period of time. This change of pH was due to the presence of pH-increasing (calcium nitrate) and decreasing (ammonium nitrate, ammonium phosphate) ingredients in the fertilizer mixes (Hanan, 1998). The effect of the fertilizer composition on soil pH can only be seen on a long term basis and constant monitoring of the soil pH is therefore crucial when plants are grown for extended periods of time.

Fafard 4 and Metromix 500 would be acceptable alternatives to the UC mix, with the use of Fafard 4 resulting in a higher germination rate, and with the use of Metromix 500 giving a more favorable pH and, although not statistically different, causing no micronutrient deficiencies in the plants.

Seedling growth was compared with that obtained at the Rubidoux indexing facility in Riverside, California (Roistacher, 1991). Growth of grapefruit in our greenhouse using the UC mix was 2.17 cm/week, compared to 2.5 cm/week in California. However, instead of measuring plant growth as the time needed to reach 1 m, plant height was measured as height reached after five months. We expect that the growth in our greenhouses will compare to that in California when measuring growth in the same fashion.

In our experiment we have compared only a small fraction of all commercially available potting mixes. Fafard 4 and Metromix 500 have been found to be most comparable to the UC mix and superior to the other tested mixes, based on seed germination, plant growth, soil pH and the absence of micronutrient deficiencies. Plant growth data did not reveal any correlation with the soil characteristics given in Table 1. Perhaps there are interactions between ingredients, but a more probable explanation would be that soil mix manufacturers only reveal limited information on their mixes, and do not provide information on the composition of initial fertilizers, pH-regulating components, or types of wetting agents used. It is therefore more difficult to predict or explain soil mix performance using commercial mixes based on information provided by manufacturers. For example, the mix produced specifically for citrus by Fafard (Citrus Mix) was not the best performing mix in our experiment. This can be avoided when using a self-made mix where all ingredients are known, like the UC mix.

It is advisable to test more mixes against these two for further optimization of the system, and for comparison of different uses (germination, seedling growth, different plant species).

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DIVERSITY OF FROST PROTECTION METHODOLOGY

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Abstract. **Diversity of frost protection methodology is broad when viewed over a long period. Heating methodology is especially diverse. A rule is apparent: growers used readily available materials. Prunings were burned during frosts at the height of the Roman Empire. A broad spectrum of heater types began to appear in more recent centuries. Wood, charcoal, oil, gas, and other fuels were burned in heaters so diverse in design that one's imagination is staggered. Development in design and management continues in some areas of the world in contrast with local opinions that such methods are of only historical interest. Wind machines of various shapes and sizes began to appear in the early part of the 20th Century in response to concerns about air pollution and labor availability. These solutions include the helicopter. Orchard covers, later row and individual plant covers were tried and found effective. Irrigation, the current choice in citrus, was in use in the form of flooding during the earliest days of the past century. Smudges, fogs, steam, heated irrigation, and windbreaks have been tried and in most cases, used effectively. The probability that a freeze will occur in a particular year is low. Authors have published extensive explanations and models. They have advised use of alarms, forecasts, site selection, satellite images, and networking in conjunction with a recommendation to limit attention to the method du jour. Most authors implied the field of work was mature and additional change seemed unlikely. In a longer view change, at times rapid, is an apparent characteristic of the field. Diversity of methodology and grower ingenuity suggests that change will characterize the future as it has the past. Diversity abounds.**

This is a philosophical summary aimed at the grower, production manager, and especially the consultant. It is too easy to ignore the possibility of a freeze during a warm series of years, and to forget the rich diversity of methods available for frost control when a single method, sprinkler irrigation, is so widely used.

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Few have the opportunity this writer has to review the literature with an eye toward the future. The diversity of past methodology will persist into the future. Efforts to find the best method characterize the literature. Growers demanded answers to the question: "What is the best method?" Yet they seem to have practiced convenient, diverse, and innovative methodology. Good site selection which equates to avoiding the problem has been and continues to be popular.

Materials and Methods

Literature: An award-winning paper by Katharine Perry (1998) is the inspiration for initiation of this effort. Other reviews, Bush (1945), Rieger (1989), Kalma et al. (1992), and Martsolf (1992b), contain more detail and longer lists. Collectively they provide a feel for the rich diversity of the field. Turrell (1973) deserves special mention, for it is without doubt the most detailed description of the methods used to protect citrus.

Method: A recent survey (Ferguson and Israel, 1998) is contrasted with historical documentation of interests and practices. In the development of a cold protection module for the Decision Information System for Citrus (Lin et al., 1999) an effort was made to identify rules.

Discussion

Diversity: A common characteristic of reviews of frost control is diversity of the methodology. Successful methods include covers, windbreaks, heating with wood, oil, coke, via pipeline, wind machines, helicopters, irrigation from flooding to microsprinklers, fog, and combinations of several methods, especially heaters and wind machines. Growers used material close at hand innovatively. This may be one of the rules. There are few, if any, descriptions of consistent failure of a particular method but there are numerous precautions. Most admit its easy to fail to forecast a frost or mild freeze. This is unfortunate for the mild cases are easiest to avoid. Subtle methods supply sufficient protection in mild frosts. In most cases frosts and freezes are rare events. Their character may vary extensively from location to location. Horticulturalists have traditionally taught good site selection. One of the rules may be that the broad diversity of methodology had a common characteristic, success.

Covers: Broad diversity in covers is apparent in the past (e.g., Hume, 1926), the present (Martsolf et al., 1988) and it seems likely to extend into the future. Soil banks, or tree wraps, were and are used to protect young trees. Windbreaks were used to protect groves from cold and hurricane damage. With clearer views of turbulence, their usefulness in hurricanes has been questioned and this has impacted use in cold protection as well. Competition for land, nutrients, water, and sunlight aided their demise.

Foams and fogs add to the diversity of covers. As plastic films replaced heavier and more expensive glass in greenhouses, horticulturists predicted disaster. Many of the plastics, such as polyethylene, were transparent to infrared radiation. Glass traps infrared radiation, the so-called "greenhouse effect." Plastic covered greenhouses containing plants were much warmer on clear nights than expected. Waggoner (1948) provided an explanation by running a simple experiment contrasting shelters with and without water sources (Fig. 1). So, a cover provides protection if there is sufficient moisture beneath it to permit condensation on the underside of the cover regardless of whether it is a good insulator or transparent to infrared radiation. Therefore the effectiveness of the cover lies in how well it reduces convective heat loss, since the interruption of radiant transfer is provided by the condensation of water. There may be a subtle rule here. Growers initiate an investigation of new methodology as they recognize they have incentive to do so. Scientists and authors aid in the refinement of the methodology, and in its transfer to other situations.

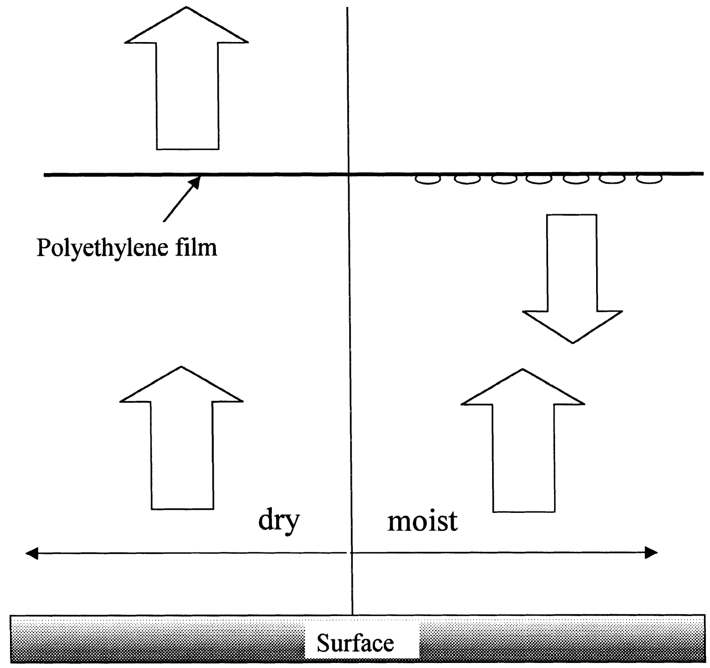

Figure 1. A film transparent to infrared radiation, such as polyethylene, when covering a dry environment permits heat to escape (indicated by the arrows on the LH side of the diagram) but when covering a moist environment traps the heat at night. Waggoner (1948) found water droplets (which absorb infrared radiation) condensed on the under surface of the cover film making it similar to glass in its ability to trap infrared radiant energy, the so called "greenhouse effect."

Heating: Prunings were burned during the height of the Roman Empire to protect vineyards (Blanc et al., 1963) and ever since, fuels of wood, straw, oil, coke, wax and gas have been used in innovative ways to protect plants (Hume, 1926; Turrell, 1973). As in the case of covers, the radiant transfer (Perry et al., 1977) proved to be a poorer indicator of the effectiveness of a heater than expected (Welles et al., 1981). Contentions that smoke cannot interrupt radiant loss from the surface fail to show sufficient respect for the tendency of smog to act like fog, an effective cover. Older literature (e.g., Hume, 1926) applauding the effectiveness of smudging has yet to be exonerated. But it may be used to support the wisdom of combining heating and sprinkling. Moving the fire to a central location where it can be burned efficiently and where the risk of a fuel spill is minimized is gathering interest somewhat similar to that shown in the combination of heaters and wind machines. The general rule may be that effect of a combination is greater than the sum of the individual effects taken separately.

There is evidence that the convective plume from the heaters is more effective in supplying the observed protection than previously thought (Martsolf, 1992a). The "rock in the bottom of the stream" description developed from recognition of the role of turbulent port in the heated boundary layer (Martsolf and Panofsky, 1975; Bland et al., 1980). The rules that apply to the plumes from heaters may be found to also apply to water vapor plumes from sprinklers.

Wind machines: Diversity increased rapidly. There was great variability in wind machine shape, size, and height but this variability in design decreased rapidly in the United States. Economies of scale and a patent on a propeller hub design were likely causes. An apparent increase in the ratio of advective freezes to radiant frosts and perhaps an impression that undertree sprinkling is a superior method have led to a decrease in use of this method in Florida. The 1997 frost and the possibility of a combination of wind machine use with irrigation seems to be leading to some re-evaluation of wind machine use in Florida (Adams, 1998; Reiter et al., 1998).

A firm in Latin America recommends wind machine placement by mapping the cold airflow and temperature distribution before and after machines are installed. The effect of the machine is often the most pronounced in pockets or valleys where cold air accumulates. The cold air is lifted by a propeller rotating in a horizontal plane inside a duct that looks much like a silo.

Helicopters: The helicopter is considered a special case under wind machines, but the diversity is apparent. Wind machines are sited in a particular location but helicopters are mobile. The helicopter is a relatively popular frost control device, perhaps because it is at hand for other uses that do not compete with its use as a frost control device. Usually helicopters are owned and operated by service companies. They are leased, with a pilot, for particular operations. These service companies solicit clients, market the potential value of the machine as a frost control method and develop contracts under which the service is on standby during the frost season. Many pilots and nearly all owners of the machines are self-proclaimed experts in how the machine may be used for frost control. It has been suggested that a thermostatically controlled light be used to help helicopter pilots map their target and observe the effect the downdraft has on the air temperature near the light. The blinking rate increases as the temperature falls below a set threshold. This light has been called a feedback light and is described in diagrams (Martsolf, 1990, 1992b). Some built prototypes of the light but no grower has described his use of the method with as much pride and declared their intention to have more of them built as one visited recently in Argentina (Fig. 2).

The heavier the machine the greater its effect on the temperature near the ground seems to be one of the rules. There are possibilities that the combination rule will apply here. One of the possibilities is to carry water aloft to add to the machine weight and then release the water through the spray booms before landing. Increasing the humidity of the air over an orchard has long been recognized as a desirable move.

Irrigation: There is broad diversity in irrigation methodology, from flooding through sprinkling to microsprinkling or microjets. Nearly all methods have frost protection value, so much so that the fear of evaporative cooling that dominated the literature at one time is rarely mentioned in recent literature.

In mid-century, solid set overhead sprinklers became the drought control system of choice for citrus growers. The 1962 freeze in Florida may have been the largest experiment ever run in what is called cold protection. It was an advective freeze, at least in the initial phases of the freeze, and those who turned on their overhead systems, most of which provided less than 0.1 inch per hour precipitation rates, had much greater damage than their neighbors who did not.

Overhead sprinkling models were not designed to explain what happens as the sprinklers were moved downward through the canopy and onto the orchard floor. Observations verified this model deficiency (e.g., Oswalt and Parsons, 1981).

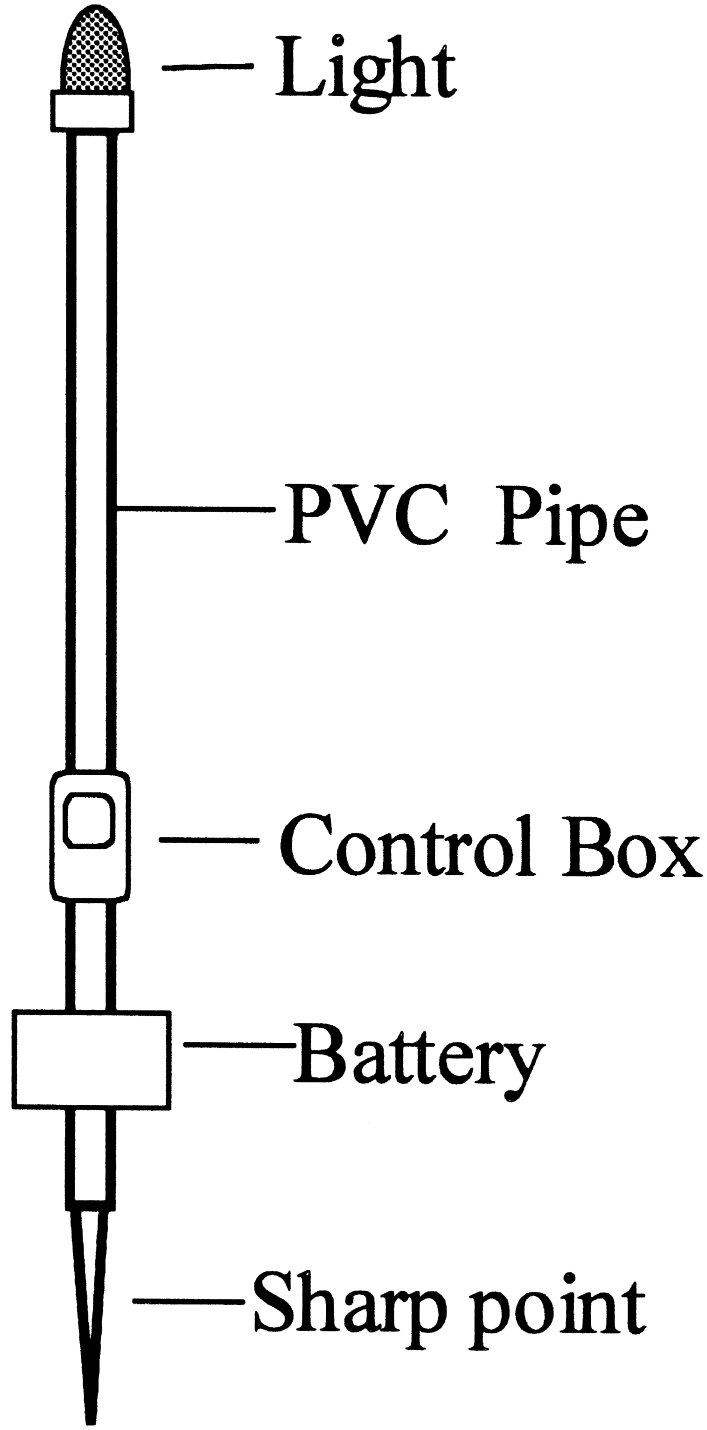

Figure 2. A simplified diagram of a commercially fabricated helicopter feedback light is shown from recall of one seen in Argentina in 1998. The control box contained an air temperature sensor, a keypad and a digital readout panel. A battery supplied power to the light and the control box permitting the user to program the light to come on below a set temperature and blink more rapidly as the temperature decreased below the set point. The grower indicated the instrument was designed after a diagram in Martsolf (1992b).

The mixing mechanism is missing in the sprinkling models (Martsolf, 1992a; Cooper et al., 1997). Mixing is driven by the surprisingly large difference between the weights of dry air and air saturated with water. A sponge is a very poor model of air parcels because a sponge gets heavy as it gets wet. Air becomes lighter as water vapor molecules replace molecules of nitrogen or oxygen. The buoyancy of the moist air drives a mixing process in the canopy that effectively transfers heat from where it is available to evaporate available water to surfaces falling below the dew point temperature which rises as the canopy air is saturated (Martsolf, 1996). This sounds complex because it is. The amount of water necessary to protect various canopy dimensions and planting configurations, given the temperature, wind speed, humidity and turbidity is not yet known. The rule seems to be the more water the better. Competition for water will increase rapidly. Consensus suggests that 2,000 gals per acre is an appropriate compromise (Gardner, 1999).

A widely accepted practice is to turn on the drought control system as a freeze approaches and let it run until the freeze has passed. This rule is not as simple as it sounds. A decision is made during the design of an irrigation system as to the number of zones. There is a trade-off in cost between the number of zones that can be served at one time and the size and cost of pumps as well as the size of the main laterals. Also, there is increasing concern about the ability of the soil to absorb the water applied. There is incentive to avoid moving water completely through the root zone for it carries with it nutrients intended for the roots. Some of these nutrients, such as nitrogen, become dangerous pollutants of the ground water. Ice formation stores some of the flow until the ice melts making it feasible to avoid the problem. Strategies are developing for dealing with zoned systems. Once started, a system is not stopped until the freeze has passed. This rule developed in the overhead sprinkler case. It is questionable in the under-canopy case. Some growers are using diesel powered pumps to avoid the possibility that power failure will interrupt sprinkling during a freeze. Others are recognizing the advisability to irrigate zones before the freeze and in particular those that cannot be irrigated during the freeze. The moist soils store more heat and return some of this heat to the atmosphere during the freeze. Cost accounting is revealing the true cost of designing a system with cold protection capability and charging these costs off against the risk of a relatively rare event in most locations (Martsolf, 1999).

There has been periodic interest in pulsing or cycling the sprinkler irrigation systems to increase the area that can be covered by a zoned system as well as to conserve water (e.g., Koc et al., 2000). The testing of models needed to control the pulsing rate (given the meteorological conditions) has been problematic. Funding experiments in large blocks where the edge effects are small has not been popular. Results from relatively small plots are difficult to interpret (Ferguson and Davies, 1999; Martsolf 1996, 2000).

Hopefully, diversity of irrigation methodology will be respected in the search for Best Management Practices (Allen, 2000; Boman et al., 2000).

Site Selection: It is hard to over-emphasize site selection. Horticulturists have shown great respect for this element of frost avoidance by writing about it frequently in prominent positions in their publications. The question, "What is the best method of frost control?" is so often asked that it frequently shows up on examinations. One is tempted to defend "good site selection" as the correct answer. Cold air drainage, using water flow analogies complete with such terms as cold air dams and lakes, has been described so well in the literature that the well-schooled horticulturist can stand on a slope and visualize the flow of cold air down the slope and where it may pool and cause problems.

Good site selection is a method of avoiding the need to be concerned about cold damage. Economists have not recorded [to this author's knowledge] their conviction that one of the most effective ways to deal with rare events such as freezes is to simply ignore them, but they admit in conversation that this simple approach to risk management is condoned, if not promoted, by many workers in their field. Reduced freeze risk is only one of the elements considered in site selection. Soil, water, transportation, proximity to the marketplace, availability of resources necessary to the production, harvesting, and marketing of the contemplated product all come into play and are evaluated on a level playing field.

Cultural Practices: In some of the literature methodology is divided into active and passive methods with the latter category including what horticulturists commonly call cultural practices. The rule seems to be to use practices that reduce the risk of cold damage. For example, clean cultivation was recommended (Hume, 1926) until recently (Jackson and Davies, 1999). This seems like a change in the rules. However when one looks closely it seems the rule was stated too simply (Krezdorn and Martsolf, 1984). The intent was to maximize the storage of heat in the soil and facilitate its transfer to the air near the surface where it can retard the cooling. It is now apparent that closely mowed grass covering a relatively moist and compacted soil has greater heat storage potential than does a dust mulch. So the rules must be simple but the true meaning should be clear (Lyrene and Williamson, 2000).

Integration: Broad diversity leads to an integration challenge (Martsolf et al., 1984, 1998). Acquisition and retention of information can be delegated to computers. Its delivery to the decision maker conveniently, rapidly and in terms easily understood, facilitates information integration (Lin et al., 2000). There is a race between the increase in ability to make integration tools and the increase in volume of information to be integrated. Hope lies in a growing appreciation for explanations in terms the decision makers can readily understand (e.g., Lyrene and Williamson, 2000).

Summary

The diversity documented in the literature is impressive and it is expected to persist if not increase. Methods were designed to capitalize on several physical mechanisms. Those methods modified energy transfers near the surface to moderate cold temperatures permitting the plant to avoid damage. In the future, bioengineering is likely to increase diversity in the methodology and strategies by adding options, many quite different that those reviewed. In the past the environment was modified to benefit the plant. In the future the plant is likely to be modified to better fit its environment. Diversity is likely to increase. The recommended strategy is to capitalize on the increased diversity. Perhaps numerous strategies will be used in the same locality if not in the same production unit.

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