THE ABCS OF FROST MANAGEMENT[1]

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INTRODUCTION

Methods and protection programs to minimize cold temperature injury to crops must be thought of as combinations of many small measures that incrementally achieve relatively small increases in ambient and plant tissue temperatures to minimize the risk of cold temperature injury. Orchardists should be thinking of these systematic efforts in terms of risk management strategies to minimize cold temperature damage to crops rather than a single practice. These frost management programs can and often will affect a grower's entire operation. The following discussion will generally refer to frost risk avoidance and frost management systems with regard to the wide variety of countermeasures growers may use to minimize cold temperature injury to plant tissues.

The following discussion will briefly cover the physiological and physical basics of risk management for cold temperature damage. It will also present the concepts of: passive strategies for frost risk avoidance and active strategies for frost management including supplemental heating (e.g., water and heaters), heating by mixing (e.g., wind machines and fountains) and heating by conservation (e.g., covers and fogs). However, before we discuss the means of frost management, there are three important concepts that must be understood before designing integrated systems for successful frost management, which are: 1) critical temperatures, 2) dew point temperatures, and 3) the two types of frost or freeze conditions.

Critical Temperatures

Critical temperature is defined as the temperature at which tissues (cells) will be physiologically killed and determines what is often referred to as the cold hardiness level of the plant. Different tissues will have different critical temperatures. Thus, the objective of any crop frost management system is to keep all plant tissues above their critical temperatures.

Plant tissues cool at a rate that depends on the temperature difference between the plant and its surroundings. Damage occurs whenever ice forms in the plant tissue, regardless of how long it took to reach that point. If the air temperature suddenly drops several degrees, even for a short period, the tissues can rapidly cool below critical temperature and cold injury can result.

Critical temperatures must be known throughout the year for good frost (risk) management. However, critical temperatures vary with the stage of development and, for many tree and vine crops grown in temperate climates, can range from well below -20°F in midwinter to near +32°F in the spring. Damage in the winter months can occur to dormant buds, branches (or canes) and trunks, and can vary depending on general weather patterns for 7-14 days preceding the cold temperature event and physiological adaptations. Rapid decreases in temperature over a few hours can also affect the plant's ability to protect itself. Critical temperatures of crops (and their

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ability to supercool) can be influenced by site selection, variety, cultural practices, aspect, climate, age, root stock, previous cold temperature injuries and many other factors. Critical temperatures can also vary across a single block due to microclimate and factors including disease and drought stresses. Plants at higher elevations with good cold air drainage may have higher critical temperatures than plants in lower areas of the same block.

Critical temperatures are most commonly reported for the 10%, 50% and 90% mortality levels, and very often there is less than 1ºF difference between the three values. Generally, these should be considered as ball park values, but they can give a 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 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 usually lowered in small predetermined steps and held there for 20 to 30 minutes or more to allow the buds to come into equilibrium. However, general knowledge of this scientific procedure may have 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 (its critical temperature) there will be damage regardless of how long it took to reach that point.

Dew Point Temperatures

Dew point temperature is defined as the temperature at which condensation of the water vapor in the air first condenses from a gas to a liquid. This is a general property of the air mass in the region. Dew point temperatures do not only occur near 32ºF, but can range from above 80ºF to less than -20ºF.

The importance of dew point temperatures in frost protection strategies is often misunderstood, but it is the one of most significant factors in cold temperature injury management over which a grower has no control. This huge latent heat reservoir in the air can potentially provide great quantities of free heat to any frost protection program.

This large potential impact is due to the fact that the general rate of temperature decrease due to nighttime radiation loss of heat (discussed below) can be fairly rapid until the air approaches the dew point temperature. When this water condenses from the atmosphere, the latent heat of condensation (9000 BTU/US gallon at 32ºF) is directly released to the object or air. It is usually more than sufficient to replace radiation heat losses and averting further temperature decreases (at least temporarily). In addition, because the exposed plant parts are usually 1º to 3ºF colder than air temperature on a clear night, they will reach dew point temperature before the air. Air temperature will reach dew point temperatures shortly after the exposed tissues, and the condensation (i.e., dew) will also provide heat to the air. Therefore, further ambient air temperature decreases will be quite small and occur over much longer time periods as more and more water condenses out of the air mass. In short, the dew point temperature is approximately the minimum air temperature for the night (may not always get there), unless a whole new air mass with a different dew point moves into the area. There is little anyone can do to raise dew point temperatures in a block.

Thus, having a dew point temperature below the plant's critical temperature is extremely beneficial because the heat of condensation tends to keep the plant from reaching damaging cold temperatures. Whereas dew point temperatures that are above critical temperatures do not provide this heat when its needed to keep the plant tissues above critical temperatures; and supplemental heating and frost protection methods that a grower might use are often unable to compensate for this missing heat contribution, resulting in considerable crop damage. Therefore, economically and practically, most cold temperature modification systems rely on the heat of condensation from the air as a major component of their success or failure.

It should be mentioned that the wet bulb temperature, which is the minimum temperature obtained by a moist, evaporating body, is only slightly higher than the dew point temperature. Wet bulb temperatures are much easier to measure, are inexpensive, and can serve as a good approximation of the actual dew point temperature in a field.

Types of Frosts

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 (< 32°F). However, there are basically two dominant types of frost situations which will be encountered, and each will affect frost management strategies differently. The two types are advection freezes and radiation frosts. Both types will usually be present in all frost events, but the general type of frost is classified by its dominant characteristics.

Advection Freezes. Destructive cold temperature events under advective (windy) conditions are often called freezes rather than frosts. These advection freezes occur with strong cold (below plant critical temperatures) winds of at least 5 mph or more that are part of large, regional cold air masses (e.g., 500 to 5000 ft thick). These large-scale winds tend to persist throughout the night and sometimes during the day. They may or may not be accompanied by clouds. Advective conditions do not permit thermal inversions to form although radiation losses are still present. The cold damage is caused by the rapid, cold air movement which advects or steals away the heat in the plant. There is very little which can be done to protect against advective-type freezes (i.e., overtree sprinking). However, it should be pointed out that winds greater than about 5 mph where the ambient air temperatures are above critical plant temperatures are beneficial on clear-sky radiation frost nights because they keep the warmer, upper air mixed into the orchard, destroying the inversion and replacing radiation heat losses.

Radiation Frosts. Most cold temperature damage to crops occurs when large amounts of cold, dry air moves into an area and there is almost no cloud cover at night. These types of frost events are called radiation frosts. The plants, soil and other objects are much warmer than the clear night sky which has an apparent temperature around -20°F. During these times, solid objects will radiate their own heat back into space and become progressively colder. In fact, the plants cool themselves by radiating their own heat to the point that they are damaged. The plant tissues which are directly exposed to the sky become the coldest. The net amount of heat lost by nocturnal radiation of heat can be 20 BTU/hr/ac to 35 BTU/hr/ac depending on plant, environmental and soil conditions. Objects will not lose heat as rapidly to clouds which are relatively much warmer than a clear sky, depending on cloud type and height. Almost all frost protection systems/methods available today (except for overcrop sprinkling, which also protect under advective conditions) are designed to protect against radiant-type frost/freezes.

Thermal Inversions. Radiation heat loss can cause the buds, blossoms, twigs, leaves, etc., to become 1º to 3°F colder than the surrounding air which radiates very little of its heat. The warmer air in direct contact with the plant and the soil then tries to warm the colder plant parts, and the air near the plant (and soil) also becomes colder. When regional wind speeds are low (1-2 mph), the cooled air, which is now denser than ambient air, settles toward the ground and begins slowly flowing (drifting) toward lower elevations. As this cold air flows downhill it continues to lose heat to the ground and to the atmosphere and can become several degrees colder than the general air mass above it. This process also pushes the warmer air upward and leads to the development of a thermal inversion condition where the air temperature a few tens of feet above the ground may be as much as a 5º to 15°F warmer than the air near the ground in the orchard or vineyard. Springtime temperature inversions will often have a 2°to 6°F temperature difference (moderate inversion strength) as measured between 6 and 60 feet above the surface. Mid-winter inversions may be much stronger. The use of heaters, wind machines and undertree sprinkling all rely on the strength of the thermal inversion to either help hold supplemental heat within the orchard canopy or to provide the heat (e.g., wind machines)

Cold Air Drift. The heavier, colder, shallow layer of air moves slowly down the slope under the influence of gravity and collects in low areas or cold pockets, which is one of the main reasons that site selection is so important in cold temperature management. These cold air flows are commonly referred to as drift.

Cold air movement during radiative conditions can often be visualized as similar to molasses flowing slowly down a tilted surface at about 1 to 3 mph. The cold air movement starts in shallow layers only a few inches deep and accumulates to depths of 10 to 20 feet as other cold air flows contribute over distance and time. However, it has little effect on the temperature of air directly above it. A relatively steep slope will help minimize the depth of cold air movement and reduce potential cold injury with height.

These cold air flows get progressively colder as the night progresses and tend to accumulate into pools when the slope flattens or obstacles prevent or reduce further movement. These pools of cold air may be fed from several directions and may become tens of feet thick, which may be sufficient to render wind machines ineffective in valleys and low lying areas.

Cold air drift can be dammed or diverted like any other fluid flow, which is why row orientation should be parallel to the slope to minimize any obstruction to cold air as it flows through the orchard or vineyard. Windbreaks are often used for aesthetic purposes, to reduce effects of prevailing winds or to divide blocks, but there is often no thought about their frost protection consequences. They can be advantageous in advective frost conditions, but they often create problems in radiation frosts. Windbreaks, buildings, stacks of bins, cold air diversion curtains, road fills, fences, tall weeds, etc., can all serve to retard cold air drainage and can cause the cold air to pond in the uphill areas behind them if not sited and maintained properly. The size of the potential cold air pond will most likely be 4 to 5 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 windbreaks and other barriers to control or manage air flow in radiation frost protection situations is very important. Remember that wind management and frost management are not always compatible.

Another undesirable effect of drift is that it carries heat out of the block. This is sometimes referred to as the good neighbor effect, which gives your pre-warmed air to the neighbors downgrade from you. However, this lost heat must be replaced at least at the same rate or greater just to keep the orchard at the same air temperature. For example, if the drift is moving at 2 mph , it will move 660 ft in less than 4 minutes, which totally changes the air in a quarter-mile block eight times every hour with colder air. This is one reason that extra heaters are often placed on the upwind side where the drift first enters a block.

GENERAL COLD TEMPERATURE MANAGEMENT STRATEGIES

Because of the extreme complexity of the interactions between the varying 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. There is no perfect frost management system for field protection of crops against cold temperature injury, and the capacity of any system or combined systems is likely to be exceeded at some point in time.

Any crop can be protected against any cold temperature event if economically warranted. The selection of a frost management system is primarily a question of economics. The questions of how, where, and when to protect a crop must be addressed by each grower after considering crop value, expenses, cultural management practices and historic frequency and intensity of cold temperature events. These decisions must be based on local crop prices plus the cost of the equipment and increased labor for frost protection activities. Thus, the implementation of frost protection strategies must be balanced against risk assessments of both the probabilities of annual and longer term costs of lost production (including lost contracts and loss of market share) and possible long-term tree or vine damage (sustainability).

Frost protection or risk management strategies are commonly divided into passive and active categories. Passive methods include site selection, variety selection and various cultural practices that can greatly reduce potential cold temperature damages. Active methods are necessary when passive measures are not adequate and can include wind machines, fossil fuel heaters and sprinklers that may be used individually or in combination. Active or direct frost protection systems are efforts to modify field microclimates in order to inhibit the formation of ice in plant tissues. They are implemented just prior to and/or during the frost event.

Successful frost protection programs are always a mix of passive and active measures. Careful consideration of various combinations of several potential passive and active scenarios in the initial planning before planting will make active frost protection programs more effective and minimize costs of using active methods without significantly increasing the cost of orchard establishment.

Often, the air temperature only needs to be raised a couple of degrees to avoid substantial cold temperature crop injuries. Producers will commonly use two or more cold temperature modification techniques (e.g., wind machines and undertree sprinklers) simultaneously in the same field depending on the severity of the event.

Passive Frost Avoidance Strategies

Passive or indirect frost protection measures are risk minimization 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 strategies of an integrated passive and active frost protection program.

Site Selection. The best time to protect a crop from frost is before it is planted, and good site selection is the most effective passive risk avoidance strategy. The importance of good site selection in the long term sustainability of a commercial fruit operation cannot be over emphasized. It will influence the overall health and productivity of the plants through: soil depth, texture, fertility, water holding capacities, slope, elevation, latitude, aspect (exposure), subsurface and surface water drainage patterns, microclimates, disease and pest pressures and cold air sources. 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 trees and vines. The availability of natural heat sources such as large water bodies and rivers can also have a large effect on warming cold air masses, and can be an important factor in site selection.

Carefully defining sources of cold air drainage into and out of a block is probably the most overlooked aspect of site selection, but it is one of the most important factors. Ignoring cold air drainage patterns leads to many potentially avoidable frost problems. Obtaining a good site with good air drainage, especially in a premier growing area, can be very expensive, but it is often an investment with a very high rate of return.

Cultural Practices. Proper cultural practices are extremely important in minimizing cold injury to crops. It is obvious that healthy trees and vines will be more resistant to cold temperature injury. Selecting the proper cultural practices for each location and each variety will encourage good plant health. Poor irrigation practices (over- or under-irrigation), improper timing of irrigations and over-fertilization can decrease hardiness and lower carbohydrate reserves leading to excessive cold temperature injury. Avoidance of mechanical injuries to trunks, roots and branches in addition to soil and row middle management (e.g., grass cover crops) including mowing and weed control, pruning and crop load management, spray programs are essential to long term, sustainable production.

Other Techniques. The use of chemical sprays (e.g., zinc, copper, crop oils, alginates, etc.) to improve frost hardiness of deciduous trees in the Northwest has been found to offer no measurable benefit in limited scientific investigations. Likewise, sprays to eliminate ice nucleating bacteria (e.g., *Pseudomonas syringea, Erwinia herbicola)* have not been found beneficial because of the great abundance of natural ice nucleators in the bark, stems, dust, etc., which more than compensate for any lack of bacteria.

Frost Monitoring Systems. Distributed temperature monitoring stations across an orchard or vineyard are an essential part of frost risk management by providing warnings and data for tracking long term trends. 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 to protect it from radiation heat loss that could provide false readings. All the readings should be correlated with all other orchard thermometers that have been placed around the block(s) to set the alarm levels (after considering the probable range in critical bud temperatures). It is important to have enough thermometers and/or temperature sensors to monitor what is actually happening across the entire orchard.

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 mistake that gives misleading high readings). Thermometers and alarm systems should be checked and re-calibrated each year. Thermometers should be stored upright inside a building during the non-protection seasons.

Active Frost Management Strategies

Active or direct frost management systems are efforts to modify orchard or vineyard microclimate or inhibit the formation of ice in plant tissues. These frost avoidance practices 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 management technologies will use one or more of three processes: 1) addition of heat, 2) mixing of warmer air from the inversion (under radiation conditions) and 3) conservation of heat. Options for active frost protection systems include covers, fogging systems, various systems for overcrop 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 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, tree condition and age, land contours, and orchard cultural practices must all be evaluated. Active frost management systems should be simple, durable and non-polluting, and they must always work when needed. However, these systems can be expensive because of purchases of supplemental equipment, labor, fuel and operation.

Addition of Heat

The addition of heat for frost management is basically limited to the application of water by the use of various overtree or undertree sprinklers and to the use of fossil fueled heaters. Water-based methods are generally the most economical, which is the main reason for their popularity. However, water-based frost systems can create problems with disease, saturated soils, runoff and leaching of nutrients and other agrochemicals.

Sprinkling for Frost Management. Large amounts of water are required for overtree and undertree sprinkling for frost management. Therefore, many orchard managers in frost prone areas drill wells and build large holding ponds to hold supplemental 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. The use of water for frost protection in *V. vinifera* blocks in the Columbia River drainage is not recommended because of the need to carefully manage soil water levels to control winter hardiness levels, especially in the fall.

Overtree Sprinkling. Overtree sprinkler irrigation systems (addition of heat) have been used for frost protection since the early part of the 20th century. However, they were not generally used for cold temperature protection by growers until the late 1940's. There was wide spread expansion of their use beginning in the early 1960's. Nevertheless, cold temperature protection by overtree sprinkling requires great amounts of water, large pipelines and big pumps. Thus, it is often not practical because of water availability problems and consequently is not as widely used as other frost protection systems. Most of these overtree sprinkler systems are also used for irrigation, but with smaller sets or zones.

Overcrop 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. 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 applied water must supply enough heat by freezing to compensate for all the losses due to radiation, convection, and evaporation. However, overtree systems should also never be used in conjunction with wind machines for frost protection because of the high potential for evaporative cooling of the ice-water mixture.

The principle of overtree sprinkling for frost protection is based on the release of the latent heat of fusion (1200 BTU/US gallon). During operation, water should slowly but continuously drip from the ice when the system is working correctly. Steady deposition of new ice on the plant from the continuously applied water keeps the temperature of an ice-water mixture at about 31°F throughout the frost event. If the temperature of this ice-water mixture is not constantly maintained, the temperature of the ice-covered plant tissues may quickly fall to the wet bulb temperature (approximately the dew point temperature) due to evaporative cooling. This could result in severe damage to the plant and buds, if the wet bulb temperature is below the critical temperature. The ice should appear relatively clear. Milky-colored or opaque ice contains air bubbles from the evaporation process that indicate inadequate application rates.

The level of protection with overtree sprinkling is directly proportional to the amount (mass) of water applied. Applications ranging from 0.15 to 0.18 in/hr (70-80 US gpm/ac) averaged over the total area will typically protect crops down to air temperatures in the range of 24ºF to 26ºF as long as the dew point temperature is not less than about 22°F. A general rule-of-thumb is that water application rates should be increased by about 0.02 in/hr for every dew point degree (°F) lower than 22°F for most situations. Lower water application rates will provide correspondingly less protection capacity. The entire block should be sprinkled at the same time.

Sprinklers are usually turned on around 34°F, or at higher air temperatures (i.e., earlier in the day) if dew point temperatures are below 22ºF, in order to reduce the chance of injury from the short term temperature dip caused by the droplet cooling to wet bulb temperature by evaporation as they move through the air. The overtree systems also need to be turned on early to prevent freezing of the risers and heads. Overtree protection under advective conditions may require application rates greater than 80 US gpm/ac depending on wind speed and dew point temperature. Tables providing guidance on overtree turn on temperatures based on wet bulb temperatures and wind speeds can be found in various extension bulletins and web sites.

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 (3 to 5 BHP/ac) must be sized so that the entire orchard or vineyard block can be sprinkled at one time. A smaller pump is often installed for irrigation purposes and the block watered in smaller sets.

Traditional impact type sprinklers as well as microsprinklers can be used as long as adequate amounts of water are uniformly applied. Impact and other rotating sprinkler heads should rotate at least once a minute and should not permit ice to build up on the actuator spring or other parts of the sprinklers and stop the rotation. Pressures range from 25 to 55 psi and should be fairly uniform across the block (e.g., less than 10% variation). Many impact and rotator sprinkler heads will fail to operate correctly at temperatures below 20°F.

Because the heat taken up by evaporation at 32°F is about 7.5 times as much as the heat released by freezing (9000 BTU/US gal vs. 1200 BTU/US gal), 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 orchard 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 clear mornings is to wait until after sunrise when the melting water is running freely between the ice and the branches and the ice falls off easily when the branches are gently shaken. If the morning is cloudy or windy, it may be necessary to keep the system on well into the day to avoid cold temperature damage to the plant due to evaporative cooling of the ice-water mixture.

Spreading Overtree Water Applications**.** Because of the large amounts of water required for overtree sprinkling for frost protection, some growers have attempted to spread overhead water applications by wide spacing of sprinkler heads or by cycling of water applications on and off to reduce the total water supply needs across a block. However, these techniques do not apply adequate water directly to the plant canopy to account for evaporation, and these systems are not recommended because of the high level of risk.

Some orchardists have also installed overtree microsprayer misting systems for frost protection as a way to reduce water requirements. These should not to be confused with very high pressure (≥ 200 psi) systems that produce thick blankets of very small suspended water droplets that fill an orchard with dense fogs 20 to 40 feet thick. Overtree microsprayer misting systems are not recommended for frost protection because of the very low average application rates, which makes them extremely risky. 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 overtree sprinkling conditions and should be avoided.

<u>Targeting Overtree Water Applications</u>**.** One method of overtree sprinkling that reduces total water supply requirements on widely spaced crops and still provides some level of protection is called targeting. This technique targets the overcrop water applications to apply water only to the plant's canopy (e.g., one microsprinkler per tree or every other tree) and can reduce overall water requirements by 50% or more. However, the water actually applied on the plant must still be in the range of 0.15 to 0.18 in/hr depending on the amount of protection needed. The total area which receives water is reduced which reduces the total water needed. However, the same rules apply and the entire block must still be sprinkled at the same time when targeted applications are used for cold temperature protection. A risk associated with targeted applications under low dew point temperature conditions is that significant damage may result due to higher evaporation losses (cooling), especially when less than 50% of the total area is wetted.

Undertree Sprinkling. Another commonly used frost protection method in Pacific Northwest orchards is the application of water through undertree sprinklers. Research and experience has shown that the success of undertree sprinkler systems (used both with and without wind machines) is influenced by the following factors (in approximate order of importance): 1) the height and strength of the temperature inversion, 2) the amount (mass) of water applied and the temperature of the applied water, 3) the volume of air flow moving into the orchard (drift) which can remove much of the added heat, 4) the release of latent heat from the freezing of the applied water (a small contribution), and 5) the intercepted radiation heat fluxes from the soil. Other important, but less significant, parameters are the height and type of a cover crop and water droplet sizes. The relative contribution of any one factor will vary with site and existing climatic conditions at the time. However, the expected maximum amount of temperature increase is about 3°to 4°F using cold canal water (e.g., 36º to 42ºF) in the spring, depending on inversion strengths.

Undertree systems are very compatible with wind machines and the respective individual heat contributions are additive up to a point limited by the resistance to heat transfer of the air and the strength of the inversion. Many of the systems are being used in conjunction with wind machines and with heaters. There are fewer risks, less disease problems and lower water requirements than with overtree systems because the water does not come in direct contact with the buds.

Most undertree systems use small, low-trajectory (e.g., ≤ 7°), impact sprinklers and microsprinklers. Because the level of protection is directly proportional to the amount of water applied, applications range from 0.08 to 0.12 in/hr (36 to 55 US gpm/ac) or about half of overtree sprinkling requirements for frost protection. Undertree sprinklers are usually turned on around 32°to 34ºF, or at higher ambient temperatures if dew point temperatures are low, in order to maintain higher air temperatures as long as possible and prevent freezing of the risers and heads. The system can usually be turned off in the morning when air temperatures at 4 to 6 ft above the ground are above 34°F.

It has been experimentally determined that almost all the heat measured in an undertree-sprinkled orchard under freeze conditions can be attributed to just the sensible heat released by the water (8.3 BTU per US gallon per ºF) as it cools to wet bulb temperature as the droplets fly through the air. Unfortunately, the contribution of the latent heat of fusion from the freezing water (1200 BTU per US gallon) in heating the air in undertree orchard frost protection is minimal because much of the heat from the freezing of water is picked-up by water that is subsequently applied and infiltrates into the soil. In other words, the freezing of water is ineffective in heating the air, and most of the air heating is supplied by the cooling of water droplets. Thus, the most logical improvement in the technology is to pre heat the applied water (e.g., diesel-fueled flow through heaters, using warm groundwater or by solar heating of supply ponds) before distribution to the field, especially when water supplies are limited.

The sequencing or cycling of blocks or sprinkler laterals and other means of stretching water to cover more area with less water with undertree sprinklers is generally not recommended. As pointed out above, the level of protection is directly proportional to the mass of water applied, and stretching effectively decreases the average depth applied for lower protection levels. The whole undertree block should be irrigated continuously, and main lines, pumps and pump motors must be sized accordingly. Trees should be trained and pruned so that the water does not reach any buds and flowers on the lower branches because of the low application rates. Sprinkler risers should be maintained in a vertical position at all times.

<u>Use of Warm Water Undertree.</u> The warmer the water, the lower the average application rate required to achieve the same protection levels for a given inversion strength. In addition, many orchardists do not have the availability of the relatively large amounts of water required for adequate frost protection with undertree sprinklers. However, it is possible to preheat the water for application through lower volume undertree sprinkler or microsprinkler systems and have similar effectiveness with equivalent amounts of sensible heat released into the orchard as standard high volume undertree systems. Research has shown that, depending on water temperatures and flow rates, applications of pre-heated water can be an economical, alternative heating system with about the same effectiveness as oil-fueled heaters but using about 20% of the fuel. Applications of preheated water on short risers (e.g., 12 to 18 inches) can also be very effective as border heat.

One technique is to use large stationary, flow through oil or propane fueled heat exchangers (boilers) at the side of the field that preheats water to temperatures less than 120º F for application through the existing undertree irrigation system. The applied heat is thereby more uniformly spread over the orchard floor than with heaters, and because the heat is supplied at a much lower temperature than with oil or gas heaters, much more of the applied heat stays within the orchard boundaries. Low application rates also reduce water logging of orchard soils and reduce leaching of nutrients and other chemicals towards the groundwater. Heat input can be quickly adjusted to match environmental conditions at a single point in the field. Compared to oil-fueled heaters (e.g., return stacks), air pollution is also substantially reduced with a heat exchanger based frost protection system. Research has shown that sprinkler systems applying pre-warmed water also work well in combination with wind machines.

Analyses of Pacific Northwest spring frost conditions indicate that the boiler/heat exchanger should be sized to produce about 750,000 to 1,000,000 BTU's per acre per hour (about 35-40 boiler horse power per acre). Generally, individual boilers with heat exchangers should probably be less than 800 HP because of size and cost considerations (each boiler covering 20-30 acres), which also serves to reduce conveyance heat losses. The cost of a new boiler/heat exchanger can range from $2,500 to $3,500 per acre. These systems (e.g., 800 BHP) can also be seasonally rented (perhaps in combination with a mint still operation) for about $8,000-10,000 per season (plus fuel).

Heaters for Frost Management. Heating for frost protection (addition of heat) in orchards and vineyards has been practiced for centuries with growers using whatever fuels were available. Heaters were once the mainstay of cold temperature protection activities but fell into disfavor when the price of fossil fuels became prohibitive and other alternatives were adopted. Smoke (particulates) is also a major air quality concern for oil-fired heaters, and the use of oil fueled heaters has been banned in many areas. In addition, dense clouds of smoke do not serve as barriers to radiation losses and provides no frost management benefit.

Current fossil-fueled heater technology which was developed in the early 1900's through the 1920's was designed to maximize radiant heating by greatly increasing the radiating surface area. Arguably, the last major advancement of commercially available fossil fuel heating technology was the oil-fired return stack heater developed by the University of California at Davis in the 1930s. Since that time there have been relatively few minor refinements and improvements to the return stack, cone and other similar designs. Propane-fired heaters made their appearance in the 1950s but suffer from many of the same problem, including poor efficiencies. Newer technologies such as electric radiant heaters suspended on trellises have not proved economical.

Based on empirical and theoretical evidence, conventional field heating devices operate most effectively under low wind conditions with stable thermal inversions. Typically there are about 40 return stack oil heaters (without wind machines) or about 60 propane heaters per acre. 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 side where the drift enters the block) with undertree sprinkler systems. Fewer total heaters may be required when used in combination other techniques.

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 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 (e.g., stack effect) where it is no longer able to be recaptured and reused.

Heaters are the applications of large amounts of heat in a very small area. Their heat distribution is also severely affected by even gentle winds. Much of the effectiveness of heaters in protecting a crop is by their radiant heating. However, the effectiveness of radiant heat is proportional to the inverse square of the distance, and only nearby objects benefit. For example, the amount of radiant heat intercepted 10 feet from a heater is only one one-hundredth of the radiant heat at 1 foot from the heater.

The primary recommendation on the use of heaters in vineyards and orchards has been to use many small heaters to raise temperatures to the desired level with minimum heat loss due to excessive buoyancy of the heated air columns above the heaters. Due to lower heat contents, liquid propane and natural gas fired heaters produce less heat per unit volume of fuel than diesel oil and therefore require more heaters per unit area for the same total heat output.

Many types of oil fueled heaters are being used. The most common types are probably the cone and return stack oil burning varieties. A wide range of propane burning heaters are also commonly used. Systems have also been designed which supply oil or propane through pressurized pipelines, either as a part of or separate from the irrigation systems.

As with undertree sprinkling, the combination of heaters with wind machines not only produces sizeable savings in heater fuel use (up to 90%), but increases the overall effectiveness of both components. The total 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. Some of the heat which is normally lost by rising above the tree canopy may be mixed back into the orchard by the wind machines. At the same time heat is also added from the inversion. The wind machines are usually turned on first and the heaters are used only if the temperature continues to drop.

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 and heaters so the moving air plume would distribute large quantities of supplemental heat throughout a block. These efforts have been uniformly unsuccessful. The high temperatures (e.g., 1300°F) of the added heat at the base of the wind machine caused the air plume to also become buoyant and quickly rise above the tops of the trees so that mixing with the colder orchard air was minimal. These designs have ranged from small ram jet engines on the propeller tips to the use of large propane space heaters at the base of the wind machine. When used in combination with wind machines, current commercially available heaters are placed at least 130 to 150 ft from the base of a full-sized wind machine (e.g., 10 ac) because, if the heaters are placed closer, the high temperature of the introduced heat into the wind machine’s jet of air also becomes highly buoyant and the machine becomes much less effective. Placing heaters at a recommended distance from the wind machine reduces the number of heaters by about half, but due to inherent inefficiencies of current designs, thermal effectiveness is still quite low.

Pulse Jet Heaters. The only heating devices that can be placed near (within 50 ft) of a wind machine are the new generation pulse jet heaters, which are essentially small jet engines with no moving parts. These advanced heaters introduce heat into the orchard by means of relatively high temperature, high velocity exhaust streams and ejectors that provide effective mechanical mixing of the heat into the cold ambient air over a relatively large area. This results in low net effective temperatures (e.g., 3º to 8 °F above ambient temperatures) compared to 1000º to 1500°F from a conventional oil fueled return stack heater, so that hot air buoyancy is minimized, mixing of heat into the cold orchard air is maximized and much of the supplemental heat stays within the crop canopy. These modern heating systems can be used with or without wind machines. These machines can be made in several sizes to fit individual needs. When used without wind machines, its estimated that one modern pulse jet heater, producing approximately the same total heat output as one return stack heater, can cover about 4 times the area with proper placement.

When used with wind machines, the individual pulse jet heaters can be made much larger, the number of heaters per acre can be reduced (e.g., 1 or 2 per acre) and overall per acre fuel consumption can be greatly reduced compared to conventional supplemental heaters. Fewer, high heat output pulse jet heaters that effectively result in low apparent ambient temperature increases (low buoyancy) could be placed near the wind machines (e.g., 50 ft) letting the wind machine distribute the heat throughout the orchard or vineyard. Smaller pulse jet heaters could also be concurrently used as border heat. At the present time a couple of sizes of diesel fueled pulse jet heaters are being manufactured in New Zealand.

Mobile Heaters. There are numerous variations of relatively large propane fueled heaters with fans that are pulled around the block by small tractors. Their intent is to provide heat to protect the crop as the machine is driven back and forth through the block. These are generally limited to small blocks as the heater should return to each spot every 4 to 6 minutes to be most effective. The use of these devices can be compared to trying to heat a room with a candle.

Heating by Mixing

Heating by mixing provides no new heat into the system. These technologies totally rely on mixing the warmer air from the thermal inversion into the colder air near the ground to raise air and plant temperatures and mixing it with the cold air below to minimize cold air stratification in the block. There are basically three technologies that use heating by mixing, which are discussed below.

Wind Machines. Wind machines, or fans as they are often called, are used in many orchard and vineyard applications. These devices consist of large propellers on stationary towers which pull vast amounts of warmer air from the thermal inversion above an orchard. They have greatly increased in popularity because of energy savings compared to some other methods, and they can be used in all seasons. The first use of wind machines was reported in the 1920's in California. However, they were not generally accepted until the 1940's and '50's. They have gone through a long trial-and-error evolutionary process with wide ranges in configurations and styles over many years.

Wind machines work by pulling warm air from the thermal inversion up to about twice the height of the fan hub. Consequently, the higher the fan's hub, the more heat that is available (up to a point); however, the hub height should be at least 2X the height of the crop.

A single, large machine can protect 10 to 12 acres under calm conditions. The actual amount of protection or temperature increases in the orchard or vineyard from wind machines depends on several factors. As a general rule, the maximum that the air temperature can be increased within the orchard canopy is about 50% of the temperature difference (thermal inversion strength) between the 6 and 60 ft levels with standard machines. However, the air temperature increase in the orchard is usually less than 4° F depending on the strength of the thermal inversion. Furthermore, wind machines are also expensive (~\$2500 ac^{-1}) making combined cold temperature protection systems quite costly. These machines are not very effective if the inversion strength is small (e.g., < 2°F).

These machines rely on the simple principle that a large, slow-moving cone of warm air will produce the greatest temperature modification. Currently, the most common wind machine is a stationary, two-bladed vertical fan that is usually powered by large gasoline or liquid propane engines that produce about 125 to 160 HP at the blade hub for the larger machines. Smaller, lowered powered machines can be purchased for smaller areas. Two blades (e.g., 18 -19.5 feet in length tip-to-tip) rotate at about 600 rpm producing 800,000 to 1,200,000 cubic feet per minute mass air flows. The height of the head (hub) is commonly 36 to 39 ft in height in orchards and vineyards. The propeller assembly also rotates 360° about its vertical axis every 4-5 minutes parallel to the ground. The rotation direction can either be clockwise (looking down from above the wind machine) or counterclockwise depending on how it is ordered. Different field situations dictate different rotational needs. The blade assembly is oriented with approximately a 5º to 6º downward angle so air is directed a long distance downward and outward. Improved blade design and the use of space age materials in their construction have resulted in major performance improvements in recent years. A general rule is that about 12-15 blade horse power is required for each acre protected.

A wind machine should be located only after carefully considering the prevailing drift patterns and topographic surveys. In reality, the protected area is usually an ellipse rather than a circle due to distortion by wind drift with the upwind protected distance about 250 to 350 ft and the downwind distance about 400 to 460 ft. Thus, these devices are often placed in the upper third of a block. Several wind machines are often placed in large orchard or vineyard blocks with synergistic benefits from carefully matching the head assembly rotation direction with spacing. Wind machines may also be located so as to push cold air down hill out of particularly cold problem areas. In addition, some full sizes as well as smaller portable wind machines are sometimes moved from orchards after the spring frosts to vineyards to protect the grapes against late spring, fall and winter cold temperature events.

Many growers turn on wind machines at about 32º to 34°F, which is appropriate for many radiation frost situations. However, if the forecast is for temperatures to drop well below critical temperatures and/or accompanied by low dew point temperatures (e.g., < 20°F), it may be advisable to turn on the wind machines at 36º to 39°F to start moving the warmer air through the block even with weak inversions. This will help to reduce the rate of radiation heat losses and strip cold air layers away from the buds while replacing some of the lost heat. Thus, buds and other sensitive tissues will be kept relatively warmer for a longer period of time because of the slower net rate of heat loss. Hopefully, the cooling process can be delayed under these conditions long enough for the sun to come up and avoid reaching critical temperatures.

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 because they can adjust to the height of an inversion and move to cold spots in the orchard. 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 capability to raise orchard air temperatures during radiation frost events and to protect larger areas. A single large machine can protect areas of about 40 acres under the right conditions, but they are generally limited to just one farm. However, due to the large standby and operational costs as well as safety considerations associated with night time flying, the use of helicopters for frost protection is limited to special cases or emergencies.

Helicopters should work from the side where the drift enters the orchard or vineyard making slow passes (1-3 mph) back-and-forth below this border. 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.

Fountains. “Fountains” are a relatively new device that has come into use within the past 10 years which uses the principle of heating by mixing. These large, stationary machines come in electric and tractor powered versions (3 to 75 HP) with fans (e.g., 9 to 19 ft in diameter with their axis parallel to the ground) inside a 4.5 to 6 feet high sheet metal shroud. The fan is located 3 to 5 feet above the ground and rotates in the approximate range of 280 to 400 rpm. These machines are generally located near the lowest elevations in an orchard or where cold air pools. Their purpose is to prevent the shallow layers of cold air from the drift from accumulating to depths where they can cause damage to buds. The device only pumps cold air and no new heat is introduced from the inversion.

The fan pulls in cold air that has accumulated in its vicinity from the drift process and forces the air directly upward at high velocities into the inversion layer. This cold air does not disappear and it is not carried away from the orchard because there is little to no wind in the inversion layer. Rather, the cold air from the orchard floor is mixed with the warmer air in the inversion as it is lifted adiabatically. However, it is still colder and heavier than air in the inversion layer and it begins to settle back to the ground. This circulation pattern creates an effect very similar to a water fountain spraying vertically upward into the air.

Meanwhile, cold air continues to accumulate in the vicinity and the large horizontal fan continues to push the cold air up into the inversion. This process also re-circulates the cold air that was pushed up earlier and has resettled back to the ground. Thus, over time the cold air pool will deepen to pre-fountain levels, perhaps to the point where cold injury occurs. Hopefully, this time is delayed until after sunrise and the potential for crop damage is averted.

Conservation of Heat

Covers. Fully covering a crop with greenhouses or tunnels should be considered as among the best cold temperature management practices, but it is also probably the most expensive. Electric or propane heaters are often placed inside to provide supplemental heat. However, greenhouses and related structures are usually not practical for large areas of vineyards, orchards and many other small fruit and vegetable crops, unless other benefits could also be derived from the installation.

Overhead fabric covers for hail or sunburn protection of an orchard or vineyard (conservation of heat) may also provide frost benefits, but these are very expensive (e.g., $10,000 to $20,000 per acre). Undertree sprinkling, heaters and even flood irrigation may also be used under the covers, which greatly increase the effectiveness of all methods by reducing radiation losses and trapping some of the supplemental heat.

Fogs. Special fogging systems which produce a 20 to 40 feet thick fog layer that acts as a barrier to radiation losses at night have been developed. They operate at very high pressures with small nozzles suspended about 30 ft above the ground. 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 cross a road. It has been shown that the droplet size has to be in the range of a 10 microns in diameter to be able to affect radiation losses, whereas the smallest microsprinkler droplets are at least 100 times larger and have no heat trapping effect.

Foams. There are also experimental soy oil-based, gelatin-based or starch-based spray-on foams that are applied 2 to 4 inches thick just prior to a frost event. These are being investigated in several locations as temporary thermal insulators for low growing high-value fruit, vegetable and nursery crops. However, to date, these foams have had limited success, are quite expensive and are not yet practical for tree and vine crops.

CONCLUSIONS

Successful programs for protection of crops from cold temperature injury will consist of many small measures to incrementally achieve relatively small increases in ambient and plant tissue temperatures. There is no perfect, and the capacity of any system or combined systems will likely be exceeded at some point in time.

In selecting an orchard or vineyard heating system to protect plants against cold injury, the manager/owner must consider the prevailing climatic conditions which occur during the cold protection season. Thus, a blend of preplanned passive and active frost management measures designed to keep plant tissues above their critical temperatures will be the most successful. A well-maintained and calibrated frost monitoring network will always be required to support a mix of frost risk management strategies.

Protection against advective (windy) freezes is much more difficult to achieve than protection against radiation 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 re-circulate heat. In addition, a high dew point temperature is probably the most powerful and effective mechanism available for reducing cold temperature damage to plants.

Quite often combinations of active methods such as undertree sprinklers and wind machines are advantageous. Heat from water is more efficient than some other sources because it is released at low temperatures into the environment, is less buoyant (no "stack" effect), and may selectively warm the coldest plant parts.

There is a general need in agriculture, as in all natural resource industries, to conserve energy and other resources as well as to minimize negative environmental impacts. Frost protection activities must also move in that direction. Current technology for active frost protection is wasteful and inefficient in energy (e.g., heaters) and other resources. For example, development of new heater technologies could provide the same amount of heat in the orchard or vineyard as current heaters (e.g., return stacks) with 20% as much fuel resulting in substantial savings in energy and expenses. Wind machine technologies could also become more efficient and quieter. Further resource conservation efforts will have to be aided by the improved ability to predict the severity and timing of frost events.

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