Chapter 15

Energy Requirements for Frost Protection of Horticultural Crops

J. DAVID MARTSOLF

1. INTRODUCTION

1.1. Semantics

Traditionally, horticulturists have described methods used to protect plants from cold damage under the term "frost protection" (e.g. Hume, 1937; Janick, 1963; Childers, 1983). However, an argument that damage does not occur in many crops until the plant temperature is below the frost point suggests that it is more correct to speak of these methods as "cold protection methods" (Gerber, 1969). This term has been a characteristic of popular literature originating in Florida for some time (Camp, 1957). Other authors speak of the same methods as "freeze protection methods" (Bartholic, 1979; Rieger, 1986). Such practices reduce appreciation for the differentiation that most meteorologists make between freezes and frosts. Freezes are reserved for the windy and severe cold periods, while frosts denote calm and clear conditions during which radiant energy loss from exposed surfaces is the dominant cooling mechanism. Most methods are more accurately termed *frost protection methods*, for in fact they are effective during frosts and lose their effectiveness as wind speed increases. The term "cold protection" is seldom found in literature originating outside the State of Florida. Generally, the term "freeze protection" can be traced back to works in the Rio Grande Valley of Texas, where the term is appropriate since their protection problem generally focuses on the advective (windy) situation. Covering is perhaps the only method that can claim to be a freeze protection method (Martsolf, 1987a, b, 1988).

1.2. Literature

Most of what is known about frost protection may be considered art (Martsolf, 1974). By trial and error more than by mathematical modeling it has been found that a given heating rate, wind machine size or irrigation rate provides protection during typical frosts (Bagdonas et al., 1978). A method may be in use for some time before, if ever, a convincing argument is published describing the dominant meteorological mechanism. While there are thousands of papers published regarding frost protection, only a few papers or reviews attempt to document the quantitative aspects (e.g., Businger, 1965; Turrell, 1973).

Turrell (1973) provides an exhaustive list of publications which describe methodology used in citrus production. Barfield and Gerber's (1979) collection of chapters reviewing frost protection methods provides a view of the current state of the art. While these chapters vary in the extent to which the particular author attempts to exhaustively document the previous literature, the publica-

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tion fills a void in Turrell's (1973) classic work, i.e., the few, but important, works outside the citrus field. A revision of a textbook on microclimate (Rosenberg et al., 1973) cites key papers from previously published reviews and adds most of the pertinent and more recent publications. Martsolf and Jackson (1985) edited a series of contributions from Florida workers following the Florida freezes of 1983 and 1984. Evans (1985, 1986) reviewed recent experiences in the State of Washington. Ezell (1988) provided a recent summary of methods. Rieger (1989) has recently completed a rather complete review of the subject.

1.3. Avoidance

The best method of frost protection is to avoid the problem by selecting a site on which to grow cold-sensitive crops that is free of periods during which the temperature drops below the critical temperature of the crop. During frosts, cold air drains down slopes and accumulates in pockets and behind barriers, giving rise to the use of the water analogy as a well used tool of horticulturists to visualize cold air drainage, one of the important mechanisms in good horticultural site selection (e.g. Janick, 1963; Bartholic and Martsolf, 1979; Krezdorn and Martsolf, 1984).

If climatological data have been collected at a site close to the site under consideration, analyses of these data can be valuable in the site-selection decision. The utility of these analyses is directly proportional to confidence in sameness of the observed microclimate under frost conditions to that of the site under consideration. Unfortunately, the largest microclimate variations develop under the stable conditions characteristic of frosts (e.g., Hocevar and Martsolf, 1971).

Thermistors, thermocouples, and remote sensors are frequently useful tools for the site selector in that they can provide comparative observations on typical frost nights. Thermistor thermometers mounted on vehicles have proven to be excellent site selection evaluation tools in mountain and valley terrain (Hocevar and Martsolf, 1971).

Remote sensing technology has added another effective tool, especially in the case of thermal data from geostationary meteorological satellites. All frosts and many freezes are accompanied by clear skies during which the satellite "sees" the radiation from the ground, and the resulting thermal maps are very convincing in evaluation of differences between sites because all site temperatures are sensed with the same instrument (Martsolf, 1981, 1982; Sutherland et al., 1981; Heinemann and Martsolf, 1988).

2. ENERGY CONSERVATION STRATEGY

2.1. Temperature versus time: the fundamental concept

The concept depicted in Fig. 15.1 seems useful in defining the goal of frost protection methodology. The energy conservation strategy is to intervene when and only when necessary. The concept clearly points to temperature monitoring as a crucial process. Risk increases as the critical temperature is approached. Both conservation and risk increase in the same direction on the chart. The chart brings into focus the "turn on" and "turn off" decisions in relation to risk and conservation. Alarms and forecasts play important roles in reducing the possibility that the operator will be unaware of and/or unprepared for the frost or freeze. But the final process on which success depends is local temperature monitoring.

Temperature traces are never as smooth as suggested by Fig. 15.1. Even

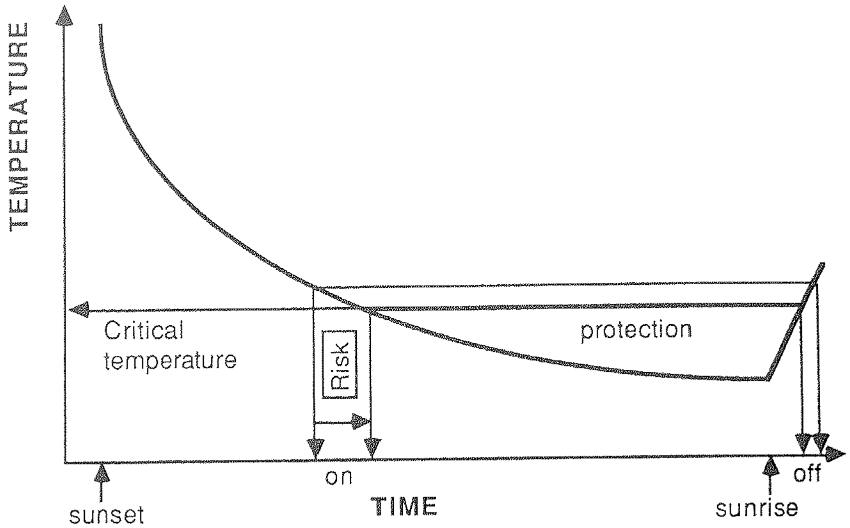

Fig. 15.1. Nocturnal cooling curve for idealized radiant frost night during which protection is provided just as cooling reaches the critical temperature of the protected plant and continues till energy from the sun takes over the task.

when temperature data from numerous locations are averaged with a computer and the mean is displayed, the trace is poorly behaved. The size of the volume over which the temperatures of plant parts are averaged to arrive at the average temperature trace depicted is generally the smallest volume that can be managed individually, e.g., fired as a block; protected by a single wind machine; served by a singularly controlled irrigation system. This volume is referred to as a block in this and many such descriptions.

2.2. Air temperature versus plant temperature

Generally air temperature is monitored. And generally, air temperature is sensed with a liquid-in-glass thermometer (Wolnick et al., 1974). So air temperature is actually thermometer temperature. But it is a plant part for which the critical temperature is known (if the hardiness condition of that organ is specified). For example, fruit blossoms mature through stages in the spring, and the critical temperature for each of these stages has been carefully determined in freezing chambers. Such chambers cannot be expected to adequately emulate radiant cooling of the blossoms. A model seems to be needed that accepts such horticultural information as the stage of development and the scion variety, and combines that with such meteorological information as the wind speed, net radiation, and dew point temperature. The output should not only be an estimate of the expected departure of the blossom temperature from air temperature but quantify the risk in statistical terms (e.g., Proebsting and Mills, 1978; Welles et al., 1979). So a complication in the concept is that air temperature is monitored while it is really the plant temperature that is predicted from two meteorological parameters: the air temperature, and an estimate of radiational cooling, i.e., the number of degrees that the plant material is likely to be cooled below ambient air temperature.

Another example is provided to describe the complication that preconditioning of the plant organ adds to effective use of the conservation strategy. Most subtropical plants tend to harden, i.e., develop the ability to tolerate colder temperatures when exposed to winter conditions. While much is known about plant hardiness, no operational models exist that permit the user to input the variety, the rootstock, and prior weather conditions (temperature and mois-

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ture, primarily) to have an estimate of the critical temperature returned. However, hardiness of citrus leaves from several locations in Florida continues to be measured in the laboratory and the results distributed to extension workers for dissemination to the public (Wiltbank and Oswalt, 1984). In the deciduous orchard case, some progress in this direction can be cited (Proebsting and Mills, 1978).

2.3. Space and time

The temperature trace in Fig. 15.1 could represent the temperature of the microclimate of the particular plant part to be protected. To let the curve represent the situation for the block, the variation of the particular temperatures within the block should be considered. One method of simplifying this process is to choose the operational blocks in such a manner that the particular temperatures can be expected to be as nearly the same as possible. In practice, only one air temperature sensor is monitored per block and the manager mentally integrates all the temperature variation expected within the block into the decision as to when to initiate a protection method. After a protection method such as firing is initiated, the process of regulating the heaters is more art than science, since only the most sophisticated of temperature monitoring methods is useful after heaters are burning, due to the effect of the radiant output of the heaters on the temperature sensors (Welles et al., 1979, 1981). In a 1-ha research block, an attempt was made to permit feedback of plant temperature to control the heater burning rate (through pressure regulation of a pipeline heating system) only to learn that the controller generally drove to the upper limit and remained there (Martsolf, 1974). Apparently, in small blocks at least, increasing the burning rate does not always result in increases in plant temperature. This suggests that feedback of temperature information into decision making is likely to be a sophisticated mechanism, i.e., more complex than simply placing a temperature probe in the middle of the orchard to be protected and arranging for it to control the burning or sprinkling rate of the protection system.

2.4. Conservation: Matching response to precise need

Maximum energy conservation is achieved when the minimum amount of energy necessary to provide protection is used. This is, or should be, the goal of all frost protection systems. A major deterrent to reaching this goal is the tendency to minimize cost of the protection system (including the monitoring subsystem). This frequently results in the design of a fixed-rate system, i.e., one in which regulation of the rate of energy use is not possible. Rather, the system is either turned on or left off. Wind machines are an example and there is little opportunity to change this. But in the case of many irrigation systems there are good opportunities to make the system a variable rate system as has been accomplished with pipeline heating systems (Martsolf, 1974, 1988; Perry et al., 1980). Ability to regulate the amount of protection that the system must deliver is the key to producing a system that has the ability to maximize energy conservation.

2.5. Conservation: a trade-off in risk

Risk is a central issue in frost protection strategy. But risk has not been analyzed quantitatively; rather, it is left to the judgment of the system operator. To maximize energy conservation, the grower must permit the temperature to approach the critical temperature of the plants to be protected as closely as he dares, and maintain the temperature just above that critical temperature throughout the period of protection. The degree that the operator is willing to conserve energy is directly dependent upon his confidence in the temperature information that he is using in the decision-making process. In this light, most operations have inadequate temperature-monitoring equipment, and that which they have has questionable accuracy. One of the services that is popular and used extensively in areas having mature frost protection programs is thermometer calibration. On the other hand, the argument is that the protection system is in place and the consequences of failure are so expensive (as well as embarrassing) that the protection systems are used even when it is doubtful that they are needed. This tendency defeats energy conservation goals. Only the most seasoned frost-protection system operator avoids panic under the pressure of deciding when to start.

Systems that failed are frequently those which were not started because the operator failed to realize there was a possibility of frost and so was not present when it occurred. But unfortunately some systems are installed with design flaws that prevent their success even when managed properly; for example, fixed-rate irrigation systems with low application rates. Seldom have systems failed because operators permit the temperature to approach the critical limit too closely before starting the protection system. Operators tend to pad that process sufficiently to avoid failure. Consequently, there is a tendency for systems to be used when unnecessary, and at rates above those necessary. A key process in the conservation strategy is to attack this tendency (Martsolf and Morrow, 1979). Periodic reassessment of the risk and the cost of the unnecessary energy expenditure in quantitative terms is needed to maximize energy conservation. It may not be as obvious as it could be that this assessment depends directly on the ability to monitor temperature, dew point, and wind speed convincingly, before and during the period during which the protection system is operated.

3. HEATING

3.1. A little history

Heating for frost protection is a tried and proven method with an extensive written record (e.g., see Martsolf, 1979a; or Turrell, 1973). Elements of the art have been described more extensively than efforts to estimate the heat requirement as a function of the numerous variables in the problem. It has been found by experience more than by model that 86 heaters per hectare (35 per acre) burning oil at a rate between 2 and 4 L/ha (0.5–1 gal/ha) are necessary to protect an orchard under typical frost conditions in Florida and California. On the borders of the heated blocks it is commonly recommended that the density of the heaters be doubled, especially on the upwind border(s).

As concern increased about air quality beneath the temperature inversions that normally accompany radiant frosts in California and then in other fruit-growing states such as Florida and Washington, orchard heater design research led to clean-burning stack heaters. The additional cost of such heaters was balanced against the increase in effectiveness due to the fraction of the liberated energy that was transferred by thermal radiation from heater stacks to plant material to be protected. The more-radiant stack heaters were able to transfer as much as 25% of the 40 MJ per liter of oil combusted (140 000 Btu per gal) although claims were occasionally made by less-careful manufac-

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turers that a much higher radiant fraction was available from their stack heater (Turrell, 1973; Perry et al., 1977).

At the height of the Roman Empire, vineyard keepers burned prunings on frost nights. Later, Florida growers took advantage of the availability of pine that was cleared as fuel for fires as groves were planted on the sand ridge. But the labor required to effectively use wood, a renewable natural resource, for fuel has provided incentive for the growers to use petroleum products as fuel. Some solid fuels were developed by the oil industry during a relatively short period in the 1960's but most heating experience has been gained through the use of oil or gas-burning heaters.

As labor for lighting and refueling heaters became more expensive and the need to conserve fuel provided incentive to centrally control burning rates, the pipeline necessary for gas-burning systems was down-sized and became an attractive option in oil-burning systems. Concern for labor and fuel conservation also supported searches for alternatives to heating. The wind machine, and its combination with heaters, irrigation, covers, all are productively treated as alternatives to heating.

3.2. Pipelines: a variable rate system

Central control of burning rate by varying pressure in distribution pipelines is described by the following equation (Martsolf, 1976):

$$F = k(aP)^{1/2} \tag{1}$$

where F is the flow (L/ha), P the pressure (kPa) at the nozzle, and k the nozzle constant, which for the U.S. case is stamped on the nozzle in units of gallons per hour at a standard pressure of 100 psi (690 kPa), making $a = 0.0208$.

Lower-pressure systems were more popular because they offered a broader range of pressure regulation and less tendency toward springing oil leaks. Leaks are difficult to detect when the pipelines are buried to protect them from cultivation equipment. Labor conservation and the need to have the system available for the initial frost of the season led to the practice of installing the heating system (and the irrigation system) at the time that the orchard was planted and leaving it in place throughout the years. Since heaters were seldom stored inside even when taken out of orchards, their life was not decreased by leaving them in the orchard all year if sufficient care was taken to avoid hitting the heaters with harvesting and production equipment. Thus energy is conserved (in forms of both fuel and labor) by a system fixed in space but variable in application rate, i.e., the pipeline heating system.

3.3. Modeling the heated orchard

Several models have been developed to predict the heating requirement given the meteorological conditions and certain orchard variables. Only Crawford's (1964) model (Fig. 15.2) has been used extensively because the relationships between its inputs and outputs were described in a series of monographs republished in a popular reference volume (Turrell, 1973). A contemporary model (Gerber, 1964) was developed (Fig. 15.3) but not completely described until later (Gerber, 1969) in publications of limited distribution. Both models are briefly reviewed and relatively simple Fortran programs of the models are published in an article by Martsolf (1979a).

One of the deficiencies of the models described above is that they do not explicitly recognize turbulent transport mechanisms which are certainly modified by the buoyancy of the heating (Bland et al., 1980). Martsolf and Panofsky (1975) placed turbulence in the box model in a fundamental position. While

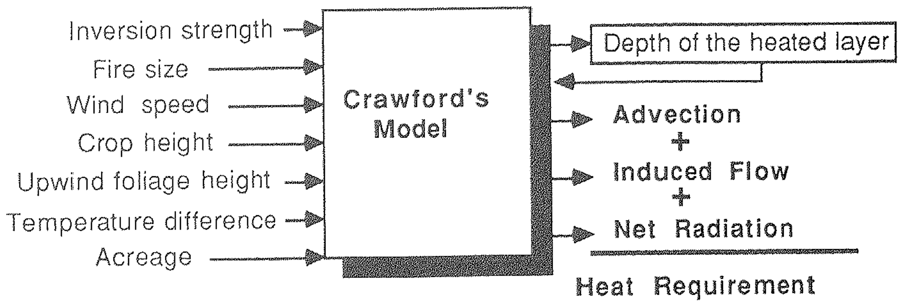

Fig. 15.2. Diagram of Crawford's model (1964) indicating that three energy loss terms are computed from seven inputs. The energy requirement for protection is the sum of the losses. An intermediate computation within the model is the depth of the heated layer.

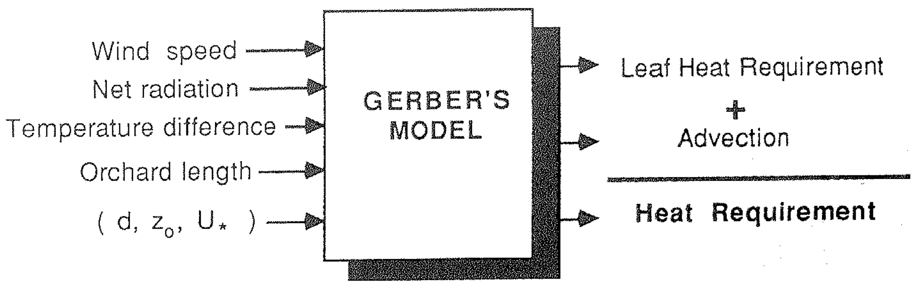

Fig. 15.3. Gerber's model (1969) requires six inputs, three of which are micrometeorological parameters that aid in a description of the wind profile, i.e., d is the displacement height, zo is a roughness parameter (both of which describe the canopy height and thickness) and U_* the friction velocity. The total heat requirement is the sum of the heat required to protect individual fruits or leaves plus that necessary to warm the air lost from the orchard by advection.

that model served as a framework around which experiments with individual transport mechanisms could be executed (Stepp and Martsolf, 1973; Fritton et al., 1976; Martsolf, 1976; Perry et al., 1977; Welles et al., 1979, 1981; Bland et al., 1980; Fritton and Martsolf, 1980a, b; 1981) it has yet to be programmed into a predictive form.

3.4. Non-fossil fuel

The effectiveness of alternatives to heating with oil is frequently judged by using the effectiveness of oil heating as a scale against which the alternatives are compared. Fossil fuel may be conserved at some point in the future by the substitution of bio-replaceable fuels for the fossil fuels. Some experiences with the gasification of wood for distribution through a typical pipeline heating system indicate that cost of fossil fuel will have to increase appreciably before the method can be expected to attract much attention commercially (Martsolf and Hannah, 1984). Wood fires proved effective (Hume, 1937) in the early days of the citrus industry in Florida but were so labor-intensive that they are not expected to return to use except perhaps in locations where labor is not a limiting factor.

4. WIND MACHINES

4.1. Reviews

The development of the wind machine as an alternative to heating has an interesting history, reviewed in detail by Turrell (1973) with supplemental insight by Gerber (1979) and others cited in their reviews. The principle upon which the method rests is the mechanical mixing of heat in layers of the temperature inversion above crop canopies with the cooler layers which otherwise settle into the canopy. The success of the method is directly dependent on the presence of an inversion, i.e., the method is effective only in a frost situation.

Management of wind machines is covered in detail by Hansen (1951), Puffer and Turrell (1967) and by Turrell (1973). Care must be exercised that the machines are not operated under wind conditions because not only are they not effective but they may be damaged. Electrical-powered wind machines are often controlled by thermostats, and these need wind-sensing elements that prevent the machines from operating when the wind speed is above a threshold level of about 1.3 m/s (3 MPH).

Gerber (1979) reviewed the theory of wind machine design which suggests that a typical machine (75 kW delivered to a 4.67 m diameter fan on a tettering hub and mounted on a 10-m tower) is a compromise between jet penetration for area coverage and mixing power, i.e., one being achieved by a small-diameter, high-speed jet, and the other by a large-diameter, slow-moving jet. Angus (1962) suggested that two systems had emerged, one being the "American Machines System" described above. The second system involved lower-power machines evolving in Australia in combination with convective type heaters (Angus, 1955). Trial as much as design has determined that the machine described by Gerber (1979) covers about 4 ha when the fan rotates around the tower each 5 min (Griffiths and Hendershott, 1961).

Ball (1956) concluded that large slow-moving jets were most efficient in mixing the atmosphere but that smaller-diameter, higher-speed jets were required to achieve distance. So wind machine design is largely a compromise of these two criteria. Thrust is proportional to the square of the RPM of the propeller so any reduction in performance of the power unit rapidly decreases the effect of the machine (Brooks et al., 1952; Crawford, 1964). Since the period of rotation about the tower is directly proportional to the RPM of the fan, a quick check on the machine's performance can be achieved by timing the period of rotation about the tower. Typically a rotation period is 5 min and is equivalent to a blade RPM of 590. Specially designed machines have variable dwell times to provide protection over irregularly shaped orchards or where topographic features produce cold-areas (Gerber, 1979). Angus (1962) indicated that, in the case of the lower-power machines, air velocity was a better criteria than thrust for indicating relative effectiveness. Turrell (1973) also reviewed these concepts.

4.2. Size and placement

Doubling the engine on top of the tower and halving the rotational period decreases the effect that the machine has near the tower but increases the area covered to about 1.6 times the area affected by the single machine. However, the savings on the cost of towers has made this option sufficiently attractive in certain situations where many of these double machines are in use. As in heating, there is a mass effect when numerous machines are distributed through adjacent areas. Wind machines are expensive to move, so placement is considered permanent, and an art. Diagrams of the protection provided during frosts when drift was documented show a distortion of the patterns downwind from the machine location. Therefore, machines are frequently placed in the northwest quadrant of the 4 ha area they are expected to protect, because the drift is frequently from the northwest during a frost in the northern hemisphere when the terrain is flat. In rolling terrain, cold-air drainage must be considered. Machines with variable dwell times (rotational speed about the tower) are used to tailor the expected patterns of protection to fit the irregular shapes of areas to be protected or when topography produces complex cold air drainage patterns to be accommodated.

4.3. Conservation considerations

Typically, wind machines use one order of magnitude less energy per unit area than heaters. For a number of reasons, wind machines are generally run for longer periods than heaters are fired. Failure to start is a worrisome problem causing many users to start machines early. Starting early and letting the machine idle until needed solves this problem.

Ball (1956) presented a theoretical argument that as little as 185 W/ha (0.1 hp/acre) is necessary to maintain isothermal conditions in a layer 15 m thick from which heat is being extracted at the bottom by typical radiational cooling (Martsolf, 1979b). Gerber (1979) concluded from Ball's analysis that at least 50% of the energy required for cold protection by wind machines must be ineffective in providing protection. Brooks et al. (1952) set out to describe a heat transfer model that would predict the energy need from a wind machine necessary to stall the cooling of an orchard. Although his team made useful observations, Angus (1958) stated that, "The investigation has been handicapped by lack of theoretical treatment of wind machines" in regard to his studies. Later Angus (1972) apparently developed a model that predicted the center line (jet axis) as well as the jet's velocity and width along the axis as a function of the inversion strength, propeller diameter, initial jet speed, down-tilt angle, and addition of heat to the jet. But no evidence exists that the model was published. While there would appear to be room to improve the wind machine design, to this author's knowledge, no major effort in that direction is under way. However, some manufacturers continue to refine features of what Ball (1956) termed the "American Machine".

4.4. Helicopters

Capitalizing on the same mechanisms for protection that wind machines do, and subject to the same basic limitation, i.e., the presence of a temperature inversion, helicopters are frequently used because they are available between other tasks for which they were purchased. No quantitative formulae exist, to this writer's knowledge, that relates the amount of protection that can be expected under given meteorological conditions for a given-size helicopter. But enough thought has been given the situation to recognize that the heavier the helicopter the more effect it can be expected to have (Seeley, 1988). Loading the helicopter is a compromise with safety, however, since night flying near the ground and often near power lines is already quite hazardous. As fuel is consumed, the craft weight decreases and its effectiveness decreases, and this is in the opposite direction to the need. The need to refuel during the period of needed protection is another problem that is partially solved in situations in which several ships are needed and a plan is developed that has only one on the ground at a time.

In the absence of a published relationship between ship weight and acreage cover for a given inversion strength, claims by helicopter operators frequently exceed more reasonable expectations. So an innovative feedback system has been recommended. High-quality thermostats are wired into the circuits of the battery-powered caution lights developed for marking temporary highway hazards in such a way that the light blinks when below an adjustable threshold temperature. The helicopter pilot flies patterns and at elevations that minimize

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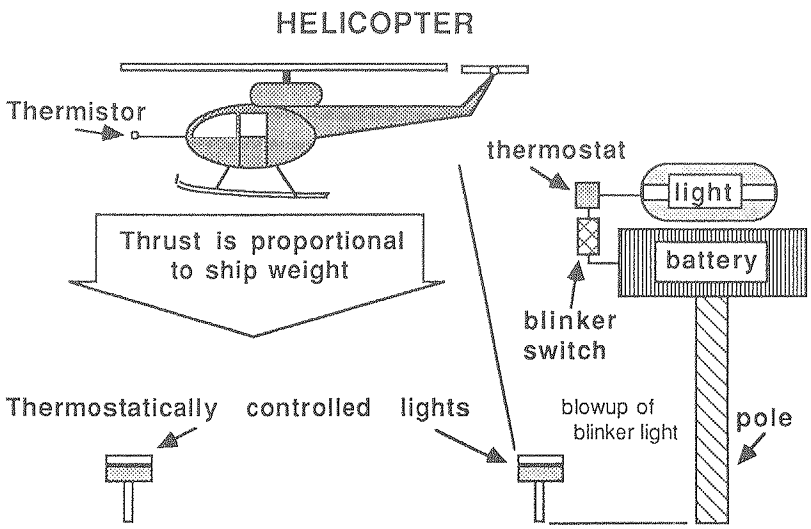

Fig. 15.4. A visual feedback system in which blinking caution lights are used to indicate areas that have fallen below a threshold temperature to the pilot who in the process develops an impression of how effective his machine is in ameliorating temperature.

the number of blinking lights (Fig. 15.4). This system also helps with the boundary-marking problem that requires a system of lights which the pilot can recognize. Ships used for frost protection are often equipped with thermistor thermometer probes that permit the pilot to locate layers of the temperature inversion and use that information in his pattern planning. While these probes are desirable, they are less than a substitute for the temperature-sensitive lights near the ground.

Effective use of helicopters requires highly reliable forecast information for the machines, and their pilots must be placed on standby for hours, if not days, before they are needed. Standby charges often run as much as 50% of the cost of the machines when flown.

5. IRRIGATION

There are a number of ways that irrigation systems can serve at least a dual purpose, i.e., both drought abatement and frost control. In some situations a third function can be added: heat suppression, utilizing the same sprinkling system. Most irrigation systems have centralized control and consequently have low labor requirements. Such systems provide hope that they can be automated at some point in the future, made to respond directly to atmospheric conditions without dependence on the presence of operators. Water does not pollute the atmosphere nor in most cases does it harm the soil environment. These, and more, are reasons for the popularity of irrigation for frost protection.

Businger (1965) listed the physical effects of preventive irrigation as:

— thermal conductivity of the soil is increased
— heat capacity of the soil is increased
— evaporation from the surface is increased
— crops generally become more susceptible to frost.

5.1. Flooding

Georg (1979) reviewed experiences with flooding for frost control in citrus groves, sugar cane fields, and truck crops of Florida and cranberry bogs of

Wisconsin. He mentioned furrow irrigation used in California citrus orchards (see also Brewer, 1983), often in conjunction with a wind machine, suggesting again that it is the combination of methods that is frequently found to be the most effective solution for a particular crop and locality. In discussing furrow irrigation, Brewer (1983) admitted that after ice forms on top of the furrow flows there is little heat transferred from the warmer water flowing beneath the ice. There is continued interest in why flood irrigation works as well as it appears to. One of the suggestions points to heat delivered by condensation of water evaporated from the open water surfaces, either in the air as fog or onto radiantly cooled plant surfaces down drift (Martsolf, 1984). Flooding is highly dependent on good forecasts since pumps are generally small relative to volume of water that must be moved and consequently they must be started days ahead of the cold period. Water management authorities are prone to rule these practices inefficient from both conservation of water and conservation of energy standpoints, pressing users toward other methods of irrigation.

5.2. Sprinkling

Gerber and Martsolf (1979) listed many of the previous contributions to the literature (e.g., Rogers and Modlibowska, 1962; Gerber and Harrison, 1964; Gerber and Martsolf, 1964, 1965; Braud and Hawthorne, 1965; Businger, 1965; Wheaton and Kidder, 1965; Chessness et al., 1968; Hewett and Hawkins, 1968; Martsolf, 1974; Modlibowska, 1975) and reviewed the calculation of the volume of water necessary to provide protection through the release of heat accompanying the change of phase during the freezing of an ice-water film on the plant part to be protected. Perry (1979) reviewed the literature extensively and developed a model (Perry et al., 1980, 1982) that combined the best attributes of the Businger (1965) and the Gerber and Harrison (1964) models. This model, termed SPAR79 for the 1979 rendition of a Sprinkling Application Rate model (Fig. 15.5), was refined, e.g. SPAR81, and it has become FROSTPRO (Perry, 1986). Barfield et al. (1981) published a model which they indicated was a modification of the model presented at a workshop held in 1978 in Florida. They also indicated that their model was based on the Businger (1965) and Gerber and Harrison (1964) models but it was understood during the early development of their model that it served as an independent check for it evolved from an independent course exercise.

These SPAR models produce tables of the required precipitation rate, given the wind speed, temperature, and characteristic dimension of the plant part over which ice with a liquid water film on its surface is to be maintained (e.g., Gerber and Martsolf, 1965; Harrison et al., 1974). Barfield et al. (1981) argued that relative humidity should be taken into consideration and provided an

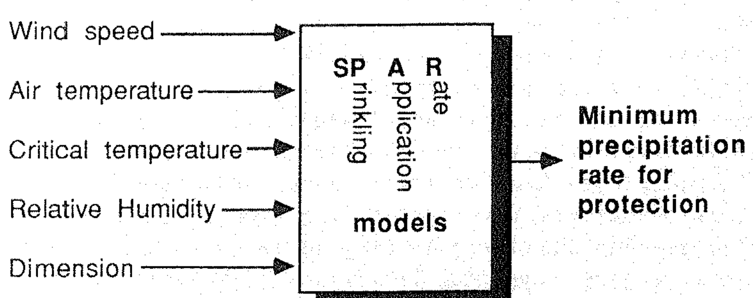

Fig. 15.5. A generalized diagram of the SPAR models showing the major inputs required. Dimension refers to a characteristic length (or width) of the plant organ to be protected, e.g., blossom width.

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example in which the precipitation rate could be underestimated by 28% when the relative humidity was 50%. Perry et al. (1982a, b) agreed by publishing an example in which SPAR79 can make an error as large as 37%. When humidities of 80% are used the errors reduce to between 12% and 19%.

All the models are for singular plant parts, e.g., leaves or blossoms, surrounded by a given environment (model inputs). The SPAR models are not two or three-dimensional as are the more recent heating models. That is to say, they do not take into consideration the immediate past history of the horizontal flow, where it has been and how the character of that flow may have been modified: its humidity, for example. The models do not recognize the edge of the orchard as opposed to the center and downwind portions. The humidity can be expected to increase as one follows the wind into the sprinkled volume. The differences in the way that the models handle, or fail to handle, humidity seems minor in the face of their deficiencies in handling 2-D or 3-D space. However, the humidity-sensitive model would seem to be necessary on the upwind border of the irrigated block.

None of the models considers condensation for they do not explicitly provide for the enrichment of the horizontal flow with moisture or its deposit on surfaces below the dew point temperature as an air parcel moves through the upwind edge of the irrigated canopy into the irrigated block (Martsolf, 1984). There seems to be a need for a 2-D model which concentrates on the phase changes of water and where they occur. These phase changes, especially evaporation and condensation, are extremely energy-intensive. To occur, energy must be available or become available within the small volume at a point in space. The model should solve the energy balance of the small volume (Martsolf and Panofsky, 1975) to determine how much the temperature of that volume is modified.

Gerber and Martsolf (1979) suggested that a simple visual check on the adequacy of operation, i.e., the formation of small clear icicles, can reveal areas such as those upwind in which the film of liquid water has not been provided, and air is entrapped within the ice formation, giving it a milk glass appearance. Breakage from ice loading is a problem with the taller and broadly branching crops. Ice pillars may form and help support the crop. Breakage tends to decrease as the practice removes the limbs prone to breakage. Deciding if the system should be used on a particular night is difficult because the decision depends on the forecast of wind, temperature and humidity for the cold period.

Using pipeline heating systems as an analog, Martsolf (1974) suggested that variable-rate irrigation systems would increase the efficiency of such systems by matching the volume to the need. Equation (1) convinces a system designer that varying the system pressure can provide less than the necessary variation leaving the option to pulse on and off the system to be investigated (Perry et al., 1980). Hamer (1980a) described a thermistor probe that could be used to control a nearby sprinkler. This system would have the advantage of adjusting the rate to fit the needs of a particular location within the orchard. Perry et al. (1980) described the use of SPAR79 to determine the maximum off-period that could be tolerated in a "pulsed" sprinkler system, showing that 4 min was often too long under rather typical conditions (see also Phillips et al., 1983). The controller for a variable-rate irrigation system could depend on a model which in turn depends on a system of sensors, or it could depend directly on a sensor if the sensor emulated closely enough the plant part to be protected (Hamer, 1980a, 1986a; Heinemann and Morrow, 1986).

Five of the authors mentioned above (Barfield et al., 1989) developed a chapter for an American Society of Agricultural Engineer's Handbook on Irrigation Management Strategies during the later portion of the period (May

1988) during which this chapter was written. It should be acknowledged that their deliberations influenced the portions of this chapter on irrigation.

5.3. Sprinkling for bloom delay

Sprinkling to evaporatively cool fruit trees as their blossom buds develop in the spring, with the purpose of delaying their bloom and thus reducing the risk of frost damage (e.g., Couvillon and Hendershott, 1974; Richardson et al., 1974; Buchanan et al., 1977, 1979; Griffin and Richardson, 1979; Hamer, 1980b, 1981, 1983, 1985, 1986b) is a subject of great interest and one not easily summarized. The method seems to have promise but results apparently are not uniform from location to location and from year to year. For apples grown in humid climates the model predicts longer delays than occurred (Smith, 1980). Bauer et al. (1976) and Stang et al. (1978) question the frost protection value of the method by indicating that while bloom was delayed in time, the sprinkled blossoms tended to be less hardy and more susceptible to disease. But the possibility that a single variable-rate sprinkling system might serve four plant stress-reducing purposes, i.e., drought abatement, frost protection, bloom delay, and heat suppression, is likely to periodically fuel additional investigations of the subject.

5.4. Micro-irrigation

It became apparent to many during the 1981 freeze that micro-sprinkling (microjet, undertree sprinkler irrigation) provided more protection than the SPAR models predicted that it would (Oswalt and Parsons, 1981). Initially, workers were concerned about the sprinkling rates (Davies, 1980; Buchanan et al., 1982; Parsons et al., 1982a, b, 1985a, b) but later caution was replaced with the contention that microsprinkler irrigation was the only method worthy of consideration (Parsons, 1983). However, the mechanism by which the obvious protection is provided remains to be clarified (Martsolf, 1979c, 1980, 1984). The possibility that the major protection mechanism may be condensation and involve a two-dimensional analysis is mentioned in Section 7.2.

6. COVERING

There has never been any doubt that covering for frost or freeze protection works (Maki, 1977). The question becomes one of whether the covering process is economically feasible.

6.1. Banking

It has been known for at least a century that the banking of soil around the base of a plant will protect that portion of the plant from frost and freeze damage (e.g., Hume, 1937). However, the energy involved in constructing the bank, replacing it when it blows away, and removing it, whether done by hand or by machine, is far from negligible. Disadvantages of banks led to the development of tree wraps (e.g., Jackson et al., 1983; Davies et al., 1986).

6.2. Tree wraps

Fucik (1979) and L.K. Jackson et al. (1983) reviewed the use of insulating wraps for protection of young trees. Some wraps (e.g., Yelenosky and Reese, 1979) have become rather elaborate in the combination of other mechanisms,

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such as the freezing of water, with the insulation of the tree trunk for protection. Tree wraps have become very popular and there are numerous questions about which is the best wrap, a question not easily answered because of the differences in cost and labor required for installation (Yelenosky and Reese, 1979; J.L. Jackson et al., 1981; Rieger, 1986). The combination of tree wraps with micro-irrigation is discussed in Section 7.3.

6.3. Fog

Mee and Bartholic (1979) provided an excellent review of the merits of fog systems from an energy conservation standpoint, building a case for fog having the potential of providing protection for 20% of the energy required for use of sprinkler irrigation and 1/400 of that needed in heating for protection. However, fog systems require special equipment, knowledgeable users, and special locations where the drifting fog will not be a problem to others for which there can be liability. Obviously, fog systems are not effective under windy conditions.

6.4. Foams

Bartholic (1979) reviewed evaluations made at numerous locations in the U.S.A. and Canada which indicate protection from a few to 10°C for periods from a few hours to more than a day. The method is restricted to relatively low-growing crops and dependent on excellent forecasting.

6.5. Windbreaks and covers

Two advective freezes in a row in Florida renewed interest in windbreaks in combination with other frost protection methods (Martsolf et al., 1986). A review of windbreak literature led to the investigation of the merits of an orchard cover (Maki, 1977; Martsolf, 1987a). Individual tree covers were tested by Parsons et al. (1985a) and J.L. Jackson et al. (1986). Covers are superior to windbreaks because they interrupt the vertical transport of heat and/or moisture from the protected plant or orchard (Martsolf and Gerber, 1969; Martsolf and Decker, 1970). It is not likely that an orchard cover alone, i.e., not in combination with another method such as heat and/or irrigation, will provide protection (see Section 7.4). However, covers such as foams (see Section 6.4) and blankets, which have good insulation qualities, placed over low-growing crops and ornamentals are always highly effective. As Waggoner (1948) was able to demonstrate in a classic experiment with polyethylene shelters, the condensation of water droplets on the underside of the radiantly cooled cover converts it from a transparent to an opaque surface with respect to infrared radiation. However, any plant parts that come in contact with a thin film will likely be damaged by the very cold surface. Also, the cover must have sides or the convective exchange through the edges of the radiation shield will wipe out most of the effect of the interrupted radiant loss (Martsolf and Gerber, 1969).

7. COMBINATIONS OF METHODS

Combining frost protection methods has proven to be a productive process in many instances, due to synergistic mechanisms. For example, in the case of the combination of heaters and wind machines, Brooks et al. (1952) reported that orchard temperature responses "showed a gain of 20 percent to 30 percent above the sum of the separate responses — verifying reports of growers that the combination increased frost protection."

7.1. Wind machines and heaters

Approximately 37 stack heaters per hectare (15 per acre) are evenly spaced around the area protected by the wind machine, except none should be placed within 30 m (100 ft) of the base of the machine. Crawford and Leonard (1962) documented the synergistic effect of multiple units of wind machines and heaters used in conjunction. There is a tendency for the wind machine jet to curve upward as it extends outward from the tower due to buoyancy of the jet. Placing heaters directly beneath the machine adds to this problem and reduces the area affected by the machine's jet. Brooks (1960) indicated that the combined response of a wind machine and 21 heaters per ha is about equal to that by 54 heaters per ha alone. Angus (1955), with regard to a low-power wind machine and lard pail heaters, recorded: "Tests with a combination of these heaters and a wind machine suggested that the areas of various temperature rises were equal to the sum of the areas produced by the two methods used separately."

When interest in freeze protection methods was high following the 1983 and 1985 freezes in Florida, a propane distributor in Florida developed a heater with a long stack that extended up next to the wind machine tower. These Petrolane heaters were demonstrated extensively before their promoters became aware of the numerous experiences with heat sources beneath the wind machine and the consequent decrease in the area protected by the machine.

A ram-jet wind machine was built and tested in California in the mid and late 1950's (Goodal et al., 1957; Gerber, 1979). The machine had a 7-m propeller tipped with ram-jet engines producing 500 kg of thrust. It operated at 550 RPM and was angled downward from horizontal at 15°C to defeat some of the effect of the added buoyancy to the jet. The machine rotated once per 6 min and consumed 363 L of jet fuel per hour. The circle of fire presented a spectacular view but the excessive noise was said to be as much a factor in the defeat of the idea as the buoyancy of the jet.

7.2. Irrigation and heating

It has been productive to consider irrigation and heating methods in similar lights (Martsolf, 1974) and at least one practitioner has reported a combination of oil burning heaters and sprinkler irrigation to be highly effective (see Martsolf, 1979a, fig. 6). The heating of the irrigation water prior to its delivery to the microjet nozzles has been tried and is the subject of an investigation (Martsolf, 1988). The work of Davies (1987) and Davies et al. (1987) might be viewed as a combination of irrigation and heating since the heat carried by the irrigation water to the undertree sprinklers was shown to be the mechanism through which such sprinklers provide protection. The buoyancy of plumes from heated water jets is high because it is contributed to by both the heating effect and the substitution of much lighter water vapor for dry air molecules. This leads to the expectation that an orchard cover may be useful in the containment of warmed and moist atmosphere of a block treated with a hot water irrigation system (Martsolf, 1987b).

7.3. Micro-irrigation and tree wraps

The protection of young citrus trees in Florida with a combination of microsprinklers and tree wraps (Davies et al., 1984, 1987; Rieger et al., 1986, 1988)

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has become quite popular in Florida as the result of a productive program in young tree care. A survey (L.K. Jackson et al., 1986) found cold protection of young trees to be of greatest concern with information about tree wraps and microsprinklers being readily adopted. A model of the microsprinkled wrap has been developed (Rieger, 1987) which includes an ice accretion submodel. The model consistently underestimated the protected trunk temperature at the 20-cm height but indicated that irrigation water temperature was a significant factor in the underestimated effect. Increasing the water temperature by 5°C had a substantial influence under radiative conditions, but the influence vanished as the conditions became advective, i.e., windspeed was a robust input parameter in the model. The possibility that water and energy can be conserved by pulsing the microsprinklers on and off is now under investigation (Davies et al., 1987). This is already a popular notion since many growers have microsprinkler systems in which all the zones cannot be operated at the same time. The possibility that they may be able to pulse them on and off, permitting a larger acreage to be protected with the same pumping system, is attractive.

7.4. Covering in combination with other methods

Many have discovered that a blanket with even a single light bulb beneath it can save a cherished ornamental from a severe advective freeze. Porous orchard covers let the rain through and some of the heat and water vapor out during a freeze (Martsolf et al., 1986). They apparently store less energy during the day and are prone to be colder at night as a result unless some energy is added beneath the cover (Opperman, 1988). The resistance that the cover provides to the escape of buoyant heat and water vapor plumes is expected to aid in the effectiveness of such combinations under advective freeze conditions, however (Parsons et al., 1985a, b; Martsolf, 1987b).

8. SUMMARY

Conservation of energy opportunities are numerous in frost and freeze protection practices. The most obvious is to avoid the problem completely by good horticultural site selection. However, if that is not possible, conservation lies in education. Conservation and assured protection become a trade-off in risk (e.g., Haan, 1979). Many high-quality temperature measurements, remoted to a command site and to alarms, are necessary. Rapid lighting or start procedures permit the go/no go decisions to be delayed. Electronic controllers that match the energy need to the actual situation are likely to become the energy conservers of tomorrow. But the models that are expected to provide the algorithms for the controllers are far from refined to the extent possible or even to the extent that they must become. Combination of methods has proven to provide more protection than the sum of the individual components and provides additional flexibility in the management of the cold period. Models of combinations, except perhaps in the microsprinkler/tree wrap case (Rieger, 1987), have yet to be attempted. Advances in conservation depend on the continued careful modeling and measuring efforts, iterated toward verification.

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