B.C. FROST PROTECTION GUIDE

Irrigation Industry Association
of
British Columbia

Province of British Columbia
Ministry of Agriculture and Fisheries
ENGINEERING BRANCH

B.C. FROST PROTECTION GUIDE

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PREFACE

This publication combines information from numerous sources under one cover. In many instances the topics covered are superficial. The user may therefore require additional reading to fully comprehend some of the material presented. The articles and publications indicated in the bibliography should be used for further reference.

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INTRODUCTION

Frost or freezing temperatures in the early spring or late fall can result in considerable damage to many of British Columbia's horticultural crops. A significant portion of this crop loss can be prevented by implementing some form of frost protection.

Frost protection is required in certain areas or small isolated locations to lengthen the growing season making it possible to grow horticultural crops which otherwise would not be feasible or economical. In B.C., frost protection systems are mostly used to ensure that maximum crop production and quality can be achieved every year. This is important, especially with kiwifruit, cranberries, tree fruits, grapes and other crops requiring high capital investments. To achieve a return on these investments, a crop loss due to frost cannot be tolerated.

In numerous cases, the frost protection method used is passive, and must be taken long before the danger of frost actually occurs. Active methods of frost protection are applied immediately prior to and during the occurrence of frost.

This publication explains the types of frosts that may occur, passive and active methods of frost protection and general guidelines on designing irrigation systems to protect against frost. Additional information on frost protection can be obtained from the publications cited in the bibliography.

The intent of this publication is to provide information on frost occurrence and protection thereof to producers and agri-business personnel. While, for the most part, the publication is of a general nature, information on designing a sprinkler irrigation system for frost protection is included.

The designer should be conversant with the irrigation design principles and procedures presented in the B.C. Irrigation Design Manual before attempting to design a frost protection system with the information presented in this publication.

SECTION 1

Explaining Types of Frosts

Frost is generally associated with the occurrence of ice crystals on exposed surfaces, of which the temperature has fallen below the freezing point of water. An understanding of the physical processes that create frost conditions is required before proper design, operation and management of frost protection systems can be achieved. In this guide "frost" is defined as a condition in which the air temperature around the plants falls below 0ºC (32ºF).

Frost is usually associate with the termcold. A cold condition occurs due to a failure to receive heat or a withdrawal of heat from the object or system. Cold cannot be added, but rather heat is removed. Heat can be transferred to or from a system or body by conduction, convection and radiation.

Conduction is the transfer of heat energy within a body or system by means of internal particle or molecular activity, without any external motion. Air is a poor conductor and is heated or cooled by this method to a limited extent. **Convection** is mass motion of a fluid resulting in transport and mixing of that fluid. In meteorology, convection is a term applied to cases of vertical motion and the word **advection** is used to describe horizontal transport and mixing of atmospheric properties. **Radiation** is the transfer of energy through free space without the requirement of a transporting medium.

Frost occurrences are usually classified into two different types, (1) radiative; primarily caused by heat loss by **radiation** and, (2) **advective;** those primarily due to the arrival of cold air masses with temperatures below freezing. A third situation that can create crop damage due to cold is **evaporative cooling**. An understanding of each of these conditions is important when designing and managing a frost protection system.

Radiative Frosts

Radiative frosts generally occur on calm, cloudless nights. Dry air, being transparent to infrared (heat) radiation, allows energy to be lost from the surface of the earth and atmosphere on nights when radiative frost conditions are present. This radiation will occur because the plants and soil are much warmer than the -273ºC temperature of outer space. Basic laws of physics force a trend to a thermodynamic equilibrium, thereby transferring heat from earth to sky. Since the air doesn't radiate it's heat as rapidly as solid objects, it is cooled as it comes in contact with the ground and surrounding objects. The air attempts to replace the heat lost from the solid object. The cooler air becomes heavier than the warm air and will settle closer to the ground, developing a nocturnal temperature inversion. The colder, heavier air will then move along the ground surface and settle in the lower portion of the planting. Energy losses due to radiation are most prevalent on cloudless nights when the humidity of the air is very low and wind speeds are near zero. If there is adequate turbulence in the air mass, inversion layers do not develop, which is why less damage occurs on windy nights.

Advective Frosts

Advective frosts occur when large masses of polar or arctic air move into an area dropping air temperatures below the plant critical level over a large area. The factors controlling a radiative frost may also be active during advective frosts, but, the inversions are usually much weaker.

Damage caused by advective conditions generally occurs by the withdrawal of heat, by the moving cold air mass, from the warmer plant surfaces.

In addition, the air mass is usually very dry, accompanied by winds, and tends to persist for several days making frost protection economically unfeasible.

Evaporative Cooling

The evaporation of water requires heat. Therefore, water evaporating from the plant surface will draw heat from the plant. At temperatures near freezing, this evaporative cooling process may drop the temperature of the plant tissue below freezing. Evaporative cooling is an important consideration when using irrigation systems as a method of frost protection. See section 3, start up and shut down of sprinkler systems, for further information.

Freeze Injury

In contrast to frost, freeze injury to plants is a complex phenomena dependent upon the physiological state of development, the temperature and its duration. The concept of “critical temperature” (discussed in Appendix A) has been developed to relate potential plant damage to these three environmental factors. The degree of damage can range from nearly undetectable cell damage to death of the entire plant. The damage is caused by freezing of the protoplasm within the cell resulting in laceration of the cell walls or the destruction of the semipermiability of the cell membranes.

SECTION 2

Frost Protection Methods

A. Passive Methods of Frost Protection

Passive frost protection methods are used to avoid frost danger, rather than protect against a frost occurrence. Passive methods of frost protection should be planned and implemented well in advance of the threat of frost dangers.

1. Location of Growing Area

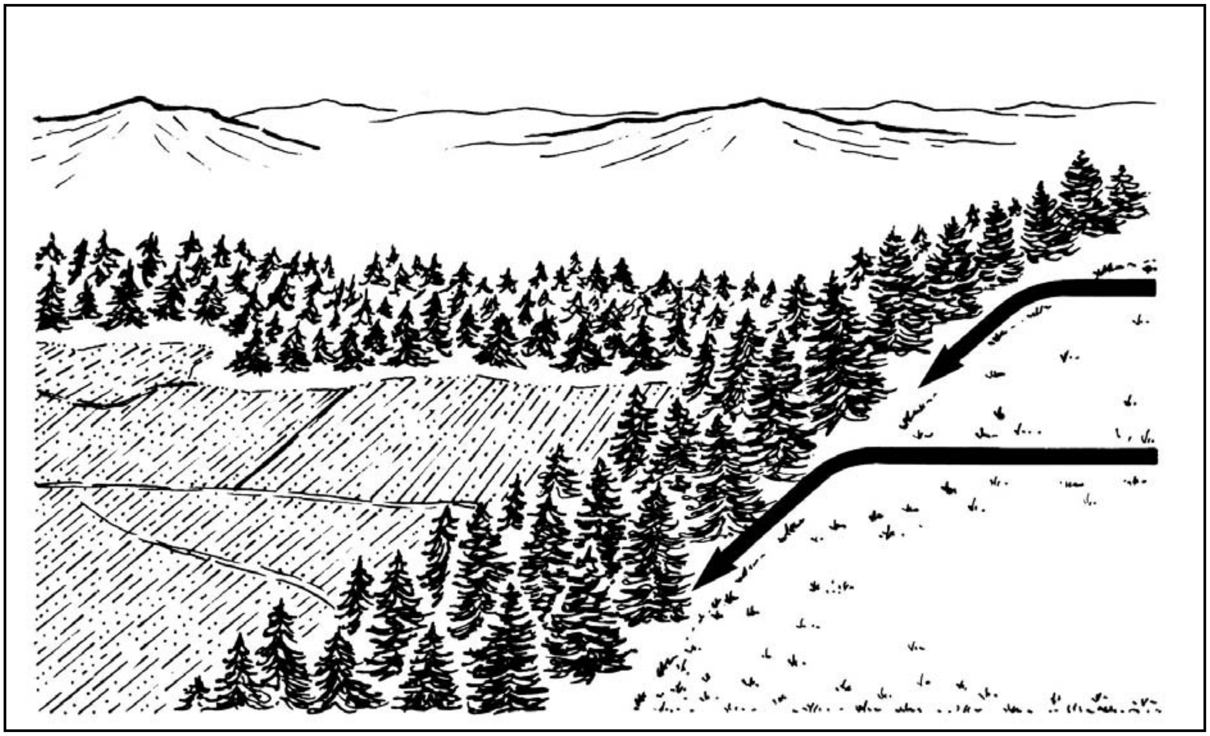
When possible, the best method for preventing frost or reducing the risks associated with frost is to avoid locations where there is a danger of frost. Avoid valley floors, narrow basins or depressions which may be frost pockets. Hillsides or areas close to large bodies of water are favorable conditions which reduce frost risk. (To assist growers frost risk maps at a scale of approximately 1:20,000 are available for selected portions of the Province including the Okanagan, Similkameen and Creston Valleys).

2. Barriers

Natural or vegetated barriers can be used to prevent the movement of cold air into cropped areas. Barriers can consist of tree rows, underbrush, shrubs, hedges, vines, building walls, highway and railway embankments, etc. Cold flowing air coming in contact with a barrier that crosses the direction of the air stream will be dammed up behind the barrier. When sufficient air has accumulated behind the barrier it will flow over the top and continue towards the lower areas. The frost danger above the top and continue towards the lower areas. The frost danger above a barrier is increased while the frost danger downstream from a barrier is somewhat reduced. Figure 1 shows the effect of barriers on air movement. Wooded strips which hold off and turn aside downward flowing cold air should be maintained and not thinned out or cut down.

Tree strips and hedges serving as barriers must be sufficiently wide and dense so that cold air cannot filter through or between bushes. Avoid the construction of ditches and cuts in the terrain which may act as channels for the passage of cold air.

Note: If installing a new barrier, ensure that neighboring orchards will not be affected by the pooling of cold air behind the barrier.



When downward flowing cold air meets a barrier crossing the direction of the cold air stream, damming of the cold air behind the barrier occurs. An outlet for this cold air, along the barrier but away from the area to be protected, may be required to prevent overtopping of the barrier. If an escape route does not exist, or the barrier is not high enough, part of the cold air mass may overtop the barrier and settle into the area to be protected.

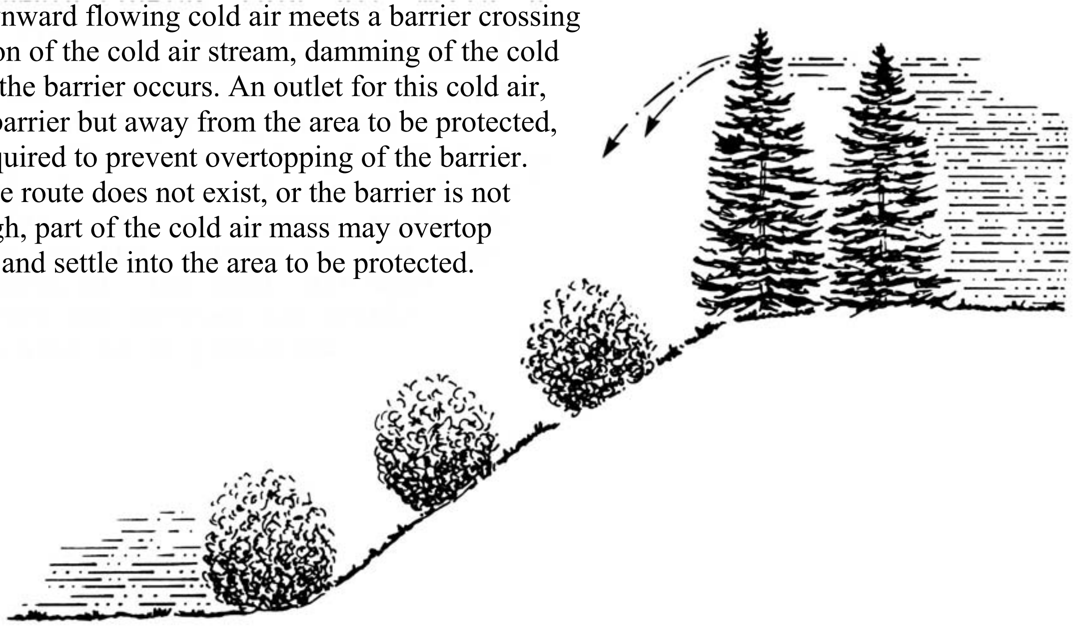


Figure 1. Cold Air Movement with Respect to Barriers

3. Choice of Growing Season

When planting, care should be taken to select crops that can be accommodated by the climatic patterns present. Small acreages of crops susceptible to frost damage can be planted if they can be covered, heated or protected by “active” frost protection methods.

Some crops may not be affected by early spring frosts but rather early fall frosts. Planting dates for annual crops may then be adjusted if possible so that a normal growing season will bring crops to maturity while the fall frost risk is still low. With perennials, the choice of the proper cultivar is critical. This will enable the grower to be certain that the crop can be harvested and the plants allowed to harden prior to the onset of frost damage.

4. Selection and Breeding

There are two objectives in crop selection and breeding to reduce the risk of frost damage. The first is to obtain plants which will develop and mature during the normal period of little or no frost danger. The second is to obtain plants which exhibit hardiness traits. Frost hardiness lies in the ability of plant cells to resist damage due to freezing.

An example of the first objective would be to plant a crop variety that blooms later in the season when frost danger has been reduced.

5. Cultural Practices

a) Soil Management

A 0.5º to 1ºC difference in minimum temperature could make a difference between minimum damage and severe crop loss from radiative frosts. Soil management can be used to limit the temperature drop, providing 1.1ºC to 1.4ºC frost protection, (Rosenberg, 1983).

For maximum protection the soil should be moist, bare, free of weeds or cover crops, smooth and consolidated. Prior to each spring’s danger period the soil should be managed as follows:

i. Bury or remove cover crops and weeds before the first irrigation.
ii. Do not let the soil dry out.
iii. Do not disturb the soil if possible.
iv. Allow cold air to drift away from the property and prevent cold air from entering the property. It is also important to manage nearby fields, especially those on higher ground. There is a danger that recently cultivated or dry or grassy land above the fields will act as a secondary source of cold air which may drain down onto the fields during radiative frost conditions.

b) Plant Management

Growing taller plants or increasing the trellis height for vineyards may be one method of avoiding frost danger. While this may appear to be a solution for localized, low lying small pockets, it is not a very practical approach to managing the crop.

c) Growth Regulators

Delaying the development of blossoms or other plant parts sensitive to frosts until the danger is past may be successful. However, a delay in blossom time could cause the plant health or yields to suffer in subsequent years.

Passive methods of frost protection can be summarized by the following rules:

1) In locations where frost may occur, it is preferable to select taller growing plant types so that the tender buds can be kept away from the cold air near the ground surface.

2) Avoid valley floors, narrow basins, pockets, etc., for the growing of frost sensitive plants. Warm, well drained sloped in hilly terrain offer the most favorable conditions for vines, fruit trees, etc.

3) Frost risks are reduced near larger bodies of water (lakes, reservoirs, etc.).

4) Frost danger above a barrier is increased, while immediately below a barrier it is reduced.

5) Upslope woodland strips which hold off and turn aside downward flowing cold air should be maintained as “wood preserves” and by no means should they be cut down or thinned out.

6) Avoid ditches and cuts in the terrain in the growing of frost sensitive plants.

7) In times of increased frost risk, refrain from any kind of soil disturbance or loosening.

8) Moistened, compacted and closely cropped surfaces may provide frost protection, but care should be taken that such actions do not interfere with other horticultural practices.

B. Active Methods of Frost Protection

Active frost protection methods are applied immediately before and during frost occurrences. The basic principle of active frost protection methods is to prevent the loss of heat or add sufficient heat to maintain the temperature of the plant above the danger point. There are many factors involved in choosing which active frost protection method may be best. Crop value, material cost, equipment, labor, and the degree of risk must be considered.

1. Covering

Covering is the simplest and most common method of frost protection for low growing crops. Covering methods that have been employed include:

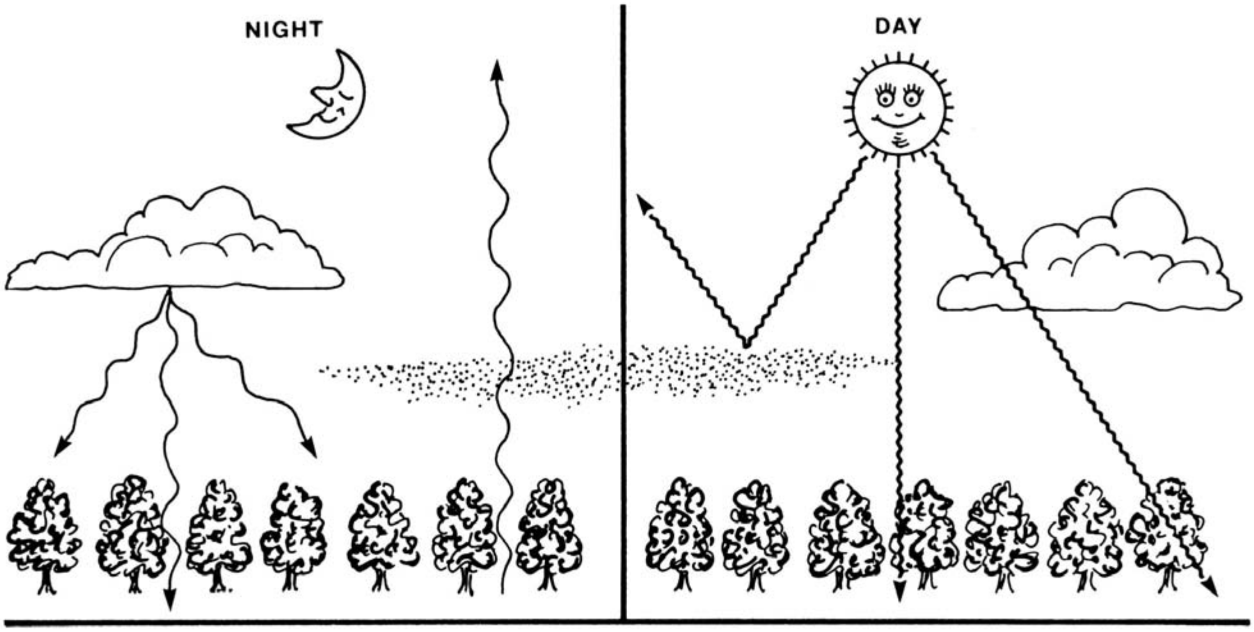
- The flooding of cranberries grown in low lying bogs or marshes during periods of frost danger.
- Soil piled around the trunk of young grafted trees to protect the bud union and root stock.
- The use of boxes, baskets and other materials to protect low plants from frost.

The cost of materials, labor required, and the time needed to put the cover material in place are the main problems with these frost protection methods.

The material used must be opaque to prevent outgoing long wave radiation. If the material used is clear, such as some plastics and glass, there is a danger that temperatures under cover will actually be lower than outside the cover. For this reason clear plastic covers, frost caps and glass houses by themselves are not very effective in preventing damage from radiative frosts. A small heat source or an opaque/thermal lining inside glass houses is required to provide adequate frost protection.

2. Artificial Fogs

The reduction in frost damage on cloudy or foggy nights and the known ability of natural clouds and fog to act as a blanket against outgoing radiation have led to many attempts to find an artificial substitute. The World Meteorological Organization does not recommend this method as a viable frost protection alternative. While it has been easy to produce fogs and smokes opaque to visible radiation, it has been difficult to produce any with particles sufficiently large enough to prevent passage of long wave infrared radiation. Smoke can actually be a detriment because it may prevent the penetration of short wave radiation from the sun at dawn, thereby extending the period to which the crop is subjected to cold temperatures. See Figure 2.



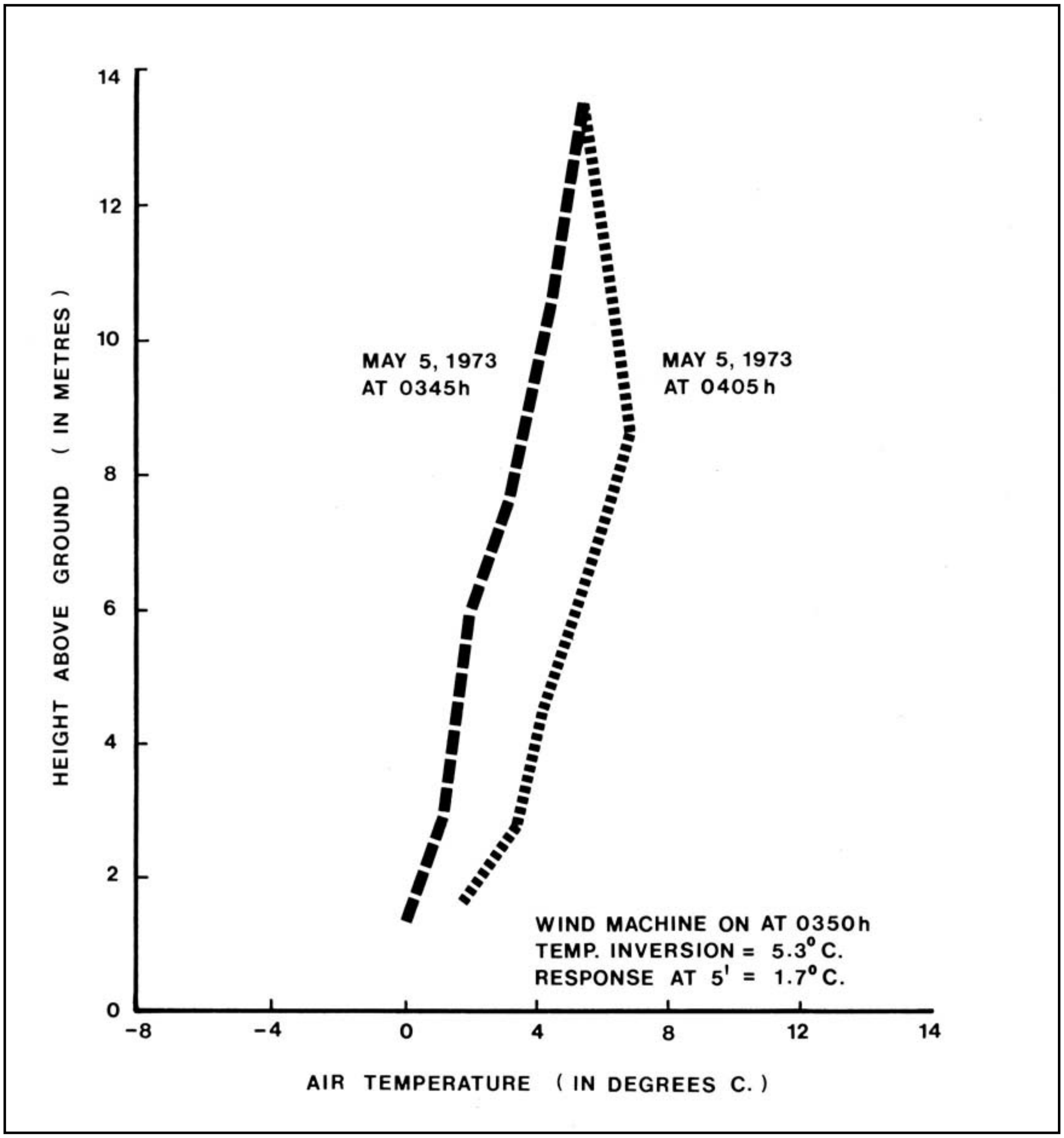
Energy radiated from the ground at night is in the form of long length waves. Long waves are absorbed and radiated back by natural clouds, but pass right through smoke.

Energy radiated from the sun during the day is in the form of short length waves. Short waves pass through natural clouds, but do not pass through smoke.

Figure 2. Smoke Effects on Radiation

3. Wind Machines

Wind machines work my mixing warm air from above the inversion with the cold air trapped underneath. The temperature of the air 15 m above the ground surface may be 6ºC to 8ºC warmer than air near the surface. Mixing the warm air with the cold air offers some frost protection. See Figure 3. The higher the temperature of the upper air layer, the greater the protection offered by a wind machine. Some protection can be provided by wind machines with weak or no inversions but the protection is quite limited. A temperature difference of less than 2ºC is considered to a weak inversion.



From: Frost Protection in the Okanagan Valley
Using Wind Machines.

Figure 3. Typical Temperature Inversion Response by Activating Wind Machine

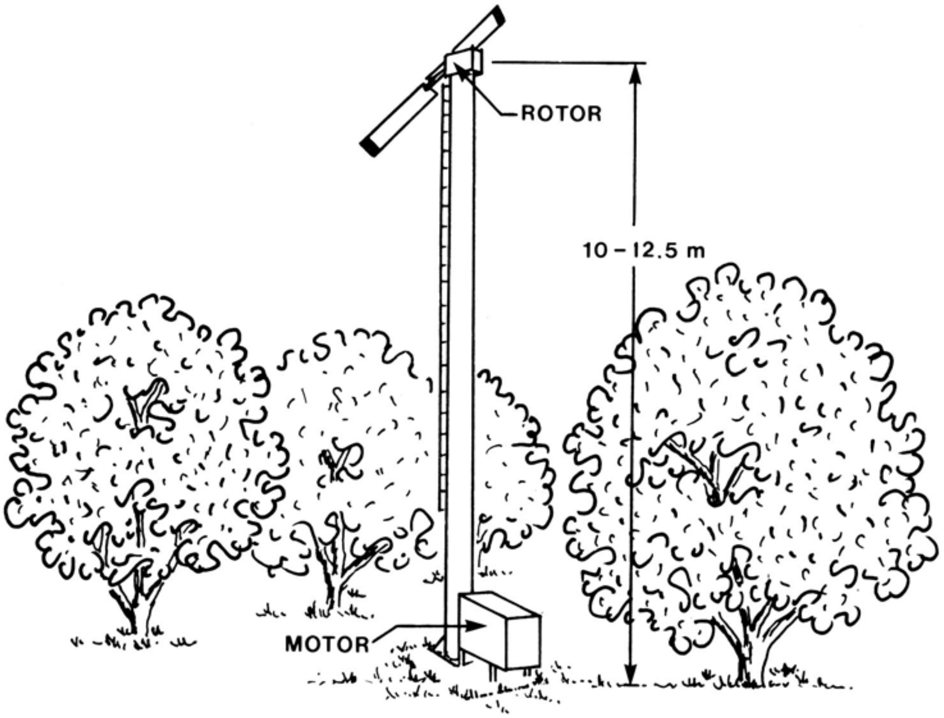


Figure 4. Overtree Wind Machine

A wind machine consists of a tower 10 – 12.5 m in height, with a propeller mounted at the top. Drive units are usually located at the bottom of the tower for ease of servicing. An efficient wind machine must have the rotor installed high enough to obtain better mixing of the inversion, while still being capable of penetrating the crop. The tower rotation speed must be capable of providing maximum area of coverage at a minimum temperature fluctuation within one rotation of the wind machine. Slow speeds of rotation result in a large temperature fluctuation during one rotation. Faster speeds of rotation will reduce temperature fluctuations as well as the area affected by the mixing of the jet.

Several low powered machines with small diameter propellers are more efficient, for a given horsepower consumption than one high powered machine with a large diameter propeller. However, the greater capital cost involved is a limiting factor in selecting numerous smaller machines over one large machine.

A large 75 kw (100 h.p.) motor moving 22,670 m^3/min of air should provide adequate protection over a 100 to 125 m radius. Normally 19 kw (25 h.p.) per hectare is required for single motored models. (The needs of each grower will depend upon the strength of the inversion, the type and density of the planting and the cost benefit of such an installation). A wind machine of this size can therefore affect up to 4 hectares, but, the effectiveness decreases as the distance from the machine increases. At a distance of 50 m from the propeller the effect may be reduced to about 20 to 25 percent of the effect near the machine. See Figure 5 for typical degrees of protection at various inversion levels. Natural air drift over the orchard will also shorten the upwind side and lengthen the downwind reach and is critically important information when determining on nights with radiation frost when skies are clear and winds are calm. Growers obtaining this information will be able to obtain the greatest benefit from a wind machine.

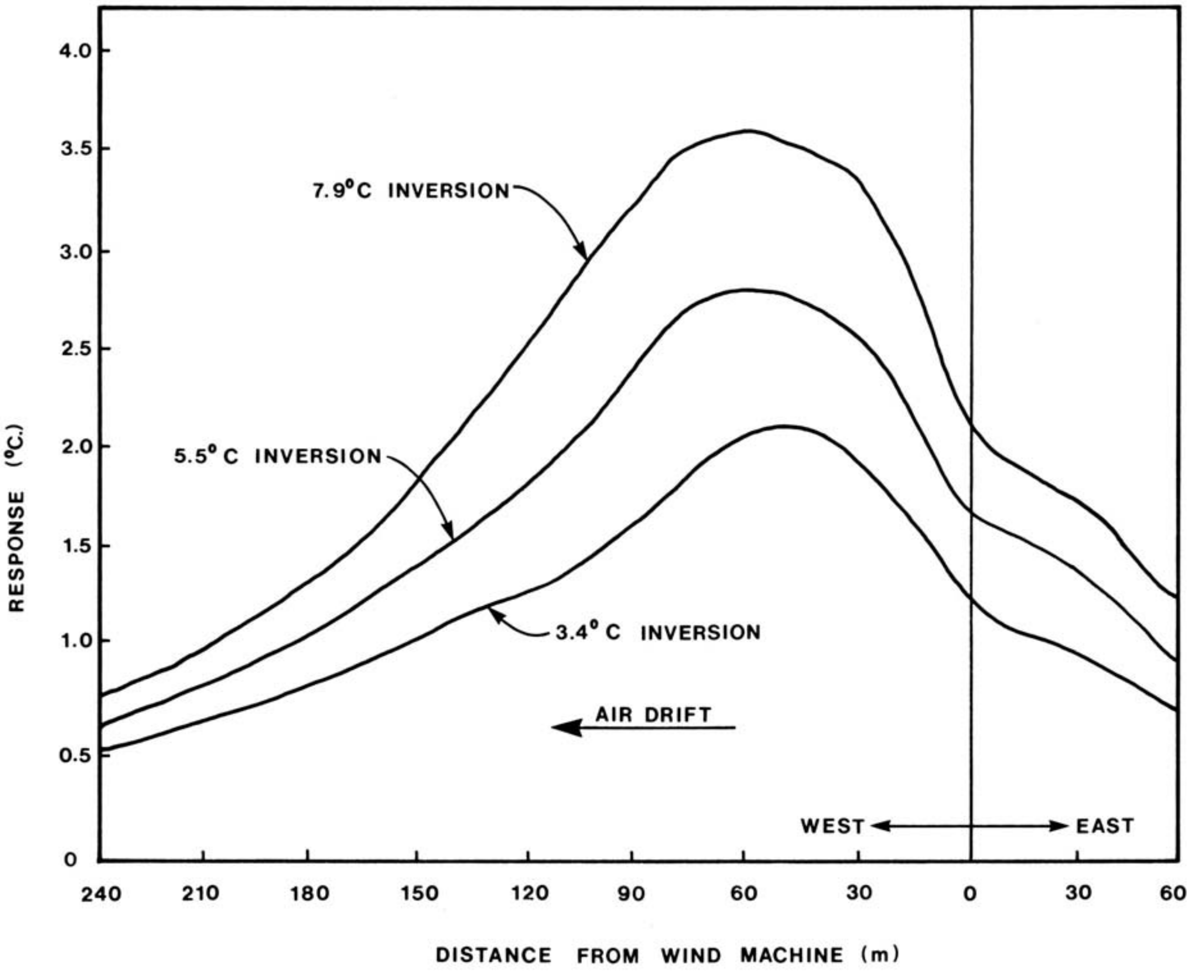


Figure 5. Temperature Rise Obtained from a 67 kw (90 h.p.) Wind Machine and Various Inversions

(from Schultz 1960)

The propeller of a wind machine normally operates at approximately 600 rpm and makes a 360º horizontal rotation every 4 1/2 minutes. A variable rotation speed of the wind machine can be used to provide a prolonged effect to the mixing action of the wind jet in the colder spots. This is an option not usually employed.

Wind machines are not as effective during frosts when the inversion is weak. In these situations supplemental back up heat supplied by fuel burning heaters will be required. Heaters should border the area to be frost protected and be lightly scattered throughout the area. The lightest heater concentration should be nearest the tower to minimize vertical current interference with the fan blast.

Ground level wind machines coupled with heaters were used in the past. However, large heaters produced a large hot air mass that rises too quickly. Overtree wind machines should not blow heat from the fan as the warm buoyant air results in shortening the radius of the coverage area.

Recent research has demonstrated that the turbulence created by a wind machine can prevent fruit buds from cooling below the air temperature. The fruit buds radiate to space at a rate different from the air and when near calm conditions are present a layer of "super-cooled" air surrounds the surface of each bud. The wind from a wind machine strips away this layer of cool air and the temperature of the bud warms to near the temperature of the air. (Seeley, E.J., 1987: Wind machines, environment: how, when they protect. The Goodfruit Grower, Vol. 38(4), pg. 3-8). This type of protection can take place without an inversion but it is unlikely that the effective coverage will be as complete.

Before selecting a wind machine for frost protection, the following parameters should be investigated:

a) The strength of the temperature inversion.

Ideally, a temperature inversion of 3ºC to 5ºC must exist between the warm air at an elevation of 12 m and the cold air situated at ground level. The inversion strength is determined by measuring the temperature difference between a height of 1.5 m and an upper level near 15 m. The temperature sensors must be shielded (see Section 4). As mentioned previously, if a weak temperature inversion exists, the amount of protection offered by the wind machine will be minimal.

b) The degree of protection required for the crop to be grown.

Appendix A indicates the critical temperatures of various crops. Temperatures below these levels will cause some damage. For example, at the full bloom stage, the critical temperature for apples is indicated as –2.2ºC. Research in Washington has shown that a 10% kill can be expected at a temperature level of –2.7ºC and a 90% kill at a temperature level of –4.9ºC. The grower must determine if the wind machine will provide sufficient protection to maintain temperatures above these critical values.

c) Siting of the Wind Machine

Proper siting of the wind machine is imperative in order to be successful. Siting of the machine must take into account natural wind drift, topography of the land, barriers, obstacles, tree size and the shape of the area to be protected.

Natural wind drift may be observed by using a smoke plume on a calm clear frost prone night. Careful observations should be made for at least one season before installation. Figure 6 shows the variation in the zone of influence of a wind machine as it is affect by wind drift. Observing wind drift throughout the frost period will provide valuable information towards the siting of a wind machine.

Operation of the wind machine can also influence the area of response. Depending on where the machine is located in relation to the frost pocket, the area of effectiveness can be increased on the downwind side by intentionally shortening the turning time of the machine on the upwind side. See Figure 7.

When a wind machine is first started, a temperature drop occurs due to evaporative cooling. This temperature drop is more pronounced when the dew point is low, consequently wind machines should be started when the air temperature is 2º-3ºC above the crop's critical temperature.

d) Economics of a Wind Machine

The following example of a wind machine cost is for a natural gas powered unit. If an electrically driven wind machine is used, the operating cost will be approximately half but the capital investment to supply power to the site can be much more. For further information regarding the economics of wind machines, contact the B.C. Ministry of Agriculture and Fisheries.

WIND MACHINE INVESTMENT

AREA COVERED BY MACHINE **4 hectares**

Initial Investment	U.S. Cost	Canadian Cost	
Machine	$14,450.00	$20,230.00	
Gas line installation (100 meters)	$1,600.00		
Sensor wire installation (400 meters)	$300.00		
Hired labor (1 day)		$70.00	
Testing		$130.00	
TOTAL INSTALLATION COST			**$22,330.00**
INVESTMENT CONSIDERATIONS			
Ownership Interest	0.06		
Operating Interest	0.12		
Per Cent borrowed	0.60		
Interest Rate on borrowed funds	0.1075		
Years of Life	30.		
Salvage Value	$2,023.00		
Term of Loan in Years	10.		
Interest Rate	0.1075		
Compounding Period	2.		
Effective Interest Rate	0.110		
Ownership Cost		$535.92	
Loan Payment		$2,278.71*	
Depreciation		$676.90	
Insurance		$55.83*	
TOTAL FIXED COSTS PER YEAR			**$3,547.36**
OPERATING VARIABLES			
Hours use per year	70.		
Liters per hour	37.5		
Fuel cost per liter	$0.17		
Labor rate per hour	$7.50		
Hours of labor per year	10		
OPERATING COSTS			
Fuel cost	$433.13		
Standby charge (Gas line 10 mos. at 5.90/mo.)	$59.00		
Oil, filters, grease	$43.31		
Repairs and maintenance	$101.15		
Labor	$75.00		
Interest on operating funds	$42.70		
TOTAL OPERATING COST PER YEAR			**$754.28***
TOTAL COST PER YEAR			**$4,301.64**
AVERAGE PRICE PER POUND OF APPLES	**$0.11**		
ADDITIONAL YIELD REQUIRED TO COVER ALL COSTS			39106 POUNDS 3911 POUNDS/AC 4.89 BINS/AC
ADDITIONAL YIELD TO COVER CASH OUTFLOW			28080 POUNDS
CASH OUTFLOW	$3,088.82*		2808 POUNDS/AC 3.51 BINS/AC

(Information provided by Howard Joynt, Economics Branch, BCMAF)

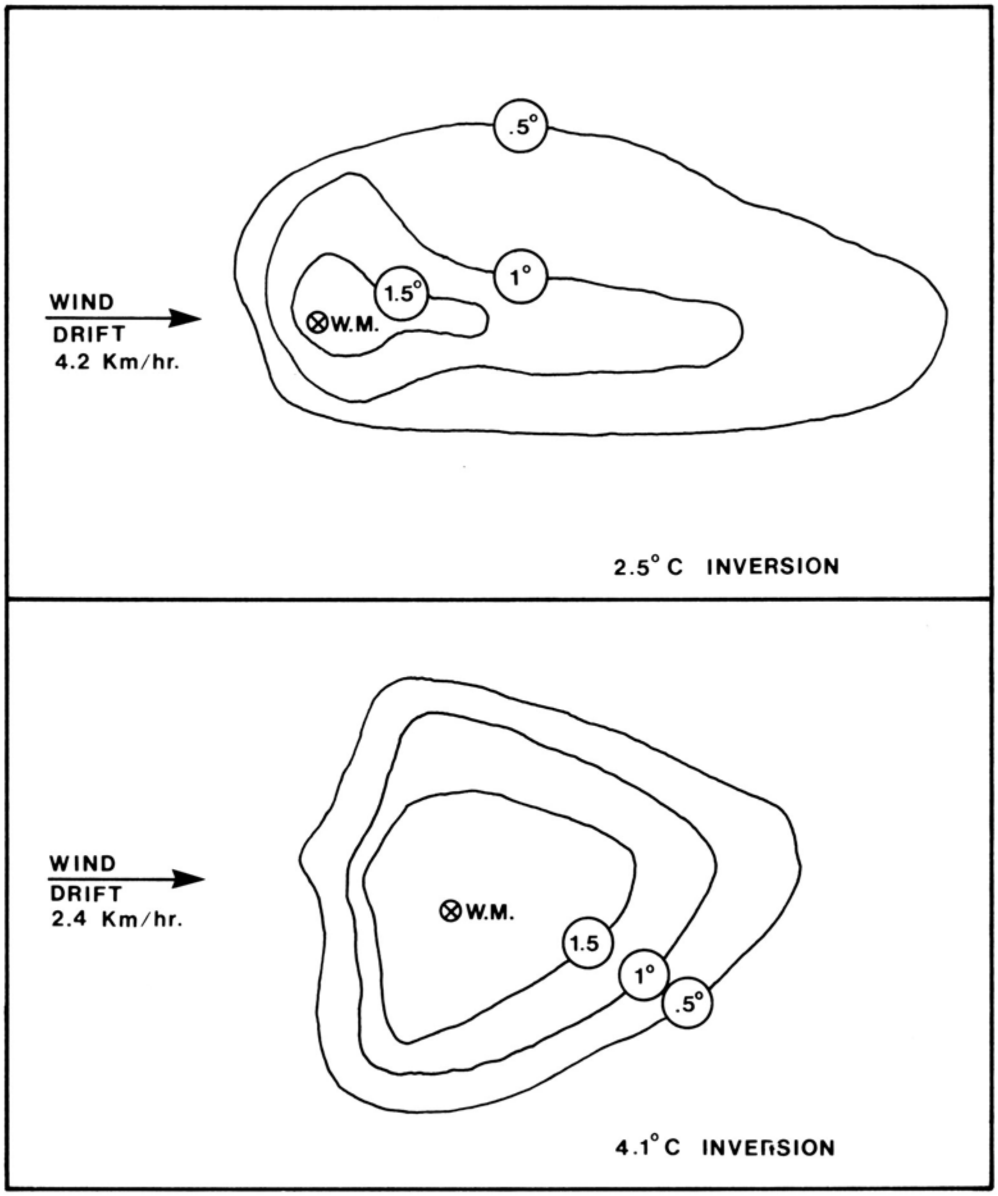


Figure 6 Effect of wind drift displacing the zone of influence of the wind machine.

The lines represent the areas of 0.5ºC, 1.0ºC and 1.5ºC responses. (after Angus,1962)

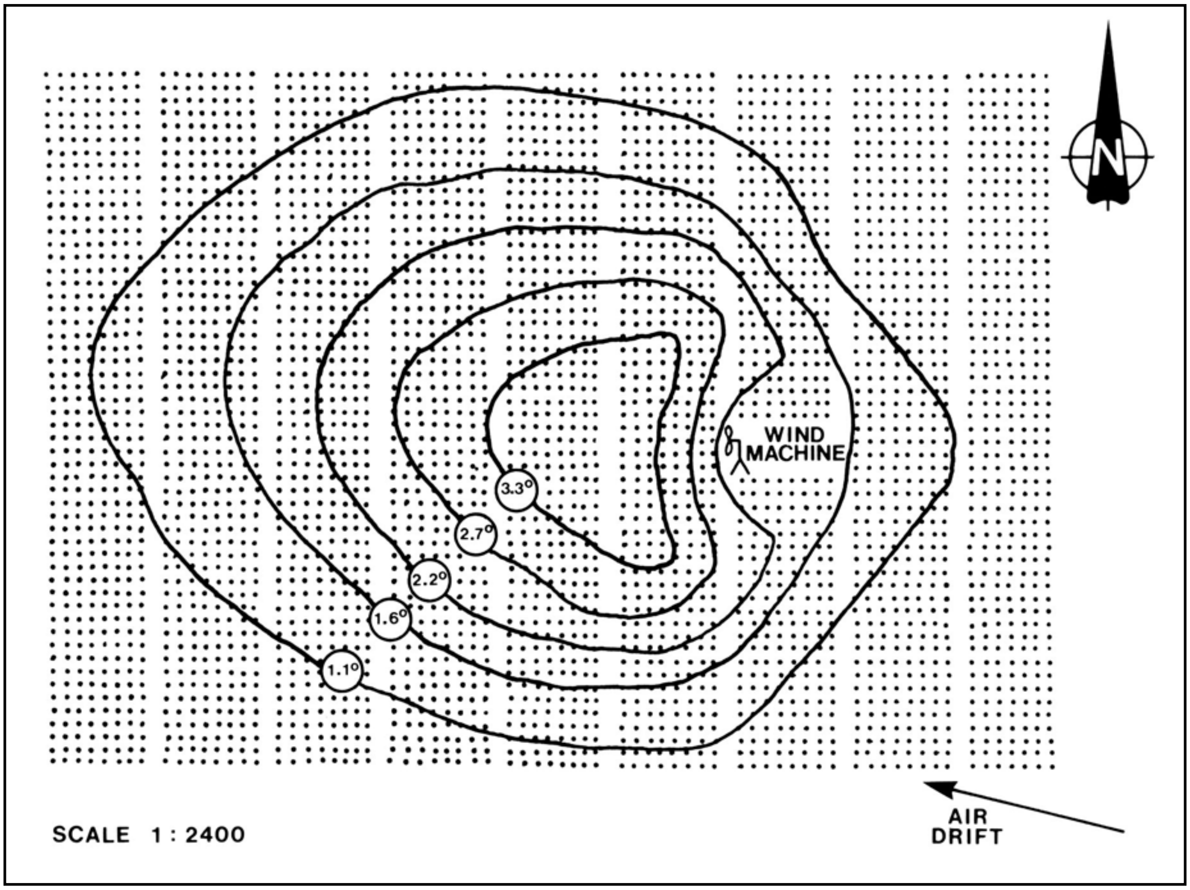


Figure 7. Area of response to a 67 kw (90 hp) wind machine on a night with a 7.8ºC inversion. The effectiveness was intentionally increased on the downwind side by shortening the turning time of the machine on the upwind side (after Books et al., 1952).

4. Heating

The use of heaters to replace the heat lost due to radiation on a clear night is a widely practiced form of frost protection around the world. Heater fuels that are used include oil, wood, coal, charcoal or other convenient available fuels.

A number of small heaters well spaced over the area is superior to a few large heaters. Large heaters can cause a powerful stream of hot air to rise rapidly and break through the temperature inversion ceiling without spreading out and mixing. This can create a chimney effect, drawing cold air in at the surface and may, therefore, actually do more harm than good.

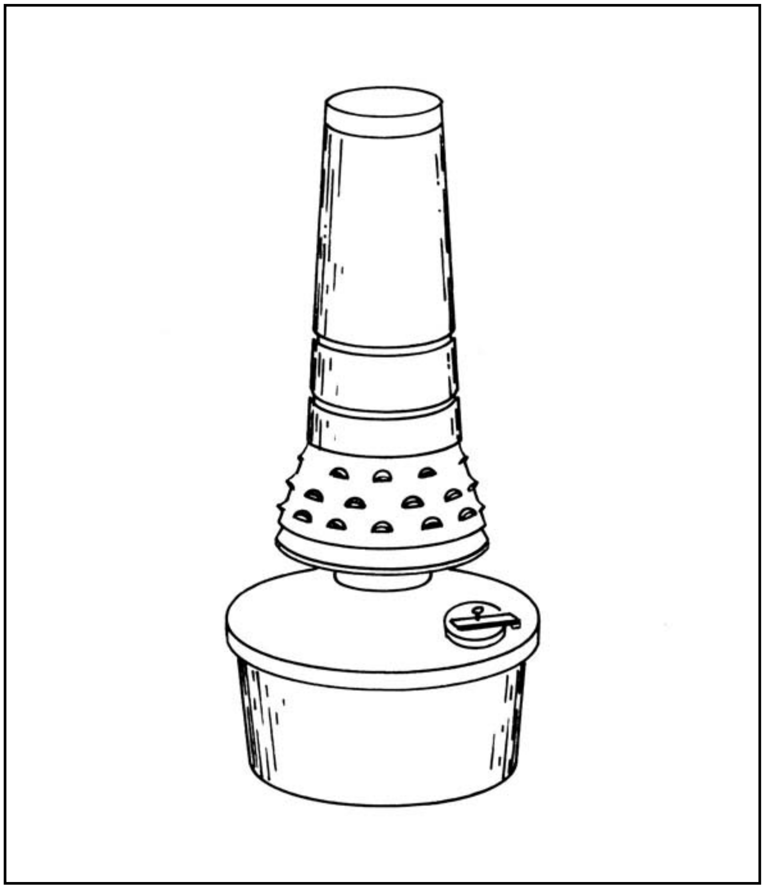


Figure 8. Large Cone Heater

A great deal of heat energy is required to replace that which is lost to outgoing radiation during the night. Theoretical losses are in the order of 0.10 to 0.15 cal/cm^2/min. Translating this in terms of hourly requirements per hectare:

0.15 cal/cm cm^2/min = 900 million cal/hr/ha
= 3.76 million kilojoules/hr/ha
= 3.57 million BTU/hr/ha

Actual heat demand may average from 5 to 10 million kilogoules/hr/ha due to heat losses by radiation to the sky, air drainage and wind drift.

These figures can be translated into fuel requirements by:

1 million kilojoules = 25 litres of oil

$$\frac{\text{5 million kilojoules}}{\text{hr/ha}} \times \frac{\text{25 litres oil}}{\text{1 million kilogoules}} = \text{125 litres oil/hr/ha.}$$

Therefore, 125-250 litres of oil/hr/hectare may be required. A guide to spacing of heaters can be found in the following table:

TABLE 1. **Maximum Heater Spacing for Frost Protection**

Number of Heaters per Hectare	Maximum Protection ºC
150 without spreaders	4º
110 without spreaders	2º
150 with spreaders	1.5º
110 with spreaders	1º

A spreader controls the rate of burning of the pots. The use of spreaders can increase the burning time of pots up to two times. The results in Table 1 are based on work carried out in Australia. The number of heaters per hectare stated provided the degree of protection indicated. Results of similar work around North America indicate that 60-100 heaters per hectare may be required. To be economical, frost protection by heating should not require more than 75 pots per hectare. Successful crop protection by heating in Florida has shown that 130 liters of oil per hour per hectare must be burned to generate enough heat to protect a -8ºC frost.

Heaters as a form of frost control are generally not practical today due to the cost of fuel and the labor input required to operate these units.

5. Irrigation

Overtree Systems

Overtree sprinkling for frost protection makes use of an important physical property of water. As water cools, approximately 1 calorie of heat must be removed per gram (or cubic centimeter) of water for every 1ºC reduction in temperature. When the temperature reaches 0ºC, 80 calories must be removed from one gram of water to form ice at 0ºC. This is called the latent heat of fusion. If a film of water is spread over a surface being cooled by radiation, the latent heat of fusion is available to prevent the surface temperature from going below 0º C. As long as the film of water is maintained, the temperature of the surface protected will not go below freezing, even though a layer of ice is steadily formed.

The film must be maintained continuously as long as the temperatures are low enough to freeze ice or until all the ice has melted. This method of frost protection prevents the plant material from dropping below the freezing point. It does not warm the plant nor does it appreciably raise the air temperatures. With overtree sprinkling for frost protection, the plant must be capable of supporting the build up of ice that will be formed throughout the frost period. The temperature of the site will drop when the system is turned on, therefore, irrigation systems should be started early, well above the crop critical temperatures.

Table 2 compares the relative heat values of burning oil with the heat values of cooling and freezing water. Table 3 provides values of the amount of heat released by freezing 100% of the water sprinkled at various application rates.

TABLE 2. **Relative Heat Values of Oil and Water**

Condensation of water at 0º C releases	- 2510 kJ/L
Evaporation of water at 0º C requires	- 2510 kJ/L
Fusion of water to ice releases	- 334 kJ/L
1ºC temperature change of water releases or requires	- 4.18 kJ/L
1 mm/hr water application over a hectare changing 1ºC releases	-41,800 kJ/º C/hr/ha
1 mm/hr /hectare water application oof which 100% freezes releases	-3,340,000 kJ/hr/ha
1 liter of oil burning releases	39,025 kJ/L
75 heaters per hectare @ 2.5 L/hr/ha releases	-7,315,000 kJ/hr/ha

TABLE 3. **Heat Releases by Freezing Water at Various Application Rates (100% Freezing Occurring)**

Application Rate mm/hr	Heat Released Kilojoules/hr/ha
1.0	3,340,000
2.0	6,680,000
3.0	10,020,000
4.0	13,360,000
5.0	16,700,000

Undertree Systems

Frost protection using undertree sprinklers has also been used with some success. Undertree systems have an advantage in that ice buildup does not occur on the trees or vines, as is the case with overtree systems. Undertree systems also do not have to be operated continuously as the bud is not being iced and, therefore, may not suffer damage should the system stop prematurely. However, undertree systems do not provide the same degree of protection as do overhead sprinkling systems. Undertree systems protect the crop by reducing the amount of outgoing radiation from the ground surface, thereby keeping the irrigation area warmer than non-irrigated areas. The formation of ice will create heat which rises and can be transferred to the crop.

Experience in other areas has shown that undertree systems can be effective in large blocks and if the dew point temperature was above 0ºC prior to the start of sprinkling. If the dew point temperatures are low and if more than 1ºC protection is desired, these systems would not be very effective.

The formation of ice from undertree systems can generate a considerable amount of heat if all the water applied is frozen. This heat can be transferred to the fruit buds by radiation and convection. If the dewpoint is above freezing, undertree sprinkling is more effective as no evaporative cooling will take place (see part 3 regarding evaporative cooling). However, if the dewpoint is below freezing, evaporative cooling may absorb all the heat released by the water freezing, thereby reducing the protection considerably.

Undertree systems are also influenced by height and type of cover crop, droplet size, net radiation, soil moisture, water temperature, sensible and latent heat fluxes, and other factors that do not affect overtree applications. Uniformity of application and application rates are assumed to be less than overtree systems. Exact design data for undertree system design for frost protection is not available at this time. The following procedures should be used to make undertree systems for frost protection more effective.

a) Small droplet size is beneficial. This can be obtained by using small nozzles at high pressures.
b) Cover crops are beneficial as they provide more freezing surface.
c) Undertree systems should be turned on early to raise the relative humidity and corresponding dew point temperatures, and also to prevent the heads from freezing before start up.
d) The larger the block, the easier it is to protect with an undertree system.
e) Undertree systems used in conjunction with wind machines and border heaters makes for more effective frost protection.

While cycling of water during frost protection should not be done with an overhead system, it can be attempted with an undertree system. Pulsing of an undertree system takes advantage of the margin between 0º C and the critical temperatures at which damage is done. By turning the system off, the plant is allowed to cool toward the critical temperature. The duration of the off period is the sum of the time it takes the applied water to freeze and the time it takes for the plant parts cool to the critical temperature. The advantage of cycling is that it reduces the amount of water required. However, it is risky and should definitely not be attempted with an overtree system.

Reduced application rates can also be achieved by using micro sprinklers for both undertree and overtree applications. While application rates can be reduced, care should be taken with these types of systems as the amount of protection may be limited. In the case of overtree systems using micro sprinklers, orchardists have tried irrigating only the crop canopy, leaving the panels dry. The water volume is greatly reduced but slight air movement could cause the applied water to drift away from the crop, eliminating the protection.

The degree of protection that may be achieved by applying water from an irrigation system are summarized in Table 4 below. The values indicated are maximum assuming all conditions are perfect.

TABLE 4. **Maximum Degree of Protection That May be Obtained by Irrigation**

	Application Rate	Protection
*Pre-wetting soil		up to 1.1ºC
Undertree sprinkling	2.25 mm/hr.	up to 2.2ºC
	4.5 mm/hr.	up to 2.8ºC
Overtree sprinkling	2.75 mm/hr.	up to 4.4ºC
	4.0 mm/hr.	up to 6.7ºC

*Pre-wetting the soil will offer some frost protection if water is sprinkled on bare, firm ground during the morning before a frost.

The degree of protection actually achieved will be dependent upon a number of factors. Additional information on the protection achieved, design and management of sprinkler frost protection systems is provided in Section 3.

SECTION 3

Irrigation System Design

Water can be used for frost protection in a number of ways; crop flooding which has been done with cranberries in some parts of North America, overtree sprinkling for bloom delay, overtree and undertree sprinkling during frost occurrences to reduce injury.

Undertree sprinkling for frost protection is discussed in the previous section. It is important to realize that this method of protection may only be successful if the crop can sustain temperatures below 0ºC and if the level of protection required from the system does not exceed 1.0ºC.

An overtree system provides protection by allowing a coating of ice to encase the plant tissue. As mentioned previously, the latent heat of fusion, 80 calories per gram of water to turn to ice at 0ºC, will provide enough heat to prevent the plant tissue from going below –0.5ºC (31.5ºF). A small film of water is maintained continuously until the ice is melting rapidly. Since this method of protection does not raise the air temperature, the effectiveness cannot be measured by air temperature.

Application Rates

The amount of water applied by the overhead irrigation system will determine the degree of protection obtained. The minimum application rate to provide protection down to -6ºC (21ºF) are:

Low growing plants-cranberries, etc.	1.5 – 2.0 mm/hr.
Fruit trees	2.0 mm/hr.
Vines	2.0 – 2.5 mm/hr

Dew point temperatures, wind velocity and sprinkler rotation speed have an affect on the level of protection achieved. Table 5 provides information on the application rates required to achieve various levels of protection at different wind speeds.

TABLE 5. **Recommended Overtree Application Rates (mm/hr) for Various Wind Speed and Temperature Conditions**

Temperature ºC	Wind Speed		
	0-2 km/hr	3-7 km/hr	8-13 km/hr
-2.8	2.5	2.5	2.5
-3.3	2.5	2.5	3.6
-4.4	2.5	4.0	7.6
-5.6	3.0	6.1	12.7
-6.7	4.0	7.6	15.2
-7.8	5.0	10.2	17.8

The values indicated in Table 5 grossly exceed the minimum application rates established earlier for wind speeds exceeding 2 km/hr. Realistically, overhead sprinkling cannot be expected to provide complete protection to –6.7ºC at wind speeds exceeding 2 km/hr. Applying water at the application rates suggested in Table 4 would lead to massive ice buildups that could damage trees and vines beyond repair. **A maximum application rate of 4.0 mm/hr is suggested.**

Sprinkler Rotation Speeds

To obtain optimum results from overhead frost protection, the sprinkler should complete one rotation every 40 seconds. With overlap, this allows for a wetting every 20 seconds on average. Maximum duration for sprinkler rotation times should not exceed 60 seconds. If the period between wettings exceeds 60 seconds, the application rate must be increased by up to 40% to obtain the same level of protection offered by wetting the plant every 20 seconds.

Start Up and Shut Down of Sprinkler Systems

Many factors determine the start up condition of a sprinkler system for frost protection. Air temperatures, wind velocity, dew point and stage of plant growth must be considered to minimize crop damage, reduce the amount of water applied and minimize ice buildup.

When water is sprayed into the air and onto plant surfaces under relatively dry air conditions, evaporation will take place. The evaporation of water requires heat and will therefore remove it from the air, plants and soil surface. Water is evaporated into the air until the air becomes saturated, and under low wind conditions the air temperature will drop to the wet bulb temperature. This is known as **evaporative cooling.** The irrigation system should be turned on when the wet bulb temperature is above the critical temperature which causes frost damage to the crop. Starting the system when the wet bulb temperature is below the critical temperature may create evaporative cooling conditions that could cause frost damage in itself.

Wet bulb temperatures are difficult to measure below 0ºC. Wet bulb temperature and relative humidity both vary with temperature and must therefore be measured frequently if used as an irrigation start up guide. Dew point temperatures, however, depend on the moisture content of the air, which does not usually alter quickly in the short time frame preceding a frost.

Dew point temperature cannot be measured, but can be determined from a psychrometric chart. Figure 9 below indicates the properties of moist air on a psychrometric chart. See Appendix B.

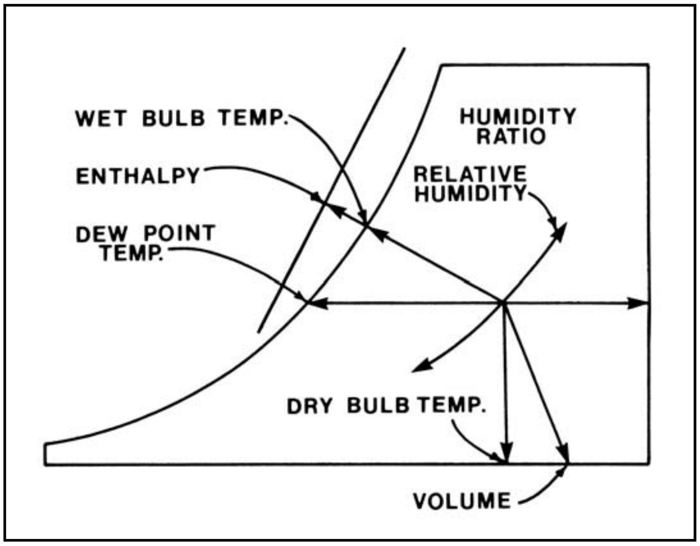


Figure 9. Moist Air Properties

The terms shown in Figure 9 are defined in the glossary. The intersection of any two property lines fixes a given state and all other properties can then be read. The dew point temperature can therefore be obtained from the psychrometric chart once the wet bulb and dry bulb temperatures are known. The dry bulb temperature is measured using an ordinary mercury-in-glass thermometer. Wet bulb temperatures are measured with the thermometer bulb wrapped in a water moistened wick and held in a moving stream of ambient air. A sling psychrometer is usually used to measure both dry and wet bulb temperatures simultaneously. Two thermometers are mounted in a hand held sling, one of the thermometers covered with a wetted wick. To operate, the sling, psychrometer is spun in the air to provide an air stream over the wick for a period of 60 seconds or more. When the two thermometers record steady temperatures between successive readings, steady state has been established and the wet and dry bulb temperatures can be recorded. Battery and wind up psychrometers are also available. In addition, the current and forecast dew point are available for your local weather office and are usually included in a frost warning bulletin.

Using a psychometric chart, the dew point temperatures can be determined. As the air temperature drops the dry bulb temperature will change. However, the dew point temperature will remain fairly constant before the irrigation system is turned on. The dew point temperature is, therefore, very useful in determining the "turn on" of the irrigation system. Once the irrigation system has been turned on, the moisture content of the air will have changed and the dew point temperature will also have changed. It is therefore important to record the data before turning the irrigation system on.

Table 6 can be used to determine the absolute minimum irrigation "turn on" temperature based upon the critical temperature of the crop and the dew point temperature. In order to maintain the wet bulb temperature above the crop critical temperature, for the ranges of dew point temperatures shown, the irrigation system should be turned on at or above the indicated air temperature.

The "turn off" temperature can be as critical as the "turn on" temperature. Heat is required to melt the ice coating off the plant. If the irrigation system is turned off too soon the temperature of the bud can fall below 0ºC. It is safe to turn the irrigation system off when free water is running between the ice and plant material. It is not necessary to wait until all the ice has melted once warm sunlight has taken over.

TABLE 6. **Irrigation Turn On Temperatures for Frost Protection**

Critical Temperature ºC	Dewpoint Temperature Range ºC			Minimum Turn On Dry Bulb ºC Temperature
0	-16.1	to	-12.2	7.2
	-12.2	to	-8.8	6.1
	-8.8	to	-6.1	5.0
	-6.1	to	-4.4	3.9
	-4.4	to	-2.2	2.8
	-2.2	to	-0.6	1.7
	-0.6	to	0.0	0.6
-1.1	-17.8	to	-12.8	5.6
	-12.8	to	-9.4	4.4
	-9.4	to	-6.7	3.3
	-6.7	to	-4.4	2.2
	-4.4	to	-2.8	1.1
	-2.8	to	-1.1	0
-2.2	-17.8	to	-13.3	3.9
	-13.3	to	-10.0	2.8
	-10.0	to	-7.2	1.7
	-7.2	to	-5.0	0.6
	-5.0	to	-2.8	-0.6
	-2.8	to	-2.2	-1.7
-3.3	-17.8	to	-12.2	1.7
	-12.2	to	-8.8	0.6
	-8.8	to	-6.7	-0.6
	-6.7	to	-4.4	-1.7
	-4.4	to	-3.9	-2.7

From: Synder, Richard L., Agricultural Biometeorologist, University of California, Davis

The values indicated for irrigation turn on temperatures are absolute minimum. Ideally, the system should be turned on 1ºC higher than the minimum temperatures shown in the Table.

Example

A producer requires frost protection for his apple crop and is using an irrigation system. The bud stage development is at post bloom. Using a sling psychrometer he has determined that the wet bulb temperature is 1.7ºC and the dry bulb temperature is 6.1ºC. What is the temperature at which point the irrigation system should be turned on?

From Appendix B	Using the psychrometric chart the dew point temperature is determined to be -5ºC
From Appendix B	The critical temperature for apples at the post bloom stage is –2.2ºC.
From Table 6	For a dew point temperature of -5ºC and a plant critical temperature of –2.2ºC the irrigation system should be turned on at a minimum temperature of 0.6ºC. It is recommended that the irrigation system be started at a temperature 1ºC higher, i.e. 1.6ºC dry bulb.

Note 1 A wet bulb temperature of 0ºC will cause the sling psychrometer to freeze. This is caused by the effect of evaporative cooling. If this happens, conditions have already exceeded the point where protection to 0ºC by overhead sprinkling may not be possible. The irrigation system should then only be turned on if the plant critical temperature is below 0ºC.

Note 2 The psychrometric chart in Appendix B provides accurate results when barometric pressure is at 101 kPa (30 inches Hg). Results will change for variations in barometric pressure.

Extra caution should be used if not enough water is applied, if windy conditions persist or if the irrigation system shuts down prematurely. These conditions may generate a refrigeration condition rather than a protective condition, with the potential of large crop losses.

Sprinkler Spacing

Spacing of the sprinklers is important to determine application rate and to achieve good uniformity. A uniformity coefficient of 85% is desired.

To obtain this, the irrigation system must be designed as follows:

- pressure variations along the lateral should not exceed 20% of the design operating pressure of the sprinkler
- the sprinkler spacing should not exceed 30% to 60% of the sprinkler wetted diameter, depending on the wind speed and operating pressure as shown in Table 7.

TABLE 7. **Maximum Allowable Sprinkler Spacing as a Percentage of Wetted Diameter**

Wind Speed km/hr.	Moderate Pressure Sprinklers (30-45 psi)	High Pressure Sprinklers (45-65 psi)
0.0	60%	60%
6.5	60%	50%
13.0	50%	40%
>13.0	40%	30%

If the irrigation system is used exclusively for frost protection, the sprinkler spacings could be stretched further apart providing that all parts of the crop are wetted at least every 40 seconds. There must still be enough overlap to insure a complete and continuous cover of water on the crop. Wind speed during most frost conditions are quite low, therefore, spacings could be stretched to 70%. However, the uniformity of application will be affected, with the system applying substantially more water in some areas than others. For B.C. conditions, it is recommended that sprinkler spacings do not exceed the values indicated in Table 7.

Sprinkler Selection

Sprinklers selected for frost protection purposes should have the following features:

- must be able to operate at temperatures below freezing
- must have a fast rotation speed
- be capable of providing relatively low application rates while still maintaining uniformity
- must have a good wetted diameter

As discussed previously, application rates of 2.0 mm/hr to 5.0 mm/hr are desired for frost protection. Application rates of 3.0 mm/hr to 4.0 mm/hr are generally being used for most crops. Approximately 0.5ºC of protection can be achieved for every 0.5 mm/hr increase in application rate. There are numerous sprinkler spacing, nozzle size and operating pressure combinations that will achieve the desired application rate. Crop spacing and type of irrigation system (overtree or undertree) will affect sprinkler spacing and thus application rates. The designer must assimilate all these factors to properly design the system.

Table 8 is included as a guide to selecting nozzle and spacing combination for frost protection design. The application rates indicated are for the spacing shown.

TABLE 8.

Sprinkler Nozzle and Spacing Selections

Application Rate mm/hr	Nozzle (inches)	Pressure (psi)	Flow Rate (U.S. gpm)	Spacing (ft x ft)
1.8	1/16”	34	0.65	30 x 30
2.0	1/16”	44	0.75	30 x 30
2.3	1/16”	55	0.84	30 x 30
	5/64”	40	1.12	30 x 40
2.5	5/64”	50	1.25	30 x 40
2.8	5/64”	34	1.03	30 x 30
	5/64”	60	1.37	30 x 40
3.0	5/64”	40	1.12	30 x 30
	5/32”	34	1.49	30 x 40
3.3	5/64”	47	1.21	30 x 30
	3/32”	40	1.62	30 x 40
	7/64”	38	2.16	40 x 40
3.6	5/64”	55	1.31	30 x 30
	3/32”	47	1.75	30 x 40
	7/64”	45	2.32	40 x 40
	1/8”	42	2.90	40 x 50
3.8	3/32”	55	1.87	30 x 40
	7/64”	53	2.49	40 x 40
	1/8”	49	3.12	40 x 50
	9/64”	47	3.89	50 x 50
	5/32”	44	4.67	50 x 60*
4.1	7/64”	58	2.66	40 x 40
	1/8”	53	3.32	40 x 50
	9/64”	53	4.15	50 x 50
	5/32”	52	4.98	50 x 60
	11/64”	53	5.98	60 x 60*
4.3	1/8”	59	3.53	40 x 50
	9/64”	38	3.53	40 x 50
	9/64”	60	4.41	50 x 50
	5/32”	40	4.41	50 x 50
	5/32”	58	5.30	50 x 60
	11/64”	40	5.30	50 x 60
	11/64”	57	6.35	60 x 60*
4.6	9/64”	43	3.74	40 x 50
	5/32”	45	4.67	50 x 50
	5/32”	63	5.60	50 x 60
	11/64”	43	5.60	50 x 60
	3/16”	45	6.72	60 x 60*

TABLE 8. **Sprinkler Nozzle and Spacing Selections** (Continued)

Application Rate mm/hr	Nozzle (inches)	Pressure (psi)	Flow Rate (U.S. gpm)	Spacing (ft x ft)
4.8	9/64”	48	3.94	40 x 50
	5/32”	48	4.93	50 x 50
	11/69”	50	5.92	50 x 60
	3/16”	49	7.10	60 x 60

* Spacing shown exceeds the allowable based on the sprinkler wetted diameter. Care should be taken at these spacings that the sprinkler with the best wetted diameter performance be selected.

Table 8 does not list all the nozzle, pressure and spacing combinations that are possible. Often increased wetted diameter may be obtained by selecting sprinklers with a combination of nozzles (i.e. 5/32” x 3/32”). However, if selecting a sprinkler designed specifically for frost protection purposes, this is not always possible.

Table 8 provides the designer with the flow rates required to achieve the desired application rate at the spacings indicated. The corresponding nozzles and pressures are to be used as a guide only. The designer must evaluate the products available to select the approximate nozzle, operating pressure and spacing for the system to be designed.

The application rate (in mm/hr) of a sprinkler irrigation system can be calculated from the following formula:

$$A.R. = \frac{Q \times 2446}{S_1 \times S_2}$$

where A.R. = application rate in mm/hr
Q = sprinkler flow rate in U.S. gallons per minute
S_1 = sprinkler spacing along lateral (ft)
S_2 = lateral spacing (ft)

Water Supply

To effectively protect against frost with an irrigation system, the system must be operated continuously from the onset of frost until the ice encasement has sufficiently begun to melt. A large amount of water is required to provide this protection. Table 9 indicates the flow rate that must be supplied on a per hectare basis for various application rates.

TABLE 9. **Flow Rate Requirements for Frost Protection**

Application Rate	Flow Rate
2.0 mm/hr	90 gpm/hectare
3.0 mm/hr	135 gpm/hectare
4.0 mm/hr	175 gpm/hectare
5.0 mm/hr	225 gpm/hectare

From Table 9, a 4 hectare orchard requiring protection of 3.0 mm/hr will require a flow rate of 540 gpm. In numerous areas of B.C. these types of flow rates are not easily achieved, especially if water is supplied by an irrigation district. The only other option is to provide storage. Ideally, the storage reservoir should be large enough to allow for 3 nights of frost protection at 10 hours per night. Table 10 provides data to calculate the size of storage facility required for various application rates.

Note

The flow rate required per hectare for frost protection can be reduced in some instances by using irrigation systems that only cover the crop canopy. Contact the Engineering Branch, B.C. Ministry of Agriculture and Fisheries, for further information on these systems.

TABLE 10. **Storage Requirements**

Application Rate	Storage Requirement / Hectare Protected
2.0 mm/hr	5,365 gal/hr/ha
3.0 mm/hr	8,050 gal/hr/ha
4.0 mm/hr	10,730 gal/hr/ha
5.0 mm/hr	13,900 gal/hr/ha

Example

Calculate the storage volume needed for a 4 hectare orchard requiring protection at the rate of 3.0 mm/hr for 10 hours for three successive nights.

4 hectares x 8050 gal/hr/ha x 10 hrs/day x 3 days = 966,000 gallons

This converts to a pond size of 27 m x 30 m with an average depth of 4.5 m. As illustrated, while the benefits of frost protection by irrigation appears worthwhile, a reliable water source must be developed to ensure that the protection can be achieved.

SECTION 4

Monitoring Equipment **(from Washington State University)**

Frost alarms are often used to alert the grower of a frost condition. Sensors can be used to automatically start up an "active" frost protection system. The sensor can be a standard thermometer or an electronically operated device. Regardless of the type of sensor used, the accuracy of the sensor should be checked each season. The circuitry between the sensor and frost protection system controls should also be inspected.

The sensor can easily be checked by placing it in an ice water slush and comparing values with an accurate alcohol thermometer. Electronic thermometers provide greater accuracy and faster responses than standard thermometers and are therefore very popular for frost protection installations. Many electronic thermometers are available with built in alarms to warn the grower of the onset of dangerous temperatures.

The sensor for any frost protection system should be placed in a standard thermometer shelter. Sensors exposed to open air will be affected by radiative cooling at night, thereby registering lower temperatures. The critical temperatures listed in Appendix A have been developed from readings taken from sheltered thermometers. To ensure that an accurate correlation exists between the readings taken and the plant's critical temperature, be sure that only readings from a covered sensor are used.

If a thermometer is exposed to the sun, the alcohol can become separated and give erroneous readings. Separation can also be caused by jolting the thermometer or by carrying the thermometer with the bulb end up. If separation leaves alcohol on the upper part of the tube, the readings will be too low. If separation occurs near the base the readings will be too high. Separation may be removed by swinging the thermometer with the base down. If this fails, the separation can be removed by placing the bulb end in a pan of water and slowly raising the temperature until the gap is removed. Slowly reducing the temperature should eliminate the separation. After the frost season, the thermometer should be stored upright in a cool place.

Figure 10 provides an illustration of a sensor or thermometer shelter. The sensor should be placed 1.5 m from the ground, facing north to avoid direct exposure to the sun. If a thermometer is used, it should be mounted with the bulb end 15 mm lower than the top end. It should be supported with about 12 mm free space between it and the back of the shelter. The shelter should also be painted white to reflect daytime heat and to aid in locating the shelter at night.

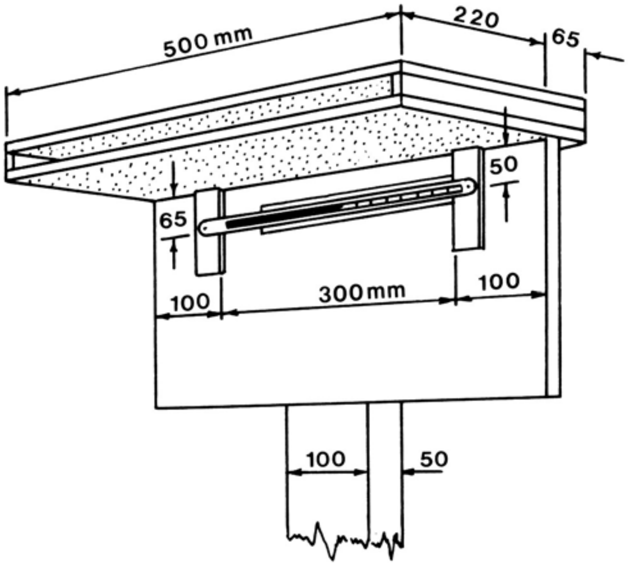


Figure 10. Sensor Shelter

Good management of a frost protection system requires accurate temperature readings. The topography and size of the area requiring frost protection will determine the number of readings needed. Sensors should be properly distributed with at least one located at the coldest section of the cropping area.

Sling psychrometers can be used to obtain the dewpoint temperature. The dewpoint temperature is important in determining when to turn on irrigation systems for frost protection. If an irrigation system is started when the wet bulb temperature is at or below the critical temperature, evaporative cooling results, with a potential of creating crop losses (see page 24). The sling psychrometer should be kept in good operating condition to ensure that accurate dry bulb and wet bulb temperatures are obtained. Evaporation of water from the muslin covering the wet bulb may leave deposits of water impurities. These may accumulate to the point where they may interfere with the readings taken. The muslin should therefore be renewed from time to time, especially in dusty areas. A good substitute for a muslin wick is a 100% cotton shoelace boiled in a lye solution for 15-30 minutes. Use caution when handling the wicks as oils from the hands can cause contamination. Finally, always use distilled water to clean and wet the wick material.

APPENDIX A

Critical Temperature

Critical temperature is the temperature, as read on a properly installed thermometer, that the buds, flowers or fruit will endure for 30 minutes or less without injury. The basis for determining when to start a frost protection system is the critical temperature.

The critical temperature of a crop will vary depending on plant variety, stage of growth, color and size of fruit, bud stage development etc. Meteorological factors can also affect the critical temperature of a crop. Air temperature 24 hrs preceding a frost can have a great effect on bud hardiness. Humidity, which is represented by dewpoint, can also have a bearing.

The following table lists the critical temperatures of various crops at different growth stages. At present, this is the best information available. As better information becomes accessible, it will be forwarded through fact sheets or other methods. The critical temperatures listed are based on the most susceptible buds. Buds that are sheltered, are higher in the tree, or are not fully developed may therefore easily survive the temperatures shown. Tree fruit values are shown for both 10% kill and 90% kill. Critical temperatures for the 10% kill values should be used. The 90% kill values are shown for comparison only.

TABLE 11.

Critical Temperatures for Various Crops (ºC)

	Showing Color	Full Bloom	Green Fruit	Mature Fruit
*Grapes	-1*	0	-1.5	-1
**Kiwifruit	-2.2	0	0	
Cole Crops	-2.2			
Blueberries	-2.0			
Cranberries	-1.7 (Spring)	-1.7 to -4.4 (Fall)		
Squash, Tomatoes, Cucumbers, Pumpkins, Melons, Peppers, Strawberries, Beans, Potatoes	All -1ºC when showing colour			

* This stage for grapes consists of clusters on 2 ft shoots as grapes don't show color.

* For Kiwifruit the fall temperatures may be more critical than spring temperatures in some locations.

TABLE 12.

Critical Temperatures for Tree Fruits (ºC)

	Bud Development			
Apples	Tight Cluster	First Pink	Full Bloom	Post Bloom
10% kill	-3.9	-2.8	-2.8	-2.2
90% kill	-7.8	-6.1	-4.4	-3.3
Pears	Tight Cluster	First White	Full Bloom	Post Bloom
10% kill	-5.0	-4.4	-2.8	-2.8
90% kill	12.8	-9.4	-5.0	-3.9
Cherries	Tight Cluster	First White	Full Bloom	Post Bloom
10% kill	-3.3	-2.8	-2.2	-2.2
90% kill	-7.8	-5.0	-3.9	-3.3
Prunes	Tight Cluster	First White	Full Bloom	Post Bloom
10% kill	-5.6	-3.3	-3.9	-2.8
90% kill	-11.7	-6.1	-7.8	-4.4
Peaches	Calyx Red	First Pink	Full Bloom	Post Bloom
10% kill	-5.0	-3.9	-2.8	-2.2
90% kill	-14.4	-9.4	-5.0	-3.9
Apricots	Calyx Red	First White	Full Bloom	Green Fruit
10% kill	-6.1	-5.0	-2.8	-2.2
90% kill	-17.2	-10.6	-6.7	-3.3

From: Goodfruit Grower, Vol 38 (4), Feb. 15, 1987.

APPENDIX B

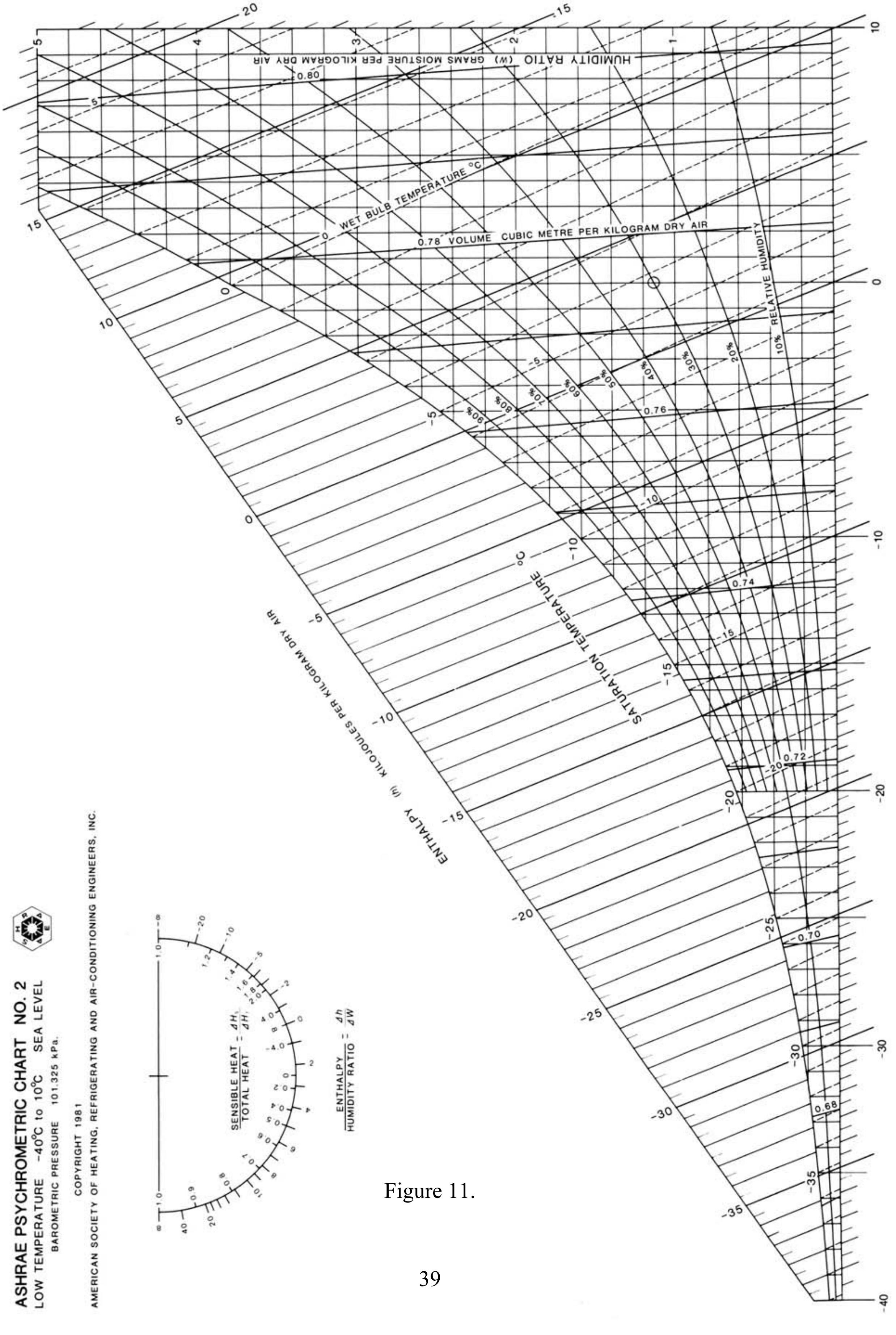


Figure 11.

APPENDIX C

Metric Conversion Table

Application Rate

0.01 in/hr = 0.25 mm/hr

Area

1 hectare = 2.47 acres
= 100 m x 100 m

Energy

1 h.p. = 0.746 Kw
1 joule = 0.239 calories

1 calorie = 4.184 joules

1 BTU = 252 calories
1.055 kilojoules

Length

1 m = 3.28 ft
= 39.37 inches

Temperature

1 degree Celsius = 1.8 degrees Fahrenheit
1 degree Fahrenheit = 0.56 degrees Celsius

Volume

1 m^3 = 264 gallons U.S.
= 35.3 ft^3
= 1000 litres

1 gallon U.S. = 3.78 litres

1ft^3 = 7.48 U.S. gallons
= 28.32 litres

GLOSSARY

Terms Commonly Used in Frost Protection Discussions

Anemometer - an instrument used to measure wind speeds.

British Thermal Unit (BTU) - a measure of heat. The amount of energy required to raise 1 lb of water 1ºF.

Calorie (cal) - a measure of heat. The amount of energy required to raise 1 gram of water 1ºC.

Dew Point Temperature - is the temperature at which moisture starts to condense when air, at constant pressure and humidity ratio, is cooled.

Dry Bulb Temperatures - can be measured with an ordinary mercury-in-glass thermometer, thermocouple or resistor.

Enthalpy - is the heat energy content of an air and water vapour mixture.

Humidity Ratio - is the ration of the weight of water to the weight of air for any given volume of air mass. (Kg of water/kg of air or lb. of water/lb of air).

Hydrometer - an instrument used to measure the amount of moisture in the air.

Latent Heat of Fusion - the heat released by water when it changes from a liquid to solid state (80 cal/g or 144 BTU/lb at 32ºF) Equal but opposite to latent heat of thawing.

Latent Heat of Vaporization - the heat released by water when it changes from a liquid to gaseous state (539 cal/g or 970 BTU/lb at 212ºF). Equal but opposite to latent heat of condensation.

Psychrometer	-	a type of hydrometer used to measure moisture. Consists of both a dry and wet bulb thermometer. Humidity is a function of the difference in readings.
Relative Humidity	-	is the ratio of partial water vapour pressure to the vapour pressure of saturated air at the same temperature. (If the air contains only half the amount of water vapour that it can hold when saturated, the relative humidity is 50%).
Wet Bulb Temperature	-	is measured with the same devices as the dry bulb temperature except that the bulb is wrapped in a water moistened wick and held in a moving stream of ambient air. The wet bulb is cooled by the evaporation of water from the wick.

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