Commercial Freeze Protection

FOR FRUITS AND VEGETABLES

Erick Smith and **Timothy Coolong,** *Department of Horticulture* **Pam Knox,** *Department of Crop and Soil Sciences*

Freeze protection efforts should be based on the type of freeze, temperature, and wind speed that is impacting your crop. To apply frost protection, consider your crop value, the freeze protection capacity of your system, and the crop's susceptibility to injury at each growth stage.

Types of Freezes

A freeze refers to the temperature at which water freezes, 32 degrees Fahrenheit (32 °F) or 0 degrees Celsius (0 °C). A frost occurs at temperatures where water condenses as ice, which directly relates to the amount of water vapor in the air. Because frost can form at varying temperatures, it is important to consider the type of freeze that is affecting your crop and when the temperature will reach the freezing point of water.

Advection Freezes are typically associated with the movement of a weather front into an area. Cold and dry air replaces the warmer air that was present before the weather change. The passage of an advective freeze front is associated with moderate to strong winds, no temperature inversion, and low humidity. Temperatures will drop below freezing and stay that way for an extended period. It's difficult to protect against advection freezes. The winds associated with advection freezes blow added heat away and cause ice to form poorly, thereby limiting the effectiveness of frost protection systems.

Radiation Freezes happen when the sky is clear and there is little or no wind. Radiation freezes occur because of heat loss in the form of radiant energy. A warm surface cooling is losing radiant energy—think of a rock in the sun that begins to lose heat when placed in the shade. Radiation freezes are often associated with a temperature inversion (Figure 1) in the atmosphere.
A temperature inversion occurs when air temperature increases as elevation increases. This is called a "temperature inversion," as temperatures normally decrease as elevation increases. Meteorologists refer to the elevation at which the temperature begins to decrease as the "top of the inversion." A weak inversion occurs when temperatures aloft are only slightly warmer than near the surface. A strong inversion is noted by rapidly increasing temperature with elevation. *Frost protection methods are more effective during strong inversion conditions.*

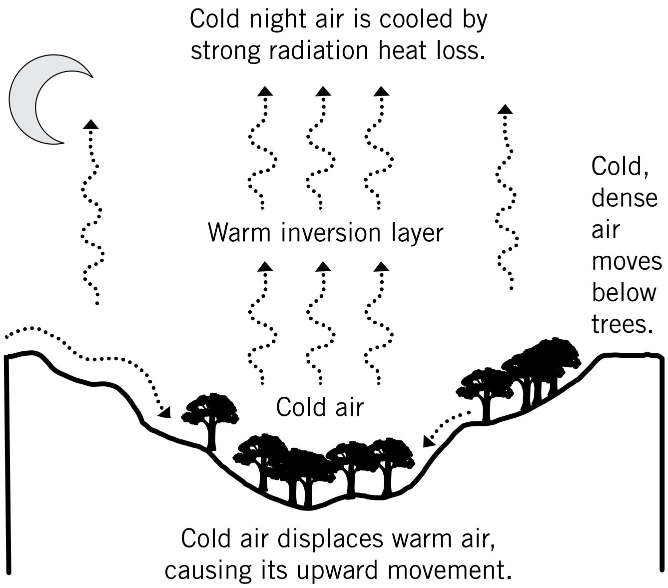

Figure 1. Radiation freezes occur on clear nights with little or no wind. Heat rises from ground level, and cold and dense air settles into low spots on the terrain (UGA Extension Circular 877).

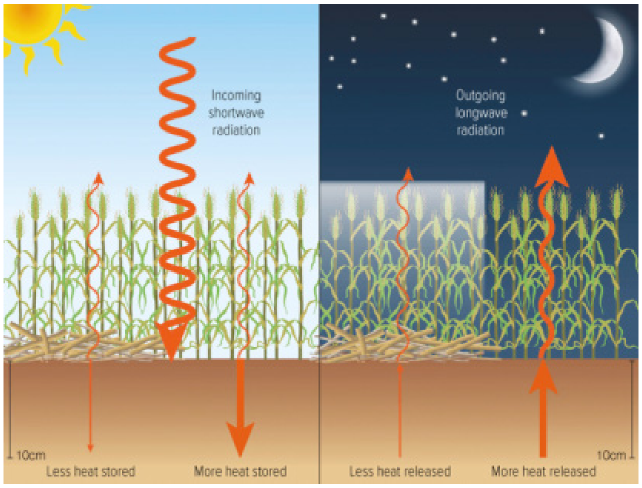

Figure 2. Daily movement of radiant heat movement in soil; 10 cm = 4 in (https://grdc.com.au).

Site selection is an important consideration when seeking to minimize the effect of freezes. Cold air is denser than warm air, so avoid planting in low spots, establish plantings to use southern exposure, and avoid areas where cold air may back up or flow toward plants, such as forested land, buildings, and solid fencing. The soil/freeze protection relationship is dependent on radiant energy, or heat rising from the ground (Figure 2). During the day, heat is transferred into the top 12 inches of soil. If the soil is moist, energy transfer is improved and will store more heat energy than dry soils, because water holds heat better than air or soil particles. Irrigating well in advance of a freeze will allow greater potential for heat energy storage than just moist or dry soil. However, if the soil is already at field capacity, more water will not improve the amount of energy stored. You can think of radiant energy transfer as a bank account—you only save during daylight hours and withdraw at night.

Soil type should be considered. Sandier soil, due to its coarse nature, has more and larger air gaps than a loamy soil. Water in sandy soils evaporates and drains faster, meaning that heat energy will be lost at a higher rate. The effect of mulches, cover crops, and organic matter in or on the soil during a freeze event can be of concern. The type of mulch being used is also an important consideration. Sunlight is reflected by white mulches, which subsequently absorb less heat energy than bare soil or black plastic mulches. A 2 °F increase in minimum temperature at plant level during a late March freeze was observed in watermelons grown using black plastic mulch compared to those grown on bare ground (Figure 3). In some cases, 2 °F may be enough to prevent crop losses.

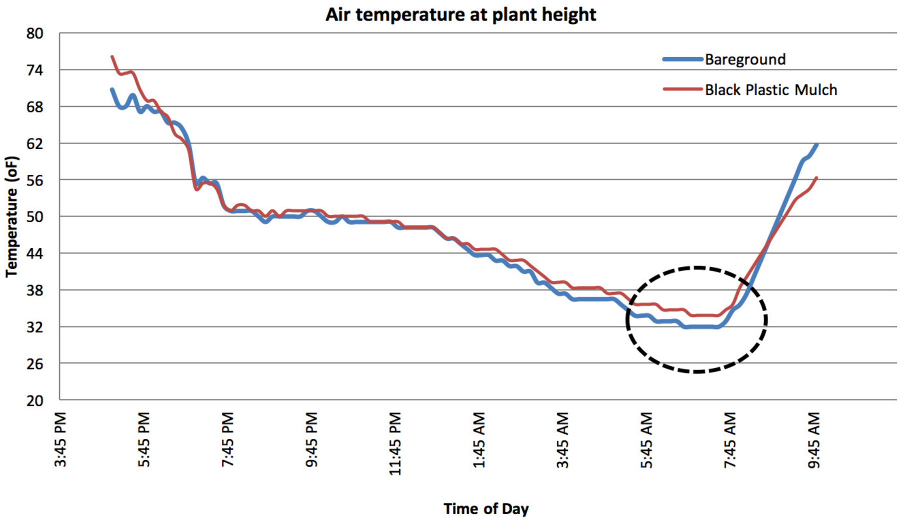

Figure 3. Air temperature recorded in the crown of watermelon plants in Cordele, Georgia, during a freeze event on March 30, 2015. Temperatures in plants grown in black, plastic mulch remained 2 °F greater than bareground-grown plants when air temperatures reached 32 °F.

Freeze protection devices

Freeze protection can be achieved to varying degrees with air movement, heaters, sprinkler irrigation, mulches/ground cover, and foliar chemical sprays. Wind machines and orchard heaters were developed for areas where water may not be available for agricultural irrigation during freeze events. For low-lying crops, plastic mulches, freeze protection fabric (floating row covers), and individual plant covers may be successfully used to cover and protect the crop. There are other products that are used for freeze protection that are applied through sprayers. In Georgia, the most effective freeze protection is overhead irrigation, which is commonly used in blueberry, strawberry, and peaches. Floating row covers are used in both vegetable and strawberry production in Georgia. In north Georgia, wind machines are used to protect grape vines and are sparingly deployed in south Georgia to freeze protect blueberry plantings. Helicopters are occasionally used for the freeze protection for both fruit and vegetable crops.

Orchard heaters have been used for centuries. A common commercial heater is called a return stack fuel oil heater (Figure 4). It is suggested that 40 pots/acre or 1 pot/1000 ft^2 be placed in a tree fruit orchard. However, the amount of pollutant discharged as smoke into the atmosphere, the cost of fuel oil, and the labor to tend the heaters may be prohibitive as a frost protection measure. Orchard heaters have some impact in a strong inversion but lose effectiveness under windy conditions.

Figure 4. Return stack fuel oil heater in a citrus grove. Photo courtesy of USC Digital Library, D. Whittington Collection.

A common misconception is that the smoke particles in the atmosphere are adding to the frost protection. However, under high humidity conditions, smoke particles can actually have a negative effect due to water condensing on the particles. As the water condenses, heat energy is released to the atmosphere. Condensation removes moisture from the air, which will lower the dew point and make freeze protection more difficult. As alternative sources of heat, producers have burned plant material such as orchard prunings, brush, and hay bales during freeze events.

Wind machines/helicopters are only effective in strong inversions. Wind machines (Figure 5) or helicopters can be used to move the warmer air of an inversion down to the ground and mix that air into the colder air around the crop. In a strong inversion, the air temperature may be warm enough to protect the plants. However, if the wind machine is operated in a weak inversion or advective freeze conditions, the air movement could cause greater damage through evaporative cooling.

Figure 5. Wind machine in a blueberry planting.

Irrigation should be applied at a rate that "keeps up" with freezing conditions, so that as ice forms, the ice is consistently wet and forms a clear layer. Freeze protection using water (Figure 6) uses latent heat released in the transition from a liquid to a solid. "Latent heat of fusion" is a scientific term used to describe heat being released into the surrounding area from a phase change such as a liquid transitioning to a solid. Like radiant heat, that energy is being passed or conducted though the ice maintaining the plant part underneath the ice at or slightly above 32 °F. Under windy conditions, air mixes with the water to form air pockets, which forms cloudy ice. This significantly decreases the effectiveness of freeze protection. Clear ice is an indication that you have good freeze protection.

Figure 6. Overhead irrigation as frost protection in blueberry. See appendix for critical bud/flower stage temperatures for blueberry.

Covering plants with plastic tarps or row covers has been used with varying success. In some cases, with plants such as watermelons, a small plant may be tucked under the mulch to provide additional protection. However, the plants must be pulled back out from under the mulch the next day before it becomes too warm, as they can then experience damage from excessive heat. If tucking the plant beneath the row cover is not practical, consider floating row covers, which are lightweight, non-woven fabric made from spun-bonded polyester or polypropylene. Floating row covers are available in various thicknesses, which allows for levels of 50 to 95 percent light transmittance, offers 2 to 4 °F freeze protection, and provides a barrier to wind and insects. Floating row covers can be placed directly over the crop or as a covering for low tunnel frames.

An important consideration when covering plants or relying on plastic mulches is how much heat has been collected in the soil prior to the freeze. Mulches and other coverings will be most effective when the preceding day has been warm and sunny. In addition, moist soil retains greater amounts of potential radiant energy, and covering the plants at least an hour before sundown will slow the rate that heat is released from the soil. If the day(s) leading up to the freeze have been cool and cloudy, this system will be less effective. Mulches and coverings are a passive system for freeze protection and are dependent upon capturing ground heat. Openings in the freeze protection material will greatly diminish effectiveness; ensure that the material is secured to the ground to maximize freeze protection.

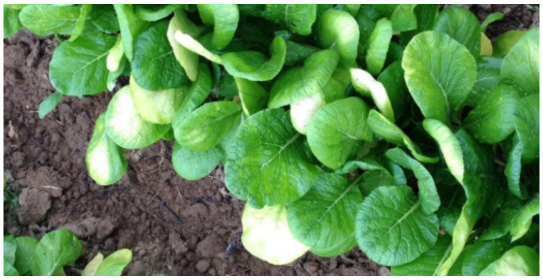

Figure 7. Cold damage during a mild freeze event (nighttime low was 32 °F) on March 26, 2014 in a freshly cultivated mustard field. An adjacent field (approximately 100 feet away) that was not cultivated had no visible injury.

Cultivating prior to a freeze

Traditionally, some growers have cultivated during cold weather or a freeze event under the theory that breaking open the soil would release some heat to the plants. However, cultivating actually creates more and larger air spaces in the soil storing less heat, allowing cold air to penetrate deeper into the soil during a freezing event. Furthermore, root damage caused by the cultivation may stress the plants, resulting in more damage from a mild freeze event (Figure 7).

Chemical frost protection

Two chemical frost protection methods are commonly used. The first is applying copper-based sprays, which kills ice-nucleating bacteria on the surface of leaves. Ice-nucleating bacteria such as *Pseudomonas syringae* can initiate ice formation on leaf surfaces, resulting in frost damage at or slightly below 32 °F (Lindow et al., 1978). The application of a spray to completely remove these bacteria from leaves, in theory, would allow plants to become supercooled and offer some protection from freeze damage. In closely managed experiments, the application of copper-based products and other antibacterial sprays have been shown to cause a significant reduction in ice-nucleating bacteria on leaves, but there was not a corresponding decrease in ice formation, suggesting that there were other non-bacterial compounds present that caused ice nucleation (Constantinidou et al., 1991). Because of the presence of non-bacterial sources of ice nucleation and the inability to completely kill ice nucleating bacteria in a field situation, the use of chemical frost protection has produced mixed results (Snyder and Melo-Abreu, 2005).

Other commonly used chemicals for freeze protection are antitranspirants. When applied to plants, they are said to prevent ice nucleation or desiccation of leaves during a freeze. There is limited research-based information for the use of these products. In North Carolina, an experiment was conducted to identify the effectiveness of a commonly available antitranspirant as a frost protectant for tomatoes and peppers. It was reported that the product had no positive effects for frost protection (Perry et al., 1992). It should also be noted that freeze damage in plants results from ice crystals that rupture cellular membranes, resulting in the collapse and internal dehydration of cells, not water loss through stomata (Snyder and Melo-Abreu, 2005).

Running a Frost Protection Irrigation System

Two critical weather conditions may render frost protection efforts ineffective regardless of whether it is an advective or radiative freeze event. Winds greater than 10 mph and temperatures falling below 23 °F are critical weather conditions that may render frost protection ineffective (Snyder and Melo-Abreu, 2005). If a freeze is anticipated, watch the wet-bulb temperature and turn on your system at or before the temperature falls to 34 °F. Run the system until ice is melting, preferably in daylight when radiant energy is being accumulated. Typically, the coldest night temperatures occur at sunrise. Table 1 provides recommendations for overhead irrigation rates in relationship to wind speed and temperature to protect citrus (Gerber and Martsolf, 1965). This work is generally used as a guide to protect other crops such as blueberry. As you look over the table, remember that the recommendation for overhead irrigation is limited to 23 °F with a wind speed of 10 mph. Based on Table 1, this would mean the system should have the capacity to deliver 0.40 acre-inches per hour to meet the most extreme demand.

Table 1. Precipitation rate in inches per hour needed for freeze protection at varying temperatures and wind speeds (University of Florida Extension Circular 287). The shaded area is outside of the recommended frost/freeze protection criteria.

Dry Leaf Temperature (°F)	Wind speed (mph)					
	0-1	2-4	5-8	10-14	18-22	30+
	Acre-inches per hour needed for freeze protection					
27	0.10	0.10	0.10	0.10	0.20	0.20
26	0.10	0.10	0.14	0.20	0.40	0.60
24	0.10	0.16	0.30	0.40	0.80	1.60
22	0.12	0.24	0.50	0.60	1.20	1.80
20	0.16	0.30	0.60	0.80	1.60	2.40
18	0.20	0.40	0.70	1.00	2.00	3.00
15	0.26	0.50	0.90	1.30	2.60	4.00
11	0.34	0.70	1.20	1.70	3.40	5.00

An important factor for determining when to start freeze protection is the amount of moisture contained in the air. Water content in the air can be measured in several ways. Relative humidity (RH) describes how much water vapor is in the air at a specific temperature relative to the maximum amount of water vapor it could hold at that temperature. Relative humidity is expressed as a percentage, where 50 percent RH would mean that the water vapor present is half of what could potentially be contained in the air at that specific temperature. However, with fluctuations in temperature, the RH will change based on the water vapor saturation point, or the maximum amount of water vapor the air can contain before water condensates. There are a number of devices that will tell you the relative humidity; however, RH alone is not an indicator of when to freeze-protect. A more useful indicator is dew point. Dew point is a function of temperature and water vapor, and varies with relative humidity. As the temperature decreases, moisture in the air transitions from a gas to a liquid. This is called the "condensation point" or "dew point."

There are two basic temperature measurements that should be defined for frost protection. The first, dry-bulb, is a measurement of air temperature. A dry-bulb thermometer should be shielded from radiation and moisture. The second, wet-bulb temperature, is a measurement of temperature in relation to the dry-bulb temperature and RH. Wet-bulb measures the lowest temperature that can be reached by evaporating water into the air. Wet-bulb temperature can equal dry-bulb temperature at 100 percent RH, but with decreasing RH, the wet-bulb temperature will also decrease. A wet-bulb thermometer is a dry-bulb with muslin cloth wrapped around the bulb and a vessel of distilled water placed below the bulb. The cloth is immersed into the vessel so a wicking action can occur through the cloth. As water evaporates from the cloth, energy is lost, and the thermometer's bulb is cooled. Similarly, when standing in front of a fan on a hot day, the air passing by feels cool. The cooling sensation is water being evaporated, which is carrying heat energy away from your skin. The lower the RH, the greater the cooling effect.

There are devices like sling psychrometers which are easy to read in the orchard and allow you to make measurements of wet-bulb temperature directly. For air at 100 percent RH, the dew point, dry-bulb air temperature, and wet-bulb temperature are the same. As the humidity decreases, so does the dew point and wet-bulb in relation to the dry-bulb temperature. Table 2 shows the relationship between dry-bulb air temperature (top axis), dew point temperature (left axis) and wet-bulb temperature (table entries).

Table 2. The dew-point temperature in relation to the air-temperature (dry-bulb) as calculated to determine wet-bulb temperature. Ta is air-temperature and DP is dew point. Blue highlighted temperatures are freezing temperatures, and the gray shading indicates 34 °F wet-bulb temperature.

Calculated Wet-Bulb Temperatures based on Ta-[(Ta-DP) x 0.3333], (Knox et al, 2017).

Dew Point (°F)	**Air (Dry-Bulb) Temperature (°F)**								
	32[z]	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**40**
34			34.0	34.7	35.3	36.0	36.7	37.3	38.0
33		33.0	33.7	34.3	35.0	35.7	36.3	37.0	37.7
32	32.0[y]	32.7	33.3	34.0	34.7	35.3	36.0	36.7	37.3
31	31.7	32.3	33.0	33.7	34.3	35.0	35.7	36.3	37.0
30	31.3	32.0	32.7	33.3	34.0	34.7	35.3	36.0	36.7
29	31.0	31.7	32.3	33.0	33.7	34.3	35.0	35.7	36.3
28	30.7	31.3	32.0	32.7	33.3	34.0	34.7	35.3	36.0
27	30.3	31.0	31.7	32.3	33.0	33.7	34.3	35.0	35.7
26	30.0	30.7	31.3	32.0	32.7	33.3	34.0	34.7	35.3
25	29.7	30.3	31.0	31.7	32.3	33.0	33.7	34.3	35.0
24	29.3	30.0	30.7	31.3	32.0	32.7	33.3	34.0	34.7
23	29.0	29.7	30.3	31.0	31.7	32.3	33.0	33.7	34.3
20	28.0	28.7	29.3	30.0	30.7	31.3	32.0	32.7	33.3
19	27.7	28.3	29.0	29.7	30.3	31.0	31.7	32.3	33.0
18	27.3	28.0	28.7	29.3	30.0	30.7	31.3	32.0	32.7

[z] Row is dry-bulb temperatures in °F
[y] Wet-bulb calculated temperatures

Frost protection through irrigation uses the latent heat generated from water transitioning from a liquid to a solid. As liquid water is applied to plants, evaporation will cool the air below the surrounding air temperature. As the temperature approaches freezing, water will begin the transition from liquid to ice, which releases heat. Most growers begin applying water at 34 °F wet-bulb temperature to minimize the effect of freezing on equipment and sensitive plant tissue. Many growers have wet-bulbs strategically placed around the field, and some have vehicle-mounted weather stations. If you are not measuring wet-bulb temperature directly, Table 2 has calculated wet-bulb temperatures. Find the appropriate dry-bulb temperature on the top and follow down to the observed dew point value on the left; this is the wet-bulb temperature. If you want to know at what dry-bulb temperature to start irrigating, look for the observed dew point on the left column and move across the columns to the corresponding 32 °F or 34 °F wet-bulb value (whichever you are using), and follow that column up to the top row for the corresponding air temperature. This is the dry-bulb temperature to start frost protection.

Irrigation Design for Frost Protection

The irrigation system must move large volumes of water, and many systems draw surface water by electrical or combustion engine pumps. The volume to be pumped depends on the irrigation rate required; many systems have sprinkler nozzles that deliver 0.24 inches/hour (in/h). Table 3 shows various sprinkler nozzle ratings and the corresponding output per minute in a 60-by-60-foot irrigation design. The last column shows the cost per sprinkler rating on the 60-by-60-foot layout for an acre. A 60-by-60-foot pattern will have 12.1 risers per acre; the efficiency rating for the pump in the calculations is 90 percent (use multiplier 1.11); and the pump lift for surface water at 45 pound-force per square inch (psi) equals 0.95 gallons of diesel per acre-inch of water (Martin et al., 2011).

Calculation:

(sprinkler rating)(number of sprinklers per acre)(pump efficiency rating)(gallons of diesel consumed per acre-inch water)(price per gallon of diesel)=(cost per sprinkler rating in a 60′ x 60′ layout)

Example:

$$\begin{array}{c|c|c|c|c} 0.11\ \cancel{\text{gal}} & 12.1 & 1.11 & 0.95 & \$2.50 \\ \hline \text{hr} & & & & \cancel{\text{gal}} \end{array} = \frac{\$3.51}{\text{hr}}$$

Considering water demand, pumping one hour of frost protection at 0.20 in/h will apply 5,430 gallons of water per acre. In the case of frost-protecting 10 acres for four hours at this rate, the reservoir must contain an excess of 218,000 gallons or 8 acre-inches of water. At 0.40 in/h, water demand is 10,862 gallons of water for an hour per acre or 434,400 gal (16 acre-inches) for the same period. When designing a field for frost protection with overhead irrigation, use the natural slope of the field so that surface water may return to the irrigation reservoir. Some farms have the capacity to pump well water into the reservoir. Although irrigation sprinklers may be spaced in a variety of configurations, many growers will set the system in a square or triangular pattern at 40 by 40 feet to 80 by 80 feet. It's most important to have coverage over the crop: a rule of thumb is to have uniform sprinkler coverage where spacing will provide 50 to 60 percent of the wetted diameter, and avoid exceeding 70 percent of the effective diameter of coverage or overlapping pattern. To identify the appropriate sprinkler nozzle capacity, the following equation can be used to calculate irrigation rates:

Example:

$$R = \begin{array}{c|c} 96.3 & Q \\ \hline S & L \end{array}$$

R = application rate (in/h)
Q = output of one sprinkler (gal/min)
S = spacing between sprinklers (ft)
L = spacing between rows of sprinklers (ft)

When pumping from a surface source, remember to screen the inlet pipe. This reduces debris from entering and clogging the system.

Table 3. Sprinkler nozzle rating (in/h, inches per hour), the pumping capacity per sprinkler (GPM, gallons per minute), the pump capacity required to deliver the irrigation water over an acre (GPM/A), and cost per hour based on sprinkler output. Costs are calculated based on 90 percent operation efficiency.

Sprinkler nozzle rating in/h	Pumping Capacity Required (GPM/A)	Cost per in/h/A at 90% Operation with electricity ($0.10/ kW-h)	Cost per in/h/A at 90% Operation with diesel ($2.50/ gal)
0.11	49.8	1.98	3.51
0.12	54.3	2.16	3.83
0.13	58.8	2.34	4.15
0.14	63.4	2.52	4.47
0.15	67.9	2.70	4.78
0.17	76.9	3.06	5.42
0.19	86.0	3.42	6.06
0.20	90.5	3.60	6.38
0.22	99.6	3.96	7.02
0.25	113.1	4.50	7.97
0.28	126.7	5.04	8.93
0.30	135.8	5.40	9.57
0.35	158.4	6.31	11.16
0.40	181.0	7.21	12.76

Before installation of a freeze protection system, it is important that the design delivers the desired flow out of the sprinklers; pressures and water volume is matched to the capacity of the system; and ample water is available.

Freeze protection systems in blueberry plantings are usually plumbed with PVC large diameter pipe with risers interspersed in a pattern of 60-by-60 feet or less to facilitate good coverage over the field. There are various types of sprinkler heads, but the best options are heads with the desired irrigation rate and a rotation rate of 60 seconds or less. Plants must be wetted at least once per minute to provide frost protection. Figure 8 is a graphical representation of the effect of temperature and the time a sprinkler head rotates. Notice the peaks and valleys for the 30-second rotation. The range of 30 s rotation is ±1 °C (±1.8 °F) compared to 60 s at ±2 °C (±3.6 °F) and 120 s at ±4 °C (±7.2 °F). This is the effect of applying water at higher frequency, which minimizes the plant tissue's exposure to freeze. Sprinkler heads should be made of durable materials that resist temperature extremes, sunlight exposure, and impacts.

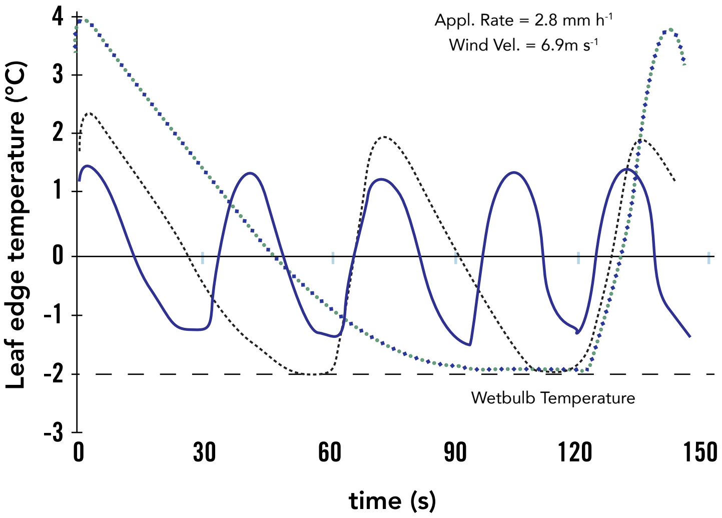

Figure 8. Temperature of a bud wetted by a sprinkler system with an irrigation rate of 2.8 mm/h (0.12 in/h) when exposed to a wind speed of 6.9 m/s (15 mph). The dotted line is for a 120 s rotation, the dashed line is 60 s rotation, and the solid line is for a 30 s rotation (Snyder, 2000).

Disease management

Damaged plant tissue is an infection point, especially after a freeze. In Georgia, temperatures that are ideal for plant tissue infection may follow a freeze, so be prepared to mitigate disease infection. This can be challenging for growers with overhead irrigation, because the soil is saturated and operating a tractor in the field may not be possible. Aerial applications may be the only alternative. Common disease problems to freeze-damaged tissue are *Botrytis* and *Botryosphaeria* in aboveground tissue. For plants where overhead irrigation is used, root rots may occur. For further information on disease management after a freeze, contact your county Extension agent.

Summary

Freezing temperatures can kill a crop. However, you may be able to reduce losses by setting up a freeze protection system. If irrigating, the system should be designed with ample water reserves, delivery water pressure, and sprinkler heads that can cover the crop for the duration of the freeze. In addition, careful consideration of the type of freeze event (advective or radiative), wind speed (10 mph maximum) and temperature (below 23 °F) should be factors that limit freeze protection. Of the types of freeze protection available, overhead irrigation is much more promising in consideration of the freezes experienced in Georgia. Set up wet-bulb thermometers in production areas and use 34 °F as the trigger point. Always be prepared to manage disease after a freeze event.

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Appendix

Figure A. Tight bud (1), bud swell (2), and bud break (3). Tight bud and bud swell can tolerate cold temperatures of 10 to 15 °F (-12 to -9 °C). Bud break is more sensitive to cold, and damage can occur at 20 °F (-7 °C).

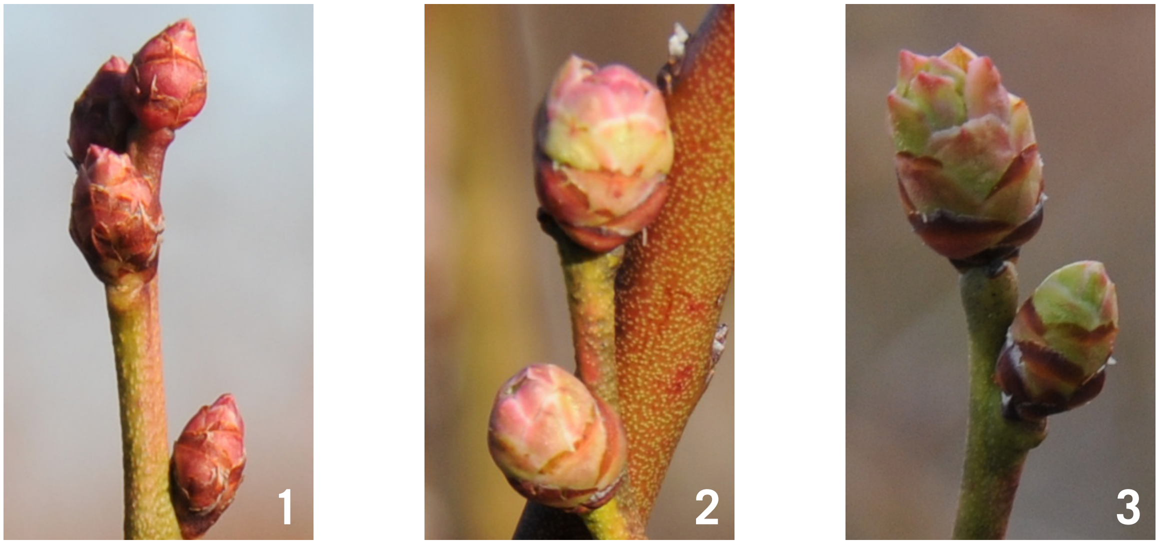

Figure B. Tight cluster (4) and early pink (5) bud, which tolerate cold to 20 to 23 °F (-7 to -5 °C) and 23 to 27 °F (-4.4 to -2.8 °C), respectively.

Figure C. Pink (6) and late pink (7) bud stages, which are cold tolerant to 23 to 25 °F (-5 to -4 °C) and 24 to 27 °F (-4.4 to -2.8 °C), respectively.

Figure D. Full bloom (8) and petal fall (9), which are cold tolerant to 28 °F (-2.2 °C) and 32 °F (0 °C), respectively.

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