Frost protection with irrigation: taking another look

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1. Introduction

Irrigation is used in temperate zones throughout the world to protect high-value crops against damaging cold temperatures. It is estimated that 5 to 15 percent of the total world crop production is affected by cold injury each year (Evans and van der Gulik 2011). Although growers have used irrigation to protect their stock for almost a century, some new and practical information has recently come to light.

Sprinkler irrigation can protect sensitive crops from freezing temperatures because of the high latent heat of fusion of liquid water (Figure 1). For every 1 gallon (3.8 L) of water that freezes into ice, 144 British Thermal Units (BTU) of heat are released and it is this heat that protects the plants. Likewise, 972 BTU of heat must be supplied to change 1 gallon (3.8 L) of liquid water into water vapor (Schroeder and Buck 1970). This latent heat of vaporization can actually increase the cold injury to plants if sprinkler irrigation is applied unevenly or is stopped before the ambient temperature rises above freezing because water evaporation of actually drives temperatures below ambient conditions.

2. Frosts versus Freezes

Two types of cold-weather injury can be damaging in forest, conservation, and native plant nurseries: advection freezes (when a cold air mass moves into an area) and radiation frosts (when heat is lost from an area). Advection freezes happen after cold fronts introduce large subfreezing air masses that affect large regions; radiation frosts, on the other hand, occur on clear cold nights and typically affect relatively small areas (“frost pockets”).

During any kind of cold-weather injury, four weather elements come into play: temperature, humidity, wind, and cloud cover.

2.1 Temperature

The terms frost and freeze are often used interchangeably to describe injury cased by temperatures below 32°F (0°C). Plants cool in relation to ambient temperatures and damage occurs when ice forms within their tissues. The critical temperature at which plant tissues are damaged by cold is known as cold hardiness, and varies by species, ecotype, season, and type of tissue.

So, what happens inside plant tissues when they freeze? Cells are enclosed by flexible walls made primarily of cellulose, which is stiff and strong. Living cells that function in photosynthesis and other physiological processes are filled with cytoplasm, which is surrounded by a semipermeable membrane composed of a fatty material called lipid in which protein molecules are embedded. This membrane plays a key role in plant cold hardiness; everything within the membrane is referred to as symplast and is living tissue. Everything outside this membrane (cell walls, vessels, intercellular spaces, empty cells, etc.) is referred to as apoplast and is not living (Figure 2A).

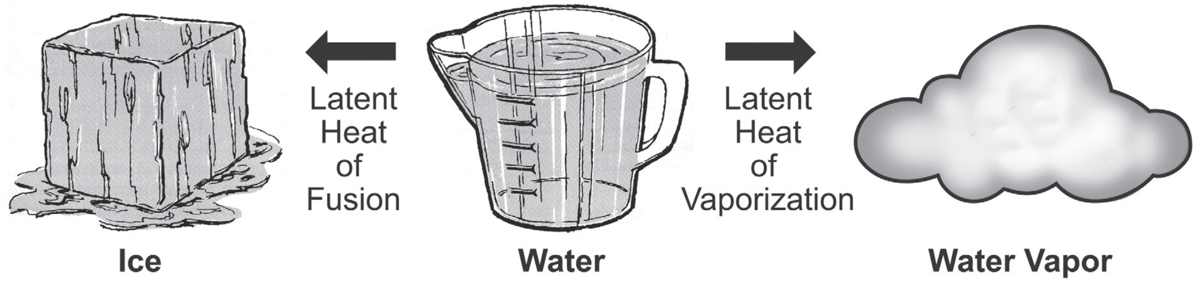


Figure 1 - Frost protection with sprinkler irrigation depends on the energy released or absorbed when water changes from one physical state to another. When water freezes into ice, each pound of water releases 144 BTU of heat (latent heat of fusion). To change one gallon of liquid water to water vapor requires much more heat: 972 BTU (latent heat of vaporization) (modified from Schroeder and Buck 1970).

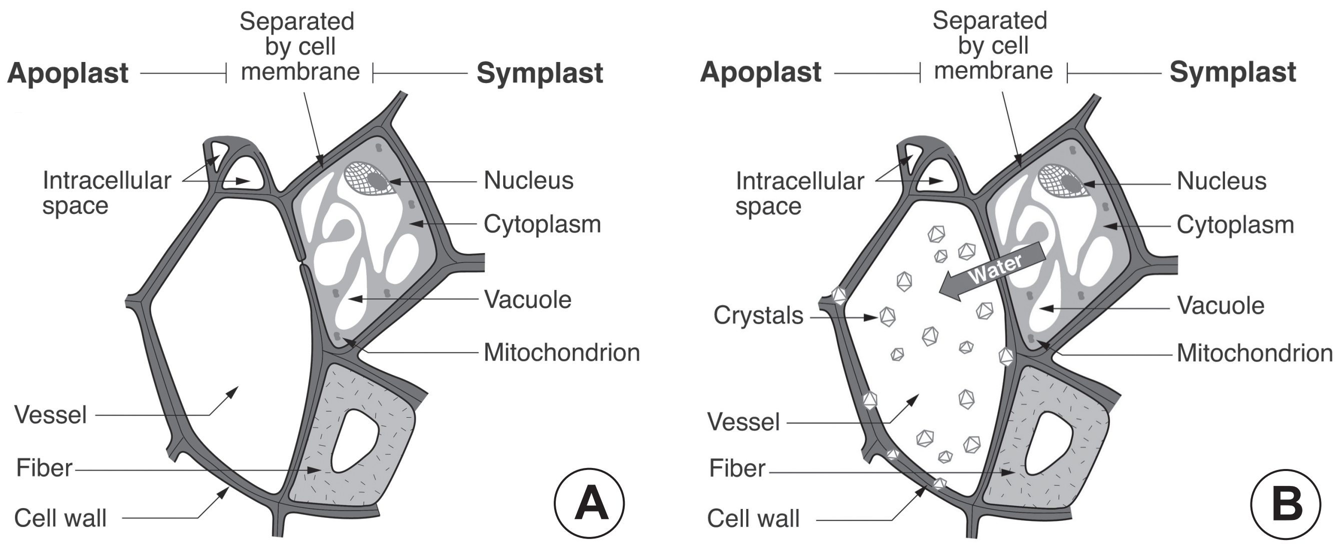


Figure 2 - The water in living cells (symplast) has a lower freezing point than the purer water in nonliving cells (apoplast). The symplast is separated from the apoplast by a cell membrane (A). When temperatures fall below freezing, ice crystals begin to form in the apoplast. As these crystals grow (B), they can rupture cell membranes and cause dehydration of the symplast (Ritchie and others 2010).

Both the symplast and apoplast contain some water. Apoplast water is nearly pure, so its freezing point is close to 32 °F (0 °C). In contrast, the symplast contains dissolved sugars and salts, suspended starch granules, and protein molecules. These solutes act as "antifreeze," depressing the freezing point of the symplast to considerably below freezing. When cells are exposed to sub-freezing temperatures, the apoplastic water begins to freeze. As it does, small ice crystals form within the cell walls, intercellular spaces, and other voids within the apoplast (Figure 2B). The symplast water, with its lower freezing point, resists freezing. Therefore, the ice that forms within the plant tissue is contained in the apoplast and does little or no damage.

Ice, however, has a very strong affinity for water – so strong that ice crystals pull water tenaciously across the membrane and out of the symplast. Because the membrane is permeable only to water, the dissolved sugars and other materials remain in the symplast even as water is drawn out. This raises the concentration of the dissolved solutes, further lowering the freezing point of the symplast water. When plant tissues are not cold hardy, or when the temperature falls below the plant tissues' seasonal level of hardiness, the cytoplasm can become severely dehydrated. Thus, plant tissue can be damaged by cold temperatures or by the resultant desiccation. In severe freezes where the temperature drops rapidly, direct cold injury is more common compared with more gradual freezes that lead to cell desiccation (Ritchie and others 2010)

2.2 Humidity

The amount of water in the air has a significant effect on cold injury to crops. The dew point is the temperature at which water vapor in the air condenses, and can be measured as the wet bulb temperature, which is very close to the actual dew point. The importance of the dew point is often not appreciated, but it is the single most important weather factor in frost protection. High dew point temperatures are beneficial because the high humidity retards heat loss by radiation, whereas low dew points are extremely detrimental because the low humidity increases evaporation from plant surfaces and drives their temperatures even lower (Evans and van der Gulik 2011). Therefore, growers should monitor atmospheric humidity by means of dew points or wet bulb temperatures before and during frost events; this information is provided by most weather services or can be easily measured in nursery weather stations.

2.3 Wind

Advection freezes are characterized by lateral movement of large subfreezing air masses (cold fronts) driven by winds more than 5 mi/h (8 km/h)(Evans and van der Gulik 2011). Wind also increases evaporative cooling when dew points are low and thereby increases cold damage to crops.

2.4 Cloud cover

Radiation frosts occur on clear cold nights with little or no wind. Because plants and other objects radiate heat into a colder environment in proportion to their relative temperature differences, crops will lose heat at a faster rate when exposed to a clear night sky, compared with much slower heat loss rates under cloudy conditions (Evans and van der Gulik 2011).

3. Types of cold weather injury

Two types of cold weather injury can occur in forest, conservation, and native plant nurseries (Table 1), and irrigation can protect against both. Cold injury is the most common type of overwinter injury, and is caused by sudden cold or frosts. It can happen almost anywhere during unseasonably cold weather, and any succulent or meristematic tissue can be injured: shoot tips and bud meristems (Figure 3A) as well as the lateral cambium (Figure 3B). Although roots are insulated by soil in bareroot crops, the exposed roots of container plants are especially susceptible to cold injury. Roots do not harden very much and so can be damaged by minor freezing events, especially if they last for an extended period. Frost damage is especially common on species that are not native to the area. Cold injury is directly linked to seedling hardiness and dormancy so cultural treatments to stop shoot growth and increase tissue hardiness, such as late-summer moisture stress and nutrient management, can minimize damage. Symptoms of cold injury typically develop within a few days and damaged tissue can be diagnosed with a cut that exposes browned tissue (Haase 2011).

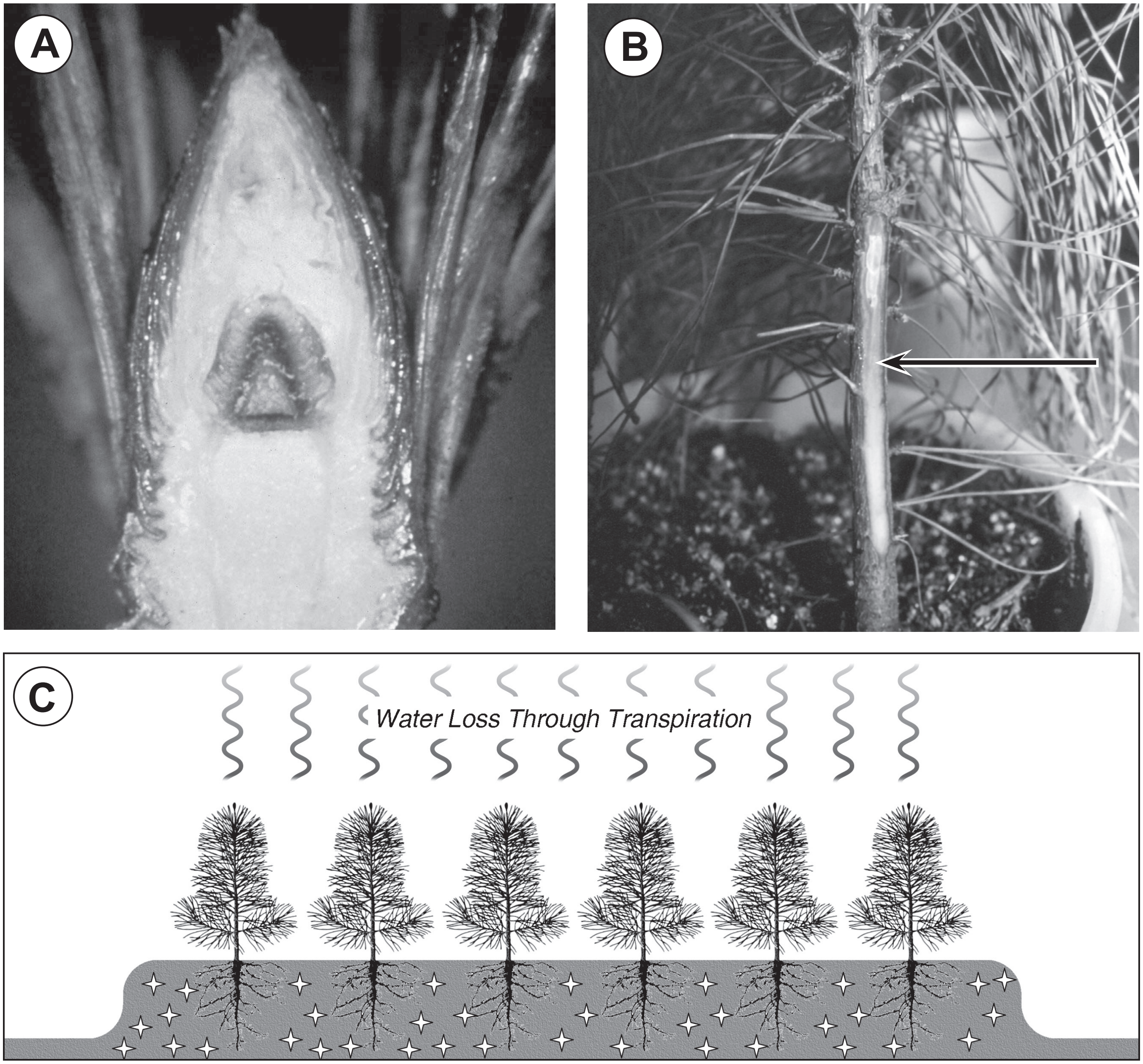
Winter desiccation ("winter burn") occurs when soils or growing media are frozen (Figure 3C) and nursery stock is subjected to extended periods of clear sunny weather. Winter burn is most common along the downwind side of mountains during warm and windy weather such as foehn or chinook winds (Figure 3D). Winter desiccation can even occur in normally wet climates such as western Washington and Oregon during atypical strong east winds (Moore 2014). Because of their relatively small volume of roots and lack of soil buffer, container plants are much more susceptible to this type of injury. Winter desiccation is not related to seedling hardiness or dormancy so protection is the only option. Symptoms of winter drying are slower to develop than cold injury, usually requiring weeks rather than days.

3.1 Cold hardiness

Cold hardiness refers to the ability of a plant tissue to withstand injury from below-freezing temperatures, and varies among species, ecotypes, and different plant tissues. The shoots of boreal conifers, such as black spruce (*Picea mariana*), white spruce (*P. glauca*) and jack pine (*Pinus banksiana*) can tolerate extreme cold during their period of maximum hardiness, and have been tested down to -112 °F (-80 °C). Due to climatic similarities, many Rocky Mountain conifers, such as lodgepole pine (*P. contorta*) and Engelmann spruce (*P. engelmannii*), can also tolerate extreme winter cold (Figure 4). Species at lower elevations, especially species with indeterminate shoot growth such as coast redwood (*Sequoia sempervirens*) and western redcedar (*Thuja plicata*) rarely acclimate to temperatures below -20 °C (-4 °F). Indeteriminate species are also much more prone to dehardening following periods of unusually warm winter weather. Interestingly, cold tolerance of wide-ranging species, such as Douglas-fir (*Pseudotsuga menziesii*), vary tremendously by ecotype; low elevational coastal ecotypes in Washington State can tolerate -4 °F (-20°C) whereas high elevation sources in Montana can tolerate -22 °F (-30 °C)(Ritchie and others 2010).

Table 1 - Comparison of types of overwinter injury in nurseries

Type of injury	Caused by	Symptoms	Species affected	Stocktypes affected	Related to seedling hardiness or dormancy
Cold injury	Unseasonably cold air temperatures	Meristems most affected: buds and shoot tips, lateral cambium, root	All species, especially non-natives	Bareroot and container	Yes
Winter burn	Frozen soils and drying winds	Only exposed foliage affected	Conifers	Bareroot, and especially container	No



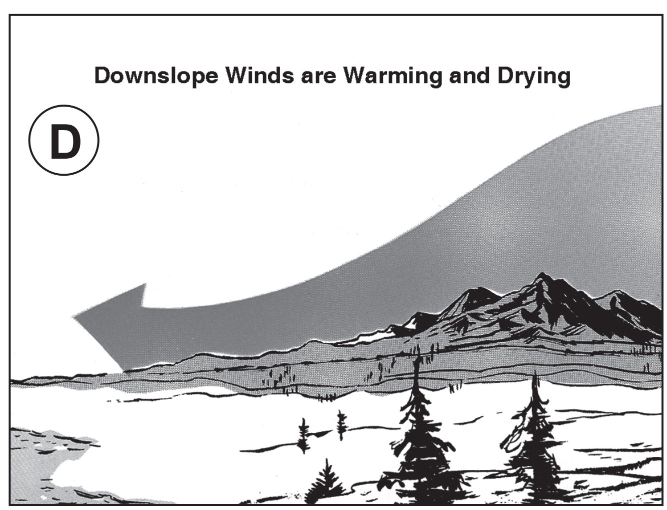


Figure 3 - Cold injury affects plant meristems such as shoot tips and buds (A), as well as the lateral cambium (B). Winter desiccation affects conifer foliage and occurs when the soil or growing media is frozen (C) and plants are exposed to warm windy weather (D) (D from Schroeder and Buck 1970).

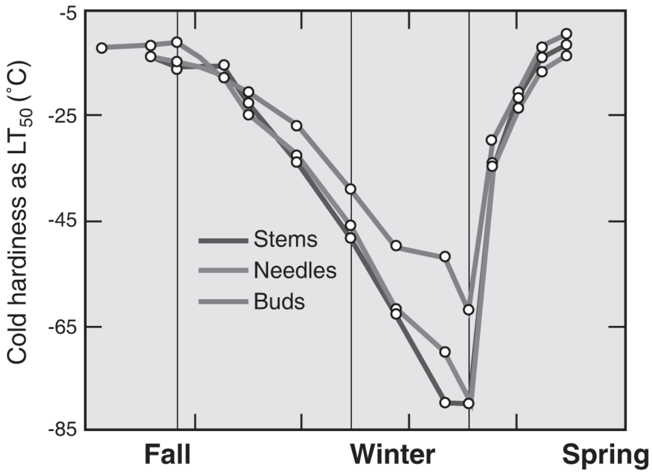


Figure 4 - Woody species from high elevations or high latitudes, such as Englemann spruce, can tolerate extreme cold in midwinter. Plant tissues, however, harden at different rates in the fall, but all deharden very rapidly in the spring (modified from Burr and others 1990).

Cold hardiness of shoots develops in the fall and early winter in response to cooler nights and shortening day length (Table 2). Burr and others (1990) tested cold hardiness of Engelmann spruce seedlings throughout winter and separately examined buds, needles, and lateral cambium. Stems and needles hardened more rapidly and achieved greater midwinter hardiness than buds. All three tissues dehardened very rapidly in late winter (Figure 4).

4. Protecting crops against frost damage with sprinkler irrigation

Growers have used irrigation to protect plant crops during freezing temperatures for about a century, having first been employed by an Ohio farmer in about 1912 (Evans and van der Gulik 2011).

4.1 Reducing cold injury using the heat of fusion

One of the basic concepts of frost protection with irrigation is based on the fact that heat is released as water freezes (Figure 1). The standard recommendation is that overhead irrigation should begin as soon as the temperature approaches the cold hardiness level of the crop, and then the sprinklers must not be turned off until temperatures rise above this threshold (Regan 1988). As crop cold hardiness increases and the starting temperature decreases, growers run the risk of having ice form in the irrigation lines; therefore, be sure that lines are adequately drained after use. As we have already discussed, humidity is as important as actual temperature, so the starting time will depend on both ambient and dew point temperatures (Table 3). If the actual cold hardiness of the crop has been tested, then the starting temperature can be adjusted accordingly. The standard practice is to keep applying water through the overhead sprinklers (thereby releasing heat) until the ambient temperature goes back above the hardiness level for the crop.

In a November 2014 trial at the Webster Forest Nursery (Olympia, WA), i-Buttons® (Maxim Integrated, San

Table 2 – Stages of cold hardening and dehardening for coastal Douglas-fir seedlings (Ritchie and others 2010)

Hardening stage	Season	Environmental cues	Temperature tolerance as LT_{50}
Hardening begins slowly	Late summer to early fall	Shortening photoperiod	28 to 23 °F (–2 to –5 °C)
Hardening increases rapidly	Late fall	Increasing lower temperatures, especially at night	14 to –4 °F (–10 to –20 °C)
Maximum hardiness	Midwinter	Very cold temperatures	5 to –40 °F (–15 to –40 °C)
Dehardening happens quickly	Late winter	Rising temperatures and longer days	Rapidly rising to 28 °F (–2 °C)

Table 3– The proper time to start irrigating for frost protection depends on both the ambient and wet bulb temperatures. Frost protection should be started at higher ambient temperatures when the air is drier (modified from Evans and van der Gulik 2011)

Starting temperature		Wet-bulb temperature	
°F	°C	°F	°C
39	3.9	15 to 16	-9.4 to -8.9
38	3.3	17 to19	-8.3 to -7.2
37	2.8	20 to 21	-6.7 to -6.1
36	2.2	22 to 23	-5.6 to -5.0
35	1.6	24 to 25	-4.4 to -3.9
34	1.1	26	-3.3

Jose, CA) were attached to bareroot seedling shoots before sprinkler irrigation was applied and also in an adjacent field with no irrigation. After the frost event was over, temperature data from the i-Buttons was recovered and downloaded (Figure 5). The plots of the two temperatures shows that seedlings protected with irrigation remained within a few degrees of 32 °F (0 °C), compared to the unprotected plants which were exposed to temperatures from 15 to 25 °F (-3.9 to -9.5 °C) for 5 consecutive nights.

4.2 Protection against winter dessication

Sprinkler irrigation is also effective against winter desiccation caused by drying winds blowing over seedlings in cold or frozen soils (Figure 3C-D). In December 2005 at Lewis River Reforestation's nursery (Woodland, WA) a severe cold snap with temperatures down to 12 °F (-11 °C) was ushered in by drying east winds that lose humidity as they move down the western slopes of the Cascade mountains. The nursery manager applied water through sprinklers and left them running until

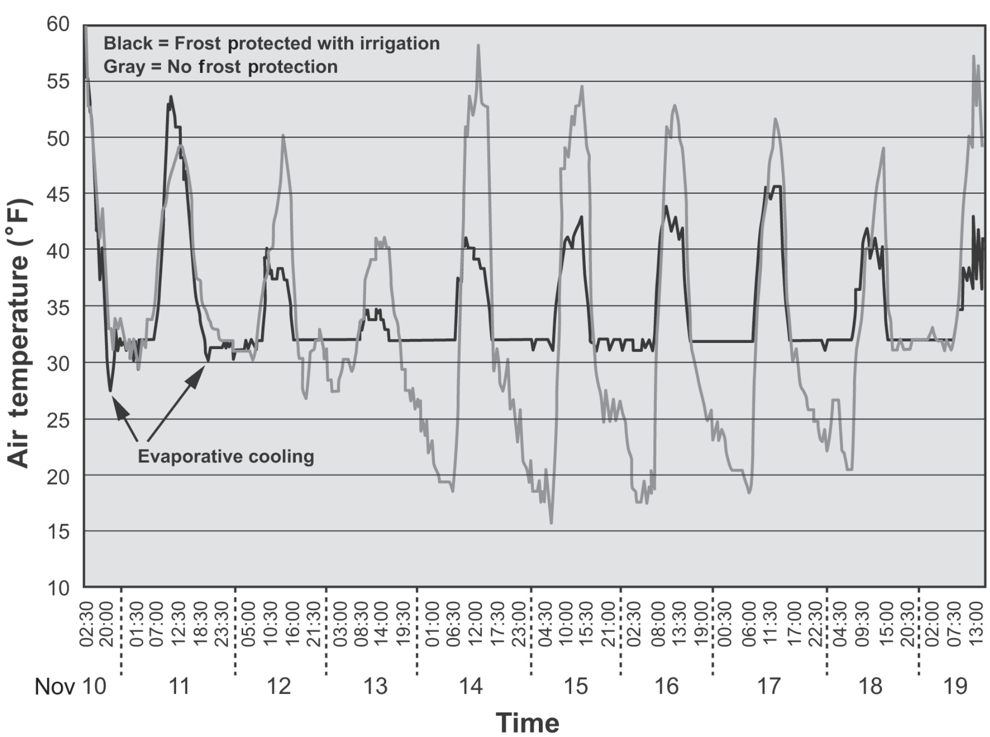


Figure 5 - A comparison of temperature from i-Buttons placed on bareroot seedlings receiving frost protection with sprinkler irrigation compared to control seedlings. Note that, when the frost protection started on November 10 and 11, the temperatures of the irrigated plants were initially lower. This was due to a cool and dry wind that decreased temperatures due to the latent heat of evaporation (see Figure 1) until the water on the plants began to freeze which protected them through the latent heat of fusion.

ice had built up 3 to 4 inches (7.6 to 10.2 cm) thick on his seedlings. Not only did the sprinkler irrigation protect his stock due to the heat of fusion, but the thick ice layer insulated the seedlings and continued protection after the water was turned off (Figure 6). Plant moisture stress (PMS) measurements of iced vs. exposed seedlings indicated reduced stress levels: 3 to 4 bars PMS in seedlings covered by ice, compared with15 bars in the exposed seedlings (Moore 2014).

To test whether a coating of ice has insulating properties, i-Buttons were frozen in varying-sized chunks of ice ranging from an ice cube to a 4 x 5 in (10.2 x 12.7 cm) block. Although the temperatures within the thicker ice were slightly higher, all the tests revealed the relatively poor insulating value of ice. The reason why the Lewis River Reforestation seedlings had some cold protection after the sprinklers was turned off (Figure 6) is probably due to the fact that they were encased in an almost solid block of ice that received some temperature buffering from the underlying soil and thereby also protected the crop from desiccation.

4.3 Operational example: the Webster nursery frost protection system

The frost protection irrigation setup for bareroot seedlings at Webster nursery employs a moveable aluminum pipe/riser setup with plastic rotary (Nelson 2000 K5 plate, 24-degree flow-control) nozzles. When this irrigation system is charged by water pressure of 50 to 60 psi (at the pump), these nozzles throw a radius of 32 to 37 ft (9.8-11.3 m) with a water stream height of 6.3 to 8.7 ft (1.9 to 2.6 m). Riser spacing is 30 ft (9.1 m) down the irrigation pipe with 42 ft (12.8 m) between lines producing an offset pattern. Previously, Webster nursery used Rainbird 7/64" brass impact sprinklers but changing to the plastic rotary sprinklers has resulted in improved frost protection. One of the challenges of frost protection with sprinklers is keeping them from "freezing up". The plastic rotary sprinklers operate with limited maintenance down to temperatures below 10 °F (-12 °C), whereas the brass impact sprinklers typically froze up around 14 to 17 °F (-10 to -8 °C). Under windy conditions, however, rotary sprinklers may not cover as well as impact sprinklers. Nelson offers a "Windfighter" rotator head, but these sprinklers have not been evaluated for frost protection.

5. Summary and recommendations

Using sprinkler irrigation to protect crops from freezing temperature can be effective if done properly. First, make certain that your irrigation system has the proper coverage and that you have enough water reserves to keep applying water as long as you need to. You may want to consider installing sprinklers with plastic

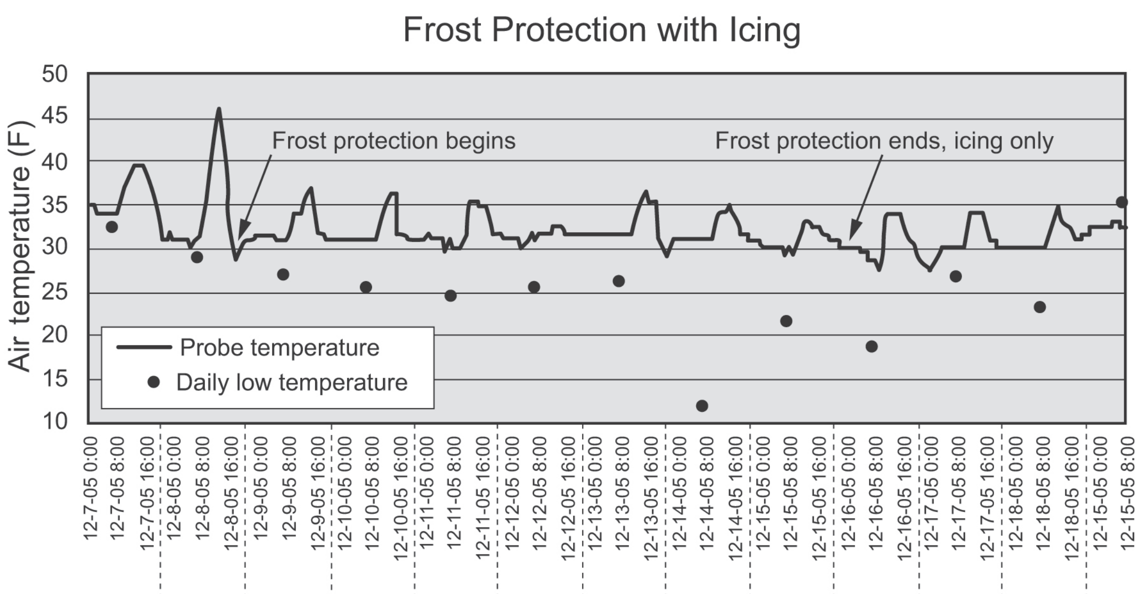


Figure 6 - Temperature probes placed on the terminal shoots of bareroot conifer seedlings and then covered with a thick layer of ice during frost protection show that ice provided some insulation value even after the sprinklers are turned off. More importantly, the ice covering reduced plant moisture stress compared to seedlings that were exposed(modified from Moore 2014).

parts to reduce the chances of them freezing up. Next, determine the frost hardiness of your crops using cold hardiness tests so that you can establish the critical temperature at which to start the sprinkler system. Install a weather station on your nursery or monitor local weather conditions diligently, and pay attention to humidity and wind as well as temperature. Adjust your start frost protection guidelines to account for dew point and wind conditions. Remember that the main frost protection comes from the latent heat released when water freezes so keep applying water until ambient temperature has risen above the danger level. Keep good records so that you can learn from experience and fine-tune your frost protection efforts.

6. References

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