(Miller Chemical & Fertilizer, Hanover, Pennsylvania) have been evaluated for increasing frost resistance or delaying bloom of many tree fruit species. In general, most are ineffective at best and some actually render buds and flowers more susceptible to frost injury (Ketchie and Murren, 1976; Durner and Gianfagna, 1988; Aoun *et al.*, 1993).

Probably the most documented and effective treatment to reduce frost injury is the fall application of the growth regulator ethephon to *Prunus* species, particularly peach. A fall application of ethylene increases peach pistil hardiness, delays bloom, and increases yield (Durner and Gianfagna, 1988). Ethephon works by prolonging dormancy and increasing the chilling requirement which delays deacclimation and bloom (Durner and Gianfagna, 1991a). In addition, ethephon-treated pistils exhibit enhanced supercooling and an increased number of pistils that supercooled after deacclimation. Concomitant with this enhanced hardiness were: (i) smaller pistils; (ii) decreased pistil water content; (iii) increased pistil sucrose and sorbitol content; and (iv) slower growth rates during bloom (Durner and Gianfagna, 1991b).

Whitewashing trees delays bloom slightly, but not enough to make it an economic option (Durner and Gianfagna, 1990, 1992). Pre-bloom application of dormant oil may be used in an attempt to reduce heat accumulation and oxygen entry into buds and thereby delay bloom. Such an application may delay bloom but it decreases blossom hardiness which may result in decreased yield (Durner and Gianfagna, 1992).

Crop Protection from Frosts and Freezes

Before embarking on an attempt to alleviate or avoid injury from frosts, it is wise to ascertain whether or not frost protection is feasible and worth the effort. Usually with an advective freeze, protective measures to avoid injury are quite limited. This is especially true if the advective freeze is accompanied by windy conditions (and most advective freezes are). The chances of protecting crops from injury are much better with radiational frosts. Besides the type of freezing event anticipated, consideration must be given to: (i) the specific crop; (ii) its stage of development; (iii) its hardiness characteristics; and (iv) the economic implications involved in a protective attempt. It makes no sense to spend more money than a crop is worth in trying to protect it.

In considering protective measures, two major methods for protection are available, passive and active protective measures. Passive methods are preventative measures taken long before a frost is at hand and involves mostly relatively low-cost, biological and ecological measures that may help reduce the need for active measures. Passive measures include such things as: (i) site and cultivar selection; (ii) cold air drainage management; (iii) plant nutrition; (iv) pruning; (v) methods to delay bloom; (vi) plant covers; (vii) irrigation; and (viii) tree-trunk painting or wrapping. Active measures are temporary and immediate, physical, energy-requiring methods used to replace the energy lost during the frost event and are often expensive and labor intensive. Active measures include: (i) heaters; (ii) wind machines; (iii) helicopters; and (iv) overhead sprinkler irrigation.

Passive methods of frost protection

Site selection

The most fundamental measure one can take to avoid injury from frosts is site selection. If the crop is already selected and a choice of site is possible, an appropriate site can almost always be found with enough investigation. When searching for a production site, talk to local agricultural advisors and growers for their input. When the site is 'preselected', these same individuals can help guide the selection of crop, cultivar, and production methods.

The topography of any site should be evaluated for potential frost pockets and low areas where cold air might drain. This is true at both a regional and a local scale. Regionally, valleys are usually colder than elevated sites, especially during the frost season. Locally, any low spot has the potential for being a frost pocket. An easy way to identify potential frost pockets is to look for locations where ground fog readily forms. Ground fogs due to radiational cooling are most prevalent in the fall. Elevated sites or sites with slopes not directly facing the sun delay spring growth reducing the chance of frost damage.

An evaluation of the soil and its drainage characteristics should be conducted. Sandy, dry soils hold less heat than clayey, wetter soils and therefore crops grown on them are more prone to radiational frosts. Organic or peat soils hold less heat, wet or dry, than either sandy or clay soils, and are therefore not a good choice if frost-sensitive crops are planned for the site.

If weather records are available for the site, they should be reviewed for evidence of frosts that may impact production. If site records are not available, regional climate data are normally always available from the local climate office or from an Internet source. In addition, anecdotal evidence may be gleaned from other growers in the area with regard to frost potential.

Sites where cold air will drain either on a local or regional scale should be avoided even if an effective screen to cold air drainage such as a wooden fence or dense planting to protect the field is planned. Cold air will pool behind the screen which would protect the production field. However, adjacent land parcels are bought and sold, buildings and roads built and demolished, thus the air drainage around any site is subject to change.

Crop selection

Only crops adapted to a specific site should be cultivated if successful production is expected. If inappropriate crops or cultivars are selected for a susceptible site, most attempts to avoid frost injury will be futile. Besides selecting spring hardy crops, care must be given to ensure that the growing season is long enough to allow the crop to mature to reach the point of harvest subsequent to plant acclimation. For example, 'Granny Smith' apple (195 days to maturity) is not an appropriate cultivar in a region with a growing season of 170 days while 'Spur Red Delicious' (150 days to maturity) is a totally acceptable choice.

Canopy trees

Planting an overstory tree is an effective way to provide a small degree of frost protection to the understory crop. Citrus growers in Southern California often interplant date palms (*Phoenix dactylifera*) as an overstory to the *Citrus* crop (Snyder *et al*., 2005). The date trees help hold in some of the heat radiating out into space and the chance of frost is reduced. Several other examples include an overstory of pine trees (*Pinus* spp.) for the satsuma mandarin (*Citrus unshiu*) crop in Alabama and shade tree overstories for coffee (*Coffea arabica*) in Brazil.

Plant health

While it may sound like common sense, healthy plants are more resistant to frost than unhealthy ones. Proper care throughout the rest of the year may add some resistance to frost in the spring. Proper nutrient management, pruning, irrigation, and pest control all support healthy plants. Another aspect of this is that frost-injured plants are often more susceptible to pest pressure, thus turning the problem into a vicious circle.

In general, excessive nitrogen increases plant susceptibility to frost injury by enhancing the growth of succulent tissue. In fact, any management practice that encourages new growth late in the season should be avoided, as new growth is likely to acclimate to a lesser degree than older growth. Two other nutrients often cited for improving frost resistance are phosphorus and potassium. However, there is no clear cut evidence that either improves frost resistance other than that exhibited to well-grown, healthy specimens.

Bloom delay

Evaporative cooling from overhead irrigation can be used to retard the accumulation of heat units in the late winter and early spring, delay bloom and thereby reduce the chances of frost injury. Since the chances of a spring frost decline rapidly over time, even a delay of several days might make the difference between no crop and a full crop. This method of bloom delay depends substantially on the weather in that air is only cooled to its dew point temperature, thus in a humid climate, little cooling below the air temperature might be accomplished with this method. During warm springs in a drier climate delays of up to 2 weeks can be achieved. While this method is included under passive measures, it actually requires substantial grower commitment of time, energy, and money to implement such a venture.

Fall applications of the growth regulator ethephon can delay bloom in peach (*P. persica*) and cherry (*P. avium*) by up to 2 weeks in a cool spring and for several days in a warm spring. An additional benefit of fall-applied ethephon is an increase in the intrinsic hardiness of peach and cherry flower buds both in the winter and during bloom.

Row covers

Synthetic row covers made of spun-bonded polypropylene are often used to increase downward long-wave radiation at night to protect from frost (Fig. 9.7). These covers are lightweight, opaque to

Fig. 9.7. A row cover such as this provides several degrees of protection against frost injury for sensitive species. The amount of protection is determined by weight of the row cover, with heavier weights providing greater protection.

long-wave radiation and allow air, water, and light to pass freely. However, they are expensive and are easily blown about even in light wind and must be secured with sandbags or other heavy weights. Straw offers an alternative; however, it must be removed to allow light exposure. Many other forms of covers are utilized depending on region and availability. Many are relatively inexpensive, however, all materials including straw and synthetic row covers require substantial labor for installation and removal.

Soil cultivation, moisture, and row middle management

When a frost is anticipated, soil should not be cultivated to maximize heat retention during the day and heat transfer to crops at night. Cultivated soil is aerated and holds less heat than non-cultivated soil. If possible, soil should be irrigated prior to a frost event. Water holds a tremendous amount of heat, thus a wet soil will store more heat during the day than a dry soil. That stored heat can then be released at night, reducing the chances of frost injury. Row middles should be mown as short as possible prior to a frost. Excess vegetation reflects solar energy and increases removal of soil moisture via transpiration. Thus crops with row middles of longer vegetation are more likely to suffer from frost injury than crops with short row middles. Grasses and weeds often have a high population of ice nucleation-active (INA) bacteria associated with them, thus mowing overgrown middles might remove some of the INA bacteria. However, bacteria will still be on the mowing litter and many frost-prone species have intrinsic nucleating agents in them. Thus reducing INA bacteria populations does not guarantee a reduced risk of frost. Removing the entire row middle down to bare soil might reduce the chances of spring frost but would make the field more prone to wind and water erosion.

By covering the soil surface with plastic sheeting heat storage during the day is increased. Clear plastic is a better choice than black plastic as more energy is stored in the soil under clear plastic. Wetting the soil before plastic application also improves heat storage. Organic mulches should not be used as they reduce the transfer of solar energy to the soil. However, midwinter organic mulching may provide protection from soil heaving.

Tree-trunk painting

The trunks of deciduous trees are often covered with a wrap or white latex paint to reduce temperature fluctuations on sunny winter days. There can be as much as a 20°C difference in trunk versus air temperature on a sunny, cold day. If the sun is suddenly blocked by clouds, trunk temperature may plummet and bark cracking can occur. Cracked trunks expose tissue to disease and insect pests, as well as creating a wound that the plant must heal. Trunk painting or wrapping has also been reported to delay bloom in apples (*M. domestica*) by a few days.

Insulated trunk wraps are often used in *Citrus* production to provide as much as 8°C protection to injury to young trunks from frosts. It is critical that the air spaces in the wrap are not filled with water during irrigation or rain, as they will lose their protective nature and may also increase the chances of injury when wet. Soil mounding can be used to protect young trunks from injury; however, the level of protection soil mounds afford is quite variable. In addition, disease pressure is often higher with soil mounds compared with trunk wraps.

Controlling INA bacteria

As previously mentioned, many plants have intrinsic ice nucleators, thus controlling populations of

INA bacteria does not guarantee reduced chances of frost injury. The main INA bacteria are *Pseudomonas syringae, Erwinia herbicola* and *Pseudomonas fluorescens* (Lindow, 1983). In crops that do not necessarily have internal ice nucleators present, controlling populations of INA bacteria may afford some protection from frost. Populations of INA bacteria can be reduced with bacteriocides or by increasing pressure from enhanced populations of non-INA bacteria. Again, this type of frost control is expensive.

Frost-protecting sprays

While there are many commercially available sprays that claim to reduce injury from frost, no reputable reports exist confirming their effectiveness. In particular, chemicals which reportedly reduce frost injury by preventing desiccation ignore the fact that injury is from the failure of desiccated cells to rehydrate upon thawing, not from transpiration-induced desiccation. In fact, chemicals that protect against freezing often render blossoms more susceptible to freezing injury.

Active methods of frost protection

Some of the methods listed under passive methods of frost protection could be included in this section, especially those requiring substantial labor and money investments. However, this section will be limited to those methods employed on the night of a frost in an attempt to reduce or avoid frost injury.

Wind machines and helicopters

If a radiational frost is the result of a loss of radiant heat from the earth to the atmosphere, what better way to reverse the situation than by bringing some of that lost heat back to earth? This is precisely what wind machines and helicopters do.

Wind machines are essentially large fans operating at about 600 rpm with two or four 3–6 m blades mounted on a tower 10 m above the field floor that rotate around the tower every 5 min while drawing air aloft towards the surface at about a 7° angle (almost horizontal). In order to be effective, the fan must have warmer air (i.e. an inversion) to draw towards the surface. Besides drawing warm air in from aloft, wind machines can blow colder air out of low spots in the field. Wind machines are environmentally friendly except for the noise pollution they cause.

Helicopters push warm air aloft towards the surface, but only if there is an inversion present. They need to fly over the field under protection once every 30–60 min to be effective. In general, helicopters can increase the surface air temperature by about 4°C with a strong inversion. Helicopters are expensive to use and are normally only used in emergencies.

Heaters

Since frosts are the result of a loss in heat energy, one way to combat their occurrence is by replacing the lost energy through field heaters. The heat released by burning any one of a number of different fuels will directly heat plants through radiant transfer and also heat the surrounding air by conduction and convection. For heaters to be effective the night must be calm with an inversion layer above the field. Heaters will often be used in combination with wind machines or helicopters to stir the heated air up and to force it back to the proximity of the crop after it rises in the atmosphere. If the inversion is strong enough, it will act as a blanket, keeping much of the heat in the air surrounding the plants. It is extremely important that heaters are placed correctly and burnt at the appropriate level so that holes aren't punched in the inversion layer creating chimneys in which most of the heat will escape to the upper layers of the atmosphere. Heaters can be units purchased for explicit use in production fields or they may be open fires in the field.

Heaters are expensive to purchase and operate and less environmentally friendly than other methods of frost protection. They are, however, a dependable form of protection for high value crops. Most of the heat released by heaters is in the form of hot gasses which rise and cool until they reach the ambient temperature when it then cools, spreads out, and begins to sink, creating a circulation pattern. Very little heat energy is moved by radiant transfer directly to plants. The energy generally required to prevent a frost is somewhere around 20–40 W/m^2; heater output is usually around 140–280 W/m^2, depending on fuel, burning rate, and the number of heaters involved. Most of the energy released during burning is lost, thus the process is extremely inefficient.

Heaters are more efficient with stronger inversions (low ceiling) because they have to heat a smaller volume of air. More heaters are needed along the edges of a field to account for cold air being drawn in from outside the field area by the rising air above the heated field. Smoke does not contribute to heat release or retention from heaters, regardless of fuel or burner type. Local regulations should be carefully reviewed before purchasing or using any type of heater.

Sprinkler irrigation

Sprinkler irrigation can be used to effectively and economically protect crops from frost. Many growers already have the irrigation equipment, thus there are only time, labor, and fuel investments with this type of protection. Labor is needed to set up irrigation equipment and also to ensure there is no ice build up on the sprinkler heads during operation. Some drawbacks to this method include: (i) fuel and water costs; (ii) labor requirements; and (iii) potential soil waterlogging.

Frost protection with water relies on the same principles regardless of the application method used. Water contains a large amount of heat energy. That heat can be transferred to the soil or to plants, raising their temperature and reducing the chance of a frost. While water adds heat energy to the environment, it can also remove heat energy through evaporation. Thus one must consider the energy added with water application plus the energy lost due to evaporation. Additionally, water releases heat when it freezes and this heat is transferred to whatever object the water is freezing on. When liquid and solid water are commingled, their temperature cannot go above or below the freezing point (0°C) until a complete phase change (all liquid or all ice) occurs. Thus if a film of liquid water is maintained on ice, the temperature will stay at 0°C. This is the key to frost protection with water. If enough water is not being applied or the system is turned off too soon in the morning, no liquid–solid interface will be maintained and damage will occur, often more than if no protection were even attempted. Additionally, if the system is not started soon enough in the evening, evaporative cooling may cause temperatures to drop sharply and cause extensive damage. Evaporation of water at 0°C removes about 2500–2800 kJ/kg from the surrounding environment, depending on whether the evaporation is from liquid water or ice (2501 and 2825.5 kJ/kg, respectively). When the same amount of water freezes 418.3 kJ/kg are released, thus it takes six times the amount of water freezing as evaporating just to break even! This is especially crucial when the air is dry (which it often is during a radiational frost) and considerable evaporation is occurring.

Overhead sprinkler irrigation systems attempt to maintain a layer of liquid water on the ice forming on plant and soil surfaces, and thereby maintain a temperature around 0°C. This system can provide up to 7°C protection under ideal conditions. Overhead systems are used on low-growing crops and larger specimens that can support the weight of ice that builds up during protection. In some cases sprinkling over the structure of covered crops (crops in unheated greenhouses or high/low tunnels) may be employed to keep the temperature inside the structure at 0°C.

Under-plant sprinklers are designed to maintain a layer of liquid water on ice forming on the soil surface and ground cover. It is used on any crop that benefits from heat movement from soil to plant during a radiational cooling event and on crops requiring only a few degrees of protection.

Computer programs are available to assist with decisions regarding on-off times and application rates based on air temperature, dew point, wind speed, and crop being protected.

Surface irrigation or flooding

Supplying water to a field via trench or furrow irrigation provides heat from the water as it cools. Similarly flooding entire fields with water provides protection from frost during radiational cooling. If the water cools enough to start freezing, any standing water will freeze from the top down due to the density properties of water. Water is most dense at 4°C, thus the warmer water will sink as the colder water rises to the surface and freezes. If a layer of ice forms, a barrier of heat transfer from the warmer, deeper water and soil develops and the ice surface and adjacent air temperature can cool to dangerous levels.

Artificial fog

High pressure lines with specialized nozzles in an irrigation system can create an artificial fog to protect against frost. The small droplets absorb long-wave radiation and re-emit them downwards providing protection from frost. Light wind and high humidity are required for this method to work and generally work best for moderate frost events. The cost of foggers is high but the operational costs are 20% or less than other conventional heating or sprinkler systems.

Controlling INA bacteria

Controlling the population of INA bacteria is not an effective means to reduce frost injury as most woody species have intrinsic ice nucleators that initiate frost formation with or without INA bacteria present (Gross *et al.*, 1984; Ashworth *et al.*, 1985; Proebsting and Gross, 1988).