	$ 2500 - $ 3700
Return Stack Oil Heat (100/ha)-used	$ 1000 - $ 1100
Return Stack Oil Heat (100/ha)-new	$ 2500 - $ 3000
Pressurized Propane Heaters (160/ha)-new	$ 6200 - $ 10000

Radiant heating is proportional to the inverse square of the distance. For example, the amount of heat 3 meters from a heater is only one-ninth the heat at 1 meter. Consequently, conventional return stack and other common oil and propane heaters have a maximum theoretical efficiency of about 25% (calculated as the sum of the convective and radiative heat reaching a nearby plant). However, field measurements reported in the literature (*e.g.,* Wilson and Jones [36]) indicate actual efficiencies in the range of 10% to 15%. In other words, 85% to 90% of the heat from both conventional oil and propane heaters is lost, primarily due to buoyant lifting and convective forces taking the heat above the plants ("stack effect"). Typically there are about 100 return stack oil heaters (without wind machines) or 160 propane heaters per hectare which produce about 11.3 million KJ of heat. If heaters were actually as much as 25% efficient, then only about 5.7 million KJ of heat would be required, a 50% savings in fuel.

Heaters are "point" applications of heat that are severely affected by even gentle winds. If all the heat released by combustion could be kept in the vineyard, then heating for cold protection would be very effective and economical. Unfortunately, however, 75% to 85% of the heat may be lost due to radiation to the sky, by convection above the plants ("stack effect") and the wind drift moving the warmed air out of the vineyard. Combustion gases may be 600°C to over 1000°C and buoyant forces cause most of the heat to rapidly rise

Table 4. Estimated approximate annual per hectare/hour operating costs (including amortization of investment, but with 0% interest and before taxes) for selected cold temperature (frost) protection systems used 120 hours per year.

Method	Estimated costs/ha/hr
Return Stack Oil Heaters (100/ha)*	$ 93.08
Standard Propane Heaters (154/ha)*	103.98
Wind Machine (130 BHP propane)	33.36
Overcrop Sprinkling	4.10
Under Canopy Sprinkling	4.25
Frost-free site	0.00

* equal total heat output

above the canopy to heights where it cannot be recaptured. There is some radiant heating, but its benefit is generally limited to adjacent plants and only about 10% of the radiant energy is captured. New heater designs are aimed at reducing the temperature of the combustion products when they are released into the orchard or vineyard in order to reduce buoyancy losses.

Many types of heaters are being used, the most common probably being the cone and return stack oil burning varieties. Systems have also been designed which supply oil or propane through pressurized PVC pipelines, either as a part of or separate from the irrigation systems. Currently, the most common usage of heaters in the Pacific Northwest appears to be in conjunction with other methods such as wind machines or as border heat (two to three rows on the upwind side) with under-vine sprinkler systems.

The use of heaters requires a substantial investment in money and labor. Additional equipment is needed to move the heaters in and out of the vineyards as well as refill the oil "pots." A fairly large labor force is needed to properly light and regulate the heaters in a timely manner. There are usually 80 to 100 heaters per hectare, although propane systems may sometimes have as many as 170. A typical, well-adjusted stand-alone heating system will produce about 11.3 million KJ/ha per hour.

Based on the fact that "many small fires are more effective than a few big fires" and because propane heaters can usually be regulated much easier than oil heaters, propane systems often have more heaters per acre but operate at lower burning rates (and temperatures) than oil systems. It is sometimes necessary to place extra heaters under the propane gas supply tank to prevent it from "freezing up."

Smoke has never been shown to offer any frost protection advantages, and it is environmentally unacceptable. The most efficient heating conditions occur with heaters that produce few flames above the stack and almost no smoke. A too-high burning rate wastes heat and causes the heaters to age prematurely. The general rule-of-thumb for lighting heaters is to light every other one (or every third one) in every other row and then go back and light the others to avoid puncturing the inversion layer and letting even more heat escape. Individual oil heaters generally burn two to four liters of oil per hour.

Propane systems generally require little cleaning; however, the individual oil heaters should be cleaned after every 20 to 30 hours of operation (certainly at the start of each season). Each heater should be securely closed to exclude rain water, and the oil should be removed at the end of the cold season. Oil floats on water and burning fuel can cause the water to boil and cause safety problems. Escaping steam can extinguish the heater, reduce the burning rate, and occasionally cause the stack to be blown off.

The combination of heaters with wind machines not only produces sizeable savings in heater fuel use (up to 90%), but increases the overall efficiency of both components. The number of heaters is reduced by at least 50% by dispersing them into the peripheral areas of the wind machine's protection area. Heaters should not be doubled up (except on borders) with wind machines and are not usually necessary within a 45- to 60-meter radius from the base of the full-sized machine. Heat which is normally lost by rising above the vine canopy may be mixed back into the vineyard by the wind machines. At the same time heat is also added from the inversion. The wind machines are turned on first and the heaters are used only if the temperature continues to drop.

Wind machines: The first use of wind machines (mixing heat from the inversion) was reported in the 1920s in California; however, they were not generally accepted until the 1940s and 1950s. They have gone through a long evolutionary process with wide ranges in configurations and styles.

Wind machines, or "fans" as they are often called, are used in many orchard and vineyard applications. Some are moved from orchards after the spring frosts to vineyards to protect the grapes against late spring, fall and winter cold temperature events.

Wind machines, large propellers on towers which pull vast amounts of warmer air from the thermal inversion above a vineyard, have greatly increased in popularity because of energy savings compared to some other methods, and they can be used in all seasons. Wind machines provide protection by mixing the air in the lowest parts of the atmosphere to take advantage of the large amount of heat stored in the air. The fans or propellers minimize cold air stratification in the vineyard and bring in warmer air from the thermal inversion. The amount of protection or temperature increases in the vineyard depends on several factors. However, as general rule, the maximum that the air temperature can be increased is about 50% of the temperature difference (thermal inversion strength) between the 2- and 20-meter levels. These machines are not very effective if the inversion strength is small (*e.g.*, 1.3°C).

Wind machines that rotate horizontally (like a helicopter) and pull the air down vertically from the inversion rely on "ground effects" (term commonly used with helicopters, *etc*.) to spread and mix the warmer air in the vineyard. In general, these designs have worked poorly because the mechanical turbulence induced by the trees greatly reduces their effective area. In addition, the high air speeds produced by these systems at the base of the towers are often horticulturally undesirable.

A general rule is that about 12-15 BHP is required for each acre protected. A single, large machine (125-160 BHP) can protect 4 to 4.5 ha or a radial distance of about 120 m under calm conditions. The height of the head is commonly 10 to 11 m in height in orchards and vineyards. Lower blade hub height for shorter crops is generally *not* advantageous since warmer air in the inversion still needs to be mixed with the cold surface air. Propeller diameters range from 3.6 to 5.8 m, depending on machine age and engine power ratings. The propeller assembly also rotates 360° about its vertical axis every four to five minutes parallel to the ground. The blade assembly is oriented with approximately a 6° downward angle for maximum effectiveness over an area.

The current "standard" is a stationary vertical fan that is usually powered by gasoline or liquid propane engines that produce about 130 to 160 HP. Two 5.8-m blades rotate at about 590 rpm producing 400 to 475 m^3/sec mass air flows. Improved blade design and the use of space age materials in their construction have resulted in major performance improvements in recent years.

Modern machines rely on the principle that a large, slow-moving cone of air to produce the greatest temperature modification is the most effective (propeller speed of about 590 - 600 rpm). A wind machine that does not rotate about its axis has an effective distance of about 180 m under calm conditions. The amount of air temperature increase decreases rapidly (as the inverse of the square of the radius) as the distance from the fan increases. In actuality, the protected area is usually an oval, rather than a circle, due to distortion by wind drift with the upwind protected distance about 90 to 100 m and the downwind distance about 130 to 140 m. Several wind machines are often placed in large orchard or vineyard blocks with synergistic benefits by carefully matching the head assembly rotation direction with spacing.

Many growers turn on wind machines at about 0°C which is appropriate for many radiative frost situations. However, if the forecast is for temperatures to drop well below critical temperatures and/or accompanied by low dew points (*e.g.,* < -7°C), it is advisable to turn on the wind machines at +2°C to +3°C to start moving the warmer air through the vineyard even with weak inversions. This will serve to at least partially replace radiative losses and strip cold air layers away from the buds. Buds and other sensitive tissues will be kept relatively warmer for a longer period of time since they have more heat to dissipate. Hopefully, the cooling process can be delayed under these conditions long enough for the sun to come up and avoid reaching critical temperatures.

In response to the chronic need to increase cold temperature protection capability, several attempts have been made over the past 40 years to design or adapt wind machines so that the wind plume would distribute large quantities of supplemental heat throughout a vineyard. These efforts have been uniformly unsuccessful. The high temperatures (*e.g.,* 750°C) of the added heat caused the buoyant air plume to quickly rise above the tops of the vines and mixing with the colder vineyard air was minimal. These designs have ranged from "ram jets" on the propeller tips to the use of large propane space heaters at the base of the wind machine. The added heat actually causes the jet to quickly rise above the tops of the trees and substantially decreases the radius of the protected area due to the increased buoyancy of the wind plume. These problems could be circumvented if large amounts of heat could be introduced/mixed at low temperatures (*e.g.,* 3°C above ambient temperature) within 30 m of the wind machine.

Wind machines apparently work well when used in conjunction with other methods such as heaters and under-vine sprinkling. They should *never* be used with over-vine sprinkling for frost protection. If they are used by themselves, bare soil may be somewhat beneficial by providing about 0.6°C additional temperature rise.

A grower planning on installing a wind machine will need detailed information on inversions in their locale. They may want to put up a "frost pole" or tower to measure the temperatures with height in the vineyard during springtime inversions. The wind machine should be located only after carefully considering the prevailing drift patterns and topographic surveys. Wind machines may also be located so as to "push" cold air out of particularly cold problem areas.

Helicopters: Helicopters are an expensive (and sometimes dangerous) variation of a wind machine which can also be used under radiation frost conditions. They can be very effective, since they can adjust to the height of an inversion and move to "cold spots" in the vineyard. The amount of area protected depends on the thrust (down draft) generated by the helicopter. Generally, the heavier (and more expensive) the helicopter, the better their protection capability. A single large machine can protect areas greater than 20 hectares in size under the right conditions. However, due to the large standby and operational costs, the use of helicopters for frost protection is limited to special cases or emergencies.

Helicopters should work from the upwind side of the vineyard making slow passes (2 - 5 m/sec). One technique used with helicopters is to have thermostatically controlled lights in problem areas which turn on at a preset cold temperature. The helicopter then flies around the block "putting out the lights." There should also be two-way radio communications between the plane and the ground. A rapid response thermometer in the helicopter helps the pilot adjust the flying height for best heating effect.

Costs of frost protection systems: It is quite difficult to present representative cost figures for frost protection systems since the installations are site-specific. Table 3 presents some "ball park" cost estimates for complete installed systems not including land value. The addition of wells and/or ponds is not included since these costs are extremely variable. The costs are additive if two or more systems are used. Economic comparison of estimated annual operating costs of the various frost protection systems are presented in Table 4 on a cost/hectare/hour basis.

Conclusions

The objective of any crop cold temperature protection program is to keep plant tissues above their critical temperatures. Programs for protection of grape vines from cold temperature injury consist of many *small measures* to achieve relatively *small increases* in ambient and plant tissue temperatures. These will be a mixture of passive and active measures that will cumulatively provide adequate protection levels, however, our ability to economically and practically protect crops during cold temperature events is more an art than a science.

Worldwide, vineyards are often severely affected frost damage to the canes, trunks, buds, shoots, flowers, and leaves. In addition to lost production for that year, cold temperature injuries can also shorten vineyard life through increased incidence of crown gall and other diseases at injury sites on the plant. Frost protection systems are expensive due to purchases of supplemental equipment, labor and operation. Prevention of cold temperature injury is a significant part of annual vineyard production costs in many areas around the world.

There is no perfect method for field protection of crops against cold temperature injury. However, a blend of preplanned passive and active frost protection measures will be the most successful. The most important passive measure is good site selection, but it must be complemented by proper variety selections and cultural practices. Quite often combinations of active methods such as heaters and wind machines are advantageous. However, the capacity of any system or combination of systems will always be exceeded at some point. In addition, a well-maintained and calibrated frost monitoring (thermometers and alarms) network will always be required.

Protection against advective (windy) freezes is much more difficult to achieve than protection against radiative freezes. Consequently, most of the methods/systems are practical and effective only under radiation situations. The formation of inversion layers is a benefit and many methods take advantage of an inversion to furnish, trap and/or recirculate heat.

A high dew point is probably the most powerful and effective mechanism available for reducing freeze damage to plants. This is due to the “heat pump” effect which replaces radiation losses with the latent heat of condensation. Any frost protection method which increases the water vapor content of the air is generally beneficial (but this is very difficult to accomplish!). Heat from water is more efficient than some other sources because it is released at low temperatures, is less buoyant (no “stack” effect), and may selectively warm the coldest plant parts.

In selecting a vineyard heating system to protect vines against cold injury, the manager/owner must consider the prevailing climatic conditions which occur during the cold protection season. Temperatures and expected durations, occurrence and strength of inversions, soil conditions and temperatures, wind (drift) directions and changes, cloud covers, dew point temperatures, critical bud temperatures, vine condition and age, grape variety, land contours, and vineyard cultural practices must all be evaluated. Both passive and active methods to protect against cold injury may be required. The equipment for active measures must be simple, durable, reliable, inexpensive and essentially non polluting. Timing is critical.

There is a general need in agriculture, as in all natural resource industries, to conserve energy and other resources, and frost protection activities must also move in that direction. Current technology for active frost protection is wasteful and inefficient in energy (*i.e.,* heaters) and other resources. Development of new heater technologies (presently underway) that are at least 60% efficient (compared to 15% maximum now) would provide the same amount of heat in the vineyard as current heaters (i.e., return stacks) with one-fourth as much fuel—a substantial savings in energy and expenses. Another example is that sprinkler systems used for frost protection require large amounts of water at times when plant needs are very low causing water logged soils and leaching nutrients and other chemicals out of the root zone.

Conservation efforts will have to be aided by the improved ability to predict the severity and timing of frost events. Automated weather stations and a detailed knowledge of critical temperatures for different varieties in different areas throughout the year will be necessary. Mathematical models that combine accurate prediction of climatic conditions, plant physiology, and resulting critical temperatures at any stage of growth will have to be developed and used to give growers more confidence in developing frost protection strategies and reducing expenses.

Literature Cited

1. Ahmedulla, M., A. Kawakami, *et al.* Effect of paclobutrazol on the vegetative growth, yield, quality, and winter hardiness of buds of *Concord* grape. HortScience 21:273-274 (1986).

2. Anderson, J. A., G. S. Howell, and J. A. Wolpert. Phenological development of different *Vitis* cultivars. Fruit Var. J. 34:5-7 (1980).

3. Blanc, M. L., H. Geslin, *et al.* Protection against frost damage. World Meteorological Org. Technical Note 51 (1963).

4. Choi, C. Y., W. Zimmit, and G. Giacomelli. Freeze and frost protection with aqueous foam development. HortTechnology 9(4):654-661 (1999).

5. de Boer, H. J. Comparison of water vapour, water and water drops of various sizes, as a means of preventing night frost. Agricultural Meteorology. Elsevier 2:247-258 (1964).

6. Dekazos, E. E. Effects of aminoethoxyvinylglycine (AVG) on bloom delay, fruit maturity and quality of ‘Tifblue’ and ‘Woodard’ rabbiteye blueberries. Proc. Fla. State Hortic. Soc. 92:248-252 (1979).

7. Dennis, F. G., C. E. Crews, and D. W. Buchanan. Bloom delay in stone fruits and apple with rhizobitoxine analogue. HortScience 12:386 (abstr.) (1977).

8. Donaldson, D. R., R. L. Snyder, *et al.* Weed control influences vineyard minimum temperatures. Am. J. Enol. Vitic. 44:431-434 (1993).

9. Evans, R. G. Frost protection techniques for trees in the Northwest. Proc. Frost Protection Strategies for Trees and Grapevines. Fresno, CA. Calif. Agr. Technol. Inst. Publ. 91 11104:85-103 (1991).

10. Evans, R. G. Irrigation choices for growing *V. vinifera* grapes in central Washington. pp. 57-74. *In:* Proceedings of Growing Grapes in Eastern Washington. J. Watson (Ed.). 5 March 1998, Richland, WA. The Good Fruit Grower, Yakima, WA (1999).

11. Evans, R. G., M. O. Mahan, and M. W. Kroeger. Utilization of Heated Water for Orchard Frost Protection. ASAE Tech. Paper 96-2041, Presented at Annual Meeting of ASAE. Phoenix, AZ. July 14-18. 15 pp. (1996).

12. Howell, G. S. Cultural manipulation of vine cold hardiness. *In:* Proc. 2nd Intl. Cool Climate Vitic. and Enol. Symp. pp 98-102 (1988).

13. Howell, G. S. Approaches to solving the problem of low temperature damage to grapevines. Proc. Frost Protection Strategies for Trees and Grapevines. Califl Agr. Technol. Ins. Publ. 91 11104:115-127 (1991).

14. Howell, G. S., and N. Shaulis. Factors influencing within-vine variation in the cold resistance of cane and primary bud tissues. Am. J. Enol. Vitic. 31(2):158-161 (1980).

15. Howell, G .S., and J. A. Wolpert. Nodes per cane, primary bud phenology, and spring freeze damage to *Concord* grapevines. Am. J. Enol. Vitic. 29:229-232 (1978).

16. John, P. H. Overhead Targeted Frost Protection. New Zealand Agricultural Engineering Institute, Lincoln College, Canterbury, New Zealand, Project Report Number 33 (1985).

17. John, P. H., P. Carran, and I. Woodhead. Targeted Frost Protection-Orchard Trails. New Zealand Agricultural Engineering Institute, Lincoln College, Canterbury, New Zealand, Project Report Number 39 (1986).

18. Johnson, D. E., and G. S. Howell. Factors influencing critical temperatures for spring freeze damage to developing primary shoots on *Concord* grapevines. Am. J. Enol. Vitic. 32:144-149 (1981).

19. Johnson, D. E., and G. S. Howell. The effect of cane morphology and cultivar on the phenological development and critical temperatures of primary buds on grape canes. J. Am. Soc. Hortic. Sci. 106(5):545-549 (1981).

20. Jones, E. H. Irrigation as frost protection in a citrus grove. Calif. Citrogr. 9(7):260 (1924).

21. Jorgensen, G., B. M. Escalera, *et al*. Microsprayer Frost Protection in Vineyards. Ca Agr. Technol. Inst. Publ. No. 960803. 12 pp. Fresno, CA (1996).

22. Kasimatis, A. N., and J. J. Kissler. Responses of grapevines to shoot break-out following injury by spring frost. Amer. J. Enol. Vitic. 25:17-20 (1974).

23. Martsolf, J. D. Heated Irrigation Cold Protection. Proc. Fla. State Hortic. Soc. 102:64-69 (1989).

24. Proebsting, E. L., Jr., and V. P. Brummund. 1978. Yield and maturity of *Concord* grapes following spring frost. HortScience. 13(5):541-543 (1978).

25. Proebsting, E. L., and H. H. Mills. Effect of growth regulators on fruit bud hardiness in *Prunus*. HortScience 4:254-255 (1969).

26. Proebsting, E. L., and H. H. Mills. Bloom delay and frost survival in ethephon-treated sweet cherry. HortScience 8:46-47 (1973).

27. Proebsting, E. L., and H. H. Mills. Time of giberellin applications determines hardiness of response of 'Bing' cherry buds and wood. J. Am. Soc. Hortic. Sci. 99:464-466 (1974).

28. Proebsting, E. L., and H. H. Mills. Ethephon increases cold hardiness in sweet cherry. J Am. Soc. Hortic. Sci. 101:31-33 (1976).

29. Rieger, M. Freeze protection for horticultural crops. Hort. Rev. 11:45-109 (1989).

30. Schultz, H. B., and R. J. Weaver. Preventing frost damage in vineyards. Ca. Agr. Expt. Sta. Ext. Serv. Leaflet 2139 (1977).

31. Snyder, R. L., and J. H. Connell. Ground cover height affects predawn orchard floor temperatures. California Agriculture 47(1):9-12 (Jan-Feb 1993).

32. Stergios, B. G., and G. S. Howell. Effects of defoliation, trellis height, and cropping stress on cold hardiness of *Concord* grapevines. Am. J. Enol. Vitic. 28:34-42 (1977).

33. Stergios, B. G., and G. S. Howell. Effect of site on cold acclimation and deacclimation of *Concord* grapevines. Am. J. Enol. Vitic. 28:43-48 (1977).

34. Swanson, F., P. Christensen, P., and F. Jensen. Preventing vineyard frost damage. Coop. Ext. Univ. California (1973).

35. Weaver, R. J. Prolonging dormancy in *Vitus vinifera* with gibberellin. Nature. 183:1198-1199 (1959).

36. Wilson, E. B., and A. L. Jones. Orchard Heater Measurements. Circular 511. Washington State University, Washington Agricultural Experiment Station. 18 pp. (1969).

37. Winkler, A. J., J. A. Cook, *et al*. General Viticulture (2nd ed.). University of California Press, Berkeley, CA (1975).