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FROST/FREEZE PROTECTION FOR HORTICULTURAL CROPS

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Each year a portion of the state's fruit and vegetable crop is lost to low temperature damage. Protection methods exist. This leaflet seeks to explain the occurrence of frosts and freezes and to provide information on protection methods.

Principles of Frost/Freeze Protection

Heat Transfer - Heat may be transferred from one material to another or from one place to another by three processes: conduction, convection, and radiation. When a metal rod is warmed, the process of heat transfer is conduction. 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 heated liquid or gas. Radiation is movement of heat energy from one object to another without being physically connected. This is how we receive the sun's energy, and it is by radiant heat transfer that crops lose heat at night.

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. 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. The soil and crops may also radiate heat energy into space. Water vapor, some of which can be seen as clouds, and CO_2 which is invisible, may absorb or reflect some of this energy, trapping it as heat near the earth's surface. This last phenomenon is known as the greenhouse effect (Fig. 1).

At night the situation reverses. There is no incoming heat to warm the soil and crops. They continue to lose heat through radiation and conduction until they are cooler than the surrounding air. The air then passes 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 will continue to decrease significantly. The greenhouse effect of cloud cover can limit this temperature decrease at night.

Inversion - On a clear night, the heat from solid objects will continue to radiate out to space. Temperatures will drop significantly at the surface. The temperature in the lower tens to hundreds of feet of atmosphere inverts, i.e. the temperature increases with altitude to the top of the air layer. 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 is important for some frost protection methods which depend on this source of heat (Fig. 2).

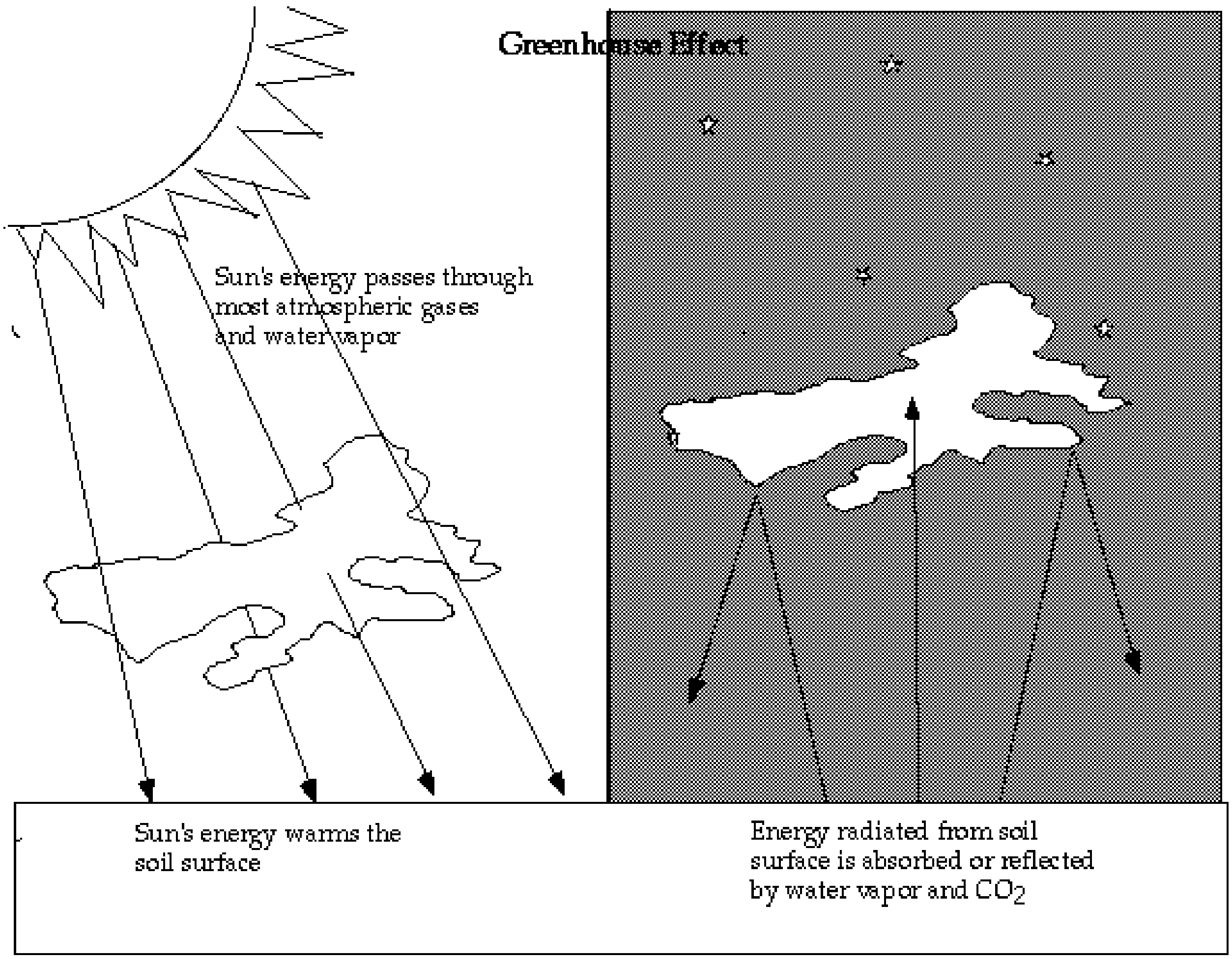

Fig. 1 Energy exchange showing the greenhouse effect of cloud cover.

Frost vs. 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 above 5 mph and clouds may be present. The thickness of the cold air layer ranges from 500 to more than 5000 feet above the surface. Attempts to protect crops by modifying the environment are very limited under these conditions.

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

Radiation Frost	Advective Freeze
Calm winds (less than 5 mph)	Winds above 5 mph
Clear Skies	Clouds may exist
Cold air mass 30 to 200 ft deep	Cold air mass 500 to 5000 ft deep
Inversion develops	Protection success limited
Two types: hoar (white) black	
Cold air drainage occurs	
Successful frost protection likely	

A *radiation frost* occurs when a clear sky and calm winds (less than 5 mph) allow an inversion to develop, and temperatures near the surface drop below freezing. The thickness of the inversion layer varies from 30 to 200 feet. There are two types of frost. A hoar frost, or white frost, results when atmospheric moisture 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 dew point, or frost point, which is the temperature to which air must be cooled to cause atmospheric moisture to condense. The drier the air, the lower the dew point.

Microclimate

Many factors are involved that affect the minimum temperatures which occur. Growers in mountainous, hilly or rolling terrain are familiar with frost pockets or cold spots. These are formed by cold air drainage, i.e. 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 micro-climates.

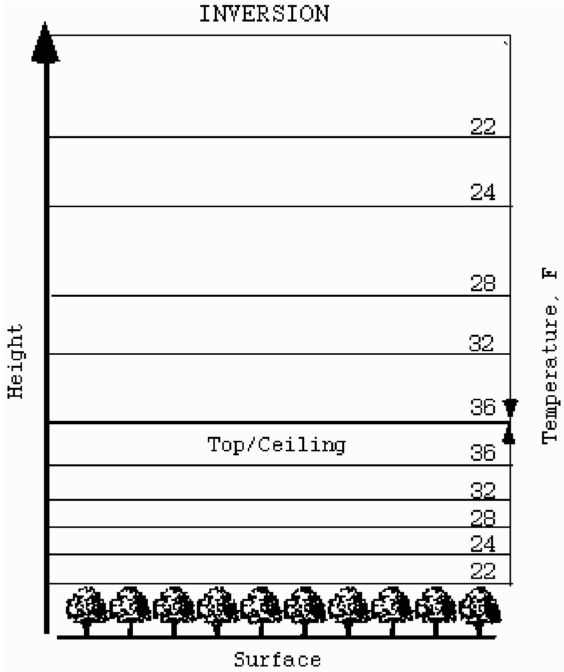

Fig. 2 Temperature zonation during an inversion. Temperature increases with height to the top of the inversion and then decreases. Frost protection techniques use the warmer air above the crop as a heat source.

Soil moisture and compaction can have a significant effect on minimum temperature. 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 prior to frost or freeze, because it loosens and dries the soil.

Ground cover also has an effect. Vegetation reflects more solar radiation during the day. It also transpires to cool its temperature. This reduces the heat that it stores and that which is stored in the soil below it. Mowing a vegetative cover to heights shorter than two inches can reduce this effect. However, the frost and freeze protection disadvantages of ground cover management must be weighed against the benefits such as erosion control, dust reduction, minimizing soil compaction, etc.

Forecasts and Warnings

Understanding weather forecasts for minimum temperatures is important. North Carolina is divided into 104 forecast zones. Each county is a zone and two counties are divided. Hyde County is divided into east and west. Jackson County is divided into north and south. The weather within a zone is fairly uniform; however, under the conditions of a radiation frost, minimum temperatures may differ widely because of the numerous microclimates within that zone. The forecast cannot consider all these subzones. The forecast minimum temperature is for 5 feet above the ground inside a National Weather Service instrument shelter. A difference of three to five (degrees F) can exist between the air temperature in such a shelter and the temperature of a crop on a frost night. For these reasons, to plan a better frost protection strategy, the grower needs to modify the zone forecast for the field to be protected.

The National Weather Service (NWS) will issue warnings according to the forecasted conditions (Table 2). The wording of these warnings tells the grower how he can react. If winds below 10 mph and minimum temperatures above or equal to 32°F are forecasted, a *frost warning* will be issued. If winds below 10 mph and minimum temperatures below 32°F are forecasted, a *frost/freeze warning* will be issued. When winds above 10 mph and minimum temperatures below 32°F are forecasted, a freeze *warning* will be 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.

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

Warning	Wind Speed	Air Temperature
Frost	Below 10 MPH	Above 32°F
Frost/freeze	Below 10 MPH	Below 32°F
Freeze	Above 10 MPH	Below 32°F

The NWS does not issue wind forecasts for the mountain zones. The current methods for predicting wind speeds together 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 below 10 mph are difficult to predict, the local forecasts can include information about whether calming is expected later in the night or if the wind is expected to fluctuate between calm and above 5 mph. The term “light winds” is used in NWS-developed wind forecasts for speeds below 10 mph.

Microclimate Monitoring

Although minimum temperatures may vary across a forecast zone because of microclimates, relative conditions for an area should be quite similar during each frost/freeze occurrence. It is very advantageous to record weather conditions for each occurrence in selected parts of the farm. 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 may need to be anticipated even when no frost is forecast.

The use of past observations can become an essential ingredient to predicting future conditions and modifying the zone forecast for a farm. The information collected will also allow the grower to place protection equipment in those areas where it will most likely be needed. During a radiation frost, careful records of past occurrences can 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 the establishment of a crop can help the grower select site, type and amount of protection equipment.

Air Temperature - Minimum recording 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 growers place one thermometer in the coldest spot and organize their protection plans around the worst possible case. This is one approach, 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 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 "decision maker." This can be misleading because the atmospheric conditions which create frosts also cause crop temperatures to be different from air temperatures (usually colder), but not always by the same amount. The difficulty in the past has been how to accurately and economically measure the crop temperature. This has encouraged growers to use the air temperature, but add a "safety factor" of several degrees. This often causes systems to be started before they actually need to be, resulting in excess water and energy use. There are also situations where by being able to confidently wait to start, the need to protect is avoided completely.

Thermocouples are temperature measuring devices small enough to be inserted into buds, blossoms or small fruit. They are inexpensive and easy to make. Digital thermometers that read thermocouples are now available. These meters and the thermocouples can be used in different ways. A grower could move through the crop measuring the temperature in various locations by inserting one thermocouple, taking a reading, removing it and going to the next location. This could be done for as little as $100.00. A grower could also place thermocouples fitted with connectors in numerous locations and then visit each with the meter to read them. Another method would be 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 will give a very accurate picture of what's happening throughout the crop area that is to be protected.

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

Methods of Frost/Freeze Protection

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

Site Selection - The best method of frost/freeze protection is good site selection. Microclimate monitoring may be used to evaluate a site before planting. Visualizing the flow of cold air and its possible buildup in low spots or behind cold air dams, such as fences, hedges, wooded areas, is the most effective, quick method of site selection. If a site has good cold air drainage, then it is likely a good production site as far as frost/freeze damage is concerned.

Heaters - Heating for protection has been relied upon for centuries. The increased cost of fuel has provided 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 free-standing units or connected by a pipeline network throughout the crop area. The advantage of connected heaters is the ability to control the rate of burning and shut all heaters down 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.

Heaters provide protection by three 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 percent of a heater's energy is released in this form. The remaining 25 percent of the total energy is released by radiation from the hot metal stack. This heat is not affected by wind and will reach any solid object not blocked by another solid object. Heaters may thus provide some protection under windborne freeze conditions. A relatively insignificant amount of heat is also conducted from the heater to the soil.

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.

Growers have also tried burning old rubber tires for frost protection. Some heat is added to the crop area by these fires, but there has been a misconception that the smoke acts like a cloud. Smoke does not provide the greenhouse effect of water vapor because the smoke particles are too small to block longwave radiation loss. In fact, smoke not only has no effect on outgoing radiation,

Table 3. Characteristics of frost/freeze protection methods

	Advantages	Disadvantages	Comments
Site Selection	Preventive measure—choose location with good cold air drainage.		Best method of frost protection; visualize air flow and/or monitor minimum temperatures.
Heaters	Radiant heat helpful in freeze; installation costs lower than irrigation; allows delay; no risk if rate not adequate.	Fuel oil expensive.	Free-standing or pipeline; free-standing heaters need no power source.
Irrigation	Operational cost lower than heaters; can be used for other cultural purposes such as drought prevention.	Installation costs relatively high; risk damage to crop if rate inadequate; ice buildup may cause limbs to break; overwatering can waterlog soils; does not provide protection in wind above 5 mph.	Plant part protected by heat of fusion; fixed rate design delivers more protection than generally necessary; irrigation must continue until melting begins; backup power source essential.
Wind machines	Can cover 10-acre area if flat and round; installation cost similar to heaters.	Not effective in wind above 5 mph or advective freeze.	Mixes warm air near top of inversion down to crop height; may be used with heaters; may use helicopters.
Fog	Blocks outgoing radiant heat and slows cooling.	Has potential but is not currently practical.	Uses greenhouse effect to trap heat in crop canopy and limit radiation cooling.

it actually impedes warming in the morning since smoke particles are the right size to block the incoming shortwave solar energy. Legal regulation of fires must also be considered before burning tires or other materials for frost protection.

Irrigation - Irrigation is another method of frost/ freeze protection. Heat lost from the crop to the environment is replaced by heat released as the applied water changes to ice. Specifically, as 1 gram of water freezes, 80 calories of heat energy are released. As long as ice is being formed, this latent heat of fusion will provide heat.

Irrigation for frost protection, often called sprinkler irrigation, is done with sprinklers mounted above or below the crop canopy. Under-canopy, usually under-tree, sprinkling with micro-sprinkler nozzles has been successful in California and Florida. This relatively new method of irrigation for frost protection has not as yet found widespread use in North Carolina.

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, evaporative cooling, 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 which will provide enough heat to protect the crop. The situation is made complex by another property of water, evaporative cooling or the latent heat of evaporation. As 1 gram 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 more than 7 $^{1}/_{2}$ times more water must be freezing than evaporating to provide a net heating effect. Otherwise the process of evaporation will take heat from the crop. An ice-covered plant will cool below the temperature of a comparable dry plant if freezing stops and evaporation begins. Since wind promotes evaporative cooling, wind speeds above 5 mph limit the success of irrigation for frost protection. Secondly, with overhead irrigation, ice buildup can cause limb breakage; and thirdly, over-watering can cause waterlogged soils and nutrient leaching problems. Lastly, at present, most systems are of 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 on the crop.

The details of designing and operating an overhead irrigation system for frost/freeze protection are contained in the NCCES bulletin *Irrigation for Apple Orchards*. Several very important points are repeated here. 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 will provide protection in wind speeds greater than 5 mph for tree crops, 10 mph for low growing crops. A backup power source is essential. Once started, irrigation must continue until 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.

Wind Machines - Wind machines capitalize on the inversion development in a radiation frost. Their purpose is to circulate the warmer air down to crop level. They are not effective in an advective freeze. A single wind machine can protect approximately ten acres, if the area is relatively flat and round. A typical wind machine is a large fan about 16 ft. 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 he will most often need protection.

Wind machines use only 5 to 10 percent 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 also been used as wind machines. They hover in one spot until the temperature has been increased enough and then they move to the next area. Repeated visits to the same location are usually required.

Chemicals - The objective of having an inexpensive material that could be stored easily until needed, easily applied and provide frost protection has existed since the mid 1950s. Numerous materials have been examined. These fall into several categories but, in general, they have been materials that allegedly either: 1) changed the freezing point of the plant tissue, 2) reduced the ice nucleating bacteria on the crop and thereby inhibited ice/frost formation, 3) affected growth, i.e. delayed dehardening, or 4) worked by some "undetermined mode of action." To this author's 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 which delay bloom seem to hold the most promise at this time.

Fog - 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 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.

Summary

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.

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 used correctly, sound judgment, attention to detail and commitment. Don't delegate protection of the crop to someone with no direct interest in the result. Complete preparation and testing of the system should be accomplished well before the frost season begins. Likewise, don't shut down 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.