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Review

Cold Hardiness and Options for the Freeze Protection of Southern Highbush Blueberry

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Abstract: Southern highbush blueberries (SHB; *Vaccinium corymbosum* interspecific hybrid) are a low chill species of blueberry that are commercially grown in sub-tropical climates. Due to the nature of SHB, the flowering and fruit set occur in mid-winter to early spring and are susceptible to freeze damage. The most effective use of freeze protection is based on climatic conditions. Identification of advective or radiative freeze, intensity of the freeze event, and the equipment deployed are the key elements for deciding if the crop can be protected and justifying the expense to operate the system. Of the various methods used in frost protection, applying overhead irrigation water is the most promising. During a freeze event, an application of 6.3 mm ha^{-1} (0.10 in A^{-1}) of water per hour is required to protect blueberries from −2.8 °C (27 °F) temperature with winds from 0 to 16 km h^{-1} (0 to 10 mph). This is 25.4 kL h^{-1} ha^{-1} (2715 gal h^{-1} A^{-1}) of water. Overhead irrigation freeze protection is dependent on large volumes of water. This paper will review methods of freeze/frost protection, importance of weather patterns, and critical temperatures based on phenology of flowering to fruit set.

Keywords: advective freeze; radiative freeze; evaporative cooling; irrigation; wind machine; orchard heaters; crop covers

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1. Introduction

For the southeastern U.S., southern highbush blueberry (SHB) production optimizes a lucrative market window from April into May [1,2]. Growers in both Florida and Georgia have increased blueberry acreage over the last seven years. Florida's harvested blueberry acreage in 2010 was 3500 A, and in 2017, it was 5200, a 49% increase [3]. Georgia has also increased its harvested acreage from 13,000 A in 2010 to 16,900 A in 2016, a 30% increase [3]. Early spring of 2017 had a severe killing freeze over the blueberry production region of southern Georgia, of which harvested acreage plummeted from 16,900 A to 8,800 A, a 52% decrease in production [3]. Killing freezes are not uncommon for the southeastern U.S. [4], which necessitates using frost protection.

Two general areas of knowledge are used to determine when to engage a freeze protection system for blueberries. The first is floral bud progression by monitoring the phenological development of the blueberries from a tight floral bud to set fruit. The second is the weather. Monitoring cold weather events and estimating its impact on the floral stage will signal when to engage a freeze protection system. Growers of fruiting crops are keenly aware of the effect of freeze on production and tend to network during freezing weather events [5]. During freeze events, growers will use macro- to micro-weather data from regional weather services to monitoring temperature within the planting. From field scouting, the grower will know the growth stages of the floral buds. When the temperature is expected to dip to a critical point at which freeze damage is certain, the frost protection system will be engaged for the duration of the freeze.

2. Floral Freeze Tolerance and Freezing Conditions

Blueberry floral bud, flower, and fruit sensitivity to freeze has been extensively researched [6–12] from which university extension systems have published guides on floral growth development. Based on this research, cold sensitivities have been suggested based on the phenological stage [13,14]. There are nine stages of flower bud development (see Appendix A) from tight bud to petal fall, at which point the small green fruit is sensitive to 0 °C (32 °F). Bud swell (stage 2) indicates the plant has deacclimated, and at bud break (stage 3), the flowers are sensitive at −7 °C (19 °F). Tight cluster (stage 4) is sensitive to −7 to −5 °C (20 to 23 °F). As the flower develops toward bloom, three stages are noted—early pink (stage 5), pink (stage 6), and late pink (stage 7)—which can tolerate −4.4 to −2.8 °C (23 to 27 °F). Floral full bloom is when the corollas are fully expanded (stage 8), which can tolerate −2.2 (28 °F). Once the petals fall (stage 9), freeze damage will occur at 0 °C (32 °F). Floral bloom for SHB is not strictly regulated by chill hours [15] and even with sufficient chill, SHB will bloom unevenly [16]. This is observed by the variation of bloom progression within a bush, causing growers to estimate the cold sensitivity of the crop. The appropriate response is dependent on the growers' desire to salvage the crop [5].

Freeze is associated to water's melting/freeze point, which is 0 °C (32 °F). Frost refers to the formation of ice crystals by freezing water vapor or dew [17]. Freezing weather is possible without frost; however, for frost to form, water is transitioning from either liquid or vapor phase to a solid phase, the temperature must be $\leq$ 0 °C (32 °F) [18]. There are two meteorological conditions during which freezing conditions occur: advective and radiative freezes.

Advective freezes are associated with a large mass-movement of cold air into a region. During an advective freeze event, conditions are windy, which mixes the cold air from ground level well into the upper atmosphere. These events are often sub-zero Celsius and freeze protection measures may not be effective [14,19]. Radiative freezes occur during calm and clear nights when the preceding day's temperature was above freezing. Radiative freeze events are associated with energy loss radiating from the soil surface into the atmosphere, then potentially becoming trapped between upper atmosphere cold air and the surface layer of cold air. This layer is called an inversion. During a temperature inversion, temperature increases with increasing elevation, and at the top of the inversion, temperature begins to decrease as elevation continues to increase. The intensity of the inversion is based on the amount of temperature increase, i.e., weak inversion has little temperature difference. During a radiative freeze, frost protection measures have a greater potential for effectiveness.

Frost and freeze are commonly used interchangeably. However, frost and freeze are two distinct phenomena. Frosts can occur on the surface and can form without freezing cells within the plant. Cell freeze damage is dependent on temperature, duration of freeze, and level of organ sensitivity (as noted by the floral stage freeze tolerance of blueberries). A freeze can cause damage to cell tissues if critical temperatures are met and the extracellular liquid fraction of the cell transitions to solid phase [17]. For both advective and radiative freezes, frost formation is dependent on the amount of moisture in the air and dew point. The dew point is when water vapor transitions from gas to liquid and condenses upon a surface. Under freezing conditions, this is called the frost point to which water vapor sublimes to a solid state. However, frost point is not an indicator of the potential of freeze damage. Following the wet-bulb temperature is a more accurate method of determining temperature, humidity, and evaporative cooling effects upon plant tissues [14].

Monitoring weather is a common practice for growers. During the SHB bloom in the southeastern U.S., growers routinely check local forecasts; monitor weather networks systems, e.g., University of Florida's Automated Weather Network (FAWN), University of Georgia's Automated Environmental Monitoring Network (GAEMN), and National Atmospheric and Oceanic Administration's National Weather Service (NOAA-NWS); and will have weather stations within each field [5]. Field monitoring environmental conditions is important during bloom and growers will use a variety of equipment from high- to low-tech instruments. The most important temperature information to gather is using a wet-bulb thermometer. These thermometers read dry-bulb temperature as affected by evaporative cooling. A wet-bulb thermometer is wrapped with a muslin cloth that is dipped in a water reservoir. The water migrates from the reservoir through the cloth, which is wrapped around the bulb of the thermometer. As water evaporates from the cloth, energy is lost and the wet-bulb will measure the temperature in relation to the relative humidity (RH) or the percentage of water vapor the air can hold at a specific temperature. At 100% RH, the dry-bulb temperature equals the wet-bulb temperature; as RH decreases so does the wet-bulb temperature [14]. Hence, a wet-bulb measures the temperature that the plants are experiencing and will be lower than the dry-bulb temperature unless at 100% RH.

3. Heat and Frost Protection

Freeze protection is used to mitigate ice formation of water in the extracellular spaces of plant cells [17]. Blueberry bloom stages have a temperature tolerance range of −12 to 0 °C (10 to 32 °F), which is dependent upon the phenological stage. Keeping plant tissue above the critical temperature to avert freeze damage requires stabilizing the environment around the plant. This is accomplished through an input of energy or by transferring heat. Heat is expressed as one body at a greater energy state than the adjacent body. The basic premise of the second law of thermodynamics has a body of a higher energy state contributing to the energy of a body of lower energy until equilibrium is met. This process goes from higher energy to lower energy and is irreversible in a closed system. For frost protection, an input of energy must be constant to keep the plant tissue at an energy state above the critical temperature. Heat can be transferred through three models: conduction, convection, and radiation.

Thermal conduction is the transfer of heat through molecular collisions. This process has bodies in direct contact passing energy from hotter to cooler molecules. An example of conduction is how heat moves through a material by applying a heat source to a single point, and over time the temperature of the whole object will increase. Thermal convection is based on warm air or liquid being less dense, allowing heat to rise, then as they cool, they will fall. Weather is strongly affected by convection, e.g., sea breezes and thermal columns forming towering cumulus clouds are the result of warm air rising and cool air falling. Thermal radiation is electrometric radiation generated by the thermal motion of particles into matter. An example of thermal radiation is the sun's light energy warming an object, e.g., soil. As sunlight reaches the soil surface, heat is transmitted into soil; when the surface is no longer in direct contact with light, thermal radiation is released to the atmosphere. In the environment, conduction, convection, and radiation work in combination to move heat. Another physical property of frost protection to consider is latent heat transfer or enthalpy of fusion. When substances transition through physical states, energy is released. Water transitioning from liquid to solid releases 333.55 kJ/kg into the surrounding surfaces, slightly increasing the temperature. When ice warms and melts, 333.55 kJ/kg are absorbed into the liquid fraction and removed from the surrounding surfaces [20]. Once the input of energy has been stopped, the water will eventually assume ambient temperature. If ice has formed and the temperature is ≤ 0 °C (32 °F), evaporation of ice can take place as sublimation, which removes 2838 kJ/kg from the ice, i.e., plant surface. Under windy conditions, sublimation is increased [21], hence energy is removed from the ice at a higher rate with increasing wind speed. This phenomenon is partially why damage from advective freezes are difficult to mitigate. For effective frost protection, some method of energy transfer should be considered.

4. Methods of Frost/Freeze Protection

4.1. Passive Frost/Freeze Protection

Freeze protection for SHB can be practiced using passive or active measures (Table 1). Passive freeze protection is implemented preceding a freeze event. These activities can be less expensive; however, with advancing stages of bloom, passive protection measures may not have enough energy to mitigate the intensity of freeze. Passive protection methods may include:

- site selection
- cold air drainage
- irrigation
- managing cover crops
- avoiding soil cultivation
- plant nutrition
- pest management
- plant covers
- wind shelters.

Table 1. Describes freeze protection measures for southern highbush blueberry.

Notes on Freeze Protection for Southern Highbush Blueberry	
Passive	
Site selection	Most important consideration when establishing SHB. Choose sites with good air and soil drainage.
Irrigation	Limited with drip irrigation, more effective with greater area irrigated. Greater potential if days presiding freeze are clear and sunny.
Cover crops	Best practice is to mow or roll over the crop. If left standing, they will reduce air drainage.
Avoid Cultivation	Cultivation allows radiative heat to be rapidly released. Increased air pockets in the soil are poor conductors of heat.
Plant Covers	Not effective for blueberry without a heat source, e.g., under bush irrigation.
Wind Shelters	Reduces the rate of wind entering the planting. Effective in advective freezes only. If using trees as a wind shelter, a 7.6 m (25 ft) buffer between plants and trees is suggested to minimize shading.
Active	
Heaters	Useful method of freeze protection on orchards. However, fuel, labor, and environmental costs are prohibitive and very rarely used for SHB.
Wind Machines	Effective in radiative freezes with strong inversions. Tower machines are best suited to freeze protect. Helicopters are extremely expensive to deploy for freeze protection.
Overhead Irrigation	Most widely used SHB freeze protection. However, expensive installation with low operational costs. Demands large volumes of water.

Site selection is important for the establishment of blueberry and avoiding frost prone areas can minimize freeze damage. Areas where the ground slopes into a bowl or at low points next to forested lots have the potential to be frost pockets. In the thermal convection model, warmer air rises and colder air sinks, and due to cold air being denser than warm air, the low spots in the field are where the colder air will collect. Soils can hinder frost protection, where dry heavy soils (clay and organic soils) do not transfer heat as well as dry sandy soils. Irrigation at least two days in advance of a freeze to saturate the soil can increase the heat holding capacity of the soil. Many SHB growers irrigate using a drip; however, effectively filling the soil profile throughout the planting will not be possible. Growers with overhead irrigation or micro-emitters will be able to fill a larger volume of soil, which can absorb greater amounts of heat when compared to drip irrigation systems. It should be noted that if the days are cloudy prior to the freeze, the amount of radiative heat introduced into the soil might be insufficient to mitigate the impending freeze.

Cover crops have been suggested to cause cold spots in plantings by blocking air drainage [17]. In the southeastern U.S., soil erosion can be very problematic due to rain events that can bring > 2.54 cm (1 in) in 30 min. Cover cropping, even with natural vegetation, can minimize erosion. Penfold and Collins [22] suggest that mowing or rolling the cover crop is similar to discing the crop under. Further, they report that allowing the cover crop to stand at 1 m (3.3 ft) will increase the susceptibility of grape vines to freeze [22]. Cultivating the alleys prior to a freeze is not recommended because breaking open the soil will release stored heat. Cultivation opens the air spaces within the soil, and because air is a poor conductor of heat, the air spaces will reduce the transfer of heat into and out of the soil.

Fertilizing appropriately is important to maximize the freeze tolerance potential of the plants. Fertilization late into the season may initiate fall growth. Young supple shoots are susceptible to late fall and early winter freezes, creating entry points to infection. Conversely, under-fertilizing SHB may leave the floral buds more susceptible to freeze. Finding the appropriate amount of fertilizer may be region- and cultivar-dependent, but ending fertilization six weeks prior to the first killing frost is important to minimize early winter freeze damage. Leaf tissue testing after harvest is a good indicator of the effectiveness of the fertilization program [23]. Concomitantly, pest management is important to mitigate freeze damage and maintain healthy plants. Disease and insect predation on the plants reduce plant productivity and potentially weaken plants to freeze.

Ice-nucleation for pure water may not happen at 0 °C without a nucleation factor. Water can supercool to very low temperatures before freezing (≥ -40 °C). At these temperatures, water organizes into a crystalline structure and freezes without any external effects upon process. In the environment, water can have numerous influences that impact the temperature at which it freezes, e.g., motion and matter. Ice-nucleation active (INA) bacteria cause water to freeze above -5 °C (23 °F) [24]. The main bacteria that nucleate are *Pseudomonas syringae*, *Erwinia herbicola*, and *Pseudomonas fluorescens*. In California-grown almonds (*Prunus amygdalus*), multiple applications of bactericide (cupric hydroxide) starting from bud break had reduced INA bacteria concentrations [25]. However, strains of *P. syringae* have demonstrated copper tolerance, which reduces the efficacy of cupric hydroxide [26]. For blueberry, the majority of INA bacteria inhabit one-year old wood under the bark [27]. This makes controlling INA bacteria difficult with spray applications due to the protective tissue of the bark and bud scales. Hence, using copper products to control INA bacteria may not be effective.

Freeze protection by other chemistries have been suggested to reduce the freeze point of plant tissue, reduce INA bacteria, delay growth (slow deacclimation), or work by some unknown mode of action. However, to date, no products available commercially have been shown to withstand scientific rigor [28]. Research continues into inexpensive materials that can mitigate freeze. At present, growers should be cautious about claims that materials being applied prior to a freeze may mitigate damage.

Covering plants is a passive method of frost protection and may be sensible for the homeowner or growers with small plantings. Covers are available as plastic tarps, spun-bonded polyester, or other materials that are durable in the environment. With covers, frost protection is dependent upon radiative heat collected in the soil. If conditions are advective, there may be no mitigation especially with strong winds. Heat will be readily mixed into the air mass and covers can be blown off target if not secured. Further, covers are generally used on crops that are close to the ground. Productive fruiting zone for SHB are generally about chest height (1.2 m or 4 ft). For blueberry grown in Florida, covers gave inadequate protection unless accompanied with micro-sprinkler irrigation at 37.9 L h^{-1} (10 gal h^{-1}) [29]. This suggests using a heat source with the cover can effectively mitigate freeze damage.

Wind shelters can provide passive protection by reducing wind speed entering the planting [30]. Recommendations for blueberry site selection are to plant in well drained soils with a pH of 4.2–5.5 [23]. These sites are usually associated with coniferous forest (*Pinus* spp.) in the southeastern U.S. and natural windbreaks are provided by adjacent tree stands. However, blueberry requires full sunlight to be productive and shading should be avoided [16]. Plantings are usually buffered from wooded areas by at least 7.6 m (25 ft). Windbreaks potentially reduce the effects of advective freezes, but will provide no protection during a radiative freeze.

Passive frost protection does not give sufficient protection for long periods. However, site selection is the most important consideration when establishing a planting. Select locations that are not prone to freezes and have good drainage (both air and soil). For SHB blueberry, bloom will start in late January and even earlier if conditions are suitable for bloom. The southeastern U.S. blueberry-growing region tends to have freeze events in March when SHB fruit can be at color change and are susceptible to 0 °C (32 °F). Passive frost protection may not have the heat in reserve to mitigate freezes at this critical point and a more active approach is required.

4.2. Active Freeze/Frost Protection

Active freeze protection systems apply heat to keep sensitive plant tissues above critical freezing temperatures to mitigate damage. Active freeze protection is expensive with costs including but not limited to labor, fuels, equipment, and maintenance. Regardless of the system, during a freeze, someone will be operating and monitoring equipment. Smaller operations may be owner/operator managed and on larger farms, supervisors may be overseeing the deployment of the freeze protection system. In some instances, equipment will be hired that includes an operator, e.g., helicopters. On blueberry farms in the southeastern U.S., some of the active freeze/frost protection systems include:

- heaters
- wind machines
- irrigation.

4.2.1. Heaters

Heaters are not widely used in blueberry plantings due to fuel costs, environmental impact, and labor. Burning a fuel in a planting is an attempt to replace natural energy losses of radiative heat during a freeze event. During a radiative freeze, the air will be calm and heat will rise in a column. If an inversion has formed (the stronger the greater the effect), there will be a convection of rising heat. The air falling back into the planting could potentially be 1 to 2 °C (2 to 4 °F) warmer than temperatures outside of the planting [17]. For burning to be effective, the heat sources must be placed throughout the planting. For return stack heaters, it is suggested to have 99 pots ha^{-1} (40 pots A^{-1}) or 1 pot/92 m^2 (1000 ft^2) in an orchard [31]. Heat sources will have an energy rating, e.g., watts per meter^2 (W m^{-2}) and protection during a radiative freeze will need to replace the radiative loss minus the downward sensible heat flux and upward soil heat flux. As an example, net radiative loss equals −70 W m^{-2}, and if the sensible and soil heat flux equals 30 W m^{-2}, then 40 W m^{-2} of heat flux needs to be applied to prevent damage [17]. The design of the heater will greatly influence how heat is distributed in the planting. Most of the heat will rise quickly above the planting and most of the heat available to the plants will be radiative heat spreading from the heat source.

Along with the design of the heater, the type of fuel used will depend on cost, availability, and labor. Return stack heaters are oil/kerosene burning devices that burn 1.1 to 2.3 L h^{-1} (0.3 to 0.6 gal h^{-1}) and are rated at 25 kWh [32]. The percent of radiative energy output of return stack heaters, based on a ratio of the gross input (e.g., #2 diesel burn rate) measured in a 260° radius with a pivot point at 2.1 m (7 ft) in height above the ground and a 2.4 m (8 ft) arc was 18% to 28%, depending on the number of ventilation holes opened [31]. From each heater, 4.5 to 7.0 kWh of radiant heat is being emitted into the surroundings. If 40 units are placed in an acre, the fuel consumption will be 44 to 92 L h^{-1} (12 to 24 gal h^{-1}) with a max of 280 kWh radiant energy. As of November 2018, the fuel cost (#2 diesel at $3.338 USD [33]) for frost protection would be $98.99 to $197.96 ha^{-1} h^{-1} ($40.06 to $80.11 A^{-1} h^{-1}). This does not include labor to fill the pots, place them in the orchard, and light the burners.

Burning wood, straw, and prunings has been observed in blueberry plantings in the southeastern U.S. Growers have placed straw bales and dried wood around plantings then ignited the material during freezes without much success. On many sites in southern Georgia where this was tried, the growers set plants on fire and did not effectively mitigate freeze damage (E. Smith pers. observ.). Unlike a citrus orchard, SHB are planted with a tighter spacing, where traditional rows are 0.9 m × 3.6 m (3 ft × 12 ft) and high-density plantings are 0.9 m × 1.5 m (3 ft × 5 ft). In both of these plantings, open burning of organic matter tends to damage plants. In addition, the radiative heat distribution is quickly lost to the atmosphere without the retention of heat provided by the metal casings of orchard heaters.

Burning emits smoke. These particles reduce air quality, reduce short-wave light from entering the planting at sunrise, and can become ice nucleation sites. Smoke particles rise in the convection currents during the burn. At dawn, the particulates can inhibit short-wave light, hence reducing light energy from entering the planting. This can delay the warmup of the planting, forcing continued burning until the temperature rises above the critical temperature. In the Yakima Valley, heavy smoke has been reported to delay morning warmup by as much as three hours [19]. Further, smoke particulates do not inhibit radiative energy (infrared waves) from leaving the planting. Smoke particulates in the atmosphere can be sites for ice nucleation. This is problematic because forming ice reduces the water vapor, thus reducing the dew point. Reducing the concentration of water vapor or RH will increase the rate at which temperature drops [14]. Burning should be carefully considered, especially if burning in densely populated areas or under burn restrictions.

4.2.2. Wind Machines

Wind machines are used sparingly in southern Georgia and Florida. During radiative freezes with strong to weak inversion, using wind machines can be effective [28]. An advective freeze brings wind into the region, nullifying the effectiveness of wind machines. During a radiative freeze with inversion, wind machines are attempting to mix the warmer inversion air layer with colder air at ground level. Commonly, wind machines move air horizontally using a fan mounted at a height of 9 to 11 m (30 to 36 ft) on a steel tower. Wind machines were first developed in California to freeze protect citrus [17]. However, the adoption of wind machines has since spread into other tree fruit crops and vineyards. Only recently have wind machines been used for blueberries, but the tower height has remained at the same as tree fruit crops. The fans are generally 3 to 6 m (9 to 20 ft) in diameter with two blades. Some of the older versions have four blades and the drive motor is mounted at the top of the tower. Most modern versions have the drive motor mounted at the base of the tower and can be operated with a variety of fuels or electricity. Dependent on power output, heat diminishes with distance from the wind machine by 35% to 70% with every 100 m (328 ft) for strong to weak inversions, respectively [34].

Helicopters are used to push the aloft warm inversion air to the surface. This is expensive, and in an advective freeze or a freeze with no inversion, there is no advantage to deploying helicopters. The strategies are varied for helicopter frost protection. There is one common factor, the pilot needs to know where to fly. Effective protection comes from monitoring temperature in both the planting and in the air. As cold spots are located in the planting by personnel or automated temperature sensors, the pilot will be signaled where to fly. The pilot will locate the warmest point in the inversion to determine the elevation of flight. Passes are dependent on the intensity of freeze; as temperatures decrease, pass frequency increases. Pass timing is important due to the potential of super-cooling plant tissue and ice nucleation by wind agitation. Constant monitoring of canopy temperature can minimize super-cooling if coordinated communication efforts between the ground and pilot places the helicopter in the optimal position. The length of the freeze should be considered because helicopters will need to be refueled and pilots given breaks. Multiple helicopters may be deployed to avoid gaps in coverage.

Upward-blowing wind machines attempt to draw the cold air from ground level and displace it into the upper atmosphere. However, considering thermal convection, this process is also removing radiative heat as well. Even under a strong inversion, upward-blowing wind machines had very limited temperature gains [35], suggesting that this type of frost protection has little value.

Wind machines have limited application and tower mounted wind machines provide the best potential protection during radiative freezes. However, inversions may not have sufficient energy to mitigate freeze. Moving air during a freeze increases the evaporative cooling and potentially could increase freeze damage in weak inversions or advective freezes. During freezes where no heat is available, a heat source can be provided through the latent heat of fusion of water.

4.2.3. Irrigation

Irrigation as frost protection is the most widely used frost protection in the southeastern U.S. In high-density SHB planting, overhead irrigation is used for irrigation and frost protection. For traditional row plantings, both drip and overhead irrigation are used. Water has two effective means of distributing heat to the plant: sensible and latent heat. Water for irrigation is either drawn from surface reservoirs or wells. For the sensible heat available from these water sources to be effective, it needs to be above freezing as it reaches the plant [17]. Once on the plant under freezing conditions, the water will freeze encasing the limbs. The plant tissue within the ice will be at 0 °C (32 °F) as long as water is being continuously applied. Water, as it freezes, releases heat (333.55 kJ kg^{-1}) into the ice, namely the latent heat of fusion. This is how the plant is being protected during a freeze event. If conditions are windy, evaporative cooling can effectively negate this process. As stated before, sublimation of water from ice to vapor carries away 2838 kJ kg^{-1}. If windy, the ice can form cloudy or with air pockets reducing its capacity to transfer heat (air is a poor conductor of heat). Concomitantly, the greater the wind speed, the greater the energy loss; potentially, causing more damage than without freeze protection. Two factors need to be observed when activating overhead irrigation for freeze protection, degree of chill, and wind speed. Generally, if the temperature is above −5.0 °C (23 °F) and wind speed below 16.0 km h^{-1} (10 mph), overhead irrigation can minimize damage if properly applied. To effectively apply irrigation water, the amount of water being applied and water delivery frequency are critical to successfully mitigate freeze. Table 2 describes the amount of water needed to effectively minimize freeze damage. As an example, if a forecast prediction has temperature falling to −5.0 °C (23 °F) with wind gusts of 8 km h^{-1} (5 mph), the irrigation system will need to deliver a minimum of 18.8 mm ha^{-1} h^{-1} (0.3 acre-inches h^{-1}). The amount of water applied in an hour is 76.3 kL ha^{-1} (8146.2 gal A^{-1}). In a planting of 4 ha (10 A), the water applied for 5 h equals 1526 kL (407K gal).

Table 2. Precipitation rate needed for freeze protection at varying temperatures and wind speeds (after Reference [29]).

Dry Leaf Temperature °C (°F)	Wind Speed km h^{-1} (mph)			
	0–1.6 (0–1)	3.2–6.4 (2–4)	8–13 (5–8)	16 (10)
	Hectare cm ≈ Acre-Inches per hour Needed for Freeze Protection			
−2.8 (27)	0.10	0.10	0.10	0.10
−3.3 (26)	0.10	0.10	0.14	0.20
−4.4 (24)	0.10	0.16	0.30	0.40
−5.5 (22)	0.12	0.24	0.50	0.60

Frequency of application is dependent on the type of sprinkler used. Impact sprinklers are used in many plantings due to their durability and the flexibility to vary irrigation line pressure. The number of sprinkler risers is dependent on the distance the water is applied under operational system line pressure. In addition, brass impact sprinklers hold up to the heat extremes and sunlight of the southeastern U.S. When installing impact sprinklers, rotational time is an important factor. The quicker the head makes a 360° rotation, the potential to protect during a freeze is increased [17]. Line pressure affects application rate and impact sprinklers are rated through a range of line pressures effectively increasing the amount of water delivered, which allows the grower to protect under colder conditions. These systems have the capacity to deliver pressures over 413.7 kPa (60 psi). Growers that do not have the capacity for a high-pressure system may use lower-volume overhead systems. Installing low-volume systems will use a larger number of risers to cover the same area as an impact sprinkler system. Unlike the brass impact sprinklers, low-volume systems have faster rotation and operate at a maximum pressure of 206.8 kPa (30 psi). Low-volume sprinklers are usually made of plastics that may become friable overtime and during freeze protection will take greater care when removing ice that blocks the spray pattern.

Freeze protection using overhead irrigation has a substantial initial investment. Dependent upon the system, costs are associated with land preparation, well or water containment pond, labor, pumping system, components (e.g., pipes, risers, poles to hold risers, sprinkler heads, and pressure valves). Preparing the site should include contouring the land in a manner in which water flows away from the plants. For containment ponds, the contour should allow water to flow back into the pond(s) to recycle water. If pumped from a well, the water should flow into an area that does not conflict with farming operations. Overhead freeze protection irrigation uses large quantities of water. Grading the planting to egress excess water improves access to the field after a freeze event and minimizes flooding of the root zone, thus preventing root rots. Further, over long periods of irrigation, the ice buildup can cause damage to the plants, requiring preventative fungicide applications that may be inhibited due to saturation of the soil.

Water will require a pump to move through the system. Well diameter and pump type determine the amount of water available for freeze protection. Water containment ponds need to have ample reserves for long periods of freeze. Many SHB growers in Georgia will pump well water into containment ponds for supplemental water. As previously calculated, water demand at 18.8 mm ha^{-1} h^{-1} (0.3 acre-inches h^{-1}) will apply 76.3 kL ha^{-1} (8146.2 gal A^{-1}) of water in an hour. The cost for the first acre of solid set overhead irrigation can be upwards of \$87K USD A^{-1} (\$217K USD ha^{-1}) for a complete system [36]. Coupled with the establishment cost, the total cost can be \$106K USD A^{-1} (\$264K ha^{-1}) at establishment [36]. However, once purchased, operation and maintenance are estimated at \$187.00 $year^{-1}$ [36], which is much less than deploying orchard heaters or hiring helicopters.

5. Typical Response toward a Freeze Event

Growers anticipating a freeze will have prepared by operating the system prior to the freeze, e.g., wind machines or overhead irrigation. System checks for growers may be days in advance to identify and fix any problems that occur. If the system is operated with an internal combustion engine, perform maintenance, e.g., check and change filters, oil, antifreeze, and fuel levels. If the freeze has the potential to be mitigated, then growers will have either supervisors and laborers ready, or themselves, in the planting monitoring temperature. For overhead irrigation systems, the critical temperature to begin the sprinklers will be a $\geq$ 1.1 °C (34 °F) wet bulb temperature. This temperature is chosen for: (1) when first applying water, the air temperature can drop to 0 °C (32 °F) or below [17]; and (2) this start temperature will ensure no sprinklers have ice formed in the emitters. Wind machines can be started at 0 °C (32 °F) wet bulb or at the critical temperature for freeze damage to be effective. Once the system has been started, the grower will need to be committed until temperatures have warmed to 1.1 °C (34 °F) wet bulb for irrigation and above 0 °C (32 °F) wet bulb for wind machines. If conditions are windy, the irrigation system should be operated until the ice is melted. During operation, the system needs periodic checks. For freeze protection systems operated with internal combustion engines, fuel levels, operating temperatures, and general performance should be checked and appropriate actions performed. Irrigation systems should be checked for performance, de-ice sprinkler heads, check line pressure, and evaluate the pumping system. Perry [28] suggests that delegation of responsibilities be given to individuals that have a direct interest in the crop. Ultimately, someone needs to be in the field for the duration of freeze protection that is capable of keeping the system operating.

6. Conclusions

The majority of freeze protection of SHB in the southeastern U.S. is accomplished with overhead irrigation. These systems are expensive to install; however, they have a low annual cost. The value of installing overhead irrigation can be observed by the huge decline in production acres after the 2017 freeze in Georgia U.S. If the crop has been damaged by freeze, there will be a reduction to no crop being harvestable. Many growers look to alternatives, e.g., wind machines, burning straw bales, and low-volume sprinklers, which have their limitations to protect under various weather conditions, e.g., radiative freezes with weak to no inversion and advective freezes. Regardless of the system deployed, growers are aware of SHB sensitivities to freeze and will monitor the floral stage and weather in preparation for freeze events. Understanding weather patterns, flower phenology, and the capacity of the freeze protection system are the basis for mitigating freeze damage to southern highbush blueberry.

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Appendix A

Figure A1. Tight bud (stage **1**), bud swell (stage **2**), and bud break (stage **3**). Tight bud and bud swell can tolerate cold temperatures of −12 to −9 °C (10–15 °F). Bud break is more sensitive to cold, where at −7 °C (20 °F), damage can occur [14].

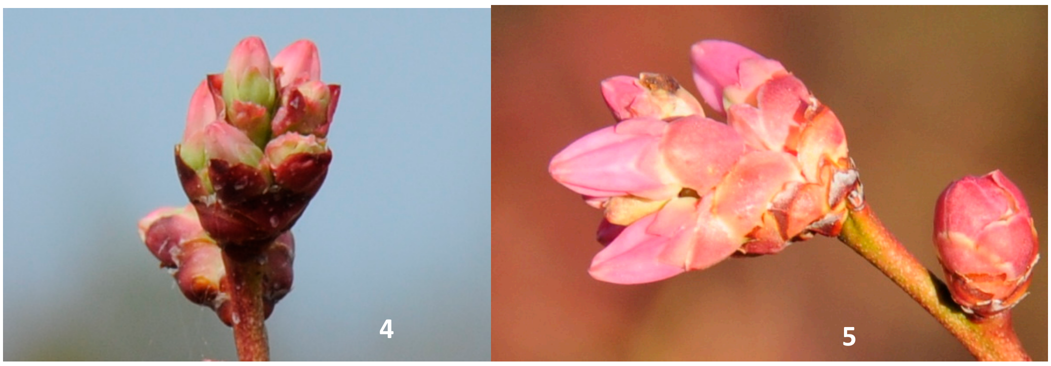

Figure A2. Tight cluster (stage **4**) and early pink bud (stage **5**), which tolerates cold to −7 to −5 °C (20–23 °F) and −4.4 to −2.8 °C (23–27 °F), respectively [14].

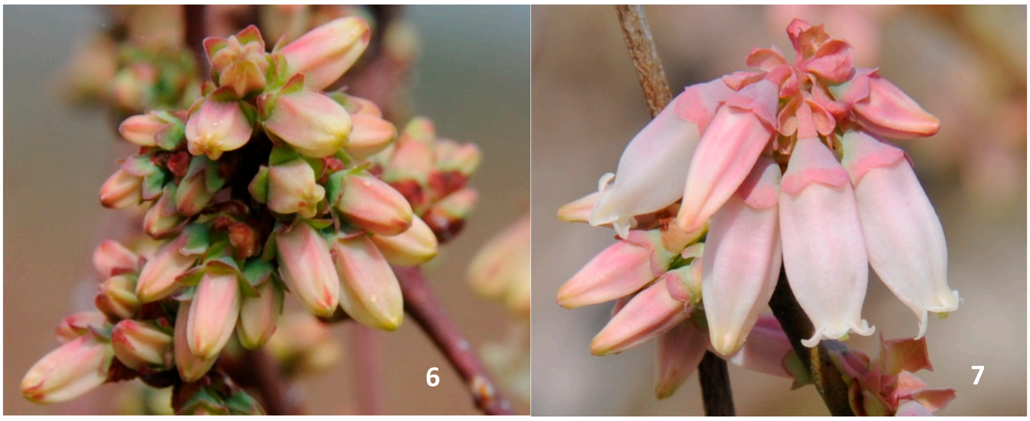

Figure A3. Pink buds (stage **6**) and late pink bud (stage **7**) stages, which are cold tolerant to −5 to −4 °C (23–25 °F) and −4.4 to −2.8 °C (24–27 °F), respectively [14].

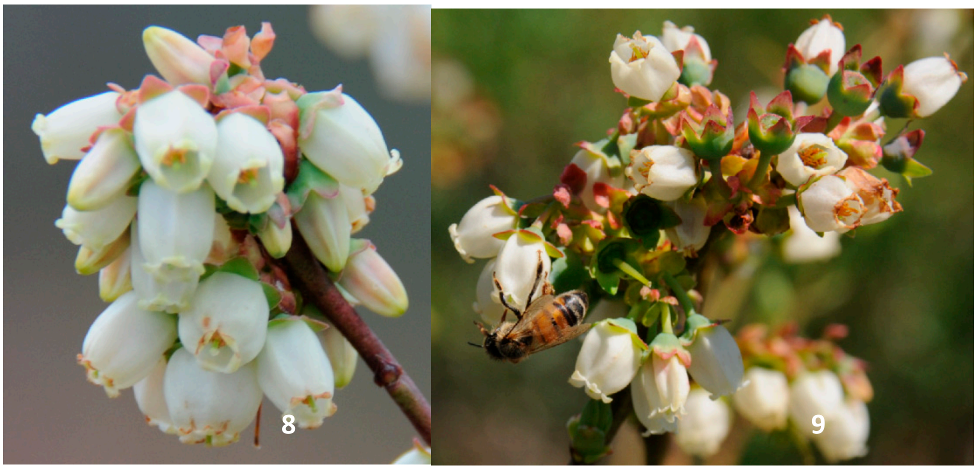

Figure A4. Full bloom (stage **8**) and petal fall (stage **9**), which are cold tolerant to −2.2 °C (28 °F) and 0 °C (32 °F), respectively [14].

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