FOCUS ON FROST PROTECTION

Frost definitions, history and forecasting

Weather, energy and passive frost protection

Active frost protection

Photo by Jim Garden
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Frost definitions, history and forecasting

Neil O’Connell, Joseph Connell and Richard L. Snyder

Frost protection categories
The United States has more economic losses to frost damage than to any other weather-related hazard, and unfortunately, many of those losses occur in the citrus industry. As a result, decades of trial and error as well as detailed research efforts have resulted in considerable information on both passive and active frost protection methods to minimize damage to citrus.

Passive protection methods include practices done before a frost night that reduce the potential for damage. Active protection methods, which vary in cost effectiveness, include energy-intensive practices (heaters, sprinklers, wind machines, etc.) that are used during the frost night to replace natural energy losses.

In this article, we first discuss inversions, types of frost events, frost sensitivity, and the history of citrus frost occurrences in California. Finally, we discuss frost forecasting products that are available as well as a model that growers can use to predict trends in temperature during frost nights.

Inversions, types of frost events, and frost sensitivity

Inversions
All objects with a temperature radiate energy. During nighttime, there is more upward than downward radiation, resulting in a net loss from the surface to the sky. As energy at the surface is lost to radiation, the surface and air cool. The cooling rate is fastest at the radiating surfaces (i.e. at the tops of trees and the ground surface), and the rate of cooling decreases with height above the ground. The entire temperature profile above the surface cools due to net radiation losses, but air near the surface cools faster and this leads to an inversion (i.e. the temperature increases with height). Inversions are typical of radiation frost events, which are characterized by clear skies and calm winds, but not advection frost events which are characterized by windy conditions (Figure 1).

Advection frost
An advection frost occurs when cold air blows into an area to replace warmer air that was present before the weather change. An advection frost is also called a “freeze” in some publications, but they are interchangeable terms. In this article, we will use the term “freeze”.

A freeze is associated with moderate to strong winds, no temperature inversion, and low humidity. Often temperatures will drop below 32°F (0°F) and stay there all day. Freezes are difficult to protect against, but fortunately they are rare in California’s fruit growing regions.

Whenever the wind speed is greater than about 5 mph, there is sufficient mixing of the air that either a weak inversion or no inversion forms. If the temperatures near the surface fall below a critical damage temperature and there is little or
no inversion, then most active frost protection methods are less effective. In fact, under strong wind conditions, active protection can sometimes cause more damage than good.

If the temperatures near the surface fall below a critical damage temperature and there is little or no inversion, then most active frost protection methods are less effective. In fact, under strong wind conditions, active protection can sometimes cause more damage than good.

Radiation frost

Radiation frost—or simply “frost”—is a common occurrence in California. Frost events are characterized by clear skies, calm winds, and temperature inversions. Frost events occur because of heat losses in the form of radiant energy. Under clear, nighttime skies, more heat is radiated away from an orchard than it receives, so the temperature drops. The temperature falls faster near the ground or orchard floor causing a temperature inversion to form—i.e., temperature increases with height above the ground.

If you measure high enough, the temperature will reach the point where it begins to decrease with height, known as a lapse condition. The level where the temperature profile changes from an inversion to a lapse condition is called the ceiling. A weak inversion (high ceiling) occurs when the temperatures aloft are only slightly higher than near the surface. When there is a strong inversion (low ceiling), temperature increases rapidly with height. Most frost protection methods are more effective during low ceiling, strong inversion conditions.

In an inversion, temperature increases with height up to a point. The ceiling of an inversion is the height where temperature begins to decrease with increasing height. This decrease with additional height is known as a lapse condition.

Frost sensitivity

Citrus plants are indigenous to the humid tropical regions of China, the Southeastern Asian countries including the western border areas of India and Pakistan, and the islands of the Philippines and Indonesia. Cultivation of citrus was introduced into the West Indies by Columbus, and it later spread to Florida and eventually to California.

In the tropical citrus producing regions, citrus grows continuously where warm weather prevails throughout the year, and frost injury is not a problem. In California, however, citrus is grown under a variety of weather conditions ranging from a moderate coastal climate to warm inland valleys to hot dry desert conditions, and intermittent frost events can sometimes cause severe damage. Frost protection methods are used to avoid or ameliorate freezing temperatures that can lead to injury and reduced yield.

Plants are not damaged by freezing temperature but by ice formation inside plant tissues. Ice crystals, which are large relative to plant cells, form in the space between cells. Ice crystals grow by drawing water out of the cells leading to dehydration of the cell. Subsequently, when the ice melts, the cell wall is damaged. Thus, anything that reduces the chance of ice formation inside the plant tissue helps to avoid freeze injury.

Also, any factors that resist cell dehydration help the plants to tolerate ice formation and avoid injury. It is well known that drought-tolerant plants also tend to be tolerant of frost injury because those plants tend to have more soluble solids (sugars) in their cells, and more solids work against dehydration. Thus, plant tissue that accumulates soluble solids in the hardening process (i.e., when plants are exposed to cold temperature) has more time to accumulate solutes and tends to be freeze-injury tolerant.

The longer the temperature is below the critical temperature, the more likely that ice crystals will form and cause damage. Florida studies have reported that the number of frozen fruit increases with the time the temperature remains below the critical temperature (Table 1).

Fruit damage can occur in the peel or the pulp. Peel damage occurs as moisture on the surface freezes. Following the frost event, the damaged area collapses and is invaded by decay organisms followed by premature fruit drop. Note that water spots can freeze on the peel when temperatures are above 32°F (0°C) when the dew point temperature is low. If the fruit is wet going into a light frost event night, operating wind machines to dry the fruit during the day could reduce peel damage (Figure 2). During a hard frost or freeze, juice moves from the juice vesicles and into the peel. Later, this water evaporates

<table>
<thead>
<tr>
<th>Time (hours)</th>
<th>Damage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 – 1.0</td>
<td>5</td>
</tr>
<tr>
<td>2.0 – 3.0</td>
<td>35 – 40</td>
</tr>
<tr>
<td>4.0 – 5.0</td>
<td>55 – 60</td>
</tr>
<tr>
<td>6.0 – 7.0</td>
<td>65 – 70</td>
</tr>
<tr>
<td>8.5</td>
<td>80</td>
</tr>
</tbody>
</table>

Source: Nov. 1980 “Citrus Notes”, UCCE Tulare County. Based on studies conducted in Florida.
to the atmosphere, the vesicles dry and collapse, and crystals (hesperidin) may form in 5-10 days, giving the fruit an off-flavor (Figure 3).

On frost nights, if the temperature is low enough, extracellular water freezes, drawing water out of the plant cells. If cell desiccation is limited, the water will move back into the cells as temperatures rise the next morning without causing damage. During this process the leaves will take on a black water-soaked appearance, but they regain a normal appearance as warming takes place. If desiccation is severe, cell wall damage causes cell death.

Either ice marking of the peel or internal damage of pulp can result in fruit loss as a packable unit. When frost events occur, packing houses and regulatory organizations such as the agricultural commissioner’s office initiate an intensive fruit inspection program to examine each lot of fruit harvested for the presence of damage.

Scion varieties vary in their sensitivity to frost damage. Based on records of severe frost events in Texas and California, oranges are the most frost tolerant and limes are the most sensitive. Tangelos, grapefruit, and lemons are moderately tolerant. Mandarins exhibit variable degrees of injury; Early maturing varieties should be planted in frost prone areas. Fruit should be harvested prior to the frost season (i.e. November to early December).

Rootstock has an influence on frost tolerance. As early as 1911, it was known that trifoliate orange rootstock improved frost tolerance. Navel oranges are more frost hardy

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when grown on trifoliate rootstock than on sweet orange rootstock. Rough lemon was the most susceptible rootstock, sweet orange was less tender, sour orange was fairly hardy, and trifoliate was very frost resistant. From the 1963 freeze in Florida, Cleopatra mandarin and sour orange were the most resistant rootstocks. During the severe 1990 California freeze event, trees on sour orange and trifoliate suffered the least amount of damage whereas trees on rough lemon rootstock suffered the most.

Hardening occurs when temperatures decline in the fall and the physiological activity level of the tree begins to drop. In this lowered state of activity, the tree is “hardened” and less susceptible to potentially damaging temperatures. Generally, daytime temperatures below 60°F (15.6°C) and nighttime temperatures below 40°F (4.4°C) will harden the trees. This tolerance is lost following a few days of warmer weather.

Late-season pruning tends to maintain a higher level of physiological activity as the trees enter winter; therefore, pruning activity should be completed well in advance of the frost season. For example, mature Valencia trees topped in October experienced severe splits in eight-inch scaffold branches during the 1990 freeze in the San Joaquin Valley. The application of pesticide oils to the trees can exacerbate frost injury, so avoid applications shortly before the frost season.

**Critical damage temperatures for citrus are related to:**
- Scion variety
- Rootstock variety
- Physiological activity
- Maturity of foliage, fruit
- Time of pruning
- Age of tree

Critical damage temperatures for citrus are related not only to scion and rootstock variety but also to the maturity of foliage and fruit. Mature citrus leaves can tolerate 23° to 29°F (-6.1° to -1.7°C), and dormant wood will stand 20°F (-6.7°C) for up to four hours. Immature feather growth can be damaged on a night with a low temperature as high as 30°F (-1.1°C). Young orchards cool more quickly and the trees experience lower temperatures for a longer duration than large trees in a mature orchard. Therefore, active frost protection methods should be started earlier in young orchards. Fruit that is more mature and higher in soluble solids (sugars) will withstand lower temperature as will larger fruit and fruit with a thicker peel. Critical damage temperatures for citrus fruits are listed in Table 2.

<table>
<thead>
<tr>
<th>Fruit Type</th>
<th>Temperature (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green oranges</td>
<td>28.5 to 29.5</td>
</tr>
<tr>
<td>Half-ripe oranges, grapefruit and mandarins</td>
<td>28.0 to 29.0</td>
</tr>
<tr>
<td>Ripe oranges, grapefruit and mandarins</td>
<td>27.0 to 28.0</td>
</tr>
<tr>
<td>Button lemons (up to ½-inch diameter)</td>
<td>29.5 to 30.5</td>
</tr>
<tr>
<td>Tree-ripe lemons</td>
<td>29.5 to 30.5</td>
</tr>
<tr>
<td>Green lemons (larger than ½-inch diameter)</td>
<td>28.5 to 29.5</td>
</tr>
<tr>
<td>Buds and blossoms</td>
<td>27.0</td>
</tr>
</tbody>
</table>

*Data are from the former US Weather Bureau - Fruit Frost Service.

### History of California frost events

**Frequency**

Radiation frost conditions are common in California, occurring on several nights in a typical winter - particularly in inland and desert valleys. Freeze (or advection frost) events are less common but far more damaging. On average, major freezes occur every 10 to 20 years with the most recent in December 1990. The most recent severe radiation frost events were in 1998 and 2007.

Losses due to these events are illustrated in Table 3 with information pertaining to Tulare County.

### Post-freeze remedial action

Following a frost event, proper management is required to recover from the damage. The management includes: fruit salvage, care for damaged trees, and modified cultural practices.

**Fruit salvage:** Generally, removing frozen fruit is not cost-effective unless there is some economic value. Damaged lemons and navels will substantially drop fruit on their own. Valencias and 2,4-D treated navels may drop fruit but over a longer period time. Decisions on such removal may involve consideration of the aggravation of red scale control from the presence of scale-infested fruit left on the tree or the interference of the frozen fruit with the new crop harvest. Removal of dropped fruit from the orchard floor is recommended to minimize the spread of fungal pathogens such as Septoria and Phytophthora.

**Care of frost/freeze damaged trees:** It is impossible to determine the full extent of severe frost/freeze injury for several months; therefore, avoid pruning until 6-12 months after the frost/freeze event. In severe cases, dieback may continue for the entire season and in subsequent years. Early pruning often leaves limbs that continue to die back and/or the removal of some limbs that could recover. Early pruned trees do not recover as quickly as trees pruned later. Management depends on the severity of damage as described below.

1. **Severe damage to canopy including framework branches.** Defoliation of the entire tree is likely. The recommendation is to delay pruning to allow the tree to define the limit of damage. Topping and hedging allows for rapid and relatively inexpensive removal of damaged wood. If necessary, hand pruning allows for selective removal of damaged branches for the retraining of framework branches.

2. **Severe damage where the top and crown limbs are killed but the trunk shows little injury.** No action is needed until the full extent of injury is known (usually after midsummer). Remove the entire top of the tree – cutting below all large areas of injured bark. Numerous sprouts on the trunk commonly appear by late summer. New heads of trees will develop from these sprouts. Select the uppermost good sprout and cut off the trunk just above this sprout. Slope the cut downward away from the sprout. Then, choose 2-3 other sprouts properly spaced to form a new head and favor their growth by pinching back any sprouts that crowd them. Leave all formed sprouts

### Table 2. Fruit temperatures at which freezing begins*

<table>
<thead>
<tr>
<th>Fruit Type</th>
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</tr>
</tbody>
</table>

*Data are from the former US Weather Bureau - Fruit Frost Service.

### Table 3. Details on major citrus frost events in California.

<table>
<thead>
<tr>
<th>Year</th>
<th>Estimated fruit damage Tulare County only*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>$281,000,000 **</td>
</tr>
<tr>
<td>1998</td>
<td>$291,584,133</td>
</tr>
<tr>
<td>2007</td>
<td>$418,547,000</td>
</tr>
</tbody>
</table>

* Source: Tulare County Agricultural Commissioner. ** Estimates of carry-over damage into 1991 not available.
until a balance between root and top is established. Gradually remove unnecessary sprouts.

3. **Medium damage where a considerable part of the top is killed but the trunk and main crown limbs show little damage.** Do no pruning for several months until the full extent of damage is visible. Save as much framework as possible. Cut below all serious bark injuries. When injured limbs are removed, cut back to the best available strong new shoots. In some cases, control the distribution of the framework branches using a light pruning during the first season. However, nothing is lost by delaying pruning a full year. After injured branches have been cut to new leaders, further pruning consists of gradual thinning of excessive sprouts over a period of years.

4. **Light damage where only foliage and small twigs are damaged.** No special treatment is required when light damage occurs.

**Cultural operations:** With canopy reduction from defoliation and dieback of branches, consider the following adjustments in cultural operations:

1. **Irrigation.** Water requirements of the tree are often reduced if many branches are lost. Revise your evapotranspiration (ET) estimates based upon the canopy size.

2. **Fertilization.** Adjust applications downward because the canopy is rebuilding. Consider the application of zinc and...
Foliar applications of Lo-biuret urea to the new flush.

3. Pest Management. Because of canopy regrowth, it is necessary to monitor thrips activity for damage to new flush growth.


5. Survey of Damage following 1990 freeze. A survey of growers by UC Cooperative Extension following the freeze developed the following information:
   a. Damage was least to trees on sour orange rootstock followed by trees on trifoliate. This confirmed what had been observed historically. Regrowth was also more rapid with these rootstocks.
   b. If turned off, low volume irrigation systems froze and could not be restarted.
   c. Tree damage was less where low volume systems were turned on at the beginning and never shut down during the freeze.
   d. Tree damage was less with low volume systems particularly with mini-sprinklers rather than with furrow irrigation.
   e. With little to no inversion, some wind machines were not used after the first night of protection. Estimates of the salvageable crop remaining after the first night did not justify the operation of wind machines without an inversion.

Predicting and measuring temperature

Predicting when the temperature will fall to a critical value is important for starting active frost protection methods. In addition, the duration of temperature below the critical value is important for assessing potential damage. Starting at the proper temperature is important because it avoids losses resulting from starting too late, and it saves energy by reducing the operation time when using various methods.

The first place to start is to access your regional forecast from the National Weather Service (NWS) office. Depending on the local NWS office, considerable information is available on the forecast minimum temperature and hourly trends during the night. Internet links to regional NWS Office websites are provided on the UCD website: http://biomet.ucdavis.edu under the heading “Valuable Links”.

After selecting your regional NWS Office link, click on “Weather Tables” and you can set up the ability to monitor several important weather forecast variables on an hourly interval. For example, you can see an hourly forecast of temperature, dew point temperature, wind speed, etc. during the night. Private weather forecast services also disseminate regional forecasts on the Internet. While public and private forecasts are useful, it is also a good idea to develop your own site-specific frost night temperature forecast.

During a radiation frost event night, the temperature trend tends to follow a square root function. Assuming that the predicted minimum temperature ($T_p$) is correct and it occurs at the end of the sunrise hour, the nighttime temperature trend from the temperature $T_2$, which occurs two hours after the end of the sunset hour until the end of the sunrise hour is estimated using equations 1 and 2.

\[ T_i = T_2 + b\sqrt{i - 2} \]  \hspace{1cm} (1)

\[ b = \frac{T_p - T_2}{\sqrt{n - 2}} \]  \hspace{1cm} (2)
In equation 1, \( i = 0 \) for the time at the end of the hour when sunset occurs, \( i = 2 \) for two hours after \( i = 0 \), and \( i = n \) for the end of the hour when sunrise occurs the next morning. \( T_i \) is the temperature at the end of the \( i \)th hour following the sunset hour.

Figure 4 illustrates how the temperature trend model works using data from the University of California Lindcove Research and Extension Center (LREC) during 22-23 December 1990. The figure shows that sunset occurred at 5:08 p.m. on 22 December and sunrise occurred at 7:26 a.m. on 23 December. The end of the hour when sunset occurs is 6:00 p.m. and the model begins two hours later at 8:00 p.m. The observed temperature at 8:00 p.m. is \( T_i = 28.0^\circ\text{F} \). The prediction model stops at the end of the hour when sunrise occurs. Since sunrise occurs at 7:26 a.m., predicted minimum temperature will be reached at 8:00 a.m. The National Weather Service (NWS) or a private forecast service forecasted the minimum temperature \( (T_p = 20.7) \) to occur at 8:00 a.m.. The value for \( b \) is calculated using equation 1:

\[
b = \frac{T_p - T_i}{\sqrt{n - 2}} = \frac{20.67 - 28.04}{\sqrt{14 - 2}} = \frac{-7.3}{3.464} = -2.129
\]

Then, the predicted temperature for each hour is calculated using equation 2. Table 4 shows the hourly temperature trend calculations for \( i = 2 \) to 14 using the data from Figure 4.

<table>
<thead>
<tr>
<th>( i )</th>
<th>( \sqrt{i-2} )</th>
<th>( b \sqrt{i-2} )</th>
<th>( T_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.000</td>
<td>0.000</td>
<td>28.04</td>
</tr>
<tr>
<td>3</td>
<td>1.000</td>
<td>-2.129</td>
<td>25.91</td>
</tr>
<tr>
<td>4</td>
<td>1.414</td>
<td>-3.011</td>
<td>25.03</td>
</tr>
<tr>
<td>5</td>
<td>1.732</td>
<td>-3.687</td>
<td>24.35</td>
</tr>
<tr>
<td>6</td>
<td>2.000</td>
<td>-4.258</td>
<td>23.78</td>
</tr>
<tr>
<td>7</td>
<td>2.236</td>
<td>-4.760</td>
<td>23.28</td>
</tr>
<tr>
<td>8</td>
<td>2.449</td>
<td>-5.215</td>
<td>22.83</td>
</tr>
<tr>
<td>9</td>
<td>2.646</td>
<td>-5.632</td>
<td>22.41</td>
</tr>
<tr>
<td>10</td>
<td>2.828</td>
<td>-6.021</td>
<td>22.02</td>
</tr>
<tr>
<td>11</td>
<td>3.000</td>
<td>-6.387</td>
<td>21.66</td>
</tr>
<tr>
<td>12</td>
<td>3.162</td>
<td>-6.732</td>
<td>21.31</td>
</tr>
<tr>
<td>13</td>
<td>3.317</td>
<td>-7.061</td>
<td>20.98</td>
</tr>
<tr>
<td>14</td>
<td>3.464</td>
<td>-7.375</td>
<td>20.67</td>
</tr>
</tbody>
</table>

It is important to remember that this prediction method will work only during frosts with calm, clear nights during which the temperature drops because of long waveband radiation losses from the surface. It will not work in a location subject to micro-scale cold air drainage from nearby mountain valleys or during freezes.

Note that this prediction method is fairly accurate, but it is not perfect. In Figure 4, the observed temperatures are always slightly above the predicted temperatures, but the predicted temperatures are above the observed temperatures on some frost nights. Damage could result if you rely only on the temperature prediction; the model should be used as a guide to tell approximately when the temperature will reach a critical value. Air temperature should be monitored in the orchard during the night to accurately determine and update the time to start active protection methods.

Many types of thermometers and alarms are available for use in frost protection. Each orchard should have a minimum-temperature-registering thermometer mounted in a fruit-frost shelter. The temperature is read periodically during the night for decisions on active protection start-up and for updates on the current air temperature while sprinklers, heaters, or wind machines are in operation. Minimum-registering thermometers will also record the lowest temperature during the night. During the following day, the minimum temperature is recorded and the thermometer is reset to make it ready for use.

Ice marking on leaves, 1990 Freeze. Photo by Joe Connell
the following evening. Electronic recording devices, including wireless sensors, are available for producing a record of temperatures over time.

Mobile thermometers are available for updating temperature information and predictions during the night. These include hand-held units for orchard temperature, units for measuring the internal temperature of the fruit and units that can be mounted in vehicles for recording surrounding ambient air temperature.

**Additional information**

Cooperative extension viticulture farm advisors developed some video training units on frost protection for grapevines, but much of the material is also useful for citrus growers. There are four training units available in both English and Spanish. The training units include:

- Active Frost Protection: Water
- Active Frost Protection: Wind Machines
- Passive Frost Protection
- Methods of Measuring Temperature

*Note that over-plant sprinklers are commonly used for grapevine frost protection, but over-plant irrigation of citrus for frost protection is not recommended due to limb breakage.*

The training units are available from the UC Davis Department of Land, Air and Water Resources website http://lawr.ucdavis.edu/ce_frost_protection.htm.

*All three authors are with the University of California. Neil O’Connell has been a UC Cooperative Extension farm advisor in Tulare County since 1981, dealing exclusively with citrus and avocados. In addition to his role as citrus farm advisor, O’Connell has collaborated on a number of field studies on frost protection including several projects with co-author Snyder. Joseph H. Connell has worked with citrus for 33 years as a UCCE farm advisor in Fresno and Butte counties. Dr. Richard L. Snyder is a Biometeorology Specialist, UC Cooperative Extension, headquartered in the Department of Land, Air and Water Resources, UC Davis.*

**References**


FROST PROTECTION FACTS

In the historical studies of frost protection by universities throughout the United States, a few sound facts have been established.

The science of using the upper inversion layer of heat to assist in warming the colder air at ground level has given rise to a fact that the warm air above can be mixed with the colder air by use of wind machines with the following characteristics:

Maximum protected area is 10-12 acres due to the effectiveness of the warm air before it is diminished to zero degrees. Gains will be equal to one half of the actual inversion temperature increase above ambient at plant height. This increase diminishes to zero beyond the 12-acre area.

Adding additional horsepower to attempt to gain greater acreage per machine has not proven effective. Losses due to frost damage will increase between machines that are set further apart. It has been proven that higher horsepower machines would help to some degree; however, they would have to be much taller, and a different shaft angle would also be required.

Tower heights are a standard industry-wide, set at 35 feet with a shaft angle of 6 degrees to gain maximum travel distance of the created air patterns. Foundations are standard 7 yard.

It does no good to move cold air farther with greater horsepower without proper machine design changes. These design changes have been studied and are not cost-effective for today’s market forces.

Also, the potential for greater loss of crop is definitely a concern with fewer and larger horsepower machines in the event of failure.

Recommended machine horsepowers are 10-12 horsepower per acre. Additional horsepower has proven to be more expensive and consume more fuel.

Currently, there are only 150hp engines (Ford V-10) available on the market for this industry that are certified and consume propane. However, the wind machine industry in California has an exemption from that certification by all air quality districts in the state and the governing California Air Resources Board.

Vamco Ltd., Inc. has opted to continue to offer its growers a viable alternative with the most popular Ford 460 (7.5l) propane/natural gas engine. It is far more fuel-efficient than our V-10 150hp model and is considerably less expensive to operate and maintain as it does not have the requirement of the V-10 certification which is the huge catalytic converter that is mounted externally and alongside the engine package. This is both cumbersome and a potential obstruction to other field practices. These smog devices have already become targets for thieves, as they are quite valuable.

It is highly recommended that growers use natural gas when at all possible. With today’s high fuel prices for propane and diesel, there is a huge savings to be had.

Studies over the past 5 years have provided information with regard to actual running costs. While the V-10 consumes nearly 22 gals/hr, and the 460 consumes 16 gals/hr, and the diesel consumes 6 gals/hr, the cost to run a 460 engine on natural gas is only $7.00 per hour!!

It should be noted that running an engine on natural gas does in fact reduce the available horsepower by about 5% over its propane counterpart (a negligible difference).

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Weather, energy, and passive frost protection

Richard L. Snyder, Neil O’Connell and Joseph Connell

Types of frost and sensitivity to damage

A discussion about the types of frost events and the sensitivity of citrus to frost damage is presented in the article “Frost Definitions, History and Forecasting” in this issue of Citrograph. To briefly summarize, there are two types of frost events, and the difference is mainly related to the formation of an atmospheric inversion, i.e., when the air temperature increases with height above the ground.

An “advection frost” or “freeze” occurs when the air temperature falls below 32°F (0°C) during the night, but the wind speed is high enough (usually greater than 5 mph) so that it mixes the air and there is little or no inversion formation. In a “freeze”, the temperature often stays below 32°F (0°C) even during the day, and it can continue for several days in a row.

A “radiation frost” or simply a “frost” is common in California, and these occur when there are calm winds and clear skies, an inversion forms, and the temperature falls below 32°F (0°C). Usually, the temperature will rise above 32°F (0°C) during the day following a frost event; however, frost events can occur several nights in a row.

Both freeze and frost events are associated with low humidity. In some cases, the climate conditions start as a “freeze” on the first night and change to a “frost” on subsequent nights. Most protection methods are effective against “frost” events but not against “freeze” events. Since the damage is caused by ice formation inside the plant tissue resulting in cell dehydration and cell wall damage, the terms frost and freeze damage are interchangeable. Frost events are more common in California, so we will use the term frost damage when describing the damaging effect of ice formation to citrus fruit and other plant parts. Procedures to protect against frost or freeze injury are commonly called “frost protection” methods.

Active frost protection includes energy-intensive activities such as wind machines, helicopters, and water application that raise temperatures in the orchard. Passive frost protection includes procedures that are done in advance of a frost night to reduce the need for protection by increasing heat storage or by lowering the temperature for ice formation.

Frost protection falls into the two categories “Active” and “Passive” methods. Active protection mainly includes energy intensive methods to raise the temperature in the orchard to a temperature that will result in little or no damage. For detailed information on “active” methods, see the article “Active Frost Protection” in this issue of Citrograph.

Passive protection includes procedures that are done in advance of a frost night to reduce the need for protection by increasing heat storage or by lowering the ice formation temperature. In this issue of Citrograph, the article “Frost definitions, history and forecasting” discusses variety and rootstock sensitivity to freeze injury and how to deal with injury after it occurs. This article discusses the environment, biological, and energy factors that are important for frost protection and passive methods to avoid frost damage.

Energy transfer

Energy (or heat) transfer and storage determines how cold it will get and the effectiveness of frost protection methods. The four methods of energy transfer are radiation, conduction, convection, and latent heat. Understanding these heat...
transfer mechanisms is extremely important for good frost protection management.

Radiation

Radiation is electromagnetic energy that can transfer through air or even empty space. All objects with a temperature above absolute zero radiate energy, and the amount of energy radiated depends on the 4th power of the object temperature in Kelvin units. Note that Kelvin (K) units are the same magnitude as degrees Celsius (°C), but 273 K = 0°C = 32°F. Sunlight is a good example of radiation. Because the sun is very hot (about 6000 K), considerable energy is radiated from the sun, and the Earth receives some of that energy. Radiation from the sun is called “solar” or “short waveband” radiation. The radiation received from the sun is the main source of energy for life on Earth.

The Earth is much cooler than the sun (about 315 K), but objects on Earth also radiate energy to their surroundings depending on the 4th power of their absolute temperature and emissivity properties of the object.

The ground, which is nearly a perfect emitter, at 32°F will emit about 315 W m⁻² of energy to the sky. This is about equivalent to having three 100W light bulbs per square yard on the ground. Three 100W light bulbs per square yard is the same as 14,520 100W light bulbs per acre, so there is clearly a lot of energy loss even at 32°F.

Fortunately, the sky also has a temperature, and a clear sky emits energy downward at about 210 to 230 W m⁻² when the ground is about 32°F depending on humidity. When the sky is overcast, it is warmer than a clear sky, and the downward radiation is even higher. Therefore, less radiation energy is lost on a cloudy than a clear night. Radiation at Earth temperatures is called “terrestrial” or “long waveband” radiation. If an object emits more radiation energy than it receives from other sources, it will cool. Therefore, the ground cools at night because the warmer surface emits more energy upwards than the clear sky emits downwards.

Conduction

Conduction is heat transfer from one molecule to an adjacent molecule through a solid. A good example is the transfer of heat through a metal rod. If one end of the metal...
rod is placed in a fire, the energy will transfer by conduction to the other end of the rod. Conduction and energy storage in the soil are important for determining the energy available at the ground surface, i.e., the ground heat flux. In general, any management practice that increases heat conduction and storage in the soil is beneficial for frost protection because it allows for more energy to be stored during the day.

**Ground heat flux** is the transfer of soil heat per unit area downward or upward by conduction at the soil surface. If more heat is stored in the soil during the day, there is more upward ground heat flux and more heat to protect the orchard during the night.

**Convection**

Convection is the process where a fluid, e.g. air or water, is heated and physically moves from one place to another and takes heat with it. The air has kinetic energy because it contains air molecules that are moving at near the speed of sound. The air molecules have mass and they are moving, so when they strike something, the kinetic energy is converted to other forms of energy. The kinetic energy of the air is often called sensible heat because we sense the energy (heat) when the air molecules strike our bodies and transfer energy to our skin.

The sensible heat content of the air is quantified by measuring the air temperature, which depends on the air density and the velocity of the air molecules. If the air molecules move faster, they have more kinetic energy, the air has more sensible heat, and the temperature will read higher. Air heated by smudge pots is a good example of convection. As the air is warmed by the heaters, it becomes less dense, rises and mixes with colder air above, increases the sensible heat content, and raises the orchard temperature. It is called “natural” convection because the warmed air expands; it becomes less dense than the air above; and, it naturally rises.

Forced convection occurs when wind rather than density differences moves the air around. Using wind machines is an example of “forced” convection because the fans “force” warmer and colder air to mix and increase the sensible heat content of air within an orchard.

**Latent heat**

When water condenses, cools, or freezes, the temperature of the environment rises because latent is changed to sensible heat. Latent heat is chemical energy stored in the hydrogen bonds that join water molecules together. When ice melts, water warms, or water evaporates, the air temperature drops because sensible heat is used to break the hydrogen bonds between water molecules. This causes a change from sensible to latent heat. When the water condenses, cools, or freezes, latent heat is changed to sensible heat and the air temperature rises. Table 1 shows the amount of heat consumed or released per unit mass for each of the processes.

**Table 1. This table shows energy exchanges between latent and sensible heat in calories or energy per gram mass of water (cal. per gram) and in Joules of energy per gram mass of water (J. per gram). Positive signs indicate that the water is condensing, cooling, or freezing and energy is converted from latent to sensible heat (i.e. the air is warming). Negative signs indicate that sensible heat is converted to latent heat (i.e. the air is cooling).**

<table>
<thead>
<tr>
<th>Process</th>
<th>Cal. per gram</th>
<th>J. per gram</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water cools from 20°C (68°F) to 0°C (32°F)</td>
<td>+20.0</td>
<td>+84</td>
</tr>
<tr>
<td>Water freezes at 0°C (32°F)</td>
<td>+79.7</td>
<td>+334</td>
</tr>
<tr>
<td>Ice cools from 0°C (32°F) to -5°C (23°F)</td>
<td>+2.5</td>
<td>+10</td>
</tr>
<tr>
<td>Water evaporates at 0°C (32°F)</td>
<td>-597.3</td>
<td>-2501</td>
</tr>
<tr>
<td>Water condenses at 0°C (32°F)</td>
<td>+597.3</td>
<td>+2501</td>
</tr>
<tr>
<td>Water sublimates (ice to water vapor) at 0°C (32°F)</td>
<td>-677.0</td>
<td>-2835</td>
</tr>
<tr>
<td>Water deposits (water vapor to ice) at 0°C (32°F)</td>
<td>+677.0</td>
<td>+2835</td>
</tr>
</tbody>
</table>

1 Joule = 0.2388 calories

**Frost night energy budgets**

On all nights, energy is lost from the surface through upward terrestrial radiation from the surface, and the rate of energy loss is greater for higher surface temperatures. Surface energy is gained by: (1) downward terrestrial radiation from the sky, which depends on integrated sky temperature, (2) conduction of heat upward from the soil to the surface, and (3) convection of warmer air downward to the colder surface.

The integrated sky radiation depends on the weighted mean temperature of the entire atmosphere that is exposed to the surface. Since the sky is always colder than the surface temperature, there is less downward than upward terrestrial radiation and the net terrestrial radiation is always negative. During daylight hours, net radiation includes both solar and terrestrial radiation, and it is given a positive sign when energy is being added to the surface and a negative sign when there is a net energy loss from the surface. During nighttime, there is no solar radiation and the upward is greater than downward terrestrial radiation, so the net radiation (\(R_s\)) is negative.

**Thermal conductivity** is a property of the soil that determines how fast heat will transfer in response to a temperature gradient. It depends on soil characteristics and water content. **Heat capacity** quantifies the amount of energy needed to raise a unit volume of soil by one degree of temperature. It depends on soil characteristics and water content.

The conduction of soil energy varies with depth in the soil due to soil and water characteristics. For frost protection, the conduction at the ground surface, i.e., “ground” heat flux or “G”, is important. For optimal protection it is best to have high thermal conductivity and high heat capacity. Thermal conductivity quantifies the rate that energy transfers through the soil and the heat capacity refers to how much energy is needed to raise the temperature by one temperature unit.

The convective heat flux at the surface is called the “sen-
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sible” heat flux with the symbol “$H$”. The reason that the air temperature drops during the night is because the air is transferring heat to the surface to partially replace the surface energy losses to net radiation. The idea behind most active methods of frost protection is to try to replace the sensible heat loss from the air by using water, heaters, wind machines, etc. On a clear, calm night, the downward sensible heat flux is about 50 W m$^{-2}$, so replacing that amount of sensible heat loss would normally stop the air temperature from dropping.

If the net radiation is less negative, the transfer of sensible heat to the surface is reduced and the air will cool more slowly. Similarly, if there is more ground heat flux to the surface, i.e., a more negative $G$, then there will be less transfer of sensible heat from the air and the temperature will cool more slowly. Thus, any weather or management factor that reduces the magnitude of the net radiation loss or increases the magnitude of the negative ground heat flux is beneficial for frost protection.

Assuming no phase changes, e.g., dew or frost formation, the net radiation must equal the sum of the ground and sensible heat fluxes. The more negative the net radiation, the more downward sensible heat transfer is needed to replace the lost energy and the faster the air temperature drops. When it is clear, the sky is colder, the downward radiation is less, and the net radiation is more negative; implying a bigger radiation loss of surface energy. Consequently, the surface temperature drops faster on a clear than a cloudy night.

Table 2 shows a typical nighttime energy balance for a range of cloud cover conditions. During a typical radiation frost night, the upward ground heat flux is generally about 50% of the net radiation and the downward sensible heat flux is also about 50% of the net radiation. However, improving the transfer and storage of soil heat can increase the upward ground heat flux and reduce the downward sensible heat flux. Under cloudy or foggy conditions, the downward radiation is increased because the temperature of the clouds or fog is higher than for clear skies. This leads to more downward terrestrial radiation, less negative net radiation, and lower values for the ground and sensible heat flux to the surface (Table 2). Thus, radiation frosts are less likely when skies are overcast.

<table>
<thead>
<tr>
<th>Energy Transfer Method</th>
<th>0% Clouds</th>
<th>33% Clouds</th>
<th>67% Clouds</th>
<th>100% Clouds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conduction (from the soil)</td>
<td>-53</td>
<td>-28</td>
<td>-10</td>
<td>-1.5</td>
</tr>
<tr>
<td>Convection (from the air)</td>
<td>-53</td>
<td>-28</td>
<td>-10</td>
<td>-1.5</td>
</tr>
<tr>
<td>Downward Radiation</td>
<td>+209</td>
<td>+259</td>
<td>+295</td>
<td>+312</td>
</tr>
<tr>
<td>Upward Radiation</td>
<td>-315</td>
<td>-315</td>
<td>-315</td>
<td>-315</td>
</tr>
<tr>
<td>Net Radiation</td>
<td>-106</td>
<td>-56</td>
<td>-20</td>
<td>-3</td>
</tr>
</tbody>
</table>

Wind is a factor in frost protection because it mixes the air and increases the amount of energy transferred from the air to the crop. When wind speeds increase to more than 5 mph (2.2 m s$^{-1}$), the increased convective heat transfer is often great enough to balance the radiation heat losses, and radiation frosts are unlikely. Normally, when freezing temperatures occur under windy conditions, the event is an advection rather than a radiation frost event. Latent heat is only a factor when water is present, so it is generally ignored except when irrigation is used for frost protection.

**Humidity**

Humidity is an important factor in frost protection because of phase changes, which convert sensible to latent (evaporation) or latent to sensible (condensation) heat and because moist air absorbs more radiant energy. When the surface temperature drops to near the dew point temperature, con-
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densation can occur releasing latent heat and reducing the rate of temperature drop. Also, air with high water vapor content absorbs more upward terrestrial radiation, and thus air with higher humidity cools slower than drier air.

**Wet-bulb temperature:** If water evaporates into the air and the only source of energy for the evaporation is sensible heat in the air, the sensible heat decreases, so the temperature drops, and the water vapor content increases due to evaporation. When the air reaches 100% relative humidity, the temperature is at the wet-bulb.

**Dew point temperature:** If the air is cooled without changing the water vapor content of the air, the relative humidity will increase. When it reaches 100% relative humidity, the temperature of the cooled air will be at the dew point.

Cold, dry wind increases evaporation rates from wet surfaces and can cool wet plant parts to damaging temperatures. If an object is wetted and not rewetted during a frost night, it will cool to approximately the wet-bulb temperature, which is the temperature measured with a wet-bulb thermometer in a psychrometer (Figure 1). The wet-bulb temperature is always between the air and dew point temperatures, and it falls lower as the dew point decreases. Even when the air temperature is above 32°F (0°C), wet plants can have ice formation if the dew point is sufficiently low that the wet bulb temperature is below 32°F (0°C).

Spot damage or “ice marking” on citrus and other fruit is sometimes attributed to wet spots on fruit that were cooled to damaging temperatures because evaporation caused cooling of the wet spots to the wet-bulb temperature.

The dew point temperature is defined as the temperature at which the air becomes saturated with water vapor (reaches 100% relative humidity) when the air is cooled by removing sensible heat without changing the water vapor content of the air. When the air temperature is at the dew point, the number of water molecules evaporating from a pure, flat water surface is equal to the number condensing onto the surface.

The dew point is important in meteorology because it is directly related to the amount of water vapor in the air and it can be used to determine other humidity variables (e.g., vapor pressure, relative humidity, wet bulb temperature, and vapor pressure deficit) that are often used in agriculture. In addition, the dew point temperature is often used to predict the next morning’s minimum temperature. Consequently, it is extremely important for frost protection.

A simple method to measure the dew point temperature involves cooling a surface until water vapor begins to condense on the surface. This is the principle used in a chilled-mirror hygrometer, which is used to measure the dew point. Unfortunately, a chilled mirror hygrometer uses complicated electronics to measure the dew point temperature and therefore it is expensive. A simple, inexpensive method involves using a shiny can, a thermometer, and ice water as shown below.

**Dew point Temperature**

Slowly add ice cubes to the water to lower the can temperature. Stir the water with a thermometer while adding the ice cubes to insure the same can and water temperature. When condensation occurs, note the dew point temperature.

**Fig. 2. A simple method for determining dew point temperature.**

When the dew point is below 32°F, adding salt to the ice water can lower the temperature to identify the dew point temperature.

During low dew point, freezing conditions, since an ice-water mixture will only chill the can to 32°F, it is sometimes difficult to get the water cold enough for condensation to occur on the outside can surface. Adding salt to the ice-water mixture will help to melt the ice and cool the water to a lower temperature with a potential minimum of approximately 18°F. When the dew point temperature is well below freezing, sometimes white frost rather than dew will form on the outside of the can. When this occurs, you have measured the “frost point” rather than the dew point temperature. For the same vapor pressure, the frost point temperature will be slightly higher than the dew point temperature. However, for most agricultural operations, there is little difference and they can be used interchangeably.

**Humidity conversions**

The equations for converting humidity expressions are typically given using the metric system and degrees Celsius. To convert from degrees Fahrenheit (°F) to degrees Celsius (°C), use the following equation:

\[ °C = \frac{5}{9}(°F - 32) \]  

Example: \[ °C = -5 = \frac{5}{9}(23 - 32) \]
To convert from the dew point temperature ($T_d$) in °C to other expressions for humidity, first calculate the vapor pressure ($e$) expressed in kilopascals (kPa), where 1.0 kPa = 0.145 psi (pounds per square inch).

$$e = 0.6108 \exp \left( \frac{17.27T_d}{T_d + 237.3} \right) \text{ kPa} \quad (2)$$

where $\exp()$ is the exponential function in a computer program or $e^x$ on a calculator.

Example: For $T_d$=23°F=-5°C: $e = 0.421 = 0.6108 \exp \left( \frac{17.27(-5)}{-5 + 237.3} \right)$

Note that 1 Atmosphere of barometric pressure is the same as 101.325 kPa or 14.7 psi. To calculate the saturation vapor pressure ($e_s$) in kPa at air temperature ($T$) in °C, use the following equation:

$$e_s = 0.6108 \exp \left( \frac{17.27T}{T + 237.3} \right) \text{ kPa} \quad (3)$$

Example: For $T$=41°F=5°C: $e = 0.872 = 0.6108 \exp \left( \frac{17.27(5)}{5 + 237.3} \right)$

At the saturation vapor pressure, the number of water molecules vaporizing equals the number condensing onto a flat surface of pure water. The saturation vapor pressure is only a function of temperature, and equation 3 is a simple formula for calculating the saturation vapor pressure from the air temperature ($T$). Relative humidity ($RH$) is calculated as:

$$RH = 100 \left( \frac{e}{e_s} \right) \% \quad (4)$$

Example: For $e$=0.421 kPa and $e_s$=0.872 kPa  $RH = 48.3 = \frac{0.421}{0.872}$

If $RH$ and $T$ are available, the vapor pressure ($e$) is calculated using $T$ and equation 3 to determine $e_s$ and

$$e = \left( \frac{RH}{100} \right) e_s \text{ kPa} \quad (5)$$

Example: For $RH$=48.3% and $e_s$=0.872 kPa  $e = 0.421 = \left( \frac{48.3}{100} \right) 0.872$

The dew point temperature $T_d$ (°C) is calculated from the vapor pressure ($e$) in kPa by first calculating:

$$b = \ln(e/0.6108) \quad (6)$$

where $\ln()$ is the natural log function, which is found in computer programs and on most calculators and then calculating the dew point as:

$$T_d = 237.3 \left( \frac{b}{1-b} \right) \text{ °C} \quad (7)$$

Example: For $e$=0.421 kPa  $b = -0.02155 = \frac{\ln(0.421/0.6108)}{17.27}$

and  $T_d = -5.0 = 237.3 \left( \frac{-0.02155}{1-(-0.02155)} \right)$

Use Eq. 8 to convert from $T_d$ (°C) to $T_d$ (°F).

$$^oF = \frac{9}{5}(^oC) + 32 \quad (8)$$

Example: For $T$=5°C:  $^oF = 41 = \frac{9}{5}(5) + 32$
Phase changes

For phase changes from water vapor to liquid water and from liquid water to ice, latent heat is converted to sensible heat and the temperature rises. For phase changes from ice to liquid water and from liquid to water vapor, sensible heat is removed from the air to break the hydrogen bonds. The sensible heat is converted to chemical energy or “latent” heat as the water vapor content of the air increases and the temperature decreases. The latent is converted back to sensible heat when the water molecules condense out of the air. The energy needed to convert between the different phases of water in both directions is given in Table 1. Phase changes are important when using water for frost protection.

From Table 1, it is clear that cooling 1 gram of water from 68°F to 32°F (20°C to 0°C) will release about 20 calories of energy and freezing it at 32°F (0°C) will convert about 80 calories of energy from latent to sensible heat. Thus, cooling and freezing 1 gram of water will release 100 calories to warm the environment. On the other hand, evaporating 1 gram of water at 32°F (0°C) will convert about 600 calories of energy from sensible to latent heat, which cools the environment. Consequently, to break even, one must cool and freeze about six times more water than is evaporated:

\[ 6 = \frac{600}{20 + 80} \text{ calories}. \]

Fortunately, evaporation rates are low during frost nights, and sufficient water can usually be frozen to supply more energy than is lost to evaporation. A higher application rate is needed to compensate for greater evaporation on nights with high wind speeds and low dew points.

Ice nucleation

Water melts but it does not necessarily freeze at 32°F (0°C). For freezing to occur, either “homogeneous” or “heterogeneous” nucleation must occur. When the water temperature is below 32°F (0°C), the energy is unstable and homogeneous freezing can occur because agitation causes ice crystals to form. As the super-cooled water temperature decreases, the energy state becomes increasingly unstable and freezing is more likely to occur. Water can also freeze if ice-nucleation-active (INA) particles are introduced triggering ice crystal formation (heterogeneous nucleation). The main source of ice-nucleating materials on crop plants is bacteria, and they are most effective in the 23° to 32°F (-5º to 0ºC) temperature range. The potential for frost damage decreases as the concentration of ice nucleating bacteria is reduced. This may be accomplished using copper bactericides (although some INA bacteria are copper resistant) or by applying competitive non-INA bacteria. While this method is known to work, it is not widely used for frost protection of citrus, which harbors relatively low concentrations of INA bacteria.

Air temperature and dew formation

There are actually more molecules of air in a cubic meter than the number of stars that we know in the Universe. In addition, the air molecules commonly move at about the speed of sound. Because they move fast, they often have
collisions, so they generally don’t travel very far. When air molecules strike your skin, they transfer energy to your skin, and you sense those collisions as heat, so this type of energy is called “sensible heat”. You don’t feel the air molecules striking your skin because they are extremely small. They do, however, make you feel warmer because there are a lot of them and they constantly impart small amounts of energy to your body.

The sensible heat content of the air is quantified using a thermometer to measure temperature. When the air temperature rises, the air molecules move faster, more will strike a thermometer, more energy is transferred, and the thermometer temperature reads higher. When the temperature cools, the air molecule are moving slower, fewer will strike the thermometer, and the thermometer reading drops.

When the surface temperature cools until the air becomes saturated, dew will form. Water vapor molecules, like those in other gases, have a velocity near the speed of sound, and they continually strike nearby surfaces. When the surface air temperature is at the dew point, the same number of water molecules will condense onto a surface as evaporate from the surface. Dew forms when the number of water molecules striking the surface and forming hydrogen bonds with other water molecules is slightly greater than the number of molecules breaking hydrogen bonds and separating off as a gas.

Technically, the dew point is defined as the temperature reached when air is cooled, without changing the water vapor content of the air, until the air becomes saturated with water vapor. Once the surface temperature reaches the dew point and dew starts to form on the surface, a slower air temperature drop results as the latent heat changes to sensible heat and replaces some of the energy lost to radiation.

**Passive frost protection methods**

**Site selection**

Site selection is the single most important frost protection decision. Since cold air is denser than warm air, during radiation frost events it flows downhill and accumulates in low spots. These low cold areas should be avoided when seeking a subtropical orchard site. The tops of hills are prone to frost damage during advection frosts. In general, it is best to plant on slopes where cold air can drain away from the orchard.

Subtropical trees are best planted on south-facing slopes where the soil and the orchard can receive and store more direct energy from sunlight. It is wise to plant rows in a downhill direction to allow cold air to drain through the orchard. Cold air drains downhill much like water, so any vegetation, buildings, etc. that block the down slope flow of cold air and force it to back up into the orchard will increase frost damage potential. There are examples where berm walls, fences, etc. have been used to funnel cold air around orchards reducing the potential frost damage.

The most severe freezes often occur during micro-scale advection when cold air drains into an orchard. Cold air can accumulate in canyons upslope from orchards when the cold air is prevented from draining into the orchard by prevailing winds. If these winds stop, the cold air can drain into the orchard and cause damage. These micro-advection freezes occur frequently in California and they cause considerable damage. Real-time
measurements in the upslope canyons can identify potential problems. In some cases, helicopters or some other method of frost protection can reduce or eliminate cold accumulation in the upslope canyons and prevent damage in the orchards below.

Investigation of a possible site for an orchard should include a review of any available temperature records during frost episodes and any records on the extent of damage. Temperature recording stations can be situated at the site being considered during the winter to document minimum temperatures and the durations. This information not only provides spatial minimum temperature data but it can also be compared to a nearby reference weather recording station to improve frost forecasting.

Soil tillage and water content
Heat absorption and storage is enhanced by a firm, undisturbed soil surface, so fall tillage should be avoided. If tillage is necessary, it should be done early enough to allow the soil to settle and firm up before the arrival of the frost season.

Thermal conductivity and the 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 foot (0.3 m) of soil. When the soil is near field capacity, heat transfer and storage in the upper soil layer is better, so more heat is stored during daylight for release during the night. Field capacity is the water content after gravitational water has drained from the soil (usually 1-2 days after rainfall or irrigation).

Considerable differences between thermal conductivity and heat capacity are observed between dry and moist soils. If the soil water content is near field capacity, additional wetting of the soil is unwarranted. Wetting the soil to a depth below one foot is unnecessary because temperature variation is insignificant below that depth. On an annual basis, however, heat transfer below one foot is important and could affect frost protection if a soil profile is dry for a long period of time. Therefore, wetting is prudent when the soil is dry for several weeks prior to frost season.

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

A typical cultural practice is for tree prunings to be stacked between the tree rows and shredded in place. Research in a Kern County orchard during a frost episode where a thick layer of shredded orchard prunings was present on the orchard floor demonstrated that the mulch caused lower nighttime temperatures than where the prunings had been removed.

Large variations in ice nucleating bacteria concentrations have been observed on different crops. The concentrations of INA bacteria on citrus are low. However, the concentration of ice nucleating bacteria on grass and weed ground covers is typically high. Therefore the presence of ground cover within orchards or cereal crops around orchards increases the concentration of INA bacteria and the freezing potential.

Covers
In home orchards, covers are sometimes used to decrease the net radiation and convection energy losses from a tree reducing the potential for frost damage.
Mulches

Clear plastic mulches that increase heat transfer into the soil typically improve heat storage and hence provide passive frost protection. Black plastic mulch is less effective for frost protection than clear plastic. Wetting the soil before covering with clear plastic provides the best heat storage and protection. If there is doubt about whether to keep or remove plastic mulch from an orchard, a simple test measuring the minimum surface temperature on covered and non-covered ground will determine which is coldest.

Tree wraps

On young trees, tree wraps block light from reaching the trunks, inhibit unwanted suckers from developing on the trunk, and prevent sunburn during the summer. They also protect the bark from sprays used in weed control, and provide some protection from frost. Wraps are most effective during short duration frost episodes. Florida researchers have reported temperature increases of 4° to 8°F (2.2° to 4.4°C) from using rigid polystyrene (thick-walled) foam, and 3° to 6°F (1.7° to 3.3°C) for fiberglass and polyurethane wraps. Protection was less for rigid polystyrene (thin-walled) and closed-cell polyethylene foam.

Summary

This article discusses the basic concepts of weather and energy balance, which are important for frost protection, and provides some guidelines on passive methods of frost protection. Passive methods, including site selection, soil water management, ground cover and mulch management, tree wraps, etc., are discussed.

In general, choosing orchard sites that are less prone to freezing temperature is perhaps the best protection method. Removing objects that block cold air drainage is extremely important for existing orchards. The use of fences and berm walls to control cold air drainage can be beneficial in some locations depending on topography. If the soil is dry, then wetting the upper one foot of soil can improve soil heat storage and can provide protection. The soil should be wetted a few days prior to an expected frost event to improve daytime heat storage. In most cases, ground covers increase the potential for frost damage and should be removed at least during frost season. Tree wraps can provide protection for young trees if the right materials and procedures are used.

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References

Active frost protection

Joseph Connell, Neil O’Connell and Richard L. Snyder

Introduction

In this issue of Citrograph, types of frost events and the sensitivity of citrus to frost damage are presented in the article “Frost definitions, history, and forecasting”, and passive protection methods are discussed in the article “Weather, energy, and passive frost protection”.

Freeze or advection frost events are associated with freezing temperatures and wind speeds greater than 5 mph. These are rare in California, and most active protection methods are relatively ineffective during a freeze event, so this article will emphasize methods to protect against “radiation frost” or simply “frost” events.

Note that the damage to plants from freezing temperatures is caused by ice formation and dehydration of plant cells that leads to cell wall damage regardless of whether the event is a frost or a freeze. Since freeze events are rare in California, plant injury from ice formation will be called “frost” damage in this article, and protection methods will be called “frost” protection.

Frost events, which are common in California, occur on nights with freezing temperature, calm winds, clear skies, and inversions where temperature increases with height above the ground. Passive protection involves cultural management that is done in advance of a frost night that reduces the need for active protection and reduces the possibility of injury due to freezing temperature. It includes ground cover, soil, water, and ice nucleation active (INA) bacteria management as well as good site selection, insulation and covers.

In this article, we discuss the use of energy-intensive methods, e.g., wind machines, irrigation, etc., to replace sensible heat losses resulting from a net loss of radiation energy during the night.

Active frost protection methods

Wind machines

Wind machines provide protection by increasing the mixing of warmer air aloft with cold air near the surface, resulting in an increase in the orchard temperature (Figure 1). The amount of protection afforded depends on the inversion strength that would occur without using the wind machines.

In general, the temperature increase in an orchard, after starting the machines fans, is about equal to the sum of 1/3 of the difference between the 5-foot and 40-foot (1.5 and 12.2 m) measured temperatures. For example, if the temperature at 40 feet is 9°F higher than the 5-foot temperature, the 5-foot
temperature should rise by about $3^\circ F = 9^\circ F / 3$ after starting the fans. When using wind machines for frost protection, the fans should be started when the temperature measured at the 5-foot height reaches the critical damage temperature.

In general, one wind machine is recommended for each 10 acres, but the number can be increased in strongly frost-prone orchards. The effectiveness of the wind machines increases when there is a strong inversion with a low ceiling such that the temperature increases rapidly with height.

In an inversion, temperatures increase with height up to a point. The ceiling of an inversion is the height where temperatures begin to decrease as you go even higher.

It is important to test your orchard for inversion strength before investing in wind machines. This can be done by mounting electronic thermometers on a pole in the orchard at 5 and 40 feet in height. Keep temperature records at the two heights on clear, calm nights. The inversion strength is the difference in the upper and lower temperature; the larger the difference, the stronger the inversion. Helium-filled balloons can be used to measure the upper temperature. Tie an electronic thermometer or a minimum recording thermometer to the balloon and raise it to about 40 feet in height. Compare the temperature difference between 5 and 40 feet to determine the inversion strength.

**With Wind Machine**

![Graph showing temperature profile with and without wind machine](image)

**Fig. 1.** This figure shows the effect of wind machine operation on the temperature profile during a radiation frost event.

**Helicopters**

In an inversion, helicopters push warm air aloft down to the surface. If there is little or no inversion, helicopters are less effective. The area covered by a single helicopter depends on the helicopter size, weight, and weather conditions. Pilots load helicopter spray tanks with water to increase the weight and provide more thrust. 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 orchard every 30 minutes during mild frosts and more often during severe frosts.
Thermostat-controlled lights at the top of the canopy are used to help pilots see where passes are needed. Downward heat transfer continues to move down-slope after reaching the surface, so concentrate flying on the upper end of orchards on slopes. 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 orchard temperature and communicate with the pilot where flights are needed. Lights around the orchard perimeter are beneficial to help the pilot. Flights are stopped when the air temperature upwind from the orchard has risen above the critical damage temperature.

Sprinklers
When sprinklers are first started, the air temperature can initially drop to as low as the wet-bulb temperature, and wet plant surface temperatures can drop to the wet-bulb temperature to around 32°F. When using the system for frost protection, the sprinklers should be started when the wet-bulb temperature ($T_w$) is above the critical damage temperature ($T_c$) on the first night of a series of frost nights. If freezing conditions persist for several nights, the sprinklers can be stopped during the day if $T_w > 32°F (0°C)$, but they must be started when $T_w > 32$ on nights following the initial frost night. If the sprinklers are wet and the wet-bulb temperature is below 32°F (0°C), the heads can freeze up and become nonfunctional. Do not turn off the sprinklers during the day unless the sun is shining on the crop and the wet-bulb temperature exceeds 32°F (0°C).

The wet-bulb temperature can be measured directly with a psychrometer (see Figure 1 on p. 30). For direct wet-bulb temperature measurements, a cotton wick on the wet-bulb thermometer is wetted with distilled or de-ionized water and air is moved across the wick until the temperature of the wet-bulb thermometer stabilizes. Ventilation is accomplished by swinging a sling psychrometer; if using an aspirated psychrometer, air is blown across the wetted bulb by an electric fan. If the temperature is below 32°F (0°C), 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 frost-bulb and wet-bulb temperatures exist for temperatures below the 32°F 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 ice than to a water surface. For a given water vapor content of the air, the frost-bulb will be slightly higher than the wet-bulb temperature.

If a psychrometer is unavailable, the air temperature for starting sprinklers on the first night of a frost event is determined using the dew point temperature ($T_d$) and the critical damage temperature. To determine the starting temperature from Table 1, locate the critical temperature column and the measured dew point temperature row. (Note that critical temperatures in the heading row correspond to wet-bulb temperature.)

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temperatures). Taking the critical damage temperature and the dew point into account, select the air temperature \((T)\) to start the sprinklers from Table 1. Measure this air temperature in or upwind from the orchard. For example, if \(T_c=23\)°F \((-5.0\)°C\) and \(T_w=30\)°F \((-1.1\)°C\), then start the system when the air temperature is at or above 34.0°F \((+1.1\)°C\).

If the system is turned off when the wet-bulb temperature \((T_w)\) is greater than 32°F \((0\)°C\) during daytime following a night of frost protection, be sure to start it again before the \(T_w\) falls below 32°F \((0\)°C\) on following frost nights. If the system is started after \(T_w<32\)°F, the spray heads can ice up and not work. For example, if the dew point temperature measured upwind from your orchard is \(T_d=23\)°F in the morning following a frost night, you can stop the system during the daytime when the air temperature exceeds 37.3°F. On the second or subsequent nights of a series of frost nights, if the dew point is \(T_d=25\)°F, restart the system when the air temperature is above 36.3°F.

If wet-bulb temperature or dew point temperature data are unavailable, but relative humidity and temperature measurements are available, use Table 2 to first estimate the dew point temperature and then use Table 1 to determine the air temperature for starting and stopping the irrigation system.

### Application rate requirements

The benefit derived from using micro-sprinklers comes from energy released during the freezing process. Evaporation of water, which is always occurring, requires energy that removes heat from the orchard. The energy gained from freezing must exceed the energy lost to evaporation to have a frost protection benefit.

It is not easy to measure evaporation on frost nights, so it is also difficult to quantify the application rate needed for protection. When water is sprayed on the ground rather than on the trees, evaporation rates are small and therefore the total energy lost is not that great. As a result, the use of micro-sprinklers is likely beneficial during most frost nights since freezing water gives off large amounts of energy, keeping the energy balance positive. The goal is to maintain a liquid-ice mixture on the ground by continually adding liquid water on top of the ice so that the wetted ground temperature will stay near 32°F \((0\)°C\). Without the sprinklers, lower ground temperatures are likely. Higher application rates definitely provide more protection.

Based on observations, an application rate of 0.08 in. per hour \((2.0\) mm h\(^{-1}\)\) can increase orchard temperatures by as much as 4°F \((2.2\)°C\) under calm wind conditions \((Connell and Snyder, 1988)\). To convert from gpm per acre to inches per hour, divide the number of gpm per acre from your pump by 360. For example, 36.0, 28.8, 21.6, 14.4, and 7.2 gpm per acre corresponds to 0.10, 0.08, 0.06, 0.04, and 0.02 inches per hour. With stronger winds and low dew point temperatures, the protection can be less.

If the water freezes instantly when it strikes the ice-covered ground and the ice has a milky-white appearance, energy loss to evaporation is probably bigger than that gained from freezing, and the system precipitation rate is not adequate for the frost conditions on that night. If your water application rate is inadequate, running the system may still provide some protection, but the ice temperature will drop below 32°F and damage is possible. If there is a liquid-ice mixture on the surface, the temperature should be near 32°F. Because application rates are low, drip irrigation is even less beneficial for frost protection than micro-sprinklers (see the article on passive frost protection methods).

The use of micro-sprinklers in conjunction with wind machines is better than the use of either method alone. It is

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**Table 1. Minimum turn-on and turn-off air temperatures (°F) for sprinkler frost protection for a range of critical damage and dew point temperatures (°F)**

<table>
<thead>
<tr>
<th>Dew point (°F)</th>
<th>Critical Damage Temperature (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22.0</td>
<td>32.0</td>
</tr>
<tr>
<td>23.0</td>
<td>31.0</td>
</tr>
<tr>
<td>24.0</td>
<td>30.0</td>
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<tr>
<td>25.0</td>
<td>29.0</td>
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<tr>
<td>26.0</td>
<td>28.0</td>
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<td>28.0</td>
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<td>30.0</td>
<td>24.0</td>
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<tr>
<td>31.0</td>
<td>23.0</td>
</tr>
<tr>
<td>32.0</td>
<td>22.0</td>
</tr>
</tbody>
</table>

*Select the appropriate critical temperature column and the row with the measured dew point temperature. Then, read the corresponding air temperature from the table. This table assumes a barometric pressure of 29.92 inches of Mercury (101.3 kPa), so it is appropriate to use the table up to about 1000 feet elevation.

**Table 2. Dew point temperature (°F) for a range of air temperature and relative humidity**

<table>
<thead>
<tr>
<th>Relative humidity</th>
<th>Air Temperature (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
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</tr>
<tr>
<td>100</td>
<td>32</td>
</tr>
<tr>
<td>90</td>
<td>29</td>
</tr>
<tr>
<td>80</td>
<td>27</td>
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<td>23</td>
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<td>60</td>
<td>20</td>
</tr>
<tr>
<td>50</td>
<td>16</td>
</tr>
<tr>
<td>40</td>
<td>10</td>
</tr>
</tbody>
</table>

*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.
The use of micro-sprinklers in conjunction with wind machines is better than the use of either method alone. It is best to start the micro-sprinklers first and then use the wind machines if frost conditions worsen during the night.

Surface irrigation

Surface (flood and furrow) irrigation is commonly used for frost protection in California. The benefit derives from 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 so that water reaches 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. The furrows should be as wide as possible because the radiation and sensible heat transfer depends partially on the water’s surface area. Running water under the trees provides some protection, but damage is mostly on the top and sides of trees, so running water under the edges of the tree canopy will provide better protection.

If an inexpensive source of energy is available, heating the water will provide more protection. Cost-effectiveness from heating water depends on the capital costs for the infrastructure to heat the water, the cost of energy, and the severity of the frost event.

Heaters

In small orchards and in field-planted citrus nurseries, heaters are sometimes employed for frost protection. Emissions from heaters are regulated in California under air quality standards and are enforced by air quality control districts. A list of approved heaters that meet air quality standards is available from local air quality districts.

Oil or liquid propane fuels are commonly used in return stack heaters. Heat output from a return stack unit burning fuel at a rate of +3.28 lb/hour is 105,000 Btu/hour. About 27% of the energy output is radiation, with 10% going to the ground, 9% to the trees, and 9% to the sky.

For frost protection, radiant energy is more efficient than heated air, and the radiation emanates best from a hot, solid surface (e.g., a steel smokestack of a heater). The radiation source should be kept as close to the plant as possible without causing burn damage. A portion of the combustion is converted to sensible heat as heated air and gasses from the flame. As this heated air rises and mixes within the inversion, it can warm the leaves, fruit, and branches. If the fires are not too hot, a circulation effect can result that enhances frost protection. If the fires are too hot, the heated plume can rise above the inversion ceiling, and the energy is lost.

The number of heaters per acre depends on the heat output, typical inversion strength, and presence of cold spots that require more heat. In general, radiant energy transfer is more efficient than sensible heat transfer, so heating an orchard is more efficient with more heaters having a smaller heat output. The amount of protection for each site can be determined only by the grower and their years of experience with the frost problem on that site.

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 furrow is created (Figure 2). 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.

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

One method of heater distribution is the border heating technique. On the upwind edge, where prevailing air drift enters the orchard, use two heaters per tree on the outside and one heater per tree in the first two rows in from the edge. On the downwind side of the orchard, use one heater per tree on the outside. On the remaining two sides of the orchard, use one heater per tree on the outside and first row in from the outside. To reduce
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labor costs to fuel and maintain heaters, a central fuel supply has been used.

Wind machines help to mix heated air within an orchard, and the combination of wind machines and heaters is well-known to provide better protection than either method alone. Fewer heaters are needed when used with wind machines, and the distribution is concentrated on the outside edges of the orchard with some heaters spread throughout the orchard. When wind machines are operated, they pull in air from outside the orchard, and edge heaters help to warm that air. Avoid placing heaters too close to wind machines (e.g. 150 feet). If placed too close, the rising heated plume will block the horizontal transfer of air from the fans to the outside edges of the orchard.

**Other active protection methods**

Other active methods of frost protection include vertical blowing fans, heaters that mount on tractors that are driven through an orchard, microwave towers, artificial fog, and use of centrifugal fans to blow heated air horizontally to the trees. We can only recommend traditional methods that have received thorough scientific evaluations. There is little scientific information on whether there are benefits to any of these methods, and their cost-effectiveness is unknown. Some of these methods violate the physics that are known to provide success with traditional methods.

**Joseph H. Connell has worked with citrus for 33 years as a UCCE farm advisor, and during his career has served growers in both Fresno and Butte counties. He has conducted numerous field studies on various aspects of frost protection working in conjunction with Dr. Richard Snyder. Neil O’Connell is the UCCE citrus and avocado farm advisor for Tulare County. Dr. Snyder is a Biometeorology Specialist with UC Cooperative Extension, based in the Land, Air and Water Resources Department at UC Davis.**

**References**


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