Basics of Frost and Freeze Protection for Horticultural Crops

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Summary. Basic meteorology as it applies to frost–freeze events and a discussion of the methods of frost protection are included in this article. The presentation of basic meteorology includes descriptions of heat transfer, energy exchange, inversion, frost, freeze, microclimate, air versus crop temperature, and forecasts and warnings in the context of how each of these is involved in frost–freeze events. The second part of the paper describes the major methods of frost protection for commercial crops. The methods included are site selection, irrigation (overhead, undercanopy, man-made fog, flooding), wind machines, heaters, covers, and sprayable materials.

If frost–freeze protection is to be practiced successfully, it must be handled with the same care and attention as spraying, fertilizing, pruning, and other cultural practices. Success depends on proper equipment, sound judgment, attention to detail, and commitment.

One key to protecting a crop successfully from frost–freeze damage is a good understanding of the meteorology that creates these events. This knowledge can enhance the practitioner's ability to make the proper decisions in planning to actually provide protection. Some meteorology basics that apply to frost–freeze situations are presented here.

Heat transfer. Heat may be transferred from one material to another or from one place to another in four ways: conduction, convection, radiation, and latent heat transfer. When one end of a metal rod is warmed, heat is transferred by conduction to the other end. The molecules at the warm end of the rod are moving with high energy and colliding with nearby cooler molecules, giving them more energy. These, in turn, hit even slower molecules causing them to move faster and passing on energy. Heat is thus transferred down the rod. Convection is the transfer of heat by the movement of masses of heated liquid or gas. In the atmosphere, the lower air is warmed by heat transfer from the soil surface. This air becomes less dense, rises, and is replaced by cooler air from above. The convective mixing of these currents of warmer and cooler air is the method by which thousands of feet of the lower atmosphere are warmed. Radiation is movement of heat energy from one object to another without the need for a connecting medium. This is how we receive the sun's energy, and it is by radiant heat transfer that crops lose heat at night. When a water molecule gains enough heat to cause a phase change, e.g., liquid changes to gas or vapor by evaporation, it may move to another place. At the new location it may recondense, which releases heat energy.

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Thus, the latent heat that was added in the change from liquid to vapor is transferred to the location of the condensation. This example uses two of six phase changes possible for water. The other four are solid to liquid, liquid to solid, solid to gas, and gas to solid.

ENERGY EXCHANGE. During the day, the sun's radiant energy warms the soil and other solid objects, e.g., crops. When these objects become warmer than the air, they pass heat to the air by conduction and set up convective currents, which warm the lower atmosphere. The soil and crops may also radiate heat energy into space. Clouds, water vapor, or CO_2 may absorb or reflect some of this energy, trapping it as heat near Earth's surface. This phenomenon is known as the greenhouse effect.

At night the situation reverses. There is no incoming heat to warm the soil and crops. They continue to lose heat through radiation until they are cooler than the surrounding air. The air then begins to pass heat to the soil and crop and the lower atmosphere cools. If no cloud cover is present to block the outgoing radiation, the soil, crop, and air temperatures continue to cool significantly. Cloud cover or fog can limit this temperature decrease at night.

INVERSION. On a clear night, heat continues to radiate out into space. Temperature drops significantly and cool air collects at the surface. The temperature profile in the lower tens to hundreds of feet of atmosphere inverts, i.e., the temperature increases with altitude. The term inversion comes from atmospheric conditions' being inverse to the normal daytime condition where air temperature decreases with height. The warm air in an inversion becomes critical as some frost protection methods depend on this source of heat.

FROST VERSUS FREEZE. Although the terms frost and freeze are often interchanged, they describe two distinct phenomena (Table 1). An **advective**, or **windborne freeze**, occurs when a cold air mass moves into an area bringing freezing temperatures. Wind speeds are usually >5 mph (2.2 $m \cdot s^{-1}$) and clouds may be present. The thickness of the cold air layer ranges from 500 to 5000 ft (153.5 to 1535 m) or more. Attempts to protect crops by modifying the environment are very limited under these conditions.

A **radiation frost** occurs when a clear sky and calm winds [<5 mph (2.2 $m \cdot s^{-1}$)] allow an inversion to develop and temperatures near the surface drop below freezing. The thickness of the inversion layer varies from 30 to 200 ft. There are two types of frost. Hoar frost results when atmospheric water vapor freezes in small crystals on solid surfaces. During a black frost, few or no ice crystals form because the air in the lower atmosphere is too dry. The formation of ice crystals depends on the dewpoint, or frostpoint, which is the temperature to which air must be cooled to cause the atmospheric moisture to change from gas to solid, i.e., to sublime. The drier the air, the lower the dew or frostpoint.

MICROCLIMATE. Many things besides wind speed and cloud cover affect the minimum temperatures that occur. Growers in mountainous, hilly, or even rolling terrain are familiar with frost pockets or cold spots formed by cold air drainage. Cold, dense air flows by gravity to the lowest areas of a field where it collects. This causes temperatures to differ in relatively small areas, called microclimates.

Soil moisture and compaction can significantly affect minimum temperature and microclimate. A moist, compact soil will store more heat during the day than a loose, dry soil. Thus, it will have more heat to transfer to the crop at night. Cultivation should never be carried out before a frost or freeze.

Groundcover also has an effect. Vegetation reflects more solar radiation during the day. It also transpires as a temperature-regulating mechanism. Therefore, it reduces the heat that it stores and that is stored in the soil below it. Mowing a vegetative cover to heights shorter than 2 inches can reduce this effect. However, the frost–freeze protection disadvantages of groundcover management must be weighed against the benefits such as erosion control, dust reduction, minimizing soil, and compaction.

Microclimate monitoring

Although minimum temperatures may vary across a forecast zone because of microclimates, relative conditions for a single area should be quite similar during each frost. It is very advantageous to document weather conditions for each frost in selected parts of the crop area. One can observe and record actual and forecast temperature, cloud cover, and wind speed. In cloudy, breezy weather, the observed lows are likely to be very close to forecast values, but, under clear, calm conditions, frost often needs to be anticipated when none is forecast in the zone.

Analysis of past observations is an essential ingredient to predicting future conditions and modifying the zone forecast for a crop area. The information collected also allows the grower to place protection equipment in those areas where it will most likely be needed. During a radiation frost, careful records of past frosts can

Table 1. Characteristics of a radiation frost and an advective freeze.

Radiation frost	Advective freeze
Calm winds (<5 mph)	Winds >5 mph
Clear skies	Clouds may exist
Cold air mass 30–200 ft deep	Cold air mass 500–5000 ft deep
Inversion develops	No inversion exists
Two types: hoar (white) and black	No frost forms
Cold air drainage occurs	No cold air drainage
Successful frost protection likely	Protection success limited

help make the critical decision of whether or not to begin protection measures. This is especially critical in areas where overhead irrigation is used. Microclimate information gathered before crop establishment can help the grower select site, type, and amount of protection equipment.

Air temperature. Minimum-temperature-indicating thermometers are not expensive and are a wise investment for any grower concerned with frost–freeze protection. The placement and number of thermometers depends on the area and the grower's interest. Some factors to be considered include elevation, crop varieties, soil type, and the flexibility of the protection system. Some growers place one thermometer in the coldest spot and organize their protection plans around the worst possible case. This is acceptable, except that much of the area will receive more protection than it needs, perhaps costing the grower unnecessary time and fuel. If the protection system allows spatially variable rates of protection, then many thermometers are needed.

Crop temperature. Knowing the temperature of the crop you are trying to protect is a critical piece of information in protection decisions. It is often the practice to use air temperature as the decisionmaker. This can be misleading because the atmospheric conditions that create frosts also cause crop temperatures to be different from air temperatures (crop temperatures are usually colder), but not always by the same amount. The difficulty in the past has been how to measure the crop temperature accurately and economically. This obstacle has encouraged growers to use the air temperature but put in a safety factor, and so often systems are started before they actually need to be. There are also situations where by being able to wait confidently to start, the need to protect is avoided completely.

Thermocouples are temperature-measuring devices small enough to be inserted into buds, blossoms, and small fruit. They are inexpensive and easy to make. The meters to read them used to be expensive and complicated. However, now digital thermometers that use thermocouples are available. These meters and the thermocouples can be used in different ways. A grower can move through the crop, measuring the temperature in varying locations. This can be done by inserting one thermocouple, taking a reading, and then removing it and going to the next location. The cost can be as little as $100.00. A grower can also place thermocouples fitted with connectors in many locations and then visit each with the meter to read them. Another method is to bring the wires from the thermocouples to a central location and have a switch that enables the meter to read multiple sensors. Any of these ways gives a very accurate picture of what's happening throughout the planting that is to be protected.

The economic feasibility of the latter two methods should be assessed due to the cost of the connectors and the additional wire required. It should, however, be quite easy to customize a plan that suits the grower's needs and budget. This relatively small investment can increase frost protection decisionmaking skills significantly and will certainly add confidence in deciding when to begin protection.

Table 2. Definition of frost–freeze warnings issued by the National Weather Service.

Warning	Wind speed (mph)	Air temp (°F)
Frost	<10	>32
Frost–freeze	<10	<32
Freeze	>10	<32

Basics of weather forecasts and warnings

Understanding National Weather Service (NWS) forecasts for minimum temperatures is important. States are divided into many forecast zones that vary in size. The weather in a zone is fairly uniform; however, under a radiation frost, minimum temperatures may differ widely because of the many microclimates in that zone. The NWS forecast cannot consider all of these subzones. The forecast minimum temperature is for 5 ft (1.5 m) above ground inside a NWS instrument shelter. The difference between the air temperature in such a shelter and the temperature of a crop can be significant on a frost night. However, private agricultural weather services that provide minimum temperature forecasts for specific locations on an hourly basis exist. These site-specific, custom forecasts allow the grower to plan frost protection strategy better.

Although the NWS no longer provides agricultural weather services, it does continue to issue frost warnings. The NWS will issue warnings according to the forecasted conditions (Table 2). Private forecasters are not allowed to issue official weather warnings. The wording of these warnings tells the grower how they can react. If winds <10 mph (4.5 $m \cdot s^{-1}$) and minimum temperatures ≥32 °F (0 °C) are forecasted, a **frost warning** is issued. If winds <10 mph (4.5 $m \cdot s^{-1}$) and minimum temperatures below 32 °F are forecasted, a frost and freeze **warning** is issued. When winds >10 mph and minimum temperatures <32 °F are forecasted, a freeze **warning** is issued. Thus, the frost and frost–freeze warnings imply that the grower can likely provide successful protection, while a freeze warning means the winds will be too high to allow successful use of irrigation or wind machines.

The NWS Forecast Office does not issue wind forecasts for mountain zones. The current methods for predicting wind speeds coupled with the widely varying terrain of these zones prevent any meaningful wind forecast for an entire zone. Thus, the implied wind information in these warnings is particularly important to growers in these zones. Although specific speeds <10 mph are difficult to predict, the forecasts can include information about whether calming is expected later in the night or if the wind is expected to fluctuate between calm and >5 mph (2.2 $m \cdot s^{-1}$). The term light winds is used in NWS-developed wind forecasts for speeds <10 mph.

Methods of frost–freeze protection

All frost–freeze protection methods are based on preventing or replacing heat loss. The proper choice of protection equipment for a particular site depends on many factors. The advantages and disadvantages, relative costs, and operating principles of the predominant methods are discussed below (Table 3).

Site selection. The best method of frost–freeze protection is proper site selection. Microclimate monitoring may be used to evaluate a site not yet committed to crop production. Visualizing the flow of cold air, as if it were water, and its possible buildup in low spots or behind cold air dams is the most effective and quick site-selection method. If a site has good cold air drainage, then it is likely a good production site as far as frost–freeze damage is concerned.

Irrigation. There are four methods of irrigation that are used for frost protection. The most common is **overhead irrigation**, often called sprinkler irrigation, which is done with sprinklers mounted above the crop canopy. Heat lost from the plant part to its environment is replaced by heat released as the applied water changes to ice. Specifically, as 1 g of water freezes, 80 calories of heat energy are released. As long as ice is being formed, this latent heat of fusion provides heat.

Although there is some risk involved, the advantages of irrigation are significant. Operational costs are lower since water is much cheaper than oil or gas. Irrigation systems are convenient to operate since they are controlled at a central pump house. In addition, there are multiple uses for the same system, e.g., drought prevention, heat suppression, fertilizer application, and possibly pest control.

There are some disadvantages. The first and most important is that, if the irrigation rate is not adequate, the damage incurred will be more severe than if no protection had been provided. Inadequate irrigation rate means that too little water is being applied to freeze at a rate that will provide enough heat to protect the crop. The situation is made complex by another property of water, i.e., evaporative cooling or the latent heat of evaporation. As 1 g of water evaporates, 600 calories of heat energy are absorbed from the surrounding environment. When compared to the 80 calories released by freezing, it becomes apparent that >7.5 times more water must be freezing than evaporating to provide a net heating effect. Otherwise, evaporation takes energy from plant parts. An ice-covered plant part cools below the temperature of a comparable dry plant part if freezing stops and evaporation begins. Since wind promotes evaporative cooling, wind speeds >5 mph limit the success of irrigation for frost protection.

Second, with overhead irrigation, ice buildup can cause limb breakage, and third, overwatering can cause waterlogged soils and nutrient leaching problems. Last, at this time, most systems are of a fixed-rate design. They can only be turned on and off, and no variability exists for the irrigation rate. Thus, most systems are designed for the worst possible case. This means excess water is applied in most frosts, further increasing the problems of too much water in the crop area.

The details of designing and operating an overhead irrigation system for frost–freeze protection are not included here; irrigation specialists and extension agents can give growers help in this endeavor. It is critical to realize that, if the capacity of the irrigation system is not sufficient to provide protection under the extreme conditions expected during the night, the system should not be turned on. In general, no system provides protection in wind speeds >5 mph for tree crops or 10 mph for low-growing crops. A backup power source is essential. Once started, irrigation must continue until the sun is on the crop and/or the ice is melting and loose. This usually occurs soon after the morning sun hits the trees. A power failure can be devastating due to the evaporative cooling effect.

Undercanopy, usually under-tree, sprinkling with microjet nozzles has been successful in California and Florida. This method has not been modelled as extensively as the overhead system, but the explanation of why it works involves the transfer of latent heat from the liquid spray emitted below the tree canopy up into the canopy where protection is provided.

Man-made fog has been tried as a frost protection method. The principle is to duplicate the greenhouse effect. If a "cloud" could be produced blanketing the crop area, it would decrease the radiative cooling and stop the plant parts from dropping to the critical temperature. So far, there has been some experimental success but a practical system has not been developed. The difficulty lies in producing droplets large enough to block the outgoing longwave radiation and keeping them in the atmosphere without losing them to evaporation.

Flooding is another irrigation method of frost protection. It is controversial because its ability to provide protection is limited by the existing atmospheric conditions. Like undercanopy irrigation, its mechanism has not been as thoroughly documented. The flooded furrows or channels act as small bodies of water to moderate the microclimate. In addition, water evaporates from the surface of the flooded furrows and condenses where it is needed up in the canopy. This method has been less popular among practitioners due to the lead time, usually 3 d, for its implementation.

Wind machines. Wind machines capitalize on the inversion development in a radiation frost. Their purpose is to circulate the warmer air down to the crop level. They are not effective in an advective freeze. A single wind machine can protect ≈10 acres if the area is relatively flat and square or circular. A typical wind machine is a large fan ≈16 ft (4.9 m) in diameter mounted on a 30-ft steel tower. The fan is powered by an industrial engine delivering 85 to 100 Hp. Since wind machines are only effective under radiation frost conditions, a grower choosing this method should be confident that it is under such circumstances protection will most often be needed.

Wind machines use only 5% to 10% of the energy per hour required by heaters. The original installation cost is quite similar to that for a pipeline heater system, making wind machines an attractive alternative to heaters for frost protection. However, they will not provide protection under windy conditions. Wind machines are sometimes used in conjunction with heaters. This combination is more energy-efficient than heaters alone and reduces the risks of depending solely on wind machines. When these two methods are combined, the required number of heaters per acre is reduced by about half.

Helicopters have been used as wind machines. There is diversity in the strategies that pilots use, i.e., patterns they fly, weighting of the helicopter, combining with water sprays, etc. One method uses thermostatically controlled lights, which the pilot attempts to keep off or on depending on how the thermostat is wired. This feedback of temperature information from the ground seems crucial to the effective use of helicopters. Success often re-

Table 3. Advantages, disadvantages, and comments of seven frost–freeze protection methods.

Protection method	
Site selection	
Advantages	Preventive measure—choose location with good cold air drainage.
Comments	Best method of frost protection; visualize air flow and/or monitor minimum temperatures.
Irrigation, overhead	
Advantages	Operational cost lower than heaters; can be used for other cultural purposes.
Disadvantages	Installation costs relatively high; risk damage to crop if rate inadequate; ice buildup may cause broken limbs; overwatering can waterlog soils; does not protect in windborne freezes.
Comments	Plant part protected by heat of fusion; fixed-rate design delivers more protection than generally necessary; irrigation must continue until sun is on the crop; backup power source is essential.
Irrigation, undercanopy	
Advantages	Operational cost lower than heaters; can provide protection in windborne freezes; can be used for other cultural purposes.
Disadvantages	Installation costs relatively high; risk damage to crop if rate inadequate; ice buildup may cause broken limbs; overwatering can waterlog soils.
Comments	Plant part protected by transfer of latent heat; backup power source is essential.
Irrigation, fog	
Advantages	Blocks outgoing radiant heat and slows cooling.
Disadvantages	Has potential but is not currently practical.
Comments	Uses greenhouse effect to trap heat in crop canopy and limit radiation cooling.
Wind machines	
Advantages	Can cover 10-acre area if flat and round; installation cost similar to heaters.
Disadvantages	Not effective in windborne freeze.
Comments	Mixes warm air near top of inversion down to crop level; may be used with heaters; may use helicopters in same way.
Heaters	
Advantages	Radiant heat helpful in freeze; installation costs lower than irrigation; allows delay; no risk of increasing damage if rate not adequate
Disadvantages	Fuel oil is expensive and so this method is rarely used today.
Comments	Free standing or pipeline systems available; free standing need no power source.
Covers	
Advantages	Can protect in radiation frost and/or advective freeze, no risk of increasing damage if not successful.
Disadvantages	Success limited to short duration and/or events that are not severe. Not practical on tree crops, labor intensive and expensive.
Comments	Parts of crop that are touched by the cover will likely be damaged.

quires several helicopters, unless the time period of protection is short or the area to be protected is small. Since the helicopters must land to refuel and pilots require periodic breaks, and since it doesn't take long for the inversion to reform, many helicopters are usually needed to stagger these down times or they become the downfall of the method.

HEATERS. Heating for protection has been relied on for centuries. In the last 20 years, the increasing cost of fuel has been incentive to look at other methods; however, there are several advantages to using heaters that alternatives do not provide. Most heaters are designed to burn oil and can be placed as freestanding units or connected by a pipeline network through the crop area. The advantage of connected heaters is the ability to control the rate of burning and shut down all heaters from a central pumping station simply by adjusting the pump pressure. A pipeline system can also be designed to use natural gas. Propane, liquid petroleum, and natural-gas systems have been used for citrus. The burning rate of the freestanding units may also be adjusted, but individual adjustments are required.

Heaters provide protection predominantly by two mechanisms. The hot gases emitted from the top of the stack initiate convective mixing in the crop area, tapping the important warm air source above in the inversion. About 75% of a heater's energy is released in this form. The remaining 25% of the total energy is released by radiation from the hot metal stack. This heat is not affected by wind and reaches any solid object not blocked by another solid object. Heaters may thus provide some protection under windborne freeze conditions.

Heaters provide the option of delaying protection measures if the temperature unexpectedly levels off or drops more slowly than predicted. The initial installation costs are lower than those of other systems, although the expensive fuels required increase the operating costs. There is no added risk to the crop if the burn rate is inadequate: whatever heat is provided will be beneficial.

COVERS. If plants are small enough, it is possible to protect them during short and limited-severity frosts by covering them. Covers are placed in the late afternoon and removed the next morning. Protection varies with the cover material. The better the material blocks the outgoing radiant heat from the plant and surface under it, the more protection it provides. Foam has been investigated as a cover that can be mechanically applied. Successful protection has been demonstrated, but the difficulty in removing the foam limits the use of this method. Wrapping the trunk and lowest branches of fruit trees has also been used. In this method, the upper part of the tree may be lost in a severe freeze, but the entire tree is not killed.

CHEMICALS. The objective of having an inexpensive material that can be stored easily until needed, applied easily, and provide frost protection has existed since the mid 1950s. Many materials have been examined. These fall into several categories but, generally, they have been materials that allegedly either changed the freezing point of the plant tissue; reduced the ice-nucleating bacteria on the crop, thereby inhibiting ice and frost formation; or affected growth, i.e., delayed dehardening or work by some "unknown mode of action." To my knowledge, no commercially available material has successfully withstood the scrutiny of a scientific test. There are, however, several products that are advertised as frost-protection materials. Growers should be very careful about accepting the promotional claims of these materials. Research continues and some materials have shown some positive effects. Growth-regulator applications seem to be the most promising at this time.

Conclusions

The proper method of frost–freeze protection must be chosen by each grower for the particular site considered. Once the decision has been made, several general suggestions apply to all systems.

Don't delegate protection of the crop to someone with no direct interest in the result. Complete system preparation and testing should be accomplished well before the frost season begins. Likewise, don't remove the system before the threat of frost has definitely passed. Double-check the system shortly before an expected frost. Problems that are easily handled during the warm daylight can become monumental and even disastrous during a cold, frosty night when every second counts.

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