Frost/Freeze Protection Using Irrigation

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The basics

Frost/freeze damage occurs when ice forms ***inside*** plant cells. Frost protection is a ***heat balance* process**. A risk always remains that severe weather conditions will exceed the ability of any frost protection scheme to fully protect a crop. Most successful programs for protecting crops from frost damage are a **mix of passive and active measures**.

- Passive frost protection measures include site selection, use of cold-tolerant crop varieties, and delaying planting in the spring.
- Active frost protection programs include conservation of heat, addition of heat, and mixing-in warmer air (e.g., from an inversion). Active methods include using crop covers, fossil fueled heaters, wind machines, foggers, and irrigation (alone or in combination with the other methods).

Solid-set* *sprinkler irrigation offers an economical method to protect crops from frost damage. Frost protection irrigation is different from conventional irrigation because water must be applied continuously, and at high rates to the entire crop area, for the duration of the frost event.

As long as plant surfaces are kept *wet*, even if ice forms, the plant tissue temperature will not fall appreciably below 32°F, and frost damage will not occur. Heat released by irrigation water is used to keep the crops warm, preventing ice from forming inside the plant tissue. The amount of heat released when water is cooled (**sensible heat**) is *8.4 BTU per gallon per degree Fahrenheit*. When water freezes from liquid to solid (**latent heat**) it releases *1200 BTU per gallon*. A given volume of water will release the same amount of heat when it freezes (from 32°F water to 32°F ice) as it will when it cools by 144°F (1200/8.4), say from 176 to 32°F.

> *THREE FACTORS GOVERNING REQUIRED RATE OF WATER APPLICATION*
>
> - Temperature
> - Relative humidity
> - Wind

The required rate of water application (gpm/ac or in/hr) is governed by three main factors: (1) temperature, (2) relative humidity, and (3) wind. Minimizing *evaporation* is important. When water evaporates it absorbs heat and cools the surroundings (latent heat of evaporation is *9000 BTU per gallon*). The 7.5-fold (9000/1200) difference between the latent heat of evaporation and the latent heat of freezing means that *7.5 gallons must freeze to compensate for one gallon that evaporates*. Thus, when the air is dryer (has a lower relative humidity) and/or the wind is greater, (1) more heat (more gpm/ac) is required and (2) the irrigation must be started sooner (at a higher temperature).

A rule of thumb is to *correctly* apply at least one tenth of an inch of water per hour (47gpm/ac) and to begin irrigating when the field (ambient) temperature is about 36°F. This can add as much heat as 4 million BTU's of heat per acre each hour; about 4 million BTU's is released when one tenth of an acre-inch of water (0.1 ac-in. = 2715 gallons) is cooled from 60°F and forms ice at 32°F.

Three important concepts to understand in frost protection are:

- Critical temperatures,
- Dew point temperatures, and
- The two types of frost.

Critical Temperatures

The *objective* is to keep the temperature of plant tissue *above* its *critical temperature*, e.g., the temperature at which plant cells will be damaged by a cold environment. Critical temperature (*cold hardiness*) changes with the stage of plant development and with the season. It can range from well below 10°F in midwinter for many perennial crops, to *near 32°F* in the spring and fall for young, tender plant tissue.

Dew Point Temperatures

> *DEW POINT*
>
> The temperature at which condensation of the water vapor in the air first occurs; the "minimum air temperature possible." It will change with time, and may or may not reach its lowest value before sunrise.

Dew point is the *temperature* at which condensation of the water vapor in the air first occurs. It can be greater than 70°F as well as less than -10°F, not just near 32°F. For practical purposes, *dew point temperature is the minimum air temperature possible*. It will change with time, and it may or may not reach its lowest value before sunrise.

Dew point is the most significant single factor in cold temperature injury management over which *growers have no control*. High dew point temperatures are extremely beneficial, whereas very low dew points overwhelm most frost protection methods. There is little that can be done to raise dew points in the field. Severe plant damage will occur when dew points are below critical plant temperatures, *unless* adequate heat is added to the crop/field.

Without the addition of heat (e.g., sunshine), the *rate* of temperature decrease is fairly rapid until the air temperature drops to the dew point; then atmospheric water begins to condense on the colder plant tissues, which reach dew point temperature first because they are colder due to radiation losses. When water condenses from the atmosphere, the latent heat of condensation (*9000 BTU per gallon*) is directly released at the plants. This large amount of "free" heat is more than sufficient to replace radiation heat losses from the plants. Condensation will also provide heat to the air and the air temperature will reach dew point temperature shortly after the exposed plants do. Then, further air temperature decreases will be small and occur over a much longer time as more and more water condenses out of the air mass.

The *wet-bulb temperature* is easy to measure, and is a good *approximation of dew point temperature* of an air mass. Wet-bulb is the minimum temperature obtained by a moist, evaporating body.

Two types of frost

The terms frost and freeze are often used interchangeably to describe conditions in which cold temperature injury of plants results as a consequence of subfreezing temperatures. However, two dominant types of frost situations will be encountered, and each calls for a different frost management strategy. The two types are *radiation frosts* and *advection freezes.* Both types of frost will usually be present in all frost events, but the type is characterized by the dominant type.

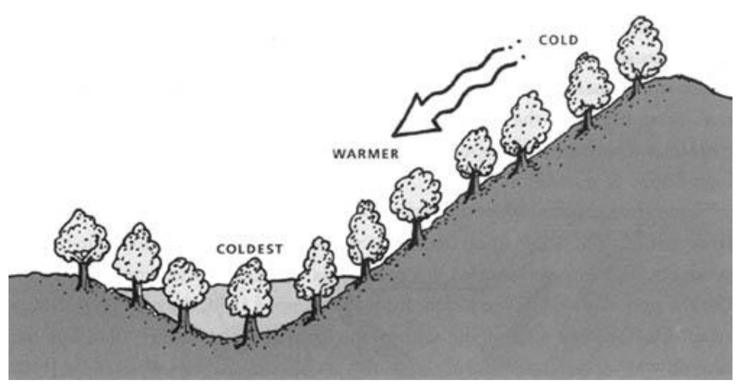
> *TWO TYPES OF FROST*
> - Radiation frost
> - Advection freeze

Radiation frost events occur when the air is dry, there is almost no cloud cover at night, and wind speeds are low (1 to 2 mph). During these times, the plants, soil, and other objects that are warmer than the very cold sky (combination of atmosphere and outer space) will radiate their own heat back to space and become progressively colder. The plant parts that are directly exposed to the sky become the coldest.

All objects radiate heat into a colder environment in proportion to their temperature differences. For example, plants will lose heat at a faster rate when exposed to a clear night sky, which can have an apparent temperature of about -20°F, than they will when exposed to clouds, which are relatively much warmer depending on cloud type and height. Radiation losses can amount to as much as *0.8 to 1.5 million BTU per acre each hour* and cause plant buds, blossoms, twigs, and leaves to become 2° to 4°F colder than the surrounding air; air radiates very little of its heat. The warmer air in direct contact with the colder plants, ground and other objects then loses heat (by conduction/contact) and, in turn, becomes colder. The chilled (denser) air settles and begins to flow toward and collect in lower elevations. To maintain constant ambient temperature in the field, the heat lost by radiation plus that carried out of fields at higher elevations to lower fields by air drift must all be replaced, and at the same rate as the losses.

As the air near the ground continues to lose heat, it can become several degrees colder than the air above it. This process also pushes the warmer, lighter 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 15°F warmer than air in the field, orchard, or vineyard. Moderate springtime temperature inversions often have 2° to 6°F colder air near the surface than that between 30 to 60 feet above the surface. Midwinter inversions may have greater temperature differences.

Both radiation losses and advection losses (air-mass/wind) must be counteracted under radiation frost conditions. All active frost protection methods (crop covers, heaters, wind machines, foggers, and undertree and overcrop irrigation) can be used protect against radiation type frost/freezes. However, heaters, wind machines, and undertree irrigation rely on a thermal inversion to help hold heat near the surface.



<u>Advection freezes</u>. Destructive cold temperature events under advection (*windy*) conditions are often called black freezes rather than frosts because they cause so much damage. Advection or advective freezes occur when *strong cold air masses* that are often 500 to 5000 ft thick, move through an area with winds at least 5 mph and temperatures below critical plant temperatures. These 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 heat losses still occurs. The cold damage is caused by the rapid, cold air movement, which advects or steals away the heat from the plant tissue.

Little can be done to protect against these freezes without applying massive amounts of heat and/or using heated tunnels or greenhouses. A reasonable method for protection against advective situations is solid-set sprinkler irrigation with application rates that are uniform and sufficiently high.

Using irrigation systems for frost management

When planning an irrigation system with a frost protection option, consider the prevailing frost conditions of the site. Such considerations include minimum temperatures and expected duration, occurrence and strength of inversions, soil conditions and temperatures, wind directions and changes, probability of cloud covers, dew point temperatures, critical bud/plant temperatures, perennial (tree or vine) and annual (vegetable) plant condition and age, and land contours and cultural practices.

CONSIDER THE PREVAILING FROST CONDITIONS

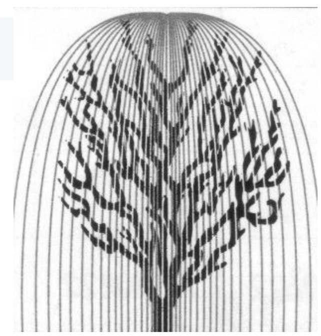
- Minimum temperatures and expected duration
- Occurrence and strength of inversions
- Soil conditions and temperatures
- Wind directions and changes
- Probability of cloud covers
- Dew point temperatures
- Critical bud/plant temperatures
- Perennial (tree/vine) and annual (vegetable) plant condition and age
- Land contours
- Cultural practices

The rate at which water is to be applied (gpm/ac) is a major design consideration. The radiant heat loss from an unprotected crop at night is in the range of *0.83 to 1.5 million BTU per ac each hour* assuming a night sky temperature of about -20°F and plant temperature of 32°F. Heat losses during an advective/air mass freeze event are *usually larger*. An application of water at *0.08 in./hour (36 gpm/ac) releases 2.6 million BTU per ac each hour* if it all freezes. Likewise, an application rate of 0.15 iph (68 gpm/ac) can provide 4.9 million BTU/ac/h.

Also, how water is to be applied is an important design consideration. Both overcrop and under-canopy irrigation systems are used for frost protection. With either, water must supply enough heat to compensate for losses due to radiation, convection, and evaporation. Overcrop (or over-canopy) sprinkler irrigation applies water to the crop surfaces. Most of the heat is released as the water freezes on the plant (i.e., latent heat of fusion which releases *1200 BTU per gallon or 144 BTU per pound of freezing water*). In contrast, under-canopy irrigation applies water beneath the canopy of tree crops, heating the air primarily due to the fact that the applied water is warmer than the cold surrounding air (i.e., sensible heat which releases only *8.4 BTU per gallon per degree Fahrenheit or 1 BTU per pound per °F of cooling water*). Water will release the same amount of heat when it freezes as it will when it cools by *144°F*.

The efficiency of heat retained in the canopy (potential versus actual for frost protection) depends on the design of the sprinkler system and how it is operated. Higher efficiencies are obtained by using sprinklers that produce larger drops, which limits evaporation and fights wind (e.g., resists skewing of the distribution pattern), and that either rotate relatively fast (e.g., impacts with frost "packages") or that throw water in all directions (e.g., Wobblers), tending to keep all surfaces wet all the time. Even with the best of systems, some of the potential heat is lost by convection and evaporation, and as heat trapped in the liquid water that infiltrates into the soil or runs off the field. Efficiencies range from only 15 percent up to about 60 percent.

Over-crop sprinkling



Over-crop (or over-canopy) sprinkling provides frost/freeze protection for both tall and short growing crops, and for both types of frosts. Drawbacks include the very large amounts of water required, possible physical crop damage due to ice buildup, and problems with disease control, nitrogen leaching on sandy soils, and other soil water management issues due to the large volumes of applied water.

With over-crop sprinkling systems, water is applied directly to the surface of the plant where much of it can freeze and release heat (latent heat of fusion). Continual freezing of the *continually applied water* keeps the temperature of an ice-water mixture at 31° to 32°F. If the ice-water mixture is not maintained, the temperature of the ice-covered plant tissues can quickly fall to the wet-bulb temperature (approximately the dew point temperature) due to the cooling of droplets by evaporation. This could result in severe damage if the wet-bulb temperature is below the critical temperature.

Adequate levels of protection require an application rate of *50 to 80 gpm/ac* (0.11 to 0.17 iph) of water, to the entire field, for the duration of the frost event. (The 50 gpm/ac value is for sprinklers like Wobblers that discharge water in all directions all the time and that produce large drops, while the 80 gpm/ac value is for sprinklers like most impact heads that discharge water as a stream that rotates.) These rates provide protection down to about 24°F when there is little wind and the dew point 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/h for every dew point degree lower than 22°F. Higher application rates provide protection to lower temperature levels and in windy situations, while lower application rates provide correspondingly less protection. When the system is working *correctly, the ice will be wet and relatively clear. Milky-colored or opaque ice indicates inadequate* application rates and/or application methods.

When over-crop systems are used for frost protection, the entire field must be sprinkled at the same time. Usually, power requirements for pumping will be in the range of 3 to 5 HP per acre. The power source must be reliable. Internal combustion engine power is recommended rather than electrical power. If electric power is used, a standby generator is advisable. Also, substantial and reliable sources of water are required to supply over-crop needs for extended periods (e.g., 8 to 10 hours/night for 2 to 3 days in a row). Application uniformity should be high (e.g., 80 percent). Plant covers can be used in combination with over-crop irrigation to provide maximum protection and/or reduce the amount of water required. Wind machines should never be used with over-crop sprinkling systems.

When over-crop sprinklers, particularly impact sprinklers, are first turned on there may be an evaporative dip for a short time. This drop in the ambient air temperature is due to cooling of the sprinkler droplets to their wet-bulb temperature. The recovery time and the extent of this dip depend on the wet-bulb temperature of the air (and the speed of rotation of the sprinkler and the size of drops). *A low wet-bulb temperature requires that the over-crop sprinklers be turned-on at a higher ambient temperature*.

Suggested system turn-on temperatures based on measured wet-bulb temperatures (°F)	
Starting/turn-on temperature	**Wet-bulb temperature**
34	26
35	24-25
36	22-23
37	20-21
38	17-19
39	15-16

When turning off over-crop sprinkler systems after a frost event, the safest option is to wait until all the ice is gone. Otherwise, on sunny, clear mornings wait until liquid water is running freely between the ice and the plant, and the ice easily falls off branches or foliage with gentle shaking. If the morning is cloudy or windy, 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.

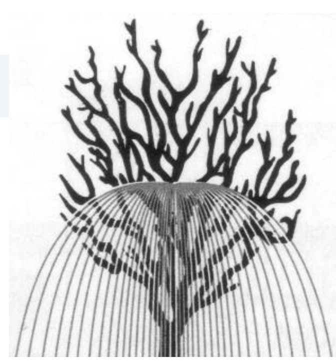
To reduce the amounts of water required, some growers have attempted such practices as *wide spacing of sprinkler heads or cycling of water applications.* However, these techniques have a **very high level of risk** and they ***should be avoided***.

Overtree misting

Also, some growers have installed over-tree microsprayer misting systems for frost protection as a way to reduce water requirements. These should not be confused with very high pressure (> 200 psi) systems that produce thick blankets of very small suspended water droplets in the 10-micron size range that fill an orchard with dense fogs several feet thick. Typically microsprinkler or misting systems produce droplet sizes that are about 100 times larger than fog droplets, and their suspended vapor layers are not sufficiently thick to offer a protection benefit.

Over-tree microsprayer misting systems are ***not recommended*** for frost protection. *There is absolutely no scientific evidence that these misting systems trap heat, reflect heat, or dam cold air away from a field*. They do not apply adequate water amounts to provide sufficient heat for bud/flower protection, and they *should be avoided.*

In-tree sprinkling



To limit limb breakage and other damage to deciduous fruit trees caused by ice build-up, in-tree sprinkling is sometimes used. A microsprinkler or jet is placed in the canopy of each tree, about 2/3 to 3/4 of the tree height above the soil surface. More ice builds up on the inner parts of the tree than on the outer parts, allowing the tree to withstand a heavier ice load without damage.

In-tree sprinkler systems are the same as over-crop sprinkling systems except for the placement of, and maybe the type and number of, sprinklers. Both systems are operated the same, and they require the same amounts of water.

Targeting water applications

One method of over-tree/over-canopy sprinkling that reduces total water supply requirements and still provides protection is called targeting. This technique uses the over-crop water applications to apply water only to the canopy of the plant (using one microsprinkler (e.g., Flipper) per plant or every other plant. The water actually applied on the plant must still be in the range of 0.15 to 0.18 in/h, depending on the amount of protection needed. The total area in the field that receives water is reduced, which reduces the total water needed.

A risk associated with targeted applications, particularly under low dew point temperature conditions and especially when less than 50 percent of the total area is wetted, is that significant damage may result because of high evaporation losses (cooling). And, the same physical rules apply for targeting as for conventional overhead sprinkling; e.g., **the entire block must still be sprinkled all the time during the frost event**.

A variation of targeted and/or in-tree methods that is sometimes used on citrus, uses under-tree sprinklers (1 or 2 per tree) that are positioned at an angle to spray relatively large amounts of high quality (low salts) water up into the canopy, where it can freeze. The green leafy canopy tends to help trap the heat released from the ice formation. ***This practice is primarily intended to save the tree for future production by protecting the main structural trunk and branches, rather than to protect the existing fruit from cold damage.***

Over-crop fogging systems

Potentially, heat retention efficiency could be increased by fogging systems that produce a 20 to 40 ft or more thick fog layer with suspended droplets in the 10-micron size range. However, fogging systems have *not proven practical* because of the difficulty in containing and controlling the drift of the fogs and potential safety/liability problems (e.g., if they cross a road). In addition, currently available fogging technologies for frost protection are expensive to install and operate.

Under-canopy sprinkling

Under-canopy sprinkling for frost protection is practical on taller crops such as trees or relatively widely spaced trellised plants, if *only a few degrees (2° – 4°F) of protection is required* to keep plant tissues above their critical temperatures. Sprinklers apply water beneath the canopy of the crop. The heat released when the water is cooled (sensible heat) raises the ambient air temperature. The warmed air, in turn, heats the plant tissue (a very inefficient heat transfer process) to keep it above *critical temperature*.

The level of protection depends on the total amount of water applied over the entire area being protected. Recommended application rates range from 0.07 to 0.12 in./h (35-55 gpm/ac), which is about two-thirds the rate required for over-crop sprinkling for frost protection. Unfortunately, much of the heat released by the cooling water goes into evaporation losses or is carried away by the water that subsequently infiltrates into the soil or runs off. Most often, at least *75 percent* of the total sensible heat that is produced is lost or unavailable with *conventional under-canopy systems*. If water applications are not adequate, total heat losses *can approach 100 percent.*

Most under-canopy systems use impact sprinklers, rotators, or microsprinkler with nozzles up to 3/32 in. These are usually turned on at about 32°F, or earlier if dew points are low in order to prevent freezing of the risers and sprinkler heads. The systems can usually be turned off in the morning when the air temperature at 4 to 6 ft is above 34°F.

Misters, jets and microsprinklers can be used for under-canopy protection systems as long as the application rates are sufficient and coverage is adequate. But, efforts to create fogs do not compensate for the lack of adequate water applications, and **can decrease protection by increasing evaporation**. Dense fogs need to be about 30 feet thick, and suspended droplet sizes must be in the 10-micron range to effectively reduce radiation losses. This does not occur with microsprinkler or misting systems. Droplet sizes from microsprinklers and misters are typically about 100 times larger than fog droplets, and their suspended vapor layers are not sufficiently thick to be beneficial.

Cover crops may add to the heat captured with under-canopy sprinkling, but they should not be taller than 12 inches to avoid interfering with the operation of the sprinkler heads and/or slowing cold air drift. Under-canopy sprinkling systems are frequently used in combination with wind machines, and the heating benefits appear to be additive. They tend to have fewer disease problems and lower water requirements than overcrop systems. Also, under-canopy systems present less risk due to system failure because the applied water does not come in direct contact with the buds or other sensitive tissues.

Heated water systems

Some sites do not have the large amounts of water required for adequate frost protection. When sensible heat is to be used to control frost, a low application rate of warmer water (e.g., from water heaters, groundwater, or solar-heated ponds) gives similar results as a standard, high application rate of cool water. The lower application rates of heated water also reduce water-logging of soils and leaching of nutrients and other chemicals. Furthermore, irrigating with *preheated water* can provide heating effectiveness similar to conventional fossil fueled heaters, but usually with as little as *20 percent of the fuel usage*. The heat applied through an irrigation system is more efficient because

1) it is more uniformly applied over the field,

2) much more stays within the crop area due to its lower temperature, and

3) heat input can be quickly adjusted (at a single location) to match the ever-changing heating requirements in the field.

Note: Preheating water to temperatures greater than 120°F is not recommended for systems with plastic pipe.