Principles of Frost Protection

(Short version – Quick Answer *FP005*)

Author: Richard L. Snyder
Extension Biometeorologist
University of California
Atmospheric Science
Davis, CA 95616, U.S.A.

PASSIVE FROST PROTECTION METHODS

Site Selection

Site selection is the single most important freeze protection. Because cold air is denser than warm air, it flows downhill and accumulates in low spots. These cold holes should be avoided when seeking a cropping site. The tops of hills are also cold and should be avoided. In general, it is best to plant on slopes where cold air can drain away from the crop.

It is best to plant deciduous crops on north facing slopes to avoid cold spots at the bottom of hills and to delay springtime bloom. Probability of freezing decreases rapidly with time in the spring, and deciduous crops on south facing slopes will bloom earlier. As a result, deciduous crops on south-facing slopes are more prone to freeze damage. Subtropical trees (e.g., citrus and avocados) are damaged by freezing regardless of the season, so they are best planted on south facing slopes where the soil and crop can receive and store more direct energy from sunlight.

Cold air drains downhill much like water. Any vegetation, buildings, etc. that block the down slope flow of cold air and force it into a crop will increase freeze potential. Also, vegetation, berm walls, fences, buildings, etc. can be used to control the flow of cold air and force it around a cropped field. There are examples where berm walls, fences, etc. have been used to funnel cold air around crops and reduce freeze potential.

Often the most severe freezes occur when the micro-scale advection happens. Cold air can accumulate in canyons upslope from crops and the cold air is prevented from draining into the crop by prevailing winds. If these winds stop, the cold air can drain onto the crop and cause damage. These micro-advection freezes occur frequently in California and they cause the most damage. Real time measurements in the upslope canyons are needed to identify potential problems. In some cases, helicopters or some other method of freeze protection could reduce or eliminate cold accumulation in the upslope canyons and prevent damage in the crops below.

Soil Water Content

Thermal conductivity and heat content of soils are affected greatly by the soil water content. On a daily basis heat is transferred into and out of approximately the top 0.3 m (1 ft) of soil. When the soil is wet, heat transfer and storage in the upper soil layer is better, so more heat is stored during daylight for release during the night. Considerable differences between thermal conductivity and heat capacity are observed between dry and moist soils. However, if the soil water content is near field capacity, wetting the soil is unnecessary. Wetting the soil to a depth below 0.3 m is unnecessary because diurnal temperature is insignificant below 0.3 m. However, on an annual basis, heat transfer below 0.3 m is important and could affect freeze protection if a soil is dry for a long period of time. Therefore, wetting is prudent when the soil is dry for several months prior to frost season.

Ground Cover and Mulches

When grass or weeds are present in an orchard or vineyard, sunlight is reflected from the surface and less energy is stored in the soil. Therefore, the crop is more prone to freeze damage. Vegetative mulches usually reduce the transfer of heat into the soil and hence make crops more freeze prone.

Large variations in ice nucleating bacteria concentrations on different crops have been observed. In some cases, the concentrations are low (e.g., citrus and grapevines). However, the concentration of ice nucleating bacteria on grass and weed ground covers and on grass type crops is typically high. Therefore the presence of ground cover within crops or cereal crops around a sensitive crop increases ice nucleating bacteria and freeze potential.

Covers

Covers are sometimes used to decrease the net radiation and convection energy losses from a crop and reduce the potential for freeze damage. The type of cover depends on the crop and the cost of labor and materials. Clear plastic mulches that increase heat transfer into the soil typically improve heat storage and hence provide passive freeze protection. Black plastic mulch is less effective for frost protection. Wetting the soil before covering with clear plastic provides the best protection.

ACTIVE FROST PROTECTION METHODS

Wind Machines

Wind machines provide protection by increasing the downward sensible heat flux density. The fans mix warm air aloft with colder air near the surface (Fig. 1). The amount of protection afforded depends on the unprotected inversion strength. In general, the temperature achieved after starting the fans is equal to the mean of the 1.5 m (5 ft) and 10 m (33 ft) temperatures.   When using wind machines for freeze protection, the fans should be started while the temperature measured at about 1.5 m (5 ft) height is above the critical damage temperature and before the 1.5 m height temperature falls much below the 10 m (33-ft) height temperature.

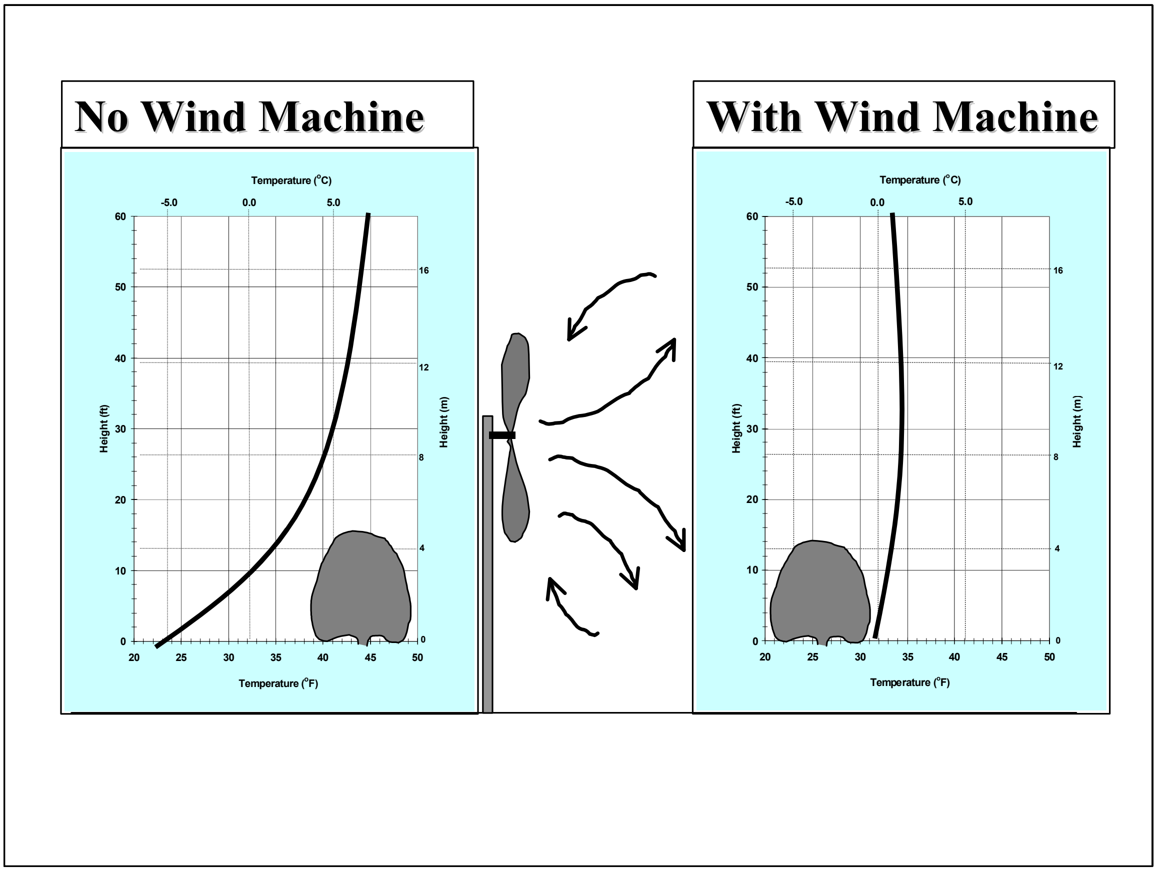


Figure 1. Schematic diagram showing the effect of wind machines on temperature profiles during a radiation frost.

Helicopters

Helicopters move warm air from aloft in an inversion to the surface. If there is little or no inversion, helicopters are ineffective. The area covered by a single helicopter depends on the helicopter size and weight and the weather conditions. Pilots often load helicopter spray tanks with water to increase the weight. Under severe freezes with a high inversion, one helicopter can fly above another to enhance the downward heat transfer.

A helicopter should pass over the entire crop every 30 minutes during mild freezes and more often during severe freezes. Thermostat controlled lights at the top of the canopy are used to help pilots see where passes are needed. On the sides of hills, downward heat transfer propagates down-slope after reaching the surface (P.W. Brown, personal communication). The pilot should monitor temperature on the helicopter and change altitude until the highest temperature is observed to determine the best flight altitude. A ground crew should monitor temperature in the crop and communicate with the pilot where flights are needed. Lights around the perimeter of the crop are beneficial to help the pilot. Flights are stopped when the air temperature upwind from the crop has risen above the critical damage temperature.

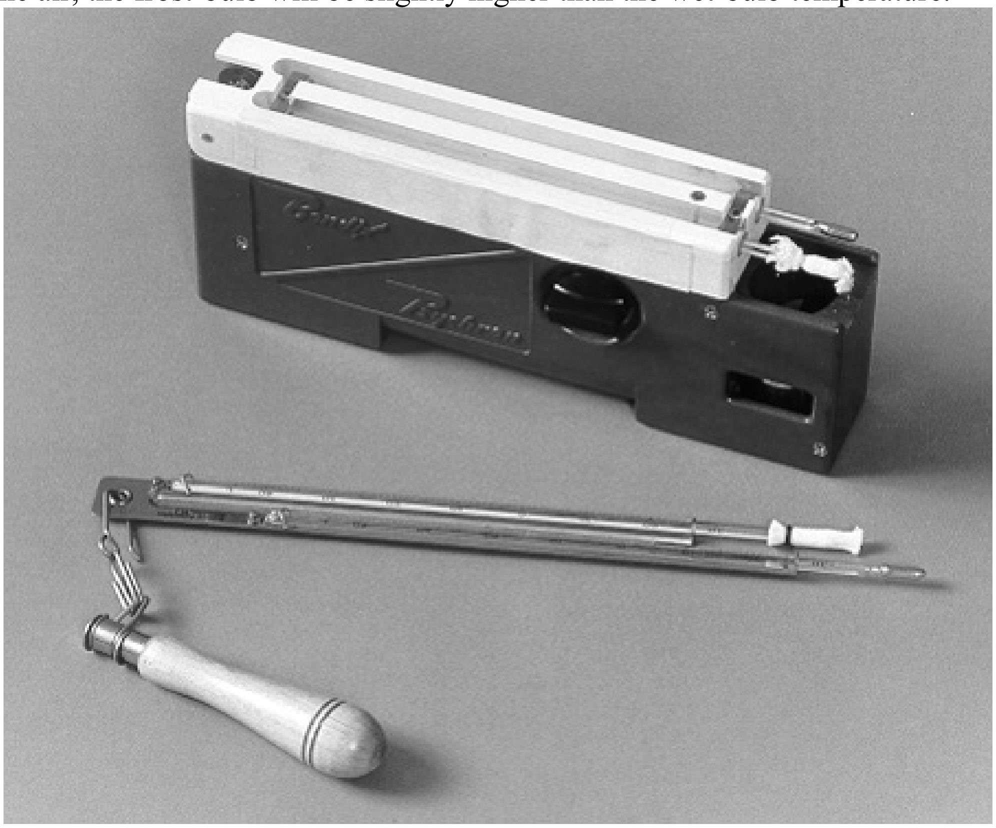
Sprinklers

When using sprinklers for freeze protection, the sprinklers should be started and stopped when the wet-bulb temperature (T_w) is above the critical damage temperature (T_c). The air temperature to start the sprinklers is estimated by first measuring the dew point (T_d) temperature (explained later). Then use Table 1 or 2 to determine the starting temperature by finding T_w=T_c in the top row and T_d in the left-hand column of the table. The sprinklers should be started when the observed temperature is at or above the corresponding air temperature (T) listed in the table. If T_d=23°F (-5.0°C) and T_c=30°F (-1.1°C), then the sprinklers should be started when the air temperature is at or above 34.0°F (1.1°C). This is because T_w=30°F (-1.1°C) when T_d=23°F (-5.0°C) and T=34.0°F (1.1°C).

The decision about when to start and stop the sprinklers for frost protection should be based on both temperature and humidity in the orchard. When a sprinkler system is first started, the air temperature in the sprinkled area will fall to the wet-bulb temperature. Of course, this initial drop will be followed by an increase in temperature as the water freezes on the ground and plant parts to release heat and warm the air. However, if the dew-point temperature is low, then the wet-bulb temperature can be considerably lower than the air temperature and the initial temperature drop can lead to damage.

Starting and stopping sprinklers for frost protection should always occur when the wet-bulb temperature is above the crop's critical damage temperature. Even if the sun is shining on the plants and the air temperature is above the melting point (0ºC or 32ºF), sprinklers should not be turned off unless the wet-bulb temperature is above the critical damage temperature. If soil waterlogging is not a problem, permitting the wet-bulb temperature to exceed the melting point (0ºC or 32ºF) before turning off the sprinklers adds an extra measure of safety.

The wet-bulb temperature can be measured directly with a psychrometer (see photo) or it can be determined from the dew point and air temperature. For direct measurements, the cotton wick on the wet-bulb thermometer is wetted with distilled or de-ionized water and it is ventilated until the temperature of the wet-bulb thermometer stabilizes. Ventilation is accomplished by swinging a sling psychrometer or by aspirating with an electric fan using an aspirated psychrometer. If the temperature is below 0ºC (32ºF), the water on the cotton wick should be frozen and aspirated until the temperature stabilizes. Touching the wick with cold metal or ice will cause freezing. When the water on the wick is frozen, the temperature is called the "frost-bulb" rather than wet-bulb temperature. Both the frost-bulb and wet-bulb temperatures exist for temperatures below the melting point. The difference is that the saturation vapor pressure over ice is lower than over liquid water. This means that water vapor that strikes the surface from the air is more likely to attach to the ice than to the water surface. For a given water vapor content of the air, the frost-bulb will be slightly higher than the wet-bulb temperature.



The upper instrument is an aspirated and the lower is a sling psychrometer. The cotton wick on a wet-bulb thermometer is wetted with distilled water. The aspirated psychrometer is ventilated with a battery-powered fan inside the instrument. Swinging the instrument ventilates the sling psychrometer. When ventilated, the temperature of the wet-bulb thermometer drops because evaporation removes heat from the thermometer. The wet-bulb temperature is noted when the temperature of the wet-bulb thermometer stops dropping.

The air temperature for a range of wet-bulb and dew-point temperatures can be selected from Table 1 or 3 for ^{o}F or ^{o}C, respectively. To determine the air temperature to start or stop sprinklers, first decide what is the critical damage temperature for your crop. Select a wet-bulb temperature that is at or above that temperature. Then find the wet-bulb temperature along the top of the table and the dew-point temperature along the left-hand side. Select the corresponding air temperature from the table. The sprinklers should be started before the air temperature falls below that value and they can be stopped after the air temperature upwind from the protected area exceeds that value. If the relative humidity and temperature are known instead of the dew-point temperature, then use Table 4 or 6, for ^{o}F or ^{o}C, respectively, to first determine the dew-point temperature and then use Table 3 or 5 to obtain the desired air temperature.

Table 3. Minimum turn-on and turn-off air temperatures (^oF) for sprinkler frost protection for a range of wet-bulb and dew-point temperatures (^oF)*

Dew-point Temperature	Wet-bulb Temperature (^oF)										
^oF	22	23	24	25	26	27	28	29	30	31	32
32											32.0
31										31.0	32.7
30									30.0	31.7	33.3
29								29.0	30.6	32.3	34.0
28							28.0	29.6	31.2	32.9	34.6
27						27.0	28.6	30.2	31.8	33.5	35.2
26					26.0	27.6	29.2	30.8	32.4	34.0	35.7
25				25.0	26.5	28.1	29.7	31.3	32.9	34.6	36.3
24			24.0	25.5	27.1	28.6	30.2	31.8	33.5	35.1	36.8
23		23.0	24.5	26.0	27.6	29.1	30.7	32.3	34.0	35.6	37.3
22	22.0	23.5	25.0	26.5	28.1	29.6	31.2	32.8	34.5	36.1	37.8
21	22.5	24.0	25.5	27.0	28.5	30.1	31.7	33.3	34.9	36.6	38.2
20	22.9	24.4	25.9	27.4	29.0	30.6	32.1	33.7	35.4	37.0	38.7
19	23.4	24.9	26.4	27.9	29.4	31.0	32.6	34.2	35.8	37.5	39.1
18	23.8	25.3	26.8	28.3	29.8	31.4	33.0	34.6	36.2	37.9	39.5

*** Select a wet-bulb temperature that is at or above the critical damage temperature for your crop and locate the appropriate column. Then choose the row with the correct dew-point temperature and read the corresponding air temperature from the table to turn your sprinklers on or off. This table assumes a barometric pressure of 1013 millibars (101.3 kPa).**

Table 4. Dew-point temperature (^oF) for a range of air temperature and relative humidity.

Relative humidity	Temperature (^oF)					
%	32	36	40	44	48	52
100	32	36	40	44	48	52
90	29	33	37	41	45	49
80	27	30	34	38	42	46
70	23	27	31	35	39	43
60	20	23	27	31	35	39
50	16	19	23	27	30	34
40	10	14	18	21	25	28
30	4	8	11	15	18	22

Select a relative humidity in the left column and an air temperature from the top row. Then find the corresponding dew point in the table.

Generally, crop sensitivity to freezing temperature increases from first bloom to the small nut or fruit stages when a crop is most likely to be damaged. Sensitivity is also higher when warm weather has preceded a frost night. Recommendations for starting and stopping temperature that are given here can be used for either over-plant or under-plant sprinklers. All sprinklers in a protection area should be on when the air temperature drops to the temperature selected from Table 3 or 5. This insures that the wet-bulb temperature will be above the critical damage temperature. Sprinklers can be turned off when the air temperature exceeds the value from Table 3 or 5.

Table 5. Minimum turn-on and turn-off air temperatures (^{o}C) for sprinkler frost protection for a range of wet-bulb and dew-point temperatures (^{o}C)*

Dew-point Temperature	**Wet-bulb Temperature (^{o}C)**					
^{o}C	-5.0	-4.0	-3.0	-2.0	-1.0	0.0
0.0						0.0
-1.0					-1.0	0.7
-2.0				-2.0	-0.4	1.3
-3.0			-3.0	-1.4	0.2	1.9
-4.0		-4.0	-2.5	-0.9	0.8	2.4
-5.0	-5.0	-3.5	-1.9	-0.4	1.3	2.9
-6.0	-4.5	-3.0	-1.5	0.1	1.8	3.4
-7.0	-4.1	-2.6	-1.0	0.6	2.2	3.9
-8.0	-3.6	-2.1	-0.6	1.0	2.6	4.3
-9.0	-3.3	-1.7	-0.2	1.4	3.0	4.7

*Select a wet-bulb temperature that is above the critical damage temperature for your crop and locate the appropriate column. Then choose the row with the correct dew-point temperature and read the corresponding air temperature from the table to turn your sprinklers on or off. This table assumes a barometric pressure of 1013 millibars (101.3 kPa).

Table 6. Dew-point temperature (^{o}C) for a range of air temperature and relative humidity.

Relative humidity	**Temperature (^{o}C)**					
%	0.0	2.0	4.0	6.0	8.0	10.0
100	0.0	2.0	4.0	6.0	8.0	10.0
90	-1.4	0.5	2.5	4.5	6.5	8.4
80	-3.0	-1.1	0.9	2.8	4.8	6.7
70	-4.8	-2.9	-1.0	0.9	2.9	4.8
60	-6.8	-4.9	-3.1	-1.2	0.7	2.6
50	-9.2	-7.3	-5.5	-3.6	-1.8	0.1
40	-12.0	-10.2	-8.4	-6.6	-4.8	-3.0
30	-15.5	-13.7	-12.0	-10.2	-8.5	-6.8

Select a relative humidity in the left column and an air temperature from the top row. Then find the corresponding dew point in the table.

Application Rate Requirements

The application rate required for over-plant sprinkling depends on the sprinkler rotation rate, wind speed, and the dew point temperature. The wind speed and dew point temperatures are important because the evaporation rate increases with the wind speed and with decreasing dew point temperatures (a measure of water vapor content of the air). Sprinkler rotation rates are important because the temperature of wet plant parts initially rises as the water freezes and releases latent heat as sensible, but then it falls to near the wet-bulb temperature, due to evaporation, before the plant is hit again with another pulse of water. This is illustrated in Figure 2.

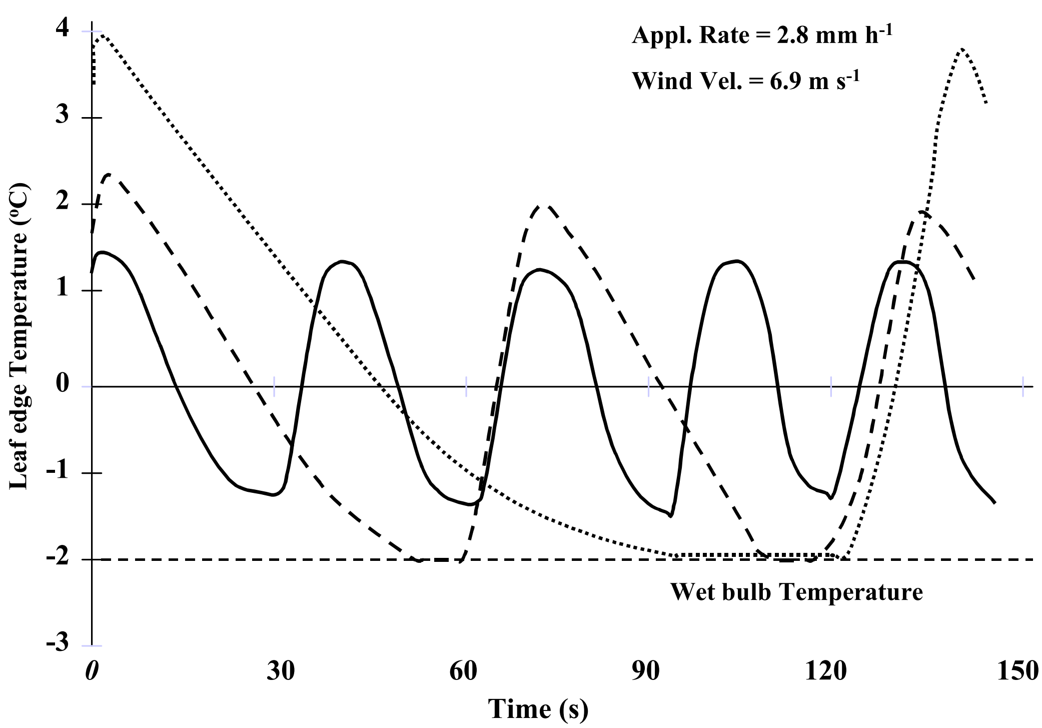


Figure 2. Temperature of a bud wetted by a sprinkler system with a precipitation rate of 2.8 mm h-1 (0.12 in/h) when exposed to a wind speed of 6.9 m s-1 (15 mph). The dotted line is for a 120 s rotation, the dashed line is for a 60 s rotation, and the solid line is for a 30 s rotation.

The idea is to rewet the plants frequently so that the interval of time when the plant temperature is below the critical damage temperature is short. Generally, the rotation rate should not be longer than 60 seconds; and 30 seconds is better. Sprinkler application rate recommendations for grapevines are given in Tables 8 and 9. Application rates for other tall crops are similar. Distribution uniformity and good coverage of the plants with water is important. Application rates are somewhat lower for low-growing crops because there is less surface area to cover and it is easier to obtain uniform wetting of the vegetation when it is shorter.

Table 8. Application Rates for Overhead Sprinklers for Frost Protection of Grapevines (English units)

Temperature	Wind Speed	30 s rotation	60 s rotation	30 s rotation	60 s rotation
^{o}F	Mph	in/hr	in/hr	gpm/A	gpm/A
29	0.0-1.1	0.08	0.10	36	45
26	0.0-1.1	0.11	0.13	50	59
23	0.0-1.1	0.15	0.17	68	77
29	2.0-3.0	0.10	0.12	45	54
26	2.0-3.0	0.13	0.15	59	68
23	2.0-3.0	0.18	0.20	81	90

Table 9. Application Rates for Overhead Sprinklers for Frost Protection of Grapevines (metric units)

Temperature	Wind Speed	30 s rotation	60 s rotation	30 s rotation	60 s rotation
^{o}C	m s^{-1}	mm h^{-1}	mm h^{-2}	lpm ha^{-1}	lpm ha^{-2}
-1.7	0.0-0.5	2.0	2.5	334	418
-3.3	0.0-0.5	2.8	3.3	468	551
-5.0	0.0-0.5	3.8	4.3	635	718
-1.7	0.9-1.4	2.5	3.0	418	501
-3.3	0.9-1.4	3.3	3.8	551	635
-5.0	0.9-1.4	4.6	5.1	768	852

Because lower branches are often wetted, the same application rates are used for under-tree impact sprinklers. Lower application rates are needed for micro-sprinklers that do not directly wet the plants. The effectiveness of the sprinklers again depends on the evaporation rate, which increases with wind speed and at lower dew point temperatures. The best way to test your system is to operate the sprinklers during various freezing conditions when the crop is dormant and/or harvested. If there is a liquid-ice mixture in the wetted area, then the application rate is sufficient that no damage is being done and it is probably adequate to provide some protection. If all of the water freezes and it has a milky white appearance, the application rate is too low for the weather conditions. The ice appears milky white because it is freezing too fast and trapping air inside the ice. If this happens, operating the sprinklers may cause more damage than good. Again, it is best to test the application rate for a variety of wind and dew point conditions during the crop dormancy. Then, if the conditions are too severe for the application rate, don't use the sprinklers.

Foggers

Natural fog is known to provide protection against freezing, so artificial fogs have also been studied as possible methods against freeze damage. Fog lines that use high pressure lines and nozzles to make fog droplets have been reported to provide excellent protection under calm wind conditions. Similarly, natural fogs created by vaporizing water with jet engines has been observed to provide protection. The jet engine approach has the advantage that it can be moved to the upwind side of the crop to be protected. However, the high pressure line approach has proven more reliable.

Surface Irrigation

Surface (flood and furrow) irrigation is commonly used for freeze protection in California. Protection is provided by the conversion of latent to sensible heat from the cooling water. Both convection of air warmed by the water and upward radiation are enhanced. In surface irrigation, freezing of the water is undesirable because the formation of ice above the liquid water prevents heat transfer from the warmer water under the ice crust.

Surface irrigation should be started early enough that the water reached the end of the field before the air falls to the critical damage temperature. As it moves down the field, the water cools, so the runoff water should not be re-circulated. Warmer water provides more protection. However, it is not believed to be cost effective to heat the water.

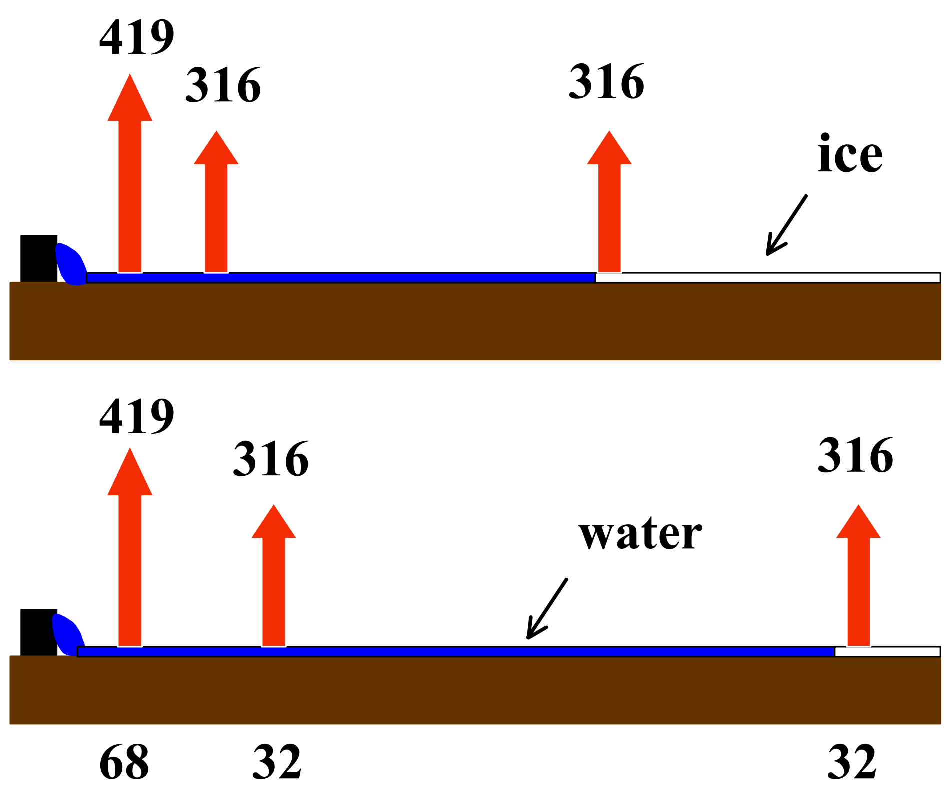


Figure 3. Schematic diagram showing the upward long-wave radiation from flood water as it cools moving down a field during a radiation frost night.

Heaters

Heaters provide freeze protection by direct radiation to the plants around them and by causing convective mixing of air within the inversion layer. When heaters are operated, the heated air rises. As the heated air rises, it cools until it reaches the height where the ambient air has the same temperature. Then the air spreads out and, eventually, the air descends again. A circulation pattern much like that of a gravity furnace is created (Fig. 4). If the inversion is weak, the heated air cools, but it rises too high and a circulation pattern is not produced. As a result, heaters are less efficient when there is no inversion. Making fires too hot will also make heaters less effective because the heated air rises above the inversion ceiling and the circulation pattern is not created.

Generally, heaters should be evenly distributed over the crop being protected. However, they should be concentrated somewhat more on the edge of the upslope or upwind side of the crop. Considerable time is needed to light heaters, so sufficient time is needed to finish lighting all of the heaters before the temperature falls to critical levels.

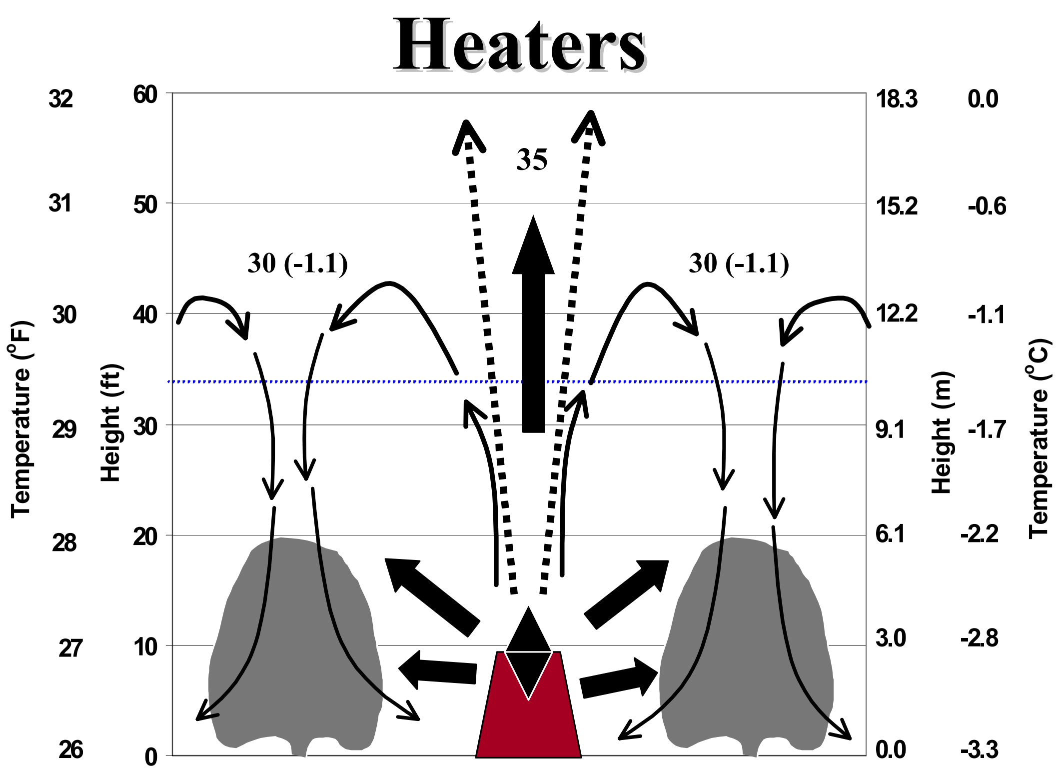


Figure 4. Schematic diagram showing the energy effect of a smudge pot heater on temperature within an inversion

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