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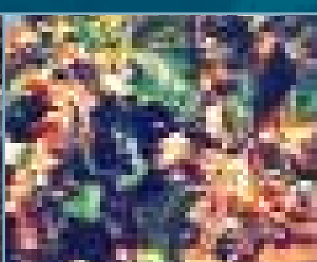
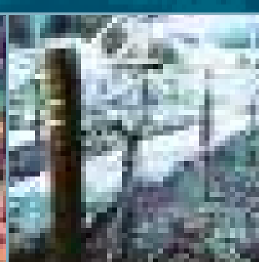
Frost protection: fundamentals, practice, and economics

Volume 1

ENVIRONMENT AND NATURAL RESOURCES SERIES

GEO-SPATIAL DATA AND INFORMATION ENVIRONMENTAL MANAGEMENT [ASSESSMENT AND MONITORING] GLOBAL ENVIRONMENTAL CHANGE

FAO FIAT PANIS

Front cover photos Left: *Ice accumulation from the use of under-tree sprinklers in Northern California* (photographer: Richard L. Snyder)
Middle: *Apple flowers damaged by frost depicting darkened petals a few days after a frost event in an orchard in Northern Portugal* (photographer: António Castro Ribeiro)
Right: *Ice accumulation from operation of targeted sprinklers over grapevines* (photographer: Robert Corrella)

Back cover photos Left: *Over-tree sprinkler experiment in Northern California* (photographer: unknown)
Middle: *Russet patches near the eyes and rings developed on small apple fruits damaged by frost in Northern Portugal* (photographer: António Castro Ribeiro)
Right: *The use of hoops and plastic to protect Alstroemeria plants in Northern California* (photographer: Richard L. Snyder)

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Frost Protection: fundamentals, practice and economics

Volume 1

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Food and Agriculture Organization of the United Nations Rome, 2005

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FOREWORD

Agrometeorology deals with the interactions between meteorological and hydrological factors, on the one hand, and agriculture in the widest sense, including horticulture, animal husbandry and forestry, on the other. Its goal is to study and define such interactions, and then to apply knowledge of the atmosphere to practical agricultural use.

Despite the impressive advances in agricultural technology over the last few decades, agricultural production remains dependent on weather and climate. It is a clear reality that climatic variability will play an even greater role than in the past, as sufficient food supplies will not be available to feed the world population adequately at its present rate of increase, unless agricultural technology is improved, natural resources are more efficiently used and decision makers are provided with up-to-date information on crop conditions.

The major role of modern agrometeorology is to ensure that data, tools and knowledge are available to researchers, planners, and farmers to cope with a variety of weather and climate-related problems in agricultural production. This book is an important contribution in this direction and it follows the philosophy of the Environment and Natural Resources Service to provide practical tools for helping the farming community; it illustrates that the interaction between agriculturalists and meteorologists can be very fruitful if respective disciplines understand their partners' needs and limitations.

Economics play an important part in any productive activity such as agriculture. In this book, various frost protection methods and associated risks are analysed from an economic point of view. National Agrometeorological Services and Extension Services will draw clear benefits from the use of simple computer applications that are provided to advise their customers on reducing losses and stabilizing their returns. Frost protection advice can constitute a valuable source of income for National Agrometeorological Services in developing countries.

Dietrich E. Leihner
Director
Research, Extension and Training Division
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ABSTRACT

This book describes the physics and biology of frost occurrence and damage, passive and active protection methods and how to assess the cost-effectiveness of active protection techniques. Night-time energy balance is used to demonstrate how protection methods are used to reduce the likelihood of frost damage. Simple methods and programs are provided to help predict temperature trends and to help determine the timing for active methods. Plant physiology related to freeze damage and critical damage temperatures for a wide range of crops and ornamentals are presented. Finally, an economic analysis program with examples is included to assist users to evaluate cost-effectiveness of various active methods.

Although the book contains considerable technical information, it was specifically written for growers rather than scientists as a practical guide for frost protection.

Frost Protection: fundamentals, practice and economics volume 1 and 2
By Richard L Snyder, J. Paulo de Melo-Abreu, Scott Matulich (vol. 2)

Vol. 1: 240 pages, 60 figures, 35 tables
Vol. 2: 72 pages, 35 figures, 5 tables
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Keywords:
Freeze protection, temperature forecasting, weather modification, wind machines, heaters, ice nucleation active bacteria, cold air drainage, microclimate, heat transfer.

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CONTENTS

ACRONYMS USED IN THE TEXT

DOY	Day of year
INA	Ice-nucleation active
NINA	Non-ice-nucleation active
P&I	Principal and interest
RMSE	Root mean square error
NWS	USA National Weather Service

NOTE:
All currency values unless otherwise specified are in United States dollars (symbol $).

LIST OF PRINCIPAL SYMBOLS

Roman Alphabet

Symbol	Unit	Definition
b'		Calibration factor for square root minimum temperature prediction
C		Certainty that an event will occur (i.e. C = 1 -R)
C_V	J m^{-3} °C^{-1}	Volumetric heat capacity of soil
E	kPa	Water vapour pressure or actual water vapour pressure
E	kg m^{-2} s^{-1}	Water vapour mass flux density
E	W m^{-2}	Energy from radiation
e_a	kPa	Saturation vapour pressure at temperature T_a
e_d	kPa	Saturation vapour pressure at the dew-point temperature T_d (note that e_d = e)
e_f	kPa	Saturation vapour pressure at the frost-bulb temperature T_w
e_i	kPa	Saturation vapour pressure at the ice point temperature T_i (note that e_i = e)
E_L	m	Elevation relative to mean sea level
E_o	MJ l^{-1}, MJ kg^{-1}	Energy output
E_R	W m^{-2}	Energy requirement
e_s	kPa	Saturation vapour pressure over a flat surface of liquid water or ice at temperature T
e_w	kPa	Saturation vapour pressure at wet bulb temperature T_w
F	—	Function to account for cloudiness effect on long-wave downward radiation
F_C	l h^{-1}, kg h^{-1}	Fuel consumption rate
G	W m^{-2}	Soil heat flux density
G_1	W m^{-2}	Soil heat flux density at the soil surface (i.e. G_1 = G)
G_2	W m^{-2}	Soil heat flux density measured with a flux plate at some depth in the soil
G_{sc}	W m^{-2}	Solar constant. G_{sc} = 1367 W m^{-2}
H	—	Number of hours from two hours past sunset until sunrise
H	W m^{-2}	Sensible heat flux density
H_H	—	Heaters per hectare
K_h	W m^{-1} °C^{-1}	Thermal conductivity
K_s	W m^{-1} °C^{-1}	Thermal conductivity of the soil
L	J kg^{-1}	Latent heat of vaporization

LE	W m^{-2}	Latent heat flux density
p	—	p = 86 400 s per day
P	—	Probability that an event will occur in any given year
P_b	kPa	Barometric pressure
R	—	Risk or probability that an event will occur during a known number of years
R_1	°C	Residual $R_1 = T_n - T_p$
R_1'	°C	Residual R_1 prediction using T_d at time t_0
R_A	mm h^{-1}	Sprinkler application rate
R_{Ld}	W m^{-2}	Downward positive long-wave (terrestrial) radiation
R_{Ln}	W m^{-2}	Net long-wave radiation ($R_{Ln} = R_{Ld} + R_{Lu}$)
R_{Lu}	W m^{-2}	Upward negative long-wave (terrestrial) radiation
$RMSE$		RMSE = $[\Sigma(Y-X)^2/n]^{0.5}$ where n is the number of pairs of random variables Y and X
R_n	W m^{-2}	Net radiation
R_o	°C	Range of soil surface temperature
R_{Sd}	W m^{-2}	Downward positive short-wave (solar) radiation
R_{Sn}	W m^{-2}	Net short-wave (solar) irradiance ($R_{Sn} = R_{Sd} + R_{Su}$)
R_{So}	W m^{-2}	Downward short-wave (solar) radiation from a clear sky
R_{Su}	W m^{-2}	Upward negative short-wave (solar) radiation
R_z	°C	Range of soil temperature at depth z in the soil
T	°C	Temperature
t	—	Time
T_{10}		The critical temperature at which 10 percent damage is expected
T_{90}		The critical temperature at which 90 percent damage is expected
T_a	°C	Air temperature
T_C	—	Critical temperature or critical damage temperature – the temperature at which a particular damage level is expected
T_{cf}	°C	Citrus fruit peel temperature
T_d	°C	Dew-point temperature
T_e	°C	Equivalent temperature (the temperature achieved if all latent heat in a parcel of air is adiabatically converted to sensible heat)
T_f	°C	Frost-bulb temperature
t_f	—	Time at the end of a sample interval
T_i	°C	Ice point temperature
t_i	—	Time at the beginning of a sample interval
T_i	°C	Temperature at the i^{th} hour following t_0
T_K	K	Absolute temperature in kelvins (273.15 K = 0°C)

T_n	°C	Observed minimum temperature at sunrise
t_0	—	Starting time for FFST.xls application (i.e. two hours past sunset)
T_0	°C	Temperature at time t_0
T_p	°C	Minimum temperature predicted from air and dew-point temperature at t_0
t_p	—	Time of sunrise for predicted minimum temperature (T_p)
$T_p{}'$	°C	Minimum temperature predicted using T_0 at time t_0
T_{sf}	°C	Soil temperature at the end of a sample interval
T_{si}	°C	Soil temperature at the beginning of a sample interval
T_w	°C	Wet-bulb temperature
V_m	—	Volume fraction of minerals in the soil
V_o	—	Volume fraction of organic matter in the soil
z	m	Depth below or height above the surface (e.g. in metres)

Greek Alphabet

Symbol	Unit	Definition
Δ	kPa $°C^{-1}$	Slope of saturation vapour pressure curve at temperature T
α	—	Albedo (i.e. reflection of short-wave radiation)
ε	—	Emissivity
ε_o	—	Apparent emissivity downward from clear sky
γ	kPa $°C^{-1}$	Psychrometric constant
κ_T	$m^2\ s^{-1}$	Thermal diffusivity in the soil
λ	MJ kg^{-1}	Latent heat of vaporization
λ_{max}	m	Wavelength of maximum energy emission (i.e. a function of temperature)
μ_d	—	Mean value for a date
θ	—	Volume fraction of water in the soil
σ	W $m^{-2}\ K^{-4}$	Stefan-Boltzmann constant $\sigma = 5.67 \times 10^{-8}\ Wm^{-2}K^{-4}$
σ	mol m^{-3}	Density of air
σ_d	Mg m^{-3}	Density of water
σ_d	—	Standard deviation of a date

Note that sprinkler irrigation rate conversions are:
1 mm h^{-1} = 1 litre $m^{-2}\ h^{-1}$ = 10^4 litre $ha^{-1}\ h^{-1}$ = 10 $m^3\ ha^{-1}\ h^{-1}$.

EXECUTIVE SUMMARY

This publication reviews the physical, chemical and biological factors involved in frost damage to agricultural and horticultural plants, and presents common methods of frost protection. In addition, computer analysis tools are provided to help growers design and manage various frost protection methods, investigate the risk of freezing temperatures and to analyse the economics of frost protection methods relative to risk, in order to decide on the costs and benefits of various protection methods.

Although the World Meteorological Organization (WMO) has published information on frost protection in the past, this is the first FAO publication specifically written on frost protection, and it greatly expands on the old WMO publication. It synthesizes and simplifies complex, technical information from the literature to provide understandable guidelines to reduce losses due to frost damage – losses that can be economically devastating for growers and their local communities.

Typical weather during freezing conditions is discussed, and computer tools are provided to predict minimum temperatures and temperature trends during radiation frost nights. In addition, the publication presents information on how environmental factors (soil conditions, clouds, fog, plant canopies, etc.) affect energy balance and how these factors affect temperature trends.

The publication discusses what happens to plant tissue when freezing temperatures occur, and it presents information on the sensitivity of plants to frost damage. The biological factors that affect freezing are presented (including growth stage, cell solute content and ice-nucleating bacteria), and the possible management methods to manipulate those factors are discussed (choice of rootstocks and varieties, water application, soil fertility, bacteria control, etc.).

The main methods of passive frost protection (no-tillage, wetting dry soils, removing litter and cover crops, etc.) are thoroughly discussed to provide growers with the most cost-effective methods of frost protection. A discussion of active frost protection (liquid- and solid-fuel heaters, surface irrigation, sprinklers and wind machines) is presented to indicate how the methods work and how to manage them – alone or in combination – for optimal protection.

Finally, a thorough discussion of the risks and economics of various protection methods is provided, together with computer applications to help simplify computations. The text and the accompanying Excel-based software applications should help growers and consultants to make wise decisions on the cost-effectiveness of alternative protection methods, depending on the local risk of frost and other factors.

CHAPTER 1

INTRODUCTION

OVERVIEW

When air temperatures fall below 0 °C, sensitive crops can be injured, with significant effects on production. For example, in the USA, there are more economic losses to frost damage than to any other weather-related phenomenon (White and Haas, 1975). Therefore, impacts on affected farmers and the local economy are often devastating. Although it is clearly important, information on how to protect crops from freezing is relatively limited. Consequently, there is a need for a widely available, simplified source of information to help farmers address this serious problem. In this book, the distribution, economics, history, physical and biological aspects of frost damage are presented and discussed, together with methods of protection.

This book contains a broad range of information from basic to complex; however, it was mainly written to help growers to better understand freeze protection and to develop strategies to combat crop losses due to freezing. References are provided for those who want to further investigate the science of frost protection. However, the objective is to provide a guidebook for practitioners, rather than a literature review. Because some aspects of frost protection are complex, user-friendly computer programs for some applications are included with the book. In addition, useful information on simple, inexpensive measurements and applications using charts and tables are provided, along with the algorithms used to make them.

For those readers who are mainly interested in management rather than science, read Chapter 2 on Recommended Methods of Frost Protection, which provides relatively non-technical information on all aspects of freeze protection. For those readers who want more detailed explanations, Chapters 3 to 8 thoroughly discuss most aspects of frost protection, including the scientific basis. Volume II of this book covers the probability, risk and economics of frost protection. While there is useful information for meteorologists, the book covers neither mesoscale or synoptic scale forecasting nor frost risk modelling. These are reviewed in other, more technical, publications (e.g. Kalma et al., 1992). However, for the local grower and farm advisor, this book should provide most of the information needed to make wise decisions about frost protection, thus helping growers and local communities to minimize the devastating effects of frost damage.

FREEZE AND FROST DEFINITIONS

Technically, the word "frost" refers to the formation of ice crystals on surfaces, either by freezing of dew or a phase change from vapour to ice (Blanc *et al.*, 1963; Bettencourt, 1980; Mota, 1981; Cunha, 1982); however, the word is widely used by the public to describe a meteorological event when crops and other plants experience freezing injury. Growers often use the terms "frost" and "freeze" interchangeably, with the vague definition being "an air temperature less than or equal to 0 °C". Examples of frost definitions in the literature include:

- the occurrence of a temperature less than or equal to 0 °C measured in a "Stevenson-screen" shelter at a height between 1.25 and 2.0 m (Hogg, 1950, 1971; Lawrence, 1952);
- the occurrence of an air temperature less than 0 °C, without defining the shelter type and height (Raposo, 1967; Hewett, 1971);
- when the surface temperature drops below 0 °C (Cunha, 1952); and the existence of a low air temperature that causes damage or death to the plants, without reference to ice formation (Ventskevich, 1958; Vitkevich, 1960).

Snyder, Paw U and Thompson (1987) and Kalma *et al.* (1992) have defined frost as falling into two categories: "advective" and "radiative". Advective frosts are associated with large-scale incursions of cold air with a well-mixed, windy atmosphere and a temperature that is often subzero, even during the daytime (Table 1.1). Radiative frosts are associated with cooling due to energy loss through radiant exchange during clear, calm nights, and with temperature inversions (i.e. temperature increases with height). In some cases, a combination of both advective and radiative conditions will occur. For example, it is not uncommon to have advective conditions bring a cold air mass into a region, resulting in an advection frost. This may be followed by several days of clear, calm conditions that are conducive to radiation frosts. In addition, the authors have observed conditions that are considered as "micro-scale-advection frosts". These occur when the region is exposed to radiation-type frost conditions, but local cold air drainage leads to rapid drops in temperature on a small scale within the radiation frost area.

TABLE 1.1
Frost event terminology and typical characteristics

FROST TYPE	CHARACTERISTICS
Radiation	Clear; calm; inversion; temperature greater than 0 °C during day
Advection	Windy; no inversion; temperature can be less than 0 °C during day

Freeze and frost definitions in dictionaries and in the literature are variable and confusing; however, on a worldwide basis, the term frost protection is more commonly used than freeze protection. Based on the literature, it was decided that the following definitions are appropriate and will be used in this book.

> A "frost" is the occurrence of an air temperature of 0 °C or lower, measured at a height of between 1.25 and 2.0 m above soil level, inside an appropriate weather shelter. Water within plants may or may not freeze during a frost event, depending on several avoidance factors (e.g. supercooling and concentration of ice nucleating bacteria). A "freeze" occurs when extracellular water within the plant freezes (i.e. changes from liquid to ice). This may or may not lead to damage of the plant tissue, depending on tolerance factors (e.g. solute content of the cells). A frost event becomes a freeze event when extracellular ice forms inside of the plants. Freeze injury occurs when the plant tissue temperature falls below a critical value where there is an irreversible physiological condition that is conducive to death or malfunction of the plant cells. This damaging plant tissue temperature is correlated with air temperatures called "critical temperatures" measured in standard instrument shelters. Subzero air temperatures are caused by reductions in sensible heat content of the air near the surface, mainly resulting from (1) a net energy loss through radiation from the surface to the sky (i.e. radiation frost); (2) wind blowing in subzero air to replace warmer air (i.e. advection frost); or (3) some combination of the two processes.

RADIATION FROST

Radiation frosts are common occurrences. They are characterized by a clear sky, calm or very little wind, temperature inversion, low dew-point temperatures and air temperatures that typically fall below 0 °C during the night but are above 0 °C during the day. The dew-point temperature is the temperature reached when the air is cooled until it reaches 100 percent relative humidity, and it is a direct measure of the water vapour content of the air. To illustrate the difference between advection and radiation frost, data from the two worst frost events in the twentieth century in the main California citrus growing region are shown in Figures 1.1 and 1.2. Notice that the daytime maximum temperatures dropped considerably as cold air moved into the region. Based on wind speed, it would not be considered an advection frost event, because there was little or no wind during the night, when temperatures were subzero. However, because it was cloudy during the first few days of the events, the subzero temperatures are attributed to advection of cold air into the area rather than resulting from a net radiation loss. Similar events to the two frosts had occurred previously in 1913 and

1937, so they are relatively rare occurrences. However, this may not be the case in more continental climate areas where subzero temperatures are more common.

Under clear night-time skies, more heat is radiated away from the surface than is received, so the temperature drops. The temperature falls faster near the radiating surface causing a temperature inversion to form (i.e. temperature increases with height above the ground). The process is shown in Figure 1.3. As there is a net loss of energy through radiation from the surface, the sensible heat content of the soil surface and air near the surface decreases. There is a flux of sensible heat downward from the air and upward from within the soil to the surface to replace the lost sensible heat. This causes the temperature to decrease aloft as well, but not as rapidly as at the surface. The depth to the top of the temperature inversion is variable depending on local topography and weather conditions, but generally ranges from 9 to 60 m (Perry, 1994).

FIGURE 1.1

Mean air and dew-point temperatures at 1.5 m height and mean wind speed at 2.0 m height recorded during the December 1990 event at Lindcove, California, USA

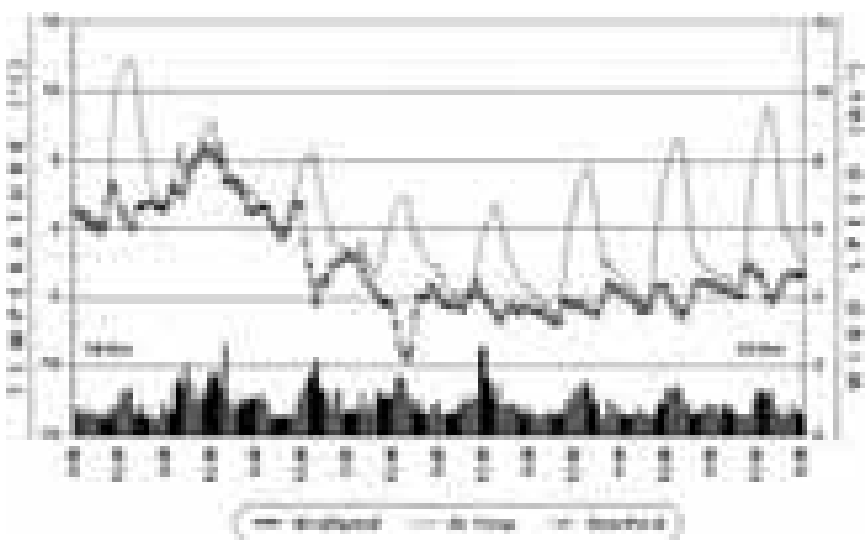


FIGURE 1.2

Mean air and dew-point temperatures at 1.5 m height and mean wind speed at 2.0 m height during the December 1998 event at Lindcove, California, USA

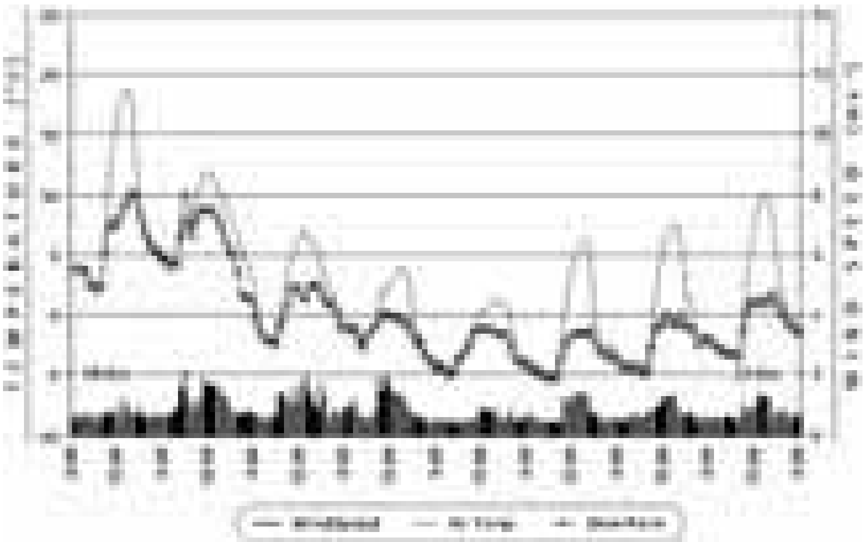
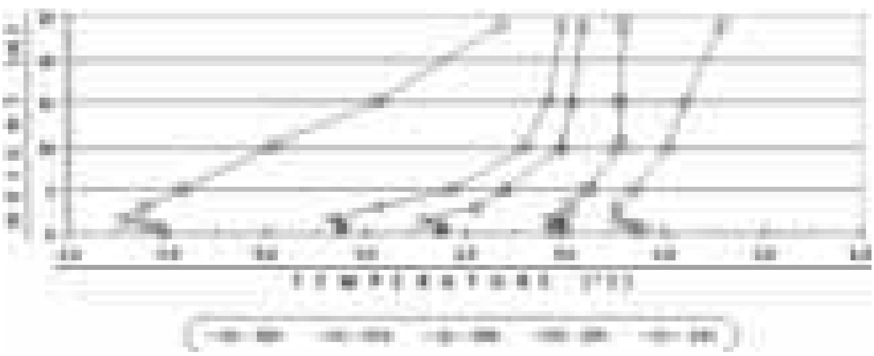


FIGURE 1.3

Development of an inversion over an apple orchard in northern Portugal



If air temperature is measured at a sufficient height above the soil surface, it will reach the point where it begins to decrease with height (a lapse condition). The level where the temperature profile changes from an inversion to a lapse condition is called the ceiling. A weak inversion (high ceiling) occurs when the temperatures aloft are only slightly higher than near the surface and a strong inversion (low ceiling) has rapidly increasing temperature with height. Energy-intensive protection methods are most effective during the low ceiling, strong inversion conditions that are typical of radiation frosts.

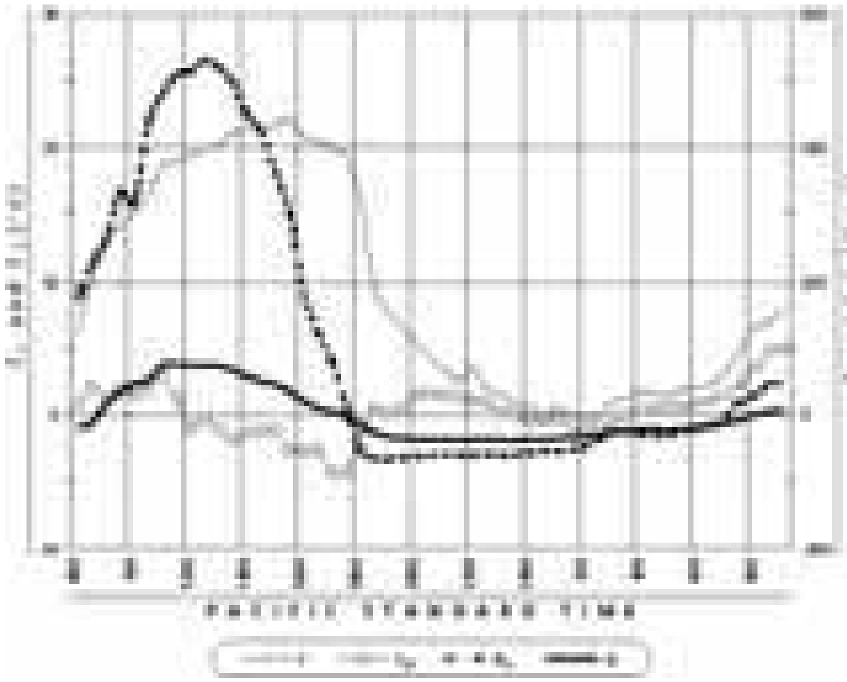
There are two subcategories of radiation frosts. A "hoar frost" occurs when water vapour deposits onto the surface and forms a white coating of ice that is commonly called "frost". A "black" frost occurs when temperature falls below 0 °C and no ice forms on the surface. If the humidity is sufficiently low, then the surface temperature might not reach the ice point temperature and no frost will form. When the humidity is high, ice is more likely to deposit and a "hoar frost" can occur. Because heat is released during the ice deposition process, hoar frosts usually cause less damage than black frosts.

Note that the plots of daily air temperature for the December 1990 and 1998 frosts in California (Figures 1.1 and 1.2) had similar shapes in both years; however, the dew-point temperature trends were different in the two years. Because the air temperature plots have a similar shape during most radiation frost nights, a good approximation for changes in night-time air temperature can be made with an empirical model. However, because of variability, it nearly impossible to generalize about dew-point temperature changes during the night.

One clear characteristic of air temperature on radiation frost nights is that most of the temperature drop occurs in a few hours around sunset, when the net radiation on the surface rapidly changes from positive to negative. This rapid change in net radiation occurs because solar radiation decreases from its highest value at midday to zero at sunset, and the net long-wave radiation is always negative. This is explained in more detail in Chapter 3. Figure 1.4 shows typical temperature, radiation and soil heat flux density trends during a radiation frost night. In this example, the temperature fell about 10 °C during the first hour after the net radiation became negative. After the net radiation reached its most negative value, the temperature only fell 10 °C more during the remainder of the night. The rate of temperature change was small (e.g. less than 1.0 °C h^{-1}) from two hours after sunset until sunrise.

FIGURE 1.4

Air (T_a) and dew-point (T_d) temperatures at 1.5 m height, net radiation (R_n) and soil heat flux density (G) measured in a walnut orchard in Indian Valley in Northern California, USA



ADVECTION FROST

Advection frosts occur when cold air blows into an area to replace warmer air that was present before the weather change. It is associated with cloudy conditions, moderate to strong winds, no temperature inversion and low humidity. Often temperatures will drop below the melting point (0 °C) and will stay there all day. Because many of the active protection methods work better in the presence of an inversion, advection frosts are difficult to combat. In many cases, a series of subzero nights will start as an advection frost and will later change to radiation frost nights. For example, the major California frosts of 1990 and 1998 shown in Figures 1.1 and 1.2 both started as advection frost events. Although the wind speeds were low, there were cloudy conditions from 18 to 20 December 1990 and from 18 to 22 December 1998. However, the temperature still fell to minimums well below 0 °C during these periods. After the skies cleared (i.e. 21–25 December 1990 and 23–25 December 1998), the subzero temperature resulted from radiation losses rather than advection of cold air.

Major frosts occur in Mediterranean climates, but they tend to be more common in the eastern part of continents where cold continental air masses occasionally advect from arctic regions into subtropical areas. Some of the best examples are in the Florida, USA, citrus growing region. Attaway (1997) describes the first "major impact" frost, which occurred in 1835, by citing John Lee Williams' account of the frost, which stated that "the northwest wind blew for 10 days and the temperature fell as low as -13.9 °C. Even the local river froze and all kinds of fruit trees were killed to the ground as far south as 28 °N latitude." Clearly, there is a big difference when trying to protect against subzero temperatures in windy conditions without an inversion than to protect against a relatively mild radiation frost. The saving grace is that major frost events tend to be sporadic, whereas radiation frost events occur often.

CLASSIFICATION OF PROTECTION METHODS

Frost protection techniques are often separated into indirect and direct methods (Bagdonas, Georg and Gerber, 1978), or passive and active methods (Kalma *et al.*, 1992). Passive methods are those that act in preventive terms, normally for a long period of time and whose action becomes particularly beneficial when freezing conditions occur. Active methods are temporary and they are energy or labour intensive, or both. Passive methods relate to biological and ecological techniques, including practices carried out before a frost night to reduce the potential for damage. Active methods are physically based and energy intensive. They require effort on the day preceding or during the night of the frost event. Active protection includes heaters, sprinklers and wind machines, which are used during the frost night to replace natural energy losses. A classification of methods is presented in Table 1.2.

GEOGRAPHICAL ASSESSMENT OF FROST DAMAGE TO CROPS

Frost damage can occur in almost any location, outside of tropical zones, where the temperature dips below the melting point of water (0 °C). The amount of injury depends on the crop's sensitivity to freezing at the time of the event and the length of time the temperature is below the "critical damage" temperature (T_c). For example, Argentina, Australia, Canada, Finland, France, Greece, Israel, Japan, Jordan, New Zealand, Portugal, Switzerland, United States of America and Zambia have developed minimum temperature forecasting techniques (Bagdonas, Georg and Gerber, 1978) to aid frost protection. Of course, many other countries in temperate and arid climates and at high elevations also have problems with frost damage.

TABLE 1.2

Categories and sub-categories for methods of frost protection

CATEGORY	SUB-CATEGORY	PROTECTION METHOD
Passive	Biological (avoidance or resistance)	Induction of resistance to freezing without modifying plant genetics
		Treatment of the seeds with chemicals
		Plant selection and genetic improvement
		Selecting species for timing of phenological development
		Selecting planting dates for annual crops after the probability of freezing lessens in the spring
		Growth regulators and other chemical substances
	Ecological	Site selection for cropping
		Modification of the landscape and microclimate
		Controlling nutritional status
		Soil management
		Cover crop (weed) control and mulches
Active	Covers and Radiation	Organic materials
		Covers without supports
		Covers with supports
	Water	Over-plant sprinklers
		Under-plant sprinklers
		Microsprinklers
		Surface irrigation
		Artificial fog
	Heaters	Solid fuel
		Liquid fuel
		Propane
	Wind machines	Horizontal
		Vertical
		Helicopters
	Combinations	Fans and heaters
		Fans and water

To a large extent, the potential for frost damage depends on local conditions. Therefore, it is difficult to present a geographical assessment of potential damage. The average length of the frost-free period, which lasts from the occurrence of the last subzero temperature in the spring to the first in the autumn, is sometimes used to geographically characterize the potential for damage.

A world map of average length of frost-free period (Figure 1.5) clearly shows that the greatest potential for frost damage increases as one moves poleward. Only at latitudes between the tropics of Cancer and Capricorn are there relative large areas with little or no subzero temperatures. Even in these tropical areas, frost damage sometimes occurs at high elevations. Damage is somewhat less likely when the land mass is downwind or surrounded by large bodies of water, because of the moderating effect of the maritime environment on humidity and temperature, and hence temperature fluctuations and dew or frost formation.

Although the map of the average length of frost-free period provides a useful general guide as to where the potential for frost damage is greater, it is not a detailed map. Again, the probability of freezing temperatures is affected by local conditions that cannot be properly shown on a global map. In fact, farmers can experience some economic losses from frost damage even if it occurs infrequently.

Although outside of the scope of this book, considerable effort has recently been expended in improving the geographical characterization of regional-scale frost damage risk. Kalma *et al.* (1992) published an extensive review on the geographical characterization of frost risk. For example, Lomas *et al.* (1989) prepared an atlas of frost-risk maps for Israel. They used more than 25 years of temperature data and topographical information to develop the maps, which clearly show a close relationship between elevation and risk of subzero temperature. Others have used mobile temperature surveys or topographical and soil information, without temperature data, to derive risk maps. Case studies on developing a frost-risk map using an elevation model were presented by Kalma *et al.* (1992) based on Laughlin and Kalma (1987, 1990), and by Zinoni *et al.* (2002b).

While more and better spatial information on risk of frost damage is needed, there is no substitute for good local information and monitoring. Most farmers have a good idea about the location of cold spots in their locality. It is definitely worthwhile to consult neighbours before planting sensitive crops at a specific site. Generally, low spots, where cold air ponds, should be avoided. Also, avoid areas where the natural or modified topography dams cold air drainage from the site. Because ground fog forms in low spots first, a good rule of thumb is to avoid places where ground fog forms early. Definitely, one should review local topographical maps before planting frost-sensitive crops on high-risk sites. For example, because bloom is late, there is rarely a need for frost protection of walnut orchards in California, but the authors have noted that a few orchards that are planted in cold spots commonly experience damage. This could easily have been avoided by checking local weather records and topographical maps. Site selection is discussed in more detail later, in the section on passive protection.

FIGURE 1.5

Geographical distribution of the average length of frost free period. See the file: "Frost free map.jpeg" on the programs CD to view the distribution in colour

ECONOMIC IMPORTANCE OF FROST DAMAGE

More economic losses are caused by freezing of crops in the USA than by any other weather hazard. In the State of Florida, the citrus industry has been devastated by frost damage on several occasions, resulting in fruit and tree costing billions of dollars (Cooper, Young and Turrell, 1964; Martsolf *et al.*, 1984; Attaway, 1997). In California, the December 1990 frost caused about $ 500 million in fruit losses and damage to about 450 000 ha of trees (Attaway, 1997). There was about $ 700 million in damage during the December 1998 frost (Tiefenbacher, Hagelman and Secora, 2000). Similarly, huge economic losses to other sensitive horticultural crops are frequently observed throughout the world.

For example, Hewitt (1983) described the effects of freezing on coffee production in Brazil during the 1960s and 1970s. Winterkill of cereals is also a major problem (Stebelsky, 1983; Caprio and Snyder, 1984a, 1984b; Cox, Larsen and Brun, 1986).

Although the losses to farmers can be huge, there are also many secondary effects on local and regional communities. For example, if there is no fruit to pick, the pickers are unemployed, the processors have little or no fruit, so their employees are unemployed, and, because of unemployment, there is less money in circulation and the local economy suffers. Consequently, considerable effort is expended to reduce damage.

The cost-effectiveness of frost protection depends on the frequency of occurrence, cost of the protection method and the value of the crop. Generally, passive frost protection is easily justified. The cost-effectiveness of active protection depends on the value of the crop and cost of the method. In this book, both passive and active methods are discussed, as well as the economics of protection.

HISTORY OF FROST PROTECTION

Frost damage to crops has been a problem for humans since the first crops were cultivated. Even if all aspects of crop production are well managed, one night of freezing temperatures can lead to complete crop loss. Except for tropical latitudes, where temperatures seldom fall below the melting point, damage due to freezing temperatures is a worldwide problem. Usually, frost damage in subtropical climates is associated with slow moving cold air masses that may bring 2–4 nights of 8–10 hours of subzero temperature (Bagdonas, Georg and Gerber, 1978). In eastern continental locations, damaging events are typically advective, with weak inversions. In western continental and marine climates, frost events with calm conditions and stronger inversions are more typical. The damaging events typically start with advection of cold air followed by a few nights of radiation frost. In temperate climates, frost periods are shorter in duration and occur more frequently than in other climates (Bagdonas, Georg and Gerber, 1978).

For deciduous fruit and nut trees, damaging frost events occur mainly in the spring, but sometimes in the autumn as well. For subtropical fruits, damage to the crops typically occurs during the winter. In tropical climates, there is normally no freezing except at higher elevations. Therefore, when tropical crops are damaged by cold, the temperature is usually above zero. When the damage occurs at temperatures above 0 °C, it is called “chilling” rather than “freeze” injury. In temperate climates, damage to grain crops can also occur before booting, under severe conditions, or to flowers even in mild frosts.

For grain farmers, the main response is to plant crops or varieties that are less susceptible to damage (e.g. planting spring wheat rather than winter wheat), or to not plant sensitive crops in the area if damage occurs too frequently. In any case, the date of planting should be adjusted to the crop, variety and microclimate. Similarly, if subzero temperatures occur too frequently, subtropical crops are preferentially grown in regions with less occurrence of damage. A good example of this is the movement of the citrus industry further south in Florida in response to several severe frosts during the 1980s and 1990s (Attaway, 1997). At the same time, due to more favourable temperatures, the olive industry is moving northward in Italy where soil and climate factors allow for production of high quality olive oil. However, this has led to an increase in frost damage to olives during severe winters in 1985, 1991 and 1996 (Rotondi and Magli, 1998). Generally speaking, the dates of the last frost occurrence in the spring and the first occurrence in the autumn will determine where particular crops are grown. For example, many of the deciduous fruit and nut crops tend to be grown in Mediterranean climates because the probability of losing a crop to frost damage is less than in more continental climates. The science of frost protection has mainly developed in response to the occurrence of intermittent damage in relatively favourable climates. If the damage occurs regularly, the best strategy is to grow the crop elsewhere, in a more favourable location.

In some cases, cropping locations change in response to climate change. For example, Attaway (1997) noted that prior to 1835 orange trees were commonly grown in South Carolina, Georgia and northern Florida, where, because of potential losses to frost damage, people today would not consider commercial production of oranges. He cited several examples of subtropical orchards that had survived up until about 1835, when a severe frost occurred. In fact, there were citations of documents recommending that subtropical fruits be grown in the American southeast to help compete with fruit produced in Mediterranean countries of Europe. With today's climate, subtropical fruit production would not be considered in these areas. Attaway (1997) makes the point that his observations are based on grower experience rather than climatology, but fewer damaging frost events must have occurred during the 1700–1800s for farmers to be producing subtropical fruits where none can be economically produced today.

The history of frost damage is more sporadic in the Mediterranean climate of California. There have been some major losses from time to time, but the diversity of crops and timing of the frosts leads to less extensive impacts in California. Recently, California suffered two major damaging events in the citrus industry. One occurred in December 1990 and the other in December 1998. The 1990 frost caused the most damage to citrus production since the 1913 and 1937 frosts (Attaway, 1997). Interestingly, some regions had little damage, while others were devastated. Attaway (1997) noted that, although the damage to fruit was immense,

> "most trees were in relatively good condition although they had endured temperatures which would have killed trees in Florida. We attribute this to the fact that morning lows in the upper 20s and low 30s [i.e. between about -4 °C and +2 °C] had occurred for the two weeks prior to the frost, putting the trees in an almost completely dormant state."

The December 2000 frost was a good example of how hardening can provide protection against frost damage. In Florida, before a cold front passes and drops the air to subzero temperatures, relatively warm temperature often precedes a severe frost. Consequently, the trees are less hardened against frost damage than those exposed to the two California frosts. Interestingly, Attaway (1997) emphasized the inconsistent nature of frost damage that was observed following the frost. For example, within a relatively small region, he noted losses of 70 to 80 percent of the oranges in Ojai Valley, 60 percent to 70 percent losses in Santa Paula Canyon, but only 20 percent losses in the Santa Clara Valley, which is relatively close. This illustrates the site-specific nature of frost damage to crops, especially in hilly and mountainous regions like Ventura County in California.

The December 1998 frost was not as bad for California citrus growers as that of 1990; however, it still is considered one of the major frosts of the twentieth century. The economic losses were high; however, unlike the 1990 frost, most growers were able to survive (Tiefenbacher, Hagelman and Secora, 2000). In their review of the December 1998 frost in California's San Joaquin Valley, Tiefenbacher, Hagelman and Secora (2000) noted that there was a clear relationship between latitude and damage and latitude and harvesting in anticipation of a frost. They noted that more northerly orchards suffered more frost damage, but they also harvested considerably earlier than the first frost, which allowed them to survive with less economic loss. They also noted a relationship between longitude and the age and size of orchards, which is also related to elevation. In the San Joaquin Valley, older orchards are located on the east side at higher elevations, with younger orchards to the west at lower elevation in the Valley. The reviewers recommended that micrometeorological models, combined with digital elevation data and detailed damage information, could help to understand spatial patterns of damage risk.

Tiefenbacher, Hagelman and Secora (2000) observed that larger operations proportionally lost more crop production, whereas smaller growers and cooperative members lost less. This was partially attributed to communication between cooperative organizations and the fact that many small growers harvested before the frost. After the 1990 frost, many farmers began to purchase catastrophic crop insurance and growers with insurance experienced more damage in 1998. This might have occurred because their orchards are more prone to damage or it might be that there was less effort to use protection methods because they had insurance. The answer is unknown. In addition, Tiefenbacher, Hagelman and Secora (2000) noted that government disaster assistance might be influencing frost protection activities by growers. In both 1990 and 1998, the government provided disaster funding to help growers recoup their losses. While this disaster relief is helpful to the farmers, it might discourage the use of active protection methods and it might encourage expansion of the industry into areas where the risk of frost damage is higher (Tiefenbacher, Hagelman and Secora, 2000).

Historically, heaters have been used to protect plants from freezing for more than 2000 years (Powell and Himelrick, 2000). Originally, the heaters were mostly open fires; however, in recent history, metal containers for the fire were used to better retain the heat for radiation and convection to the crop. Powell and Himelrick (2000) wrote that about 75 percent of the energy from stack heaters is used to directly heat the air, which then is convected to the crop directly or indirectly by mixing with air within the inversion layer. They attributed the additional 25 percent of energy as transferring from the heater stacks to the plants as direct radiation, which is effective even during advection frost events.

The earliest known metal-container heaters (i.e. stack heaters or smudge pots) for frost protection were introduced by W.C. Scheu in 1907 in Grand Junction, Colorado, USA. He found an oil-burning device for heating that was more efficient than open fires. It later became known as the HY-LO orchard heater, which was produced by the Scheu Manufacturing Company, which today produces portable space heaters. Even before the HY-LO orchard heater, growers used simple metal containers that burned heavy oils or old rubber tyres containing sawdust. These fires produced considerable oily smoke that for a long time was believed to provide protection against freezing by blocking net radiation losses from the surface. In fact, it is now known that little or no protection is afforded by adding smoke particles to the air with orchard heaters (Mee and Bartholic, 1979). The use of orchard heaters was standard practice worldwide for some time, but the smoke was terribly polluting and the use of smoke-producing orchard heaters was later banned in the USA for health and environmental reasons. It took a strong public outcry to eventually eliminate the use of smoke-producing heaters. For example, the Pasadena Star-News, 20 October 1947, published a request from Louis C. McCabe, director of the newly formed Los Angeles Air Pollution Control District, to eliminate smoke from more than 4 million orchard heaters. The Orange County Air Pollution Control District and seven other Districts in California adopted regulations banning the use of dirty fuels and smoke-producing smudge pots (SCAQMD, 2002).

In the USA, growers were given a few years to find a less polluting method of frost protection. Eventually, the “return stack” heater, which recirculates smoke and vapour, was developed and used for some time (Leonard, 1951). Today, return stack heaters and clean-burning propane-fuel heaters are legal in many locations; however, before using any type of heater, local regulations should be checked. However, the perception of increased fuel costs and pollution issues during the mid-1900s has led to the demise of most heaters for frost protection. During the 1950s, wind machines began to replace heaters as the preferred method of frost protection. They were more expensive to purchase, but the labour and operational costs were lower. By the 1970s, the use of heaters for frost protection was almost non-existent in California. Small fires and solid-fuel heaters are still used in some parts of the world. However, it is likely that the use of all but clean burning heaters will stop eventually.

CHAPTER 2

RECOMMENDED METHODS OF FROST PROTECTION

INTRODUCTION

This chapter presents information on important aspects of frost protection methods without complicated equations or concepts. More detailed information is given in following chapters. References are not included in this chapter to reduce its size and to simplify reading.

CROP SENSITIVITY AND CRITICAL TEMPERATURES

Frost damage to crops results not from cold temperature but mainly from extracellular (i.e. not inside the cells) ice formation inside plant tissue, which draws water out and dehydrates the cells and causes injury to the cells. Following cold periods, plants tend to harden against freeze injury, and they lose the hardening after a warm spell. A combination of these and other factors determine the temperature at which ice forms inside the plant tissue and when damage occurs. The amount of frost injury increases as the temperature falls and the temperature corresponding to a specific level of damage is called a "critical temperature" or "critical damage temperature", and it is given the symbol T_c. Generally, most critical temperatures are determined in growth chamber studies by cooling at a fixed rate down to a predetermined temperature that is maintained for 30 minutes. Then the percentage damage is recorded.

Categories for frost hardiness of vegetable and other horticultural plants are given in Tables 4.1 and 4.2. For agronomic and other field crops, ranges for critical damage temperature are given in Table 4.5. Critical temperature values are given for almonds (Table 4.6), other deciduous tree crops and grapevines (Table 4.7 and 4.8), small-fruit vines, kiwifruit and strawberries (Table 4.9), and citrus (Table 4.10). In most of these tables, T_{10} and T_{90} values are provided, where T_{10} and T_{90} are the temperatures where 10 percent and 90 percent of the marketable crop production is likely to be damaged. Generally, both the T_{10} and T_{90} temperatures increase with time after the buds start developing until the small-nut or -fruit stage, when the crops are most sensitive to freezing. The T_{90} value is quite low at the onset of growth but it increases more rapidly than the T_{10} and there is little difference between T_{10} and T_{90} when the crop is most sensitive. The T_c values for deciduous orchards and vineyards vary with the phenological stage (Tables 4.6–4.8). Photographs showing the common phenological stages of many of these crops can be found on the Internet, including sites such as fruit.prosser.wsu.edu/frsttables.htm or www.msue.msu.edu/vanburen/crittemp.htm.

Although the T_c values provide some information on when to start and stop active frost protection methods, they should be used with caution. Generally, T_c values represent bud, flower or small-fruit temperature where a known level of damage was observed. However, it is difficult to measure sensitive plant tissues, and these temperatures are likely to differ from air temperature, which is what growers typically measure. Except for large fruits (e.g. oranges), bud, flower and small-fruit temperature tends to be colder than air temperature, so active protection methods should be started and stopped at higher air temperatures than indicated in the tables in Chapter 4. For large fruits, like citrus, the evening air temperature will often drop faster than the fruit temperature, so heaters or wind machines can be started when the air temperature is at or slightly below the T_c temperature. The T_c values in Chapter 4 provide guidelines for timing active protection methods, but the values should be used with caution because of other factors such as the difference between plant and air temperature; degree of hardening; and the concentration of ice-nucleation active (INA) bacteria.

PASSIVE PROTECTION

Passive protection includes methods that are implemented before a frost night to help avoid the need for active protection. The main passive methods are:

- site selection;
- managing cold air drainage;
- plant selection;
- canopy trees;
- plant nutritional management;
- proper pruning;
- plant covers;
- avoiding soil cultivation;
- irrigation;
- removing cover crops;
- soil covers;
- trunk painting and wraps
- bacteria control; and
- planting date for annual crops.

Passive methods are usually less costly than active methods and often the benefits are sufficient to eliminate the need for active protection.

Site selection and management

Growers are usually aware that some spots are more prone to frost damage than others. The first step in selecting a site for a new planting is to talk with local people about what crops and varieties are appropriate for the area. Local growers and extension advisors often have a good feeling for which locations might be problematic. Typically, low spots in the local topography have colder temperatures and hence more damage. However, damage can sometimes occur in one section of a cropped area and not in another, without apparent topographical differences. In some cases, this might be due to differences in soil type, which can affect the conduction and storage of heat in the soil.

Dry sandy soils transfer heat better than dry heavy clay soils, and both transfer and store heat better than organic (peat) soils. When the water content is near field capacity (i.e. a day or two after thoroughly wetting the soil), soils have conditions that are most favourable for heat transfer and storage. However, organic soils have poor heat transfer and storage regardless of the water content. When selecting a site in a region prone to frost, avoid planting on organic soils.

Cold air is denser than warm air, so it flows downhill and accumulates in low spots much like water in a flood (Figure 6.4). Therefore, one should avoid planting in low-lying, cold spots unless adequate cost-effective active protection methods are included in the long-term management strategy. This is important on both a regional and farm scale. For example, on a regional scale, valley bottoms near rivers are usually colder than the slopes above. These spots can also be identified from topographical maps, by collecting temperature data, and by locating spots where low-level ground fogs form first. Low spots consistently have colder nights, when the sky is clear and the wind is weak, during the entire year. Accordingly, temperature measurements to identify cold spots can be made at any time during the year.

Planting deciduous crops on slopes facing away from the sun delays spring-time bloom and often provides protection. Subtropical trees are best planted on slopes facing the sun where the soil and crop can receive and store more direct energy from sunlight.

Cold air drainage

Trees, bushes, mounds of soil, stacks of hay, and fences are sometimes used to control air flow around agricultural areas and the proper placement can affect the potential for frost damage. A careful study of topographical maps can often prevent major frost damage problems. Also, the use of smoke bombs or other smoke generating devices to study the down slope flow of cold air at night can be informative. These studies need to be done on nights with radiation frost characteristics, but not necessarily when the temperature is subzero. Once the cold air drainage flow pattern is known, then proper placement of diversion obstacles can provide a high degree of protection.

If a crop already exists in a cold spot, there are several management practices that might help reduce the chances of frost damage. Any obstacles that inhibit down-slope drainage of cold air from a crop should be removed. These obstacles might be hedgerows, fences, bales of hay, or dense vegetation located on the downslope side of the field. Land levelling can sometimes improve cold air drainage through a crop so that incoming cold air continues to pass through the crop. Row lines in orchards and vineyards should be oriented to favour natural cold air drainage out of the crop. However, the advantages from orienting crop rows to enhance cold air drainage must be balanced against the disadvantages due to more erosion and other inconveniences. Grass and plant stubble in areas upslope from a crop can make air colder and will enhance cold air drainage into a crop. Air temperature measured within grape vineyards and citrus orchards with plant residue or grass cover typically varies between 0 °C and 0.5 °C colder than grape vineyards and citrus orchards with bare soil, depending on soil conditions and weather. Without the crop present, the differences would probably be greater. Therefore, having bare soil upslope from a crop will generally lead to higher air temperatures over the upslope soil and less likelihood of cold air drainage into the crop.

Plant selection

It is important to choose plants that bloom late to reduce the probability of damage due to freezing, and to select plants that are more tolerant of freezing. For example, deciduous fruit trees and vines typically do not suffer frost damage to the trunk, branches or dormant buds, but they do experience damage as the flowers and small fruits or nuts develop. Selecting deciduous plants that have a later bud break and flowering provides good protection because the probability and risk of frost damage decreases rapidly in the spring. In citrus, select more resistant varieties. For example, lemons are least tolerant to frost damage, followed by limes, grapefruit, tangelos and oranges, which are most tolerant. Also, trifoliate orange rootstock is known to improve frost tolerance of citrus compared with other rootstocks.

For annual field and row crops, determining the planting date that minimizes potential for subzero temperature is important. In some instances, field and row crops are not planted directly to the outdoors, but are planted in protected environments and transplanted to the field after the danger of freezing has passed. Several Excel application programs on probability and risk are included with this book and their use is discussed in the probability and risk chapter. If freezing temperatures cannot be avoided, then select crops to plant based on their tolerance of subzero temperatures.

Canopy trees

In Southern California, growers intercrop plantings of citrus and date palms, partly because the date palms give some frost protection to the citrus trees. Because the dates also have a marketable product, this is an efficient method to provide frost protection without experiencing relevant economic losses. In Alabama, some growers interplant pine trees with small Satsuma mandarin plantings and the pine trees enhance long-wave downward radiation and provide protection to the mandarins. Shade trees are used to protect coffee plants from frost damage in Brazil.

Plant nutrition management

Unhealthy trees are more susceptible to frost damage and fertilization improves plant health. Also, trees that are not properly fertilized tend to lose their leaves earlier in the autumn and bloom earlier in the spring, which increases susceptibility to frost damage. However, the relationship between specific nutrients and increased resistance is obscure, and the literature contains many contradictions and partial interpretations. In general, nitrogen and phosphorus fertilization before a frost encourages growth and increases susceptibility to frost damage. To enhance hardening of plants, avoid applications of nitrogen fertilizer in late summer or early autumn. However, phosphorus is also important for cell division and therefore is important for recovery of tissue after freezing. Potassium has a favourable effect on water regulation and photosynthesis in plants. However, researchers are divided about the benefits of potassium for frost protection.

Pest management

The application of pesticide oils to citrus is known to increase frost damage and application should be avoided shortly before the frost season.

Proper pruning

Late pruning is recommended for grapevines to delay growth and blooming. Double pruning is often beneficial because resource wood is still available for production following a damaging frost. Pruning lower branches of vines first and then returning to prune higher branches is a good practice because lower branches are more prone to damage. Pruning grapevines to raise the fruit higher above the ground provides protection because temperature during frost nights typically increases with height. Late-autumn pruning of citrus leads to more physiological activity during the winter frost season. Citrus pruning should be completed well before frost season. For example, serious damage has been observed in citrus that were topped in October when a freeze occurred in December. If deciduous trees are grown in a climate sufficiently cold to cause damage to dormant buds, then the trees should not be pruned. Otherwise, deciduous tree pruning can be done during dormancy with few problems.

Plant covers

Plant row covers are warmer than the clear sky and hence increase downward long-wave radiation at night, in addition to reducing convectional heat losses to the air. Removable straw coverings and synthetic materials are commonly used. Because of the labour costs, this method is mainly used on small plantings of short plants that do not require a solid frame. Sometimes, disease problems occur due to deficient ventilation. Woven and spun-bonded polypropylene plastics are sometimes used to protect high value crops. The degree of protection varies from about 1 °C to 5 °C, depending on plastic thickness. White plastic is sometimes used for nursery stock but not for fruit and vegetable crops. Partially covering grapevines with black polyethylene has been observed to increase air temperature next to the foliage by as much as 1.5 °C. However, clear plastic is generally more effective.

Avoiding soil cultivation

Soil cultivation creates air spaces in the soil and it should be avoided during frost-prone periods. Air is a poor heat conductor and has a low specific heat, so soils with more and larger air spaces will tend to transfer and store less heat. If a soil is cultivated, compacting and irrigating the soil will improve heat transfer and storage.

Irrigation

When soils are dry, there are more air spaces, which inhibit heat transfer and storage. Therefore, in dry years, frost protection is improved by wetting dry soils. The goal is to maintain the soil water content near field capacity, which is typically the water content 1 to 3 days following thorough wetting. It is unnecessary to wet the soil deeply because most of the daily heat-transfer and storage occurs in the top 30 cm. Wetting the soil will often make it darker, and increases absorption of solar radiation. However, when the surface is wet, then evaporation is also increased and the energy losses to evaporation tend to counterbalance the benefits from better radiation absorption. It is best to wet dry soils well in advance of the frost event, so that the sun can warm the soil.

Removing cover crops

For passive frost protection, it is better to remove all vegetation (cover crops) from orchards and vineyards. Removal of cover crops will enhance radiation absorption by the soil, which improves energy transfer and storage. Cover crops are also known to harbour higher concentrations of ice-nucleation active (INA) bacteria than many orchard and vine crops, so the presence of vegetation on orchard and vineyard floors increases the INA bacteria concentrations on the crop and hence the potential for frost damage.

Generally, mowing, cultivation and spraying with herbicides are methods to remove floor vegetation. If possible, the cover crop should be mowed sufficiently early to allow the residue to decompose or the cut vegetation should be removed. For grass taller than about 5 cm, there is little difference in orchard floor surface temperature, but the surface temperature increases as the canopy gets shorter, to the highest minimum surface temperature for bare soil. Orchard floor minimum surface temperature differences as high as 2 °C have been reported between bare soil and 5-cm high grass. However, the air temperature difference is likely to be less than 2 °C. Cultivation should be done well before the frost season and the soil should be compacted and irrigated following the cultivation to improve heat transfer and storage. The most effective method is to use herbicides to kill the floor vegetation or keep down the growth. Again, this should be done well in advance of the frost-prone period.

Soil covers

Plastic covers are often used to warm the soil and increase protection. Clear plastic warms the soil more than black plastic, and wetting the soil before applying the plastic further improves effectiveness. Sometimes vegetative mulches are used during dormancy of tree crops to help prevent damage to roots due to freezing and soil heaving; however, vegetative mulches reduce the transfer of heat into the soil and hence make orchard crops more frost prone after bud break. In general, vegetative mulches are only recommended for locations where soil freezing and heaving are a problem. For non-deciduous orchards, pruning up the skirts of the trees allows better radiation transfer to the soil under the trees and can improve protection.

Trunk painting and wraps

The bark of deciduous trees sometimes splits when there are large fluctuations in temperature from a warm day into a frost night. Painting the trunks with an interior water-based latex white paint diluted with 50 percent water in the late autumn when the air temperature is above 10 °C will reduce this problem. White paint, insulation and other wraps are known to improve hardiness against frost damage in peach trees. The paint or wraps decrease the late winter high cambial temperatures due to daytime radiation, which improves hardiness. Wrapping tree trunks with insulation (i.e. materials containing air spaces that resist heat transfer) will protect young trees from frost damage and possible death. Critical factors are to use insulation that does not absorb water and the trunks should be wrapped from the ground surface to as high as possible. Fibreglass and polyurethane insulation wraps with higher resistance to heat transfer provide the best protection of commercially available wraps. Typically, the trunk wraps are removed after 3 to 4 years. Wrapping young citrus tree trunks with water bags was reported to give even better protection than fibreglass or polyurethane foam.

The main drawback to trunk wraps is increased potential for disease problems, so the bud unions should be at least 15 cm above the ground. Applying fungicide sprays prior to wrapping helps to reduce disease problems.

Bacteria control

For freezing to occur, the ice formation process is mostly initiated by presence of INA bacteria. The higher the concentration of the INA bacteria, the more likely that ice will form. After forming, it then propagates inside the plants through openings on the surface into the plant tissues. Commonly, pesticides (copper compounds) are used to kill the bacteria or competitive non-ice-nucleation active (NINA) bacteria are applied to compete with and reduce concentrations of INA bacteria. However, this frost protection method has not been widely used; for further information refer to Chapter 6.

ACTIVE PROTECTION

Active protection methods include

- heaters;
- wind machines;
- helicopters;
- sprinklers;
- surface irrigation;
- foam insulation; and
- combinations of methods

All methods and combinations are done during a frost night to mitigate the effects of subzero temperatures. The cost of each method varies depending on local availability and prices, but some sample costs based on prices in the USA are given in Table 7.1. In some cases, a frost protection method has multiple uses (e.g. sprinklers can also be used for irrigation) and the benefits from other uses need to be subtracted from the total cost to evaluate fairly the benefits in terms of frost protection.

Heaters

Heaters provide supplemental heat to help replace energy losses. Generally, heaters either raise the temperature of metal objects (e.g. stack heaters) or operate as open fires. If sufficient heat is added to the crop volume so that all of the energy losses are replaced, the temperature will not fall to damaging levels. However, the systems are generally inefficient (i.e. a large portion of the energy output is lost to the sky), so proper design and management is necessary. By designing a system to use more and smaller heaters that are properly managed, one can improve efficiency to the level where the crop is protected under most radiation frost conditions. However, when there is little or no inversion and there is a wind blowing, the heaters may not provide adequate protection.

The energy requirement to match losses on a radiation frost night is in the range 10 to 50 $W m^{-2}$, whereas the energy output from heaters is in the range of 140 to 280 $W m^{-2}$, depending on the fuel, burning rate, and number of heaters. One hundred stack heaters per hectare burning 2.85 litre h^{-1} of fuel with an energy output of 37.9 MJ $litre^{-1}$ would produce approximately 360 $W m^{-2}$. The net benefit depends on weather conditions, but one can expect about 1 °C increase in the mean air temperature from the ground up to about 3 m, with somewhat higher temperatures measured at 1.5 m height. However, direct radiation from the heaters supplies additional benefit to plants within sight of the heaters. Because the energy output is much greater than the energy losses from an unprotected crop, much of the energy output from heaters is lost and does not contribute to warming the air or plants. If the heating system were perfectly designed and managed to replace the energy lost from the volume of air under the inversion layer with little or no loss of convective heat to the sky, then the energy output requirement would be close to the energy requirement needed to prevent frost damage and the heating would be efficient. To achieve the best efficiency, increase the number of heaters and decrease the temperature of the heaters. However, this is often difficult to accomplish because of equipment costs, labour, etc. If the temperature inversion is weak or if the fires are too big and hot, the heated air rises too high and energy is lost to the air above the crop, thus decreasing efficiency. Modern heaters have more control over the temperature of emitted gases to reduce buoyancy losses and improve efficiency. The most efficient systems have little flame above the stack and no smoke. Operating the heaters at too high a temperature will also reduce the lifetime of the heaters. Liquid-fuel and gas fuel heaters typically output energy at close to twice the rate of solid-fuel heaters. When there is a strong inversion (i.e. a low ceiling), the heated volume is smaller, and the heaters are more effective at raising the temperature, if the fires are not too big (i.e. the temperature of gases leaving a stack heater should be near 635 °C) so that the heated air rises slowly. Heater operation is less efficient in weak inversion (i.e. high ceiling) conditions because there is a bigger volume to heat. More frost damage occurs on the edges and more heaters are needed on the edges to avoid this damage. In the past, it was widely believed that smoke was beneficial for frost protection. However, smoke does not help and it does pollute the environment, and should be avoided.

Heater distribution should be relatively uniform with more heaters in the borders, especially upwind, and in low cold spots. Borders should have a minimum of one heater per two trees on the outside edge and inside the first row.

On the upwind border, one heater per two trees is recommended inside the second row as well. Heaters on the borders, especially upwind, should be lit first and then light every fourth row through the orchard (or every second row if needed). Then monitor the temperature and light more rows of heaters as the need increases. Heaters are expensive to operate, so they are commonly used in combination with wind machines or as border heat in combination with sprinklers. See Chapter 7 for more information on heater management.

Use of liquid-fuel heaters decreased as oil prices and concerns about air pollution increased. Liquid-fuel heaters require considerable labour for placement, fuelling and cleaning in addition to the capital costs for the heaters and the fuel. Note that isolated small orchards require more heaters than large orchards or those surrounded by other protected orchards.

Fuel recommendations for lighting heaters varies from ratios of 1 : 1 oil to gasoline [petrol] to 8 : 5 oil to gasoline [petrol]. Buckets or tanks towed by a tractor, which allow two lines of burners to be filled simultaneously, are used to refill the heaters after a frost. When direct heating is used, to minimize fuel consumption the protection is started just before reaching critical damage temperatures. The temperature should be measured in a Stevenson screen, fruit-frost shelter or Gill shield that prevents thermometer exposure to the clear sky.

Labour requirements to refill liquid-fuel heaters are high, so centralized distribution systems using natural gas, liquid propane or pressurised fuel oil have become more popular. In more elaborate systems, ignition, the combustion rate and closure are also automated, in addition to fuel distribution. The capital cost to install centralized systems is high, but the operational costs are low. Propane-fuel heaters require less cleaning and the burning rates are easier to control than oil-fired heaters. Because the burning rate is less, more heaters are needed (e.g. typically about 100 per hectare of stack heaters and about 153 per hectare of propane-fuel heaters), but the protection is better because more heaters at a lower burning rate are more efficient. Under severe conditions, the propane supply tank can sometimes freeze up, so a vaporizer should be installed to prevent the gas line from freezing.

The ratio of radiation to total energy released is 40 percent for burning solid fuels in comparison with 25 percent for burning liquid fuels, so solid fuels are more efficient at heating the plants, especially under windy conditions. The main disadvantage of solid fuels is that energy release diminishes as the fuel is used up, so the energy release becomes limiting when it is needed most. Another drawback is that solid fuels are difficult to ignite, so they must be started early. They are also difficult to extinguish, so fuel is often wasted.

Wind machines

Wind machines alone generally use only 5 percent to 10 percent of the fuel consumed by a fuel-oil heater protection system. However, the initial investment is high (e.g. about $ 20 000 per machine). Wind machines generally have lower labour requirements and operational costs than other methods; especially electric wind machines.

Most wind machines (or fans) blow air almost horizontally to mix warmer air aloft in a temperature inversion with cooler air near the surface. They also break up microscale boundary layers over plant surfaces, which improves sensible heat transfer from the air to the plants. However, before investing in wind machines, be sure to investigate if inversions between 2.0 and 10 m height are at least 1.5 °C or greater on most frost nights.

When electric wind machines are installed, the grower is commonly required to pay the power company "standby" charges, which cover the cost of line installation and maintenance. The standby charges are paid whether the wind machines are used or not. Internal combustion wind machines are more cost-effective, but they require more labour. Wind machine noise is a big problem for growers with crops near cities and towns, and this should be considered when selecting a frost protection method. Generally, one large wind machine with a 65 to 75 kW power source is needed for each 4.0 to 4.5 ha. The effect on temperature decreases approximately as the inverse square of the distance from the tower, so some overlap of protection areas will enhance protection.

Wind machines generally consist of a steel tower with a large rotating two-blade fan (3 to 6 m diameter) near the top, mounted on an axis tilted about 7° downward from the horizontal in the tower direction. Typically, the height for fans is about 10–11 m, and they rotate at about 590–600 rpm. There are also wind machines with four-blade fans. When a fan operates, it draws air from aloft and pushes it at a slightly downward angle towards the tower and the ground. The fan also blows cold air near the surface upwards and the warm air above and cold air below are mixed. At the same time that the fan is operating, it rotates around the tower with about one revolution every three to five minutes. The amount of protection afforded depends on the unprotected inversion strength. In general, the temperature increase at 2.0 m height resulting from the fans is about 30 percent of the inversion strength between 2 m and 10 m height in an unprotected crop. Wind machines are typically started when the air temperature reaches about 0 °C. Wind machines are not recommended when there is a wind of more than about 2.5 m s^{-1} (8 km h^{-1}) or when there is supercooled fog, which can cause severe fan damage if the blades ice up.

Fans that vertically pull down warm air from aloft have generally been ineffective and they can damage plants near the tower. Wind machines that blow vertically upwards are commercially available and there has been some testing of the machines. However, there were no published research reports found when preparing this book.

Helicopters

Helicopters move warm air from aloft in a temperature inversion to the colder surface. The area covered by a single helicopter depends on the helicopter size and weight and on the weather conditions. Estimated coverage area by a single helicopter varies between 22 and 44 ha. Recommendations on pass frequency vary between 30 to 60 minutes, depending on weather conditions. Waiting too long between passes allows the plants to supercool and the agitation from a passing helicopter can cause heterogeneous ice nucleation and lead to severe damage. Heterogeneous ice nucleation occurs when water is supercooled (i.e. at temperature below 0 °C) and some foreign matter or agitation initiates ice formation. In the case of helicopters, agitation can cause ice formation if the passes are too infrequent and the plant tissue temperature becomes too low.

The optimal flying height is commonly between 20 and 30 m and the flight speeds are 8 to 40 km h^{-1}. Pilots often load helicopter spray tanks with water to increase the weight and increase thrust. Under severe frosts with a high inversion, one helicopter can fly above another to enhance the downward heat transfer. Thermostat-controlled lights at the top of the canopy are used to help pilots see where passes are needed. On the sides of hills, heat transfer propagates down-slope after reaching the surface, so flying over the upslope side of a crop usually provides more protection. Flights are stopped when the air temperature upwind from the crop has risen above the critical damage temperature.

Sprinklers

The energy consumption of sprinklers is considerably less than that used in frost protection with heaters, so the operational costs are low compared to heaters. Also, the labour requirement is less than for other methods, and it is relatively non-polluting. The main disadvantages with using sprinklers are the high installation cost and the large amounts of water needed. In many instances, limited water availability restricts the use of sprinklers. In other cases, excessive use can lead to soil waterlogging, which could cause root problems as well as inhibit cultivation and other management. Nutrient leaching (mainly of nitrogen) is a problem where sprinkler use is frequent.

The secret to protection with conventional over-plant sprinklers is to re-apply water frequently at a sufficient application rate to prevent the plant tissue temperature from falling too low between pulses of water. For non-rotating, targeted over-plant sprinklers, the idea is to continuously apply water at a lower application rate but targeted to a smaller surface area. For conventional under-plant sprinklers, the idea is to apply water at a frequency and application rate that maintains the ground surface temperature near 0 °C. This increases long-wave radiation and sensible heat transfer to the plants relative to an unprotected crop. For under-plant microsprinklers, which apply less water than conventional sprinklers, the goal is to keep only the ground under the plants near 0 °C in order to concentrate and enhance radiation and sensible heat transfer upwards into the plants.

Over-plant conventional sprinklers

Over-plant sprinkler irrigation is used to protect low-growing crops and deciduous fruit trees with strong scaffold branches that do not break under the weight of ice loading. It is rarely used on subtropical trees (e.g. citrus) except for young lemons, which are more flexible. Even during advection frosts, over-plant sprinkling provides excellent frost protection down to near -7 °C if the application rates are sufficient and the application is uniform. Under windy conditions or when the air temperature falls so low that the application rate is inadequate to supply more heat than is lost to evaporation, the method can cause more damage than experienced by an unprotected crop. Drawbacks of this method are that severe damage can occur if the sprinkler system fails, the method has large water requirements, ice loading can cause branch damage, and root disease can be a problem in poorly drained soils.

Application rate requirements for over-plant sprinklers differ for conventional rotating, variable rate, or low-volume targeted sprinklers. As long as there is a liquid-ice mixture on the plants, with water dripping off the icicles, the coated plant parts will be protected. However, if an inadequate precipitation rate is used or if the rotation rate of the sprinklers is too slow, all of the water can freeze and the temperature of the ice-coated plants can fall to lower temperatures than unprotected plants.

Conventional over-plant sprinkler systems use standard impact sprinklers to completely wet the plants and soil of a crop. Larger plants have more surface area, so a higher application rate is needed for tall plants than for short plants. For over-plant sprinklers to be effective, the plant parts must be coated with water and re-wetted every 30 to 60 seconds. Longer rotation rates require higher application rates. Also, bigger plants require more water to coat the plants. See Table 2.1 for guidelines on application rates for various plants.

Sprinkler distribution uniformity is important to avoid inadequate coverage, which might result in damage. If cold air is known to drift in from a specific direction, increasing sprinkler density on the upwind edge of the crop or even in an open field upwind from the crop can improve protection. In most cases, the sprinkler heads should be mounted at 30 cm or higher above the top of the plant canopy to avoid the plants blocking the spray. For frost protection, specially designed springs are often used, which are protected by an enclosure to prevent icing of the heads. Clean filters are needed to be sure that the system operates properly, especially when river or lagoon water is used.

TABLE 2.1

Application rates for overhead sprinkler protection of tall (orchard and vine) and short (field and row) crops depending on the minimum temperature and rotation rate, for wind speeds between 0 and 2.5 m s^{-1}

MINIMUM TEMPERATURE	TALL CROPS		SHORT CROPS	
°C	30 s rotation mm h^{-1}	60 s rotation mm h^{-1}	30 s rotation mm h^{-1}	60 s rotation mm h^{-1}
-2.0	2.5	3.2	1.8	2.3
-4.0	3.8	4.5	3.0	3.5
-6.0	5.1	5.8	4.2	4.7

NOTE: Application rates are about 0.5 mm h^{-1} lower for no wind and about 0.5 mm h^{-1} higher for wind speeds near 2.5 m s^{-1}. The "short crop" rates cover field and row crops with canopies similar in size to strawberries. Taller field and row crops (e.g. potatoes and tomatoes) require intermediate application rates.

Starting and stopping the sprinklers

Over-plant sprinklers should be started when the wet-bulb temperature is higher than the critical (T_c) temperature. Starting when the wet-bulb temperature reaches 0 °C is less risky and it may be prudent if there are no problems with water shortage, waterlogging or ice loading. Even if the sun is shining on the plants and the air temperature is above 0 °C, sprinklers should not be turned off unless the wet-bulb temperature measured upwind from the crop is above the critical damage temperature. If soil waterlogging or water shortages are not problems, permitting the wet-bulb temperature to slightly exceed 0 °C before turning off the sprinklers adds an extra measure of safety.

The wet-bulb temperature can be measured directly with a psychrometer (Figure 3.9) or it can be estimated from the dew-point and air temperatures. Wet-bulb temperature measurements are explained in Chapter 3. A simple, inexpensive dew-point measurement is accomplished with a thermometer, a shiny can, water, salt and ice (Figure 7.11). First pour some salted water into the shiny can. Then start adding ice cubes to the can while stirring the mixture with the thermometer. Watch the outside of the can to see when water condenses or ice deposits on the surface. Immediately read the thermometer temperature when the water or ice forms. Shining a flashlight (pocket torch) onto the can surface will help you to see water or ice form and to read the thermometer. Under very cold, dry conditions, more salt and ice might be needed to reach the ice or dew-point temperature. There is a small difference between the ice point and dew-point temperature (explained in Chapter 3), but for estimating sprinkler start and

TABLE 2.2

A range of minimum starting and stopping air temperatures (°C) for frost protection with sprinklers as a function of wet-bulb and dew-point temperature (°C)

DEW-POINT TEMPERATURE	WET-BULB TEMPERATURE (°C)													
°C	-3.0		-2.5		-2.0		-1.5		-1.0		-0.5		0.0	
0.0													0.0	0.0
-1.0									-1.0	-0.9	-0.2	-0.1	0.6	0.7
-2.0					-2.0	-1.8	-1.2	-0.8	-0.4	-0.2	0.4	0.6	1.2	1.4
-3.0	-3.0	-2.7	-2.2	-1.9	-1.4	-1.1	-0.6	-0.3	0.2	0.5	1.0	1.3	1.8	2.1
-4.0	-2.5	-2.1	-1.7	-1.4	-0.9	-0.6	-0.1	0.2	0.7	1.0	1.5	1.8	2.3	2.6
-5.0	-2.0	-1.6	-1.2	-0.8	-0.4	0.0	0.4	0.8	1.2	1.6	2.0	2.4	2.8	3.2
-6.0	-1.5	-1.1	-0.7	-0.3	0.1	0.5	0.9	1.4	1.7	2.1	2.5	2.9	3.3	3.7
-7.0	-1.1	-0.6	-0.3	0.2	0.5	1.0	1.3	1.8	2.1	2.6	2.9	3.4	3.7	4.2
-8.0	-0.7	-0.2	0.1	0.6	0.9	1.4	1.7	2.2	2.5	3.0	3.3	3.8	4.1	4.8
-9.0	-0.3	0.3	0.5	1.1	1.3	1.9	2.1	2.7	2.9	3.5	3.7	4.3	4.5	5.1
-10.0	0.1	0.7	0.8	1.5	1.6	2.3	2.4	3.1	3.2	3.9	4.0	4.7	4.9	5.6

NOTE: Select a wet-bulb temperature that is above (warmer than) the critical damage temperature for your crop and locate the appropriate column. Then choose the row with the correct dew-point temperature and read the corresponding air temperature from the table to turn your sprinklers on or off. Use the lower air temperatures at low elevations (0–500 m) and increase to the higher temperatures at higher elevations (1500–2000 m).

stop air temperatures there is negligible error by assuming they are equal.

After measuring the dew-point temperature, the start and stop air temperatures are found using the critical (T_c) temperature for your crop, the dew-point temperature, and Table 2.2. For more exact information, see Tables 7.5 and 7.6 and the related discussion in Chapter 7.

Sprinkler application rates

The application rate requirement for over-plant sprinkling with conventional sprinklers depends on the rotation rate, wind speed and unprotected minimum temperature. Table 2.1 provides commonly used application rates for tall and short crops. For both tall and short crops, the application rates increase with wind speed and they are higher for slower rotation rates.

If there is a clear liquid-ice mixture coating the plants and water is dripping off the ice, then the application rate is sufficient to prevent damage. If all of the water freezes and it has a milky white appearance like rime ice, then the application rate is too low for the weather conditions. If the application rate is insufficient to adequately cover all of the foliage, then damage can occur on plant parts that are not adequately wetted. Under windy, high evaporation conditions, inadequate application rates can cause more damage than if the sprinklers are not used.

Targeted over-plant sprinklers

Use of targeted over-plant microsprinklers has been studied as a method to reduce application rates for over-plant sprinklers, but installation costs are high and the method has not been widely accepted by growers except those with water deficiency problems. Targeted sprinklers spray the water directly on to the plants, with minimal amounts of water falling between plant rows. A big advantage of using targeted sprinklers is that conventional sprinklers often have application rates of 3.8 to 4.6 mm h^{-1}, whereas targeted sprinklers commonly have application rates of 2.8 to 3.1 mm h^{-1}. Under windy conditions, because of non-uniform application, targeted sprinkler application rates higher than 3.1 mm h^{-1} might be needed to protect crops. In one study on the use of targeted sprinklers over grapevines, there was an 80 percent water saving over conventional over-plant sprinklers.

In grower trials, a low-volume system applied approximately 140 litre min^{-1} ha^{-1}, compared with the grower's conventional system application of 515 to 560 litre min^{-1} ha^{-1} to grapevines during two radiation frost events. In the first year, the unprotected minimum temperature was -3.9 °C, but no difference in crop loads or pruning weights were observed between the targeted and conventional systems. In the second year, -5.8 °C was observed on one night and some of the impact sprinkler heads froze up and stopped turning. The frost damage losses were similar in both the conventional and low-volume sprinkler blocks. The grower pointed out that it was important to orient the non-rotating sprinkler heads to obtain a uniform coverage of the vine rows. Consequently, the labour requirement is high. It was also important to start and stop the sprinklers when the wet-bulb temperature was above 0 °C.

Sprinklers over covered crops

Sprinkling over covered crops in greenhouses and frames provides considerable protection. Protection levels of 2.4 °C to 4.5 °C have been observed using an application rate of 7.3 mm h^{-1} over glass-covered plants. Sprinkling at 10 mm h^{-1} onto plastic greenhouses during a frost event was observed to maintain temperatures inside up to 7.1 °C higher than outside. The energy use was about 20 percent of the energy used in an identical plastic greenhouse that was heated to the same temperature difference.

Under-tree conventional sprinklers

Under-tree sprinklers are commonly used for frost protection of deciduous tree crops in regions where the minimum temperatures are not too low and only a few degrees of protection are needed. In addition to the lower installation and operational cost, one can also use the system for irrigation, with fewer disease problems and lower cost, so it has several advantages relative to over-plant sprinklers. Limb breakage due to ice loading, soil oxygen deficiency and sprinkler system failure are less of a problem with under-plant sprinkler systems, having lower application rate (2.0 to 3.0 mm h^{-1}) requirements.

Once started, the sprinklers should be operated continuously without sequencing. If water supply is limited, irrigate the most frost-prone areas or areas upwind from unprotected orchards. Good application uniformity improves protection. Hand-moved sprinkler systems should not be stopped and moved during a frost night. However, under mild frost conditions (T_n > -2.0 °C), to cover a larger area the sprinkler lines can be placed in every second row rather than every row. For moderate to severe frosts, closer spacing of the sprinkler lines may be necessary.

Several researchers found that cover crops are beneficial for protection when under-tree sprinklers are used for frost protection. This recommendation is based partially on the idea that the presence of a cover crop provides more surface area for water to freeze upon and hence more heat will be released. The recommendation is also partly based on the idea that the height of the liquid ice mixture and hence the height where the surface temperature is maintained at 0 °C is elevated closer to the tree buds, flowers, fruits or nuts that are being protected. The difficulty in having a cover crop is that although there might be additional protection, if and when the system is used, it is also more likely that active protection will be needed if a cover crop is present. Where water and energy resources are limited and frosts are infrequent, it might be wiser to remove the cover crop and reduce the need for active protection. In climates where frosts are common and there are adequate resources to operate the under-plant sprinklers, then maintaining a cover crop may improve protection. However, energy and water usage will increase.

Under-plant microsprinklers

In recent years, under-plant microsprinklers have become increasingly popular with growers for irrigation and interest in their use for frost protection has followed. More protection is afforded by covering a larger area with a full coverage sprinkler system; however, with microsprinklers, water is placed under the plants where radiation and convection are more beneficial than water placed between crop rows. However, if you spread the same amount of water over a larger area, the ice is likely to cool more than if the water is concentrated in a smaller area. Again, the best practice is to supply sufficient water to cover as large of an area as possible and be sure that there is a liquid–ice mixture over the surface under the worst conditions that are likely to occur.

Trickle-drip irrigation

Low-volume (trickle-drip) irrigation systems are sometimes used for frost protection with varied results. Any benefit from applying water comes mainly from freezing water on the surface, which releases latent heat. However, if evaporation rates are high, it is possible that more energy can be lost to vaporize water than is gained by the freezing process. Because of the wide variety of system components and application rates, it is difficult to generalize about the effectiveness of low-volume systems. One should be aware that operating a low-volume system under frost conditions might damage the irrigation system if freezing is severe. Heating the water would reduce the chances of damage and provide more protection. However, heating may not be cost-effective.

Under-plant sprinklers with heated water

Some researchers have hypothesized that freezing water on the surface to release the latent heat of fusion provides little sensible heat to air. Because of the low trajectory of the under-plant spray, evaporation is reduced relative to over-plant systems, and preheating water might provide some benefit for the under-plant sprinklers. Applying water heated to 70 °C with under tree sprinklers in a citrus orchard was reported to increase temperature by 1 °C to 2 °C on average. Where inexpensive energy is available or water is limited, or both, using an economical heating system to warm water to about 50 °C has been recommended to lower the required application rates. However, the same benefit might be realized by increasing the application rate from say 2.0 mm h^{-1} to 2.6 mm h^{-1}, so increasing the application rate might be more cost-effective if water is not limiting.

Surface irrigation

Flood irrigation

In this method, water is applied to a field and heat from the water is released to the air as it cools. However, effectiveness decreases as the water cools over time. Partial or total submersion of tolerant plants is possible; however, disease and root asphyxiation are sometimes a problem. The method works best for low-growing tree and vine crops during radiation frosts.

Because of the relatively low cost of flood irrigation, the economic benefits resulting from its use are high and the method is commonly used in many countries. As much as 3–4 °C of protection can be achieved with this method if irrigation is done prior to the frost event. The depth of water to apply depends on the night-time energy balance and the water temperature. Table 2.3 provides an estimate of the depth to apply as a function of the maximum water temperature on the day preceding the frost event.

TABLE 2.3

Depth (*d*) in millimetres of flood irrigation water to apply for frost protection corresponding to the maximum water temperature (T*wx*) in °C on the day prior to a frost night

T*wx* (°C)	35	30	25	20	15	10
d (mm)	42	50	60	74	100	150

Furrow irrigation

Furrow irrigation is commonly used for frost protection and the basic concepts are similar to flood irrigation. Furrows work best when formed along the drip-line of citrus tree rows where air warmed by the furrow water transfers upwards into the foliage that needs protection, rather than under the trees where the air is typically warmer, or in the middle between rows, where the air rises without intercepting the trees. The furrows should be on the order of 0.5 m wide with about half the width exposed to the sky and half under the tree skirts. For deciduous trees, the water should run under the trees where the warmed air will transfer upwards to warm buds, flowers, fruit or nuts. The furrows should be under the trees and 1.0 to 1.5 m wide but should not extend past the drip line.

Furrow irrigation should be started early enough to ensure that the water reaches the end of the field before air temperature falls below the critical damage temperature. The flow rate depends on several factors, but it should be sufficiently high to minimize ice formation on the furrows. Cold runoff water should not be re-circulated. Heating the water is beneficial, but it may or may not be cost-effective, depending on capital, energy and labour costs.

Foam insulation

Application of foam insulation has been shown to increase the minimum temperature on the leaf surfaces of low growing crops by as much as 10 °C over unprotected crops. However, the method has not been widely adopted by growers because of the cost of materials and labour as well as problems with covering large areas in short times due to inaccuracy of frost forecasts. When applied, the foam prevents radiation losses from the plants and traps energy conducted upwards from the soil. Protection is best on the first night and it decreases with time because the foam also blocks energy from warming the plants and soil during the day and it breaks down over time. Mixing air and liquid materials in the right proportion to create many small bubbles is the secret to generating foam with low thermal conductivity. More detailed information on the use of foam insulation is presented in the chapter on active protection methods.

Combination methods

Under-plant sprinklers and wind machines

Under-plant sprinklers with low trajectory angles can be used in conjunction with wind machines for frost protection. The addition of wind machines could potentially increase protection by up to 2 °C over the under-plant sprinklers alone, depending on system design and weather conditions. In addition to heat supplied by the water droplets as they fly from the sprinkler heads to the ground, freezing water on the ground releases latent heat and warms air near the surface. While this warmed air will naturally transfer throughout the crop, operating wind machines with the sprinklers will enhance heat and water vapour transfer within the mixed layer to the air and plants. Typically, growers start the lower cost sprinklers first and then turn on the wind machines if more protection is needed. Unlike using heaters with wind machines, the sprinkler heads near the wind machine can be left operating. Because operating wind machines artificially increases the wind speed, evaporation rates are higher and wind machines should not be used if sprinklers wet the plants.

Surface irrigation and wind machines

The combination of wind machines and surface irrigation is widely practiced in California and other locations in the USA, especially in citrus orchards. Growers typically start with the surface water and turn on the wind machines later to supplement protection when needed. As with under-plant sprinklers, the wind machines facilitate the transfer to the air and trees of heat and water vapour released from the water within the mixed layer.

Combination of heaters and wind machines

The combination of wind machines and heaters improves frost protection over either of the methods alone (e.g. a wind machine with 50 heaters per hectare is roughly equal to 133 heaters per hectare alone). A typical combination system has a 74.5 kW wind machine with about 37 evenly spaced stack heaters per hectare, with no heaters within 30 m of the wind machine. Because the fan and heater operation tends to draw in cold air near the ground on the outside edge of the protected area, placing more heaters on the outside edge warms the influx of cold air. One heater for every two trees on the outside edge and inside the first plant row is recommended. Heaters can be widely spaced within the area affected by each wind machine. There should also be one heater for every two trees inside the second row on the upwind side of the crop. The wind machines should be started first, and the heaters are lit if the temperature continues to fall.

Sprinklers and heaters

Although no research literature was found on the use of sprinklers and heaters in combination, the method has been used. It has been reported that a grower used a round metal snow sled mounted horizontally on a pole at about 1.5 m above each heater to prevent water from extinguishing the heater. The heaters were started first and the sprinklers were started if the air temperature fell too low. This combination reduced ice accumulation on the plants and, on some nights, the sprinklers were not needed.

FORECASTING AND MONITORING

Forecasting the minimum temperature and how the temperature might change during the night is useful for frost protection because it helps growers to decide if protection is needed and when to start their systems. First consult local weather services to determine if forecasts are available. Weather services have access to considerably more information and they use synoptic and/or mesoscale models to provide regional forecasts. Local (microscale) forecasts are typically unavailable unless provided by private forecast services. Therefore, an empirical forecast model “FFST.xls”, which can be easily calibrated for local conditions, is included with this book. The model uses historical records of air and dew-point temperature at two hours past sunset and observed minimum temperatures to develop site-specific regression coefficients needed to accurately predict the minimum temperature during a particular period of the year. This model will only work during radiation-type frost events in areas with limited cold air drainage. The procedure to develop the regression coefficients and how to use the FFST.xls program are described in Chapter 5.

Another application program – FTrend.xls – is included with this book to estimate the temperature trend starting at two hours past sunset until reaching the predicted minimum temperature at sunrise the next morning. If the dew-point temperature at two hours past sunset is input, FTrend.xls also computes the wet-bulb temperature trend during the night. The wet-bulb temperature trend is useful to determine when to start and stop sprinklers. FTrend.xls is explained in Chapter 5.

PROBABILITY AND RISK

Probability and risk of damage is an important factor in making frost protection decisions. Several aspects of probability and risk and computer applications are presented in Chapter 1 of Volume II.

ECONOMIC EVALUATION OF PROTECTION METHODS

Chapter 2 of Volume II discusses the economics of various frost protection methods and presents an application program to help evaluate the cost-effectiveness of all major protection methods.

APPROPRIATE TECHNOLOGIES

Although this book presents information about most known methods of frost protection, whether or not a method is appropriate depends on many factors. Chapter 8 discusses what methods are currently used and discusses what technologies are appropriate in countries with limited resources.

CHAPTER 3

MECHANISMS OF ENERGY TRANSFER

MASS AND ENERGY IN THE AIR

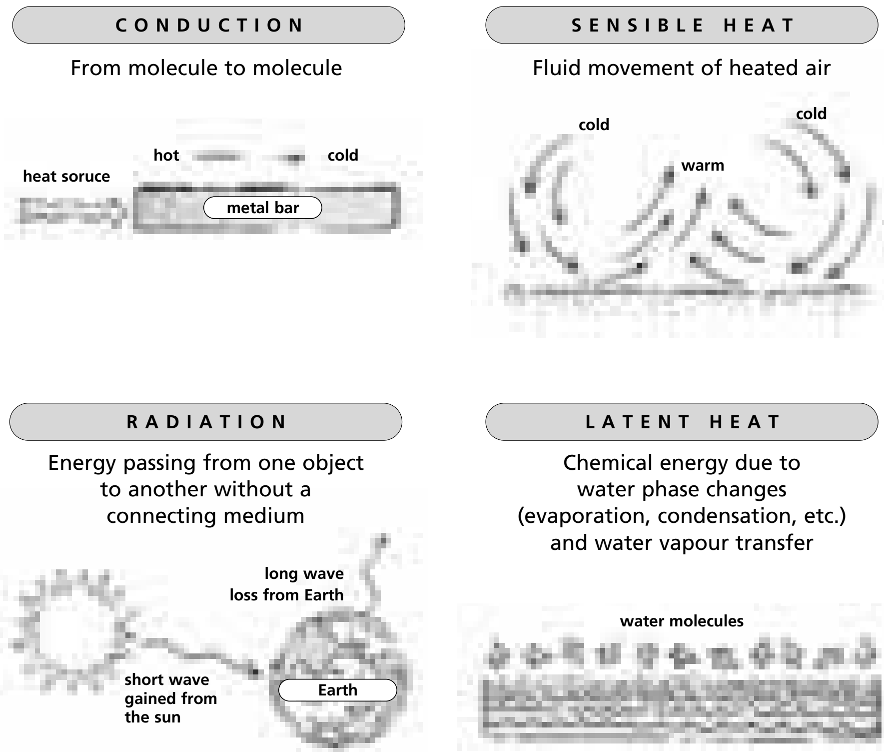
To know the concepts of frost protection, it is important to have a good description of the constituents of air and their relationship to energy content. Numerically, nitrogen (N_2) and oxygen (O_2) molecules are the main constituents of the atmosphere, with water vapour (H_20) being a minor (and variable) component. Within a cubic metre of air there are more gas molecules than stars in the universe (about 2.69×10^{25}), but the volume occupied by the molecules is less than about 0.1 percent of the total volume of the air (Horstmeyer, 2001). Therefore, while the number of air molecules within a cubic metre of atmosphere is immense, the Earth's atmosphere is mostly empty space. However, the molecules are moving at high velocity, so there is considerable kinetic energy (i.e. sensible heat) in the air. In this chapter, the methods of energy transfer that control sensible heat content and hence air temperature are discussed.

Energy transfer rates determine how cold it will get and the effectiveness of frost protection methods. The four main forms of energy transfer that are important in frost protection are radiation; conduction (or soil heat flux); convection (i.e. fluid transfer of sensible and latent heat properties) and phase changes associated with water (Figure 3.1).

Radiation is energy that comes from oscillating magnetic and electric fields and, unlike the other transfer mechanisms, can transfer through empty space. Good examples are the energy one feels from sunlight or from standing near a fire. Radiation that is intercepted by a surface is commonly expressed in terms of energy per unit time per unit surface area (e.g. W m^{-2}). In frost protection, the net radiation (R_n) is an important factor. The components that determine R_n, including short-wave (solar) radiation downward (R_{Sd}) and upward (R_{Su}), and long-wave radiation downward (R_{Ld}) and upward (R_{Lu}), are discussed later in this chapter.

Conduction is heat transfer through a solid medium, such as heat moving through a metal rod (Figure 3.1) or through the soil. Technically, soil heat can be measured with a thermometer, so it is sensible heat, but it moves mainly by conduction (i.e. from molecule to molecule) through the soil. When energy passes through the soil by conduction it is called soil heat flux density and it is commonly expressed as units of energy per unit time per unit surface area that it passes (e.g. W m^{-2}). In frost protection, the main interest is in soil heat flux density (G) at the surface of the soil.

FIGURE 3.1
The four forms of heat transfer



The four forms of heat transfer are:
conduction*, where heat is transferred through solid material from molecule to molecule (e.g. heat passing through a metal bar);*
sensible heat flux*, where warmer air is transferred from one location to another (e.g. warm air rising because it is less dense);*
radiation*, where heat is transferred as electromagnetic energy without the need for a medium (e.g. sunlight); and*
latent heat flux*, where sensible heat is converted to latent heat when water vaporizes and converts back to sensible heat when the water molecules condense or deposit (as ice) onto a surface.*

Sensible heat is energy that we can "sense", and temperature is a measure of the sensible heat content of the air. When the sensible heat content of air is high, the molecules have higher velocities and more collisions with each other and their surroundings, so there is more kinetic energy transfer. For example, a thermometer placed in warmer air will have more air molecule collisions, additional kinetic energy is transferred to the thermometer and the temperature reads higher. As sensible heat in the air decreases, the temperature drops. In frost protection, the goal is often to try to reduce or replace the loss of sensible heat content from the air and plants. Sensible heat flux density (H) is the transfer of sensible heat through the air from one place to another. The flux density is expressed as energy per unit time per unit surface area (e.g. $W\ m^{-2}$) that the energy passes through.

Latent heat is released to the atmosphere when water is vaporized and the latent heat content of the air depends on the water vapour content. Latent heat changes to sensible heat when water changes phase from water vapour to liquid water or ice. As water vapour moves, the flux density is expressed in units of mass per unit area per unit time (e.g. $kg\ m^{-2}\ s^{-1}$). Multiplying by the latent heat of vaporization (L) in $J\ kg^{-1}$ converts the water vapour flux density from mass units to energy units. Therefore, the flux is expressed in energy per unit time per unit surface area or power per unit surface area (e.g. $W\ m^{-2}$). The water vapour content of the air is a measure of the latent heat content, so humidity expressions and the relationship to energy are discussed in this chapter.

Energy balance

Sign convention

Positive and negative signs are used in transfer and balance calculations to indicate the direction of energy flux to or from the surface. Any radiation downward to the surface adds to the surface energy and therefore is considered positive and given a "+" sign. Any radiation away from the surface removes energy and it is considered negative with a "-" sign. For example, downward short-wave radiation from the sun and sky (R_{Sd}) is positive, whereas short-wave radiation that is reflected upward from the surface (R_{Su}) is negative. Downward long-wave radiation (R_{Ld}) is also given a positive sign since it adds energy to the surface and upward long-wave radiation (R_{Lu}) is given a negative sign. Net radiation (R_n) is the "net" amount of radiant energy that is retained by the surface (i.e. the sum of all gains and losses of radiation to and from the surface).

These relationships are illustrated for (a) daytime and (b) night-time in Figure 3.2. Note, in the equation, that net radiation is equal to the sum of its components and the sign indicates whether the radiation is downward (positive) or upward (negative). If the sum of the component parts is positive, as happens during the daytime (Figure 3.2a), then R_n is positive and more energy from radiation is gained than lost from the surface. If the sum of the component parts is negative, as happens during the night (Figure 3.2b), then R_n is negative and more radiation energy is lost than gained.

FIGURE 3.2

Sign convention for radiation during (a) daytime and (b) night-time

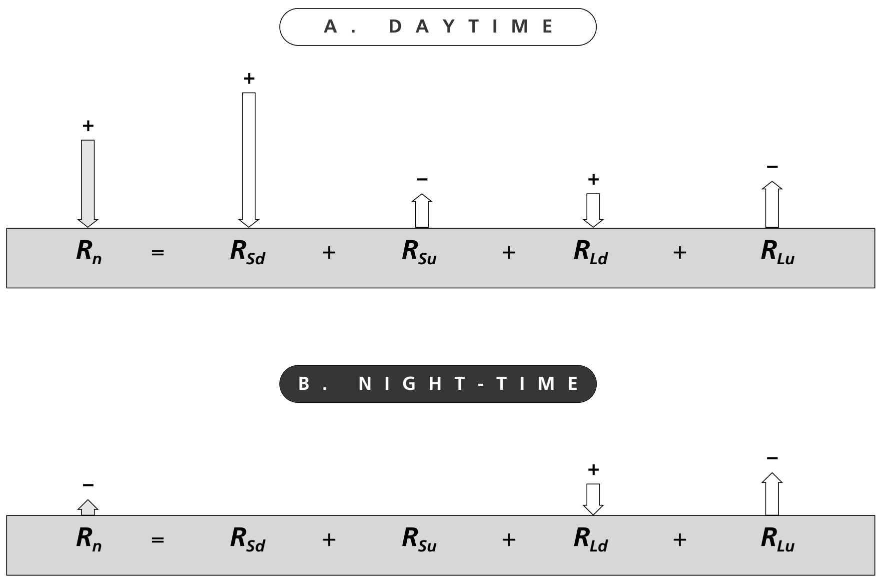
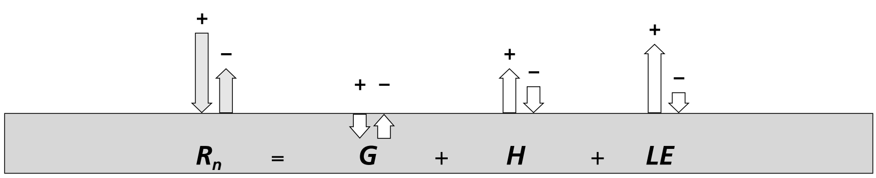


FIGURE 3.3

Sign convention for surface energy balance



R_n supplies energy that heats the air, plants and soil or evaporates water. In this book, the equation in Figure 3.3 is used for the surface energy balance. Note that energy storage in the plants, photosynthesis and respiration are generally ignored in vertical energy fluxes in frost protection. Assuming that all of the energy fluxes are vertical, energy from R_n is partitioned into the components G, H and LE, so R_n is set equal to the sum of G, H and LE (Eq. 3.1).

$$R_n = G + H + LE \quad \text{W m}^{-2} \quad \text{Eq. 3.1}$$

Again, the sign of the energy flux component indicates the direction of energy flow. Radiation adds energy to the surface, so it is positive to the surface. When G is positive, energy is going into the soil, and when H and LE are positive, the energy flux is upward to the atmosphere. Therefore, G, H and LE fluxes are positive away from the surface and negative towards the surface.

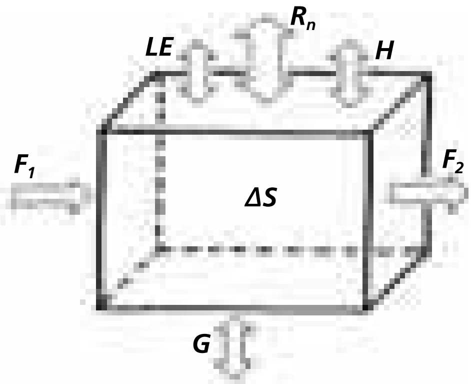
Although, most energy transfer on a frost night is vertical, a crop is three-dimensional, and energy can pass horizontally as well as vertically through a crop. Energy transfer through a crop is often depicted using an energy box diagram (Figure 3.4), which represents the volume of air to be heated in frost protection. The energy content of the box in the diagram depends on the sources and losses of energy (Figure 3.4), where most of the energy fluxes can be in either direction. The energy balance for the box is given by:

$$R_n = G + H + LE + F1 + F2 + \Delta S + P_R \quad \text{W m}^{-2} \quad \text{Eq. 3.2}$$

where R_n is a positive number when more energy from radiation is received than is emitted and reflected, and it is negative if more radiant energy is lost than gained. The variables G, H and LE are all positive when the energy is exiting from the box and are negative if the energy is entering the box. F_1 is horizontal sensible and latent heat flux into the box (a negative number) and F_2 is horizontal sensible and latent heat flux out of the box (a positive number). The sum of F_1 and F_2 is the net difference in horizontal flux of sensible and latent heat. The variable P_R is for photosynthesis (a positive number) and respiration (a negative number). However, P_R is small and commonly ignored for energy balance calculations. The variable ΔS is the change in stored energy (sensible heat) within the box, which is positive if the energy content increases (e.g. when the temperature increases) and it is negative when the energy content decreases (e.g. temperature falls).

FIGURE 3.4

A box energy diagram showing possible sources and losses of energy from a crop represented by the box



The symbols are:

*net radiation (**R_n**),*
*sensible heat flux (**H**),*
*latent heat flux (**LE**),*
*soil heat flux or conduction (**G**),*
*sensible and latent energy advection in (**F_1**)*
*and out (**F_2**),*
*and energy storage in the crop (Δ**S**)*

During a typical radiation frost night, R_n is negative, F_1 and F_2 sum to near zero, and P_R is insignificant. If water is not used for protection and there is no dew or frost formation and minimal evaporation, then *LE* is insignificant. Both *G* and *H* are negative, implying that heat is transferring into the box, but the magnitude of $G + H$ is less than R_n, so ΔS is negative and the air and crop will cool.

In many active and passive frost protection methods, the goal is to manipulate one or more of the energy balance components to reduce the magnitude of ΔS. This can be done by improving heat transfer and storage in the soil, which enhances soil heat storage during the day and upward *G* at night; by using heaters, wind machines or helicopters that increase the magnitude of negative *H*; by reducing the magnitude of the negative R_n; or by cooling or freezing water, which converts latent to sensible heat and raises the surface temperature. When the surface temperature is raised, the rate of temperature fall decreases. In this chapter, energy balance, radiation, sensible heat flux, soil heat flux or conduction, latent heat flux, humidity and water phase changes are discussed.

The energy from net radiation can also vaporize water and contribute to latent heat flux density (*LE*) or evaporation from the surface. Recall that when water is vaporized, sensible heat is converted to latent heat. When water condenses, the process is reversed and latent heat is converted to sensible heat. The *E* in *LE* represents the flux density of water molecules (kg s^{-1} m^{-2}), so *E* is the mass per unit time passing through a square metre of surface area. The latent heat of vaporization (*L*) is the amount of energy needed to vaporize a unit mass of water ($L \approx 2.45\times10^6$ J kg^{-1}). Consequently, the latent heat flux density (*LE*), like R_n, *H* and G, has the same units (J s^{-1} m^{-2} = W m^{-2}). When water vapour is added to the air (i.e. the flux is upward), it is given a positive sign. When water vapour is removed from the air in a downward flux (i.e. during dew or frost deposition), the sign is negative.

In arid climates, during the morning, when the surface temperature is higher than air temperature, it is common for R_n, G, H and LE to be positive, with LE considerably less than R_n (Figure 3.5). During the afternoon in arid climates, when the air temperature is higher than surface temperature, it is common for R_n to be positive, G to be small and negative, H to be negative and LE to be similar in magnitude to R_n (Figure 3.6). Note that H is often positive all day in humid climates where there is less horizontal advection of warm air over a cooler crop. During radiation frost conditions without dew or frost formation, typically R_n<0, G<0, H<0 and LE=0 (Figure 3.7). If and when condensation occurs, LE is negative and it supplies additional energy to help replace net radiation losses (Figure 3.8).

During a radiation frost night, there is a net loss of radiation (i.e. R_n < 0). Energy fluxes from the soil and air partially compensate for the energy losses, but as the sensible heat content of the air decreases, the temperature drops. Most active frost protection methods attempt to replace the energy losses with varying degrees of efficiency and cost.

FIGURE 3.5

Mid-morning summer energy balance with R_n, G, H, and LE

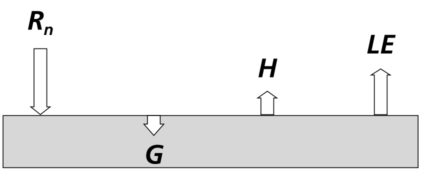


FIGURE 3.6

Mid-afternoon summer energy balance with R_n and LE (+) and G and H

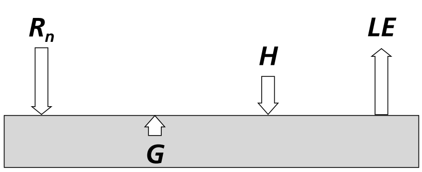


FIGURE 3.7

Pre-dawn radiation frost energy balance without condensation and with R_n, G and H

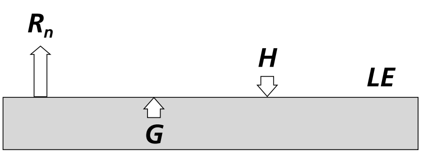
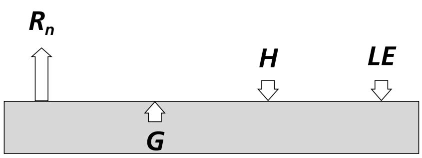


FIGURE 3.8

Pre-dawn radiation frost energy balance with condensation and R_n, G, H and LE



Humidity and Latent heat

In addition to sensible heat, air also contains latent heat that is directly related to the water vapour content. Each water molecule consists of one oxygen atom and two hydrogen atoms. However, hydrogen atoms attached to the oxygen atom are also attracted to the oxygen atoms of other water molecules. As more and more water molecules form the hydrogen bonds, they form a crystalline structure and eventually become visible as liquid water. Not all of the molecules are properly lined up to form hydrogen bonds so clumps of joined water molecules can flow past one another as a liquid. When the water freezes, most of the molecules will make hydrogen bonds and will form a crystalline structure (ice).

To evaporate (i.e. vaporize) water, energy is needed to break the hydrogen bonds between water molecules. This energy can come from radiation or sensible heat from the air, water, soil, etc. If the energy comes from sensible heat, kinetic energy is removed from the air and changed to latent heat. This causes the temperature to decrease. When water condenses, hydrogen bonds form and latent heat is released back to sensible heat causing the temperature to rise. The total heat content (i.e. enthalpy) of the air is the sum of the sensible and latent heat content.

The water vapour content of the air is commonly expressed in terms of the water vapour pressure or partial (barometric) pressure due to water vapour. A parameter that is often used in meteorology is the saturation vapour pressure, which is the vapour pressure that occurs when the evaporation and condensation rates over a flat surface of pure water at the same temperature as the air reaches a steady state. Other common measures of humidity include the dew-point and ice point temperatures, wet-bulb and frost-bulb temperatures, and relative humidity. The dew-point temperature (T_d) is the temperature observed when the air is cooled until it becomes saturated relative to a flat surface of pure water, and the ice point temperature (T_i) is reached when the air is cooled until it is saturated relative to a flat surface of pure ice. The wet-bulb temperature (T_w) is the temperature attained if water is evaporated into air until the vapour pressure reaches saturation and heat for the evaporation comes only from sensible heat (i.e. an adiabatic process). Saturation vapour pressure depends only on the air temperature, and there are several equations available for estimating saturation vapour pressure.

$$e_s = 0.6108 \exp\left(\frac{17.27\,T}{T + 237.3}\right) \text{kPa} \qquad \text{Eq. 3.5}$$

By substituting the air (T_a), wet-bulb (T_w) or dew-point (T_d) temperature for T in Equation 3.3, one obtains the saturation vapour pressure at the air (e_a), wet-bulb (e_w) or dew-point (e_d) temperature, respectively.

If the water surface is frozen, Tetens (1930) presented an equation for saturation vapour pressure (e_s) over a flat surface of ice at subzero temperature (T) in °C as:

$$e_s = 0.6108 \exp\left(\frac{21.875\,T}{T + 265.5}\right) \text{kPa} \qquad \text{Eq. 3.4}$$

where e_s is the saturation vapour pressure (kPa) at subzero air temperature T (°C). By substituting the frost-bulb (T_f) or ice point (T_i) temperature for T in Equation 3.4, one obtains the saturation vapour pressure at the frost-bulb (e_f) or at the ice point (e_i) temperature, respectively.

The latent heat content of air increases with the absolute humidity (or density of water vapour) in kg m^{-3}. However, rather than using absolute humidity, humidity is often expressed in terms of the vapour pressure. Vapour pressure is commonly determined using a psychrometer (Figure 3.9) to measure wet-bulb (T_w) and dry-bulb (T_a) temperatures. The dry-bulb temperature is the air temperature measured with a thermometer that is ventilated at the same wind velocity as the wet-bulb thermometer for measuring the wet-bulb temperature.

An equation to estimate the vapour pressure from T_w and T_a is:

$$e = e_w - \gamma\left(T_a - T_w\right) \text{kPa} \qquad \text{Eq. 3.5}$$

where

$$\gamma = 0.000660\left(1 + 0.00115\,T_w\right)P_b \quad \text{kPa °C}^{-1} \qquad \text{Eq. 3.6}$$

is the psychrometric constant (kPa °C^{-1}) adjusted for the wet-bulb temperature (T_w), the saturation vapour pressure at the wet-bulb temperature (e_w) is calculated by substituting T_w for T in Equation 3.3, and P_b (kPa) is the barometric pressure, where all temperatures are in °C (Fritschen and Gay, 1979). Alternatively, one can find the value for e_w corresponding to the wet-bulb temperature in Tables A3.1 and A3.2 (see Appendix 3 of Volume I).

FIGURE 3.9

Fan aspirated (upper instrument) and sling (lower instrument) psychrometers, which measure dry-bulb and either wet-bulb or frost-bulb temperatures to determine various measures of humidity

Barometric pressure (P_b) varies with passage of weather systems, but it is mainly a function of elevation (E_L). For any location, P_b can be estimated using the equation from Burman, Jensen and Allen (1987) as:

$$P_b = 101.3 \left[\frac{293 - 0.0065 E_L}{293} \right]^{5.26} \text{ kPa} \qquad \text{Eq. 3.7}$$

with E_L being the elevation (m) relative to sea level.

When the temperature is subzero, the water on the wet-bulb thermometer may or may not freeze. Common practice is to freeze the water on the wet-bulb thermometer, by touching it with a piece of ice or cold metal. When the water freezes, there will be an increase in the temperature reading as the water changes state from liquid to solid, but it drops as water sublimates from the ventilated ice-covered thermometer bulb. Within a few minutes, the temperature will stabilize at the frost-bulb (T_f) temperature. From the air and frost-bulb temperatures, the vapour pressure of the air is then determined using:

$$e = e_f - \gamma_f \left(T_a - T_f\right) \text{ kPa} \qquad \text{Eq. 3.8}$$

where

$$\gamma_f = \text{[illegible]} \left(1 + \text{[illegible]}\, T_f\right) P_b \text{ kPa °C}^{-1} \qquad \text{Eq. 3.9}$$

is the psychrometric constant adjusted for the frost bulb temperature (T_f), and the saturation vapour pressure at the frost-bulb temperature (e_f) is calculated by substituting T_f into Equation 3.4. Alternatively, one can find the value for e_f corresponding to the frost-bulb temperature in Table A3.3 in Appendix 3 of Volume I.

Relationships between temperature, vapour pressure and several measures of humidity for a range of subzero temperatures are shown in Figure 3.10. The upper curve represents the saturation vapour pressure over water (Equation 3.3) and the lower curve represents the saturation vapour pressure over ice (Equation 3.4). Therefore, at any given subzero temperature, the saturation vapour pressure over ice is lower than over water. Given an air temperature of T_a = -4°C and a vapour pressure of e = 0.361 kPa, the corresponding temperatures are: T_d = -7.0, T_i = -6.2, T_w = -4.9 and T_f = -4.7 °C for the dew-point, ice point, wet-bulb and frost-bulb temperatures, respectively. The corresponding saturation vapour pressures are: e_d = 0.361, e_i = 0.361, e_w = 0.424 and e_f = 0.411 kPa. The saturation vapour pressure at air temperature is e_s = 0.454 kPa.

Sometimes it is desirable to estimate the wet-bulb temperature from temperature and other humidity expressions. However, because the vapour pressure is a function of T_w, e_w, T_a - T_w and P_b, it is difficult without complicated programming. The same problem arises for estimating the frost-bulb temperature (Equation 3.8) from other humidity expressions. However, an Excel application (CalHum.xls) for estimating T_w and T_f from other parameters is included as a computer application with this book.

For any given combination of subzero temperature and humidity level, the actual and saturation vapour pressures at the dew-point and ice point are equal (i.e. e_d = e_i = e). In addition, the dew-point is always less than or equal to the wet-bulb, which is less than or equal to the air temperature (i.e. $T_d \leq T_w \leq T_a$). A similar relationship exists for the ice point, frost-bulb and air temperature (i.e. $T_i \leq T_f \leq T_a$). At any subzero temperature, $e_i \leq e_d$.

FIGURE 3.10

Saturation vapour pressure over water (upper curve) and over ice (lower curve) versus temperature

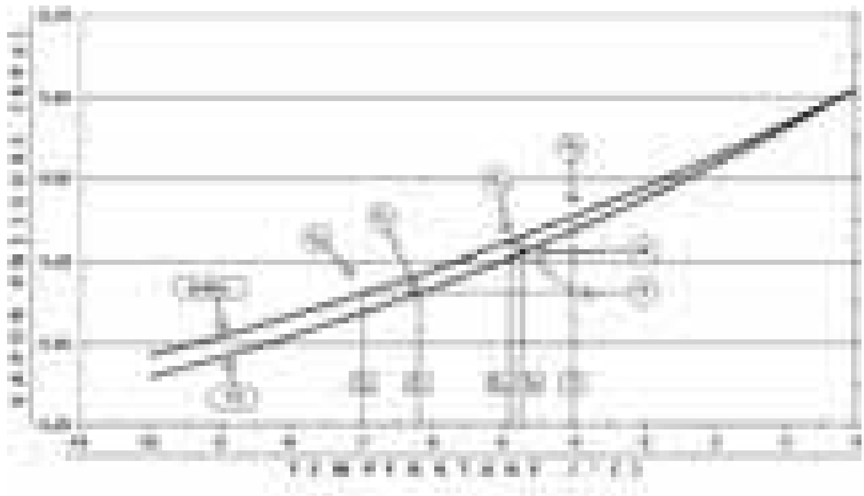


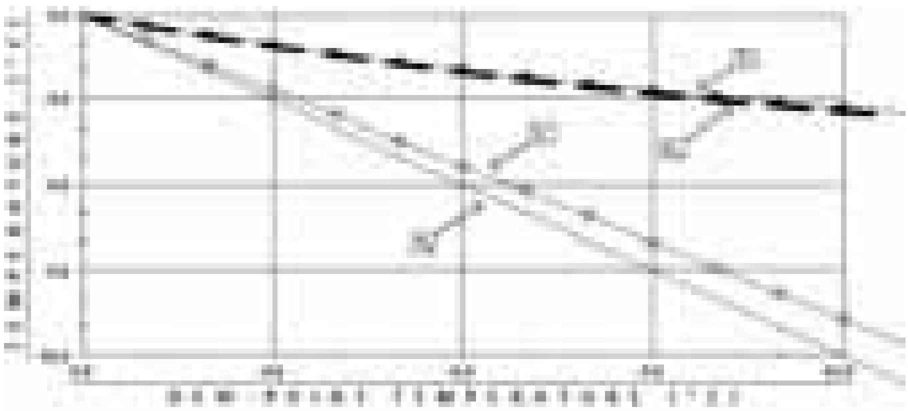
Figure 3.11 shows the corresponding air, wet-bulb, frost-bulb, ice point and dew-point temperatures at sea level for a range of dew-point temperature with an air temperature T_a = 0 °C. If the dew-point is T_d = -6 °C at T_a = 0 °C, both the wet-bulb and frost-bulb temperature are near -2 °C. In fact, there is little difference between the wet bulb and frost bulb temperatures for a given dew-point temperature in the range of temperature important for frost protection. However, the ice point and dew-point temperatures deviate as the water vapour content of the air (i.e. the dew-point) decreases. Because there is little difference between the wet-bulb and frost-bulb temperature, there is little need to differentiate between the two parameters. Therefore, only the wet bulb temperature will be used in further discussions.

The total heat content of the air is important for frost protection because damage is less likely when the air has higher total heat content. During a frost night, the temperature falls as sensible heat content of the air decreases. Sensible heat content (and temperature) decreases within the volume of air from the soil surface to the top of the inversion because the sum of (1) sensible heat transfer downward from the air aloft, (2) soil heat flux upward to the soil surface and (3) transfer of heat stored within the vegetation to the plant surfaces is insufficient to replace the sensible heat content losses resulting from net radiation energy losses.

If the air and surface cool sufficiently, the surface temperature can fall to T_d and water vapour begins to condense as liquid (i.e. dew) or to T_i and water vapour begins to deposit as ice (i.e. frost). This phase change converts latent to sensible heat at the surface and partially replaces energy losses to net radiation. Consequently, when dew or frost form on the surface, the additional sensible heat supplied by conversion from latent heat reduces the rate of temperature drop.

FIGURE 3.11

Corresponding wet-bulb (T_w), frost-bulb (T_f), ice point (T_i) and dew-point (T_d) temperatures as a function of dew-point temperature at an elevation of 250 m above mean sea level (i.e. air pressure (P_b) = 98 kPa) with an air temperature T_a = 0°C.



A good measure of the total heat content of the air is the "equivalent" temperature (T_e), which is the temperature the air would have if all of the latent heat were converted to sensible heat. The formula to calculate T_e (°C) from air temperature T_a (°C), vapour pressure e (kPa) and the psychrometric constant γ (kPa °C^{-1}) is:

$$T_e = T_a + \frac{e}{\gamma} \quad °C \qquad \text{Eq. 3.13}$$

Calculated T_e values for a range of T_a and T_i are given in Table 3.1 and for a range of T_a and T_d in Table 3.2. Values for T_d and T_i depend only on the water vapour content of the air and hence the latent heat content of the air. When T_d or T_i is high, then T_e is often considerably higher than the air temperature, which implies higher total heat content (i.e. higher enthalpy). Therefore, when T_e is close to T_a, the air is dry, there is less heat in the air and there is more chance of frost damage.

TABLE 3.1

Equivalent temperatures (T_e) for a range of air (T_a) and ice point (T_i) temperatures at sea level with the saturation vapour pressure (e_a) and the psychrometric constant (γ), which are functions of T_a

T_a	e_a	γ	T_i, ICE POINT TEMPERATURE (°C)					
°C	kPa	kPa°C^{-1}	-10.0	-8.0	-6.0	-4.0	-2.0	0.0
-10.0	0.286	0.067	-6.2					
-8.0	0.334	0.067	-4.1	-3.4				
-6.0	0.390	0.067	-2.1	-1.4	-0.5			
-4.0	0.454	0.067	-0.1	0.6	1.5	2.5		
-2.0	0.527	0.067	1.9	2.6	3.5	4.5	5.7	
0.0	0.611	0.067	3.9	4.6	5.5	6.6	7.8	9.2
2.0	0.706	0.067	5.9	6.7	7.5	8.6	9.8	11.2
4.0	0.813	0.066	7.9	8.7	9.6	10.6	11.8	13.2

TABLE 3.2

Equivalent temperatures (T_e) for a range of air (T_a) and dew-point (T_d) temperatures at sea level with the saturation vapour pressure (e_a) and the psychrometric constant (γ), which are functions of T_a

T_a	e_a	γ	T_d, DEW-POINT TEMPERATURE (°C)					
°C	kPa	kPa°C^{-1}	-10.0	-8.0	-6.0	-4.0	-2.0	0.0
-10.0	0.286	0.067	-5.8					
-8.0	0.334	0.067	-3.8	-3.0				
-6.0	0.390	0.067	-1.7	-1.0	-0.2			
-4.0	0.454	0.067	0.3	1.0	1.8	2.8		
-2.0	0.527	0.067	2.3	3.0	3.8	4.8	5.9	
0.0	0.611	0.067	4.3	5.0	5.9	6.8	7.9	9.2
2.0	0.706	0.067	6.3	7.0	7.9	8.8	9.9	11.2
4.0	0.813	0.066	8.3	9.0	9.9	10.8	11.9	13.2

Sensible heat

The energy content of the air depends on the barometric pressure, temperature and the amount of water vapour present per unit volume. The energy (or heat) that we measure with a thermometer is a measure of the kinetic energy of the air (i.e. energy due to the fact that molecules are moving). When a thermometer is placed in the air, it is constantly bombarded with air molecules at near sonic speeds. These collisions transfer heat from the molecules to the thermometer and cause it to warm up. This makes the liquid in the thermometer expand and we read the change in the level of the liquid as the temperature. When the air temperature increases, the air molecules move faster and therefore have more kinetic energy. As a result more molecules strike the thermometer and at higher speeds, causing greater transfer of kinetic energy and a higher temperature reading. Thus, temperature is related to the velocity of air molecules and the number of molecules striking the thermometer surface. Like a thermometer, air molecules strike our skin at near sonic speeds and kinetic energy is transferred from the molecules to our skin by the impact. We "sense" this transfer of energy, so it is called "sensible" heat.

If the air were perfectly still (i.e. no wind or turbulence), then the temperature that we sense would depend only on molecular heat transfer, where energy is transferred due to high-speed collisions between air molecules travelling over short distances. However, because there is wind and turbulence, air parcels with different sensible heat content move from one place to another (i.e. sensible heat flux). For example, if you stand inside of a dry sauna with relatively still air you will feel hot mainly because of molecular heat transfer through a boundary layer of still air next to your body. However, if a fan is started inside the sauna, some of the hotter air (i.e. with faster moving molecules) will be forcefully convected through the boundary layer to your skin. Because mechanical mixing, due to the fan, forced transfer to your skin, it is called "forced" convection. Hotter air is less dense than colder air (i.e. the mass per unit volume is less), so if the heat source is in the floor of the sauna, air at the surface will be less dense and it will rise into the cooler air above. When the less dense warmer air rises, the heat transfer is called "free" convection. In nature, the wind mainly blows air parcels horizontally and if warmer air blows into an area, the process is called "warm air advection". Similarly, if cold air blows into an area, the process is called "cold air advection". In frost protection, both forced and free convection as well as advection are important.

Sensible heat flux is important for frost protection on both a field scale and on an individual leaf, bud or fruit scale. Downward sensible heat flux from the air to the surface partially compensates for energy losses due to net radiation at the surface. However, as sensible heat is removed at the surface, air from above the crop transfers downward to compensate. This causes a loss of sensible heat above the crop as well as in the crop. As a result the temperature falls at all heights within the inversion layer, but most rapidly near the surface. Some protection methods (e.g. wind machines and helicopters) mainly use enhanced sensible heat transport to provide more energy to the surface and slow the temperature drop. Also, methods such as heaters partially use sensible heat flux to transport energy to a crop and provide protection.

In addition to field-scale energy transfer, the sensible heat flux through boundary layers of leaves, buds and fruit to the surface is important for determining the temperature of sensitive plant parts. A boundary layer over plant surfaces is a thin layer of still air where much of the heat transfer is by molecular diffusion. This layer tends to insulate the plant parts from sensible and latent heat transfer with the air. For example, wind machines are known to provide some frost protection even when there is no temperature inversion above a crop. This occurs because increasing ventilation will reduce the depth of boundary layer over the leaf, bud, or fruit surfaces and enhances sensible heat transfer from ambient air to the surface.

According to Archimedes principle, a body totally or partially immersed in a fluid is subject to an upward force equal in magnitude to the mass of the fluid it displaces. Totally immersed materials with an average density smaller than that of the fluid will rise and denser materials will fall towards the bottom. A good illustration of how density works is a hot air balloon. When hot air is forced into a balloon, more molecules hit the inside than the outside of the balloon, so there is more pressure on the inside and the walls expand. Eventually, the balloon becomes fully expanded. As additional hot air is introduced into the hole in the bottom, air molecules inside the balloon move at higher velocities and some air is forced out of the hole at the bottom. More molecules leave than enter through the hole in the bottom, so the mass of air inside decreases, while the volume remains relatively fixed. Consequently, the density decreases. When the density (i.e. the mass of the balloon, gondola, heater, etc., divided by the volume occupied by the balloon and its parts) is less than the density of the ambient air, the balloon will rise. If the heater is stopped, then air inside the balloon will begin to cool and air from outside will enter the hole in the bottom, which causes the density of the balloon to increase. As it becomes denser, the balloon will descend. Clearly, density is an important factor determining whether air moves up or down and therefore it is important for frost protection.

Considering the balloon example, it is clear that warmer, less dense air rises and colder, denser air will descend. During a radiation frost night, cold air accumulates near the surface and, if the ground is sloping, it will begin to flow downhill much like water flows downhill. However, like water, the flow of cold air is controllable using obstacles (fences, walls, windbreaks, etc.) to funnel the air where it will do less damage. This has been effectively used as a frost protection method. At the same time, obstacles can also block the normal drainage of cold air from a crop and increase the potential for damage.

Conduction – Soil heat flux

Like molecules in the air, molecules in solids also move faster when energy is transferred to the solid and the temperature of the solid increases. This form of energy transfer is called conduction. A good example is the transfer of heat through a metal rod if one end is placed in a fire, where the heat is transferred from molecule to molecule to the other end of the rod. Conduction is an important transfer mechanism for energy storage in the soil and therefore it is important for frost protection.

The rate that energy transfers by conduction depends on the capacity for the material to conduct energy (i.e. thermal conductivity) and the gradient of temperature with distance into the material. The thermal conductivity of a soil depends on the type and relative volume occupied by soil constituents. Air is a poor conductor of heat, so dry soils with more air spaces have lower thermal conductivities. The thermal conductivity of dry soils varies, but it is approximately 0.1, 0.25 and 0.3 W m^{-1} $°C^{-1}$ for organic, clay and sandy soils. If the soils are nearly saturated with water, the conductivity is approximately 0.5, 1.6 and 2.4 W m^{-1} $°C^{-1}$ for the three general soil types.

There is positive conduction into the soil when the surface is warmer than the soil below and the conduction is negative when heat conducts upward to a colder surface. As the sun comes up, the surface is warmer than the soil below, so heat conducts downward and is stored in the soil. As net radiation decreases in the afternoon, the surface will cool relative to the soil below and heat is conducted upwards towards the surface (i.e. negative flux). This negative heat flux continues during the night as soil heat conducts upwards to replace lost energy at the cooler surface. On an hourly basis, the soil heat flux density can change considerably but, on a daily basis, the amount of energy going into the soil is generally about the same as the quantity leaving the soil. In the longer term, there is a slight deficit each day during the autumn, so the soil gradually loses energy and cools. In the spring, there is a slight increase in energy receipt and storage each day, so the mean daily soil temperature will gradually increase. One should always remember that soil selection and management has both short-term (i.e. daily) and long-term (i.e. annual) effects on soil temperature.

Soil flux heat density (G) is estimated as:

$$G = -K_s \frac{\partial T}{\partial z} \quad \mathrm{W\ m^{-2}} \qquad \text{Eq. 3.11}$$

where K_s is the thermal conductivity (W m^{-1} $°C^{-1}$) and the second term on the right hand side is the change in temperature with depth (°C m^{-1}) called the thermal gradient. It is not possible to directly measure soil heat flux density (G) at the surface. If a heat flux plate is placed on the surface, then sunlight striking the plate will cause considerably higher flux density data than the real conduction through the soil. Burying the flux plate within 0.01 to 0.02 m of the surface can lead to errors if the soil cracks and lets sunlight strike the plate, rainfall or irrigation water drain onto the plate, or condensation forms on the plate surfaces. Generally, it is best to bury heat flux plates between 0.04 and 0.08 m deep and correct for soil heat storage above the plates to avoid these problems.

Soil heat flux density at the surface ($G = G_1$) is estimated using:

$$G_1 = G_2 + C_V\left(\frac{T_{sf} - T_{si}}{t_f - t_i}\right)\Delta z \quad \text{W m}^{-2} \quad \text{Eq. 3.12}$$

where G_2 is the heat flux plate measurement (W m^{-2}) at depth Δz (m) in the soil, C_V is the volumetric heat capacity of the soil (J m^{-3} °C^{-1}), T_{sf} and T_{si} are the mean temperatures (K or °C) of the soil layer between the flux plate level and the soil surface at the final (t_f) and initial (t_i) time (s) of sampling (e.g. $t_f - t_i = 1800$ s for a 30 minute period). Typically, a set of two to four thermocouples wired in parallel are used to measure a weighted mean temperature of the soil layer above the heat flux plates at the beginning and end of the sampling period to calculate the right-hand term of Equation 3.12. Based on de Vries (1963), a formula to estimate C_V (J m^{-3} °C^{-1}) is:

$$C_V = (1.92V_m + 2.51V_o + 4.19\theta)10^6 \quad \text{W m}^{-3} \quad \text{Eq. 3.13}$$

where V_m, V_o and θ are the volume fractions of minerals, organic matter and water, respectively (Jensen, Burman and Allen, 1990).

Thermal diffusivity (κ_T) of the soil is the ratio of the thermal conductivity to the volumetric heat capacity:

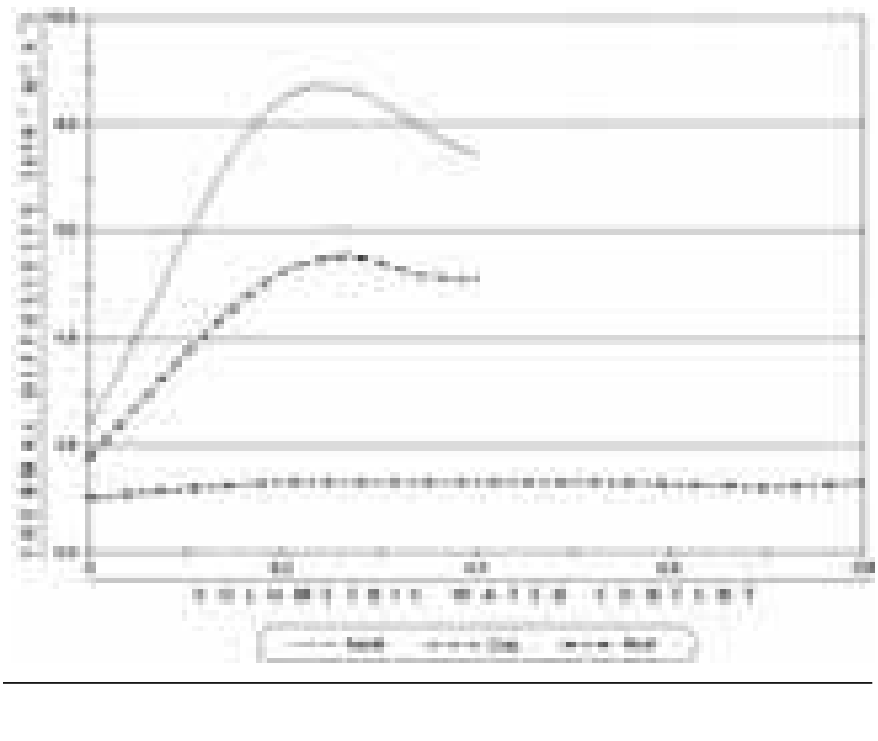
$$\kappa_T = \frac{K_s}{C_V} \quad \text{m}^2\ \text{s}^{-1} \quad \text{Eq. 3.14}$$

This parameter is useful as a measure of how fast the temperature of a soil layer changes, so it is important when considering soil selection and management for frost protection. As a dry soil is wetted, K_s increases more rapidly than C_V, so κ_T increases as the water content rises in a dry soil. However, as the soil pores begin to fill with water, the C_V increases more rapidly than K_s, so κ_T levels off near field capacity, and then decreases as the soil becomes saturated. The optimal heat transfer occurs at the peak κ_T value, so one goal for frost protection is to maintain the water content of the surface soil layer at near field capacity to maximize κ_T. For both sandy and clay soils, dry soils should be avoided and there is no advantage to have saturated clay soil (Figure 3.12). For soils ranging between clay and sand, water contents near field capacity generally have the highest κ value. Highly organic (peat) soils generally have a low thermal diffusivity regardless of the soil water content (Figure 3.12). Therefore, for frost protection, peat soils should be avoided when selecting a site for a new crop.

In addition to energy conduction into and out of the soil, there is also conduction into and out of plant materials (e.g. tree trunks, large fruit). Relative to soil heat flux density, energy storage in the plant tissues are small, but it may be important in some instances. For example, heat storage in citrus fruit causes the fruit skin temperature to fall slower and not as far as the air temperature. This requires consideration when determining when to protect citrus orchards.

FIGURE 3.12

Sample thermal diffusivities for sand, clay and peat (organic) soils as a function of volumetric water content (modified from Monteith and Unsworth, 1990)



Radiation

Electromagnetic radiation is energy transfer resulting from oscillation of electric and magnetic fields. A good example is sunlight or solar radiation, which transfers huge amounts of energy to the Earth's surface. Most of the distance between the Sun and Earth is a vacuum (i.e. empty space), so one property of radiation is that the heat transfer occurs even through a vacuum. Although much cooler, objects on Earth also radiate energy to their surroundings, but the energy content of the radiation is considerably less. The energy radiated from an object is a function of the fourth power of the absolute temperature:

$$E = \varepsilon \sigma T_K^4 \quad \mathrm{W\ m^{-2}} \qquad \text{Eq. 3.15}$$

where ε is the emissivity (i.e. the fraction of maximum possible energy emitted at a particular temperature); $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}, the Stefan-Boltzmann constant; and T_K is the absolute temperature ($T_K = T_a + 273.15$). Assuming that $\varepsilon = 1.0$, the radiation flux density from the surface of the sun at 6000 K is about 73,483,200 W m^{-2}, whereas radiation from the surface of the Earth at about 288 K is approximately 390 W m^{-2}. However, because irradiance (i.e. radiation flux density in W m^{-2}) that is received by a surface decreases with the square of the distance from the Sun and the mean distance between the Earth and Sun is about 150 660 000 km, the solar energy has reduced to about the solar constant (G_{sc} = 1367 W m^{-2}) by the time it reaches the upper atmosphere of the Earth. As the radiation passes through the atmosphere, some is reflected and some is absorbed, so, on a clear day, only about 75 percent of solar radiation reaches the surface. Because the earth receives solar energy on a surface area (πr^2) of a disk perpendicular to the sun's rays with a radius (r) the same as the earth but it emits from a surface area of a sphere ($4\pi r^2$), the input and output of radiant energy are in balance and the Earth's temperature is relatively stable.

Radiant energy can be described in terms of wavelength of the radiation. Bodies with higher temperature emit shorter wavelengths of the electromagnetic energy. Energy emitted by a perfect emitter at 6000 K falls within the range of 0.15 to 4.0 µm, where 1.0 µm = 1.0×10^{-6} m. Much of the high-energy (short wavelength) radiation is absorbed or reflected as it passes through the atmosphere, so solar radiation received at the Earth's surface mostly falls in wavelength range between 0.3 to 4.0 µm. The wavelength of maximum emission (λ_{max}) is calculated using Wein's displacement law as:

$$\lambda_{max} = \frac{2897}{T_K} \quad \mu\mathrm{m} \qquad \text{Eq. 3.16}$$

where T_K is the absolute temperature of the emitting object. For the Sun at 6000 K, the λ_{max} is about 0.48 μm. Most thermal (i.e. terrestrial) radiation from objects at Earth temperatures falls in the range between 3.0 and 100 μm, with a peak at about 10 μm for a mean temperature $T_K \approx 288$ K. There is overlap between 3.0 and 4.0 μm for the solar and terrestrial radiation, but the energy emitted in that range is small for both spectral distributions. Therefore, energy from the Sun is called short-wave (i.e. short-wave band) and that from the Earth is called long-wave (i.e. long-wave band) radiation. The two bands have insignificant overlap.

The net short-wave radiation (R_{Sn}) is calculated as:

$$R_{Sn} = R_{Sd} + R_{Su} \quad \mathrm{W\ m^{-2}} \qquad \text{Eq. 3.17}$$

where R_{Sd} and R_{Su} are the downward (positive) and upward (negative) short-wave radiation flux densities, respectively. Since the Earth is too cold to emit significant energy as short-wave radiation, R_{Su} comprises only reflected short-wave radiation. The fraction of short-wave radiation that is reflected from a surface is called the albedo (α), so the upward short-wave radiation is expressed as:

$$R_{Su} = -\alpha R_{Sd} \quad \mathrm{W\ m^{-2}} \qquad \text{Eq. 3.18}$$

Therefore, the net short-wave radiation (i.e. the amount absorbed at the surface) can be expressed as:

$$R_{Sn} = R_{Sd} + R_{Su} = R_{Sd} + \left(-\alpha R_{Sd}\right) = \left(1 - \alpha\right) R_{Sd} \quad \mathrm{W\ m^{-2}} \qquad \text{Eq. 3.19}$$

Vegetated surfaces typically absorb most of the long-wave downward radiation that strikes them. However, a minute fraction is reflected back to the sky. The surface also emits long-wave radiation according to the fourth power of its absolute temperature. The net long-wave radiation is the balance between gains and losses of radiation to and from the surface as given by:

$$R_{Ln} = R_{Ld} + R_{Lu} \quad \mathrm{W\ m^{-2}} \qquad \text{Eq. 3.20}$$

where the downward long-wave radiation (R_{Ld}) is a gain (i.e. a positive number) and the upward long-wave radiation (R_{Lu}) is a loss (i.e. a negative number). The apparent sky temperature is much colder than the surface, so downward long-wave radiation is less than upward long-wave radiation and net long-wave radiation is negative.

Downward radiation R_{Ld} is the energy emitted at the apparent sky temperature, which varies mainly as a function of cloudiness. Since the surface temperature and apparent sky temperature are usually unknown, many equations have been developed to estimate R_{Ln} as a function of the standard screen temperature T_a (°C).

The following equation for R_{Ln} gives good daytime estimates:

$$R_{Ln} = -f\varepsilon_o \sigma T_K^4 \quad \text{W m}^{-2} \qquad \text{Eq. 3.21}$$

where f is a function to account for daytime cloudiness (Wright and Jensen, 1972):

$$f = 1.35\frac{R_{Sd}}{R_{So}} - 0.35 \qquad \text{Eq. 3.22}$$

where R_{Sd} is measured total solar radiation and R_{So} is the clear-sky solar radiation. The minimum is $f = 0.055$ for complete cloud cover (i.e. $R_{Sd}/R_{So} = 0.3$) and the maximum is $f \leq 1.0$ for completely clear skies (Allen *et al.*, 1998). In Equation 3.21, $T_K = T_a + 273.15$ is the absolute temperature (K) corresponding to T_a (i.e. the temperature measured in a standard shelter). The apparent net emissivity (ε_o) between the surface and the sky is estimated using a formula based on Brunt (1932) and using coefficients from Doorenbos and Pruitt (1977):

$$\varepsilon_o = 0.34 - 0.139\sqrt{e_d} \qquad \text{Eq. 3.23}$$

where e_d is the actual vapour pressure (kPa) measured in a standard weather shelter. There is no known method to accurately estimate f during night-time; however, skies are commonly clear during radiation frost nights, so R_{Ln} can be estimated using Equations 3.21 and 3.23 with $f = 1.0$.

Depending on the temperature and humidity, R_{Ln} on a radiation frost night typically varies between -73 and -95 W m^{-2} (Table 3.3). When skies are completely overcast, R_{Ln} depends on the cloud base temperature; but $R_n = -10$ W m^{-2} is expected for low, stratus-type clouds. Therefore, depending on cloud cover, -95 W m^{-2} $< R_{Ln} <$ -10 W m^{-2}, with a typical value around -80 W m^{-2} for a clear frost night.

Figure 3.13 shows an example of changes in net radiation, soil heat flux density and air temperature that are typical of spring-time in a California mountain valley. During the day the peak $R_n \approx 500$ W m^{-2} and during the night net radiation fell to about -80 W m^{-2}. It increased after 0200 h as cloud cover slowly increased. Note that the night-time temperature starts to drop rapidly at sunset, which was shortly after R_n became negative. Starting at about two hours after sunset, the rate of temperature decrease remained fairly constant until the cloud cover increased and caused an increase in the temperature.

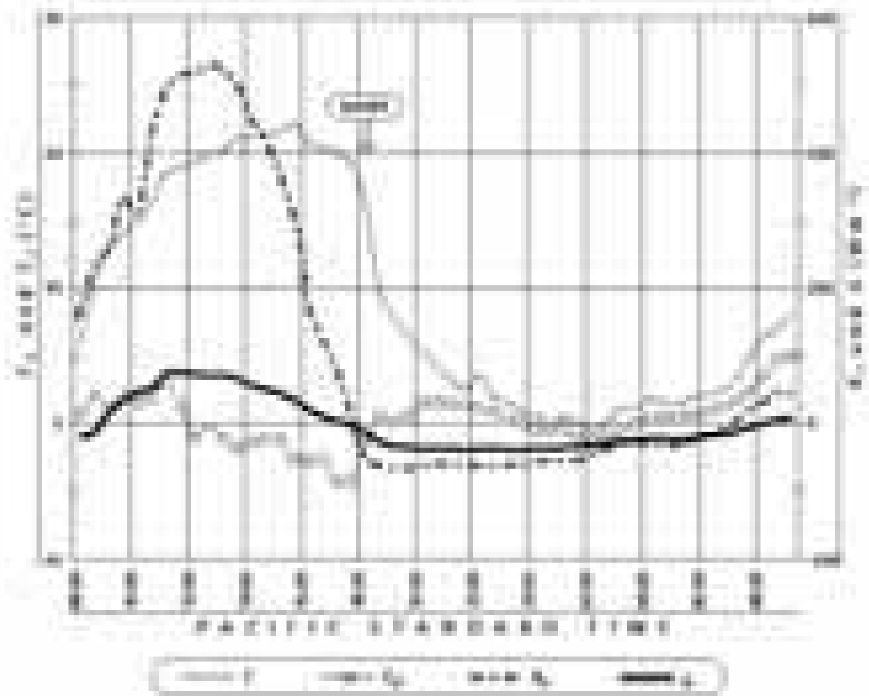
TABLE 3.3

Net long-wave radiation (W m^{-2}) for a range of air (T_a) and subzero dew-point (T_d) temperatures (°C) and saturation vapour pressure at the dew-point temperature (e_d) in kPa. The R_{Ln} values were calculated using Equations 3.21 and 3.23, and assuming f =1.0

T_a (°C)	DEW-POINT TEMPERATURE (°C)			
	0	**-2**	**-4**	**-6**
12	-86	-89	-92	-95
10	-84	-87	-90	-92
8	-82	-84	-87	-89
6	-79	-82	-85	-87
4	-77	-80	-82	-84
2	-75	-77	-80	-82
0	-73	-75	-78	-80
-2		-73	-75	-77
-4			-73	-75
-6				-73
e_d (kPa) =	0.6108	0.5274	0.4543	0.3902

FIGURE 3.13

Net radiation (R_n), soil heat flux density (G), air temperature (T_a) at 1.5 m, and dew-point temperature (T_d) at 1.5 m in a walnut orchard with a partial grass and weed cover crop in Indian Valley, California, USA (latitude 39°N) on 14–15 March 2001



Latent heat flux

When water vapour condenses or freezes, latent is changed to sensible heat and the temperature of air and other matter in contact with the liquid or solid water will temporarily rise. Latent heat is chemical energy stored in the bonds that join water molecules together and sensible heat is heat you measure with a thermometer. When latent heat is changed to sensible heat, the air temperature rises. When ice melts or water evaporates, sensible heat is changed to latent heat and the air temperature falls. Table 3.4 shows the amount of heat consumed or released per unit mass for each of the processes. When the energy exchange is positive, then sensible heat content increases and the temperature goes up. The temperature goes down when the energy exchange is negative.

Subzero temperatures can lead to the formation of ice crystals on plant surfaces. For water vapour to condense as dew or ice to deposit onto surfaces as frost, the air in contact first becomes saturated (i.e. reaches 100 percent relative humidity). With a further drop in temperature, water vapour will either condense or deposit onto the surface. These are both exothermic reactions, so latent heat is converted to sensible heat during the condensation or deposition process and the released heat will slow the temperature drop.

TABLE 3.4

Energy exchange of water due to cooling, heating and phase changes

PROCESS	ENERGY	
Water cooling	+4.1868	$J\ g^{-1}\ °C^{-1}$
Freezing (liquid freezing at 0°C)	+334.5	$J\ g^{-1}$
Ice cooling	+2.1	$J\ g^{-1}\ °C^{-1}$
Water condensing (vapour to liquid) at 0°C	+2501.0	$J\ g^{-1}$
Water depositing (vapour to ice) at 0°C	+2835.5	$J\ g^{-1}$
Water sublimating (ice to vapour) at 0°C	-2835.5	$J\ g^{-1}$
Water evaporating (water to vapour) at 0°C	-2501.0	$J\ g^{-1}$
Ice warming	-2.1	$J\ g^{-1}\ °C^{-1}$
Fusion (ice melting at 0°C)	-334.5	$J\ g^{-1}$
Water warming	-4.1868	$J\ g^{-1}\ °C^{-1}$

NOTE: Positive signs indicate release of sensible heat and negative signs indicate removal of sensible heat.

Water vapour flux density (*E*) is the flux of water molecules per unit time per unit area (i.e. kg s^{-1} m^{-2}). When multiplied by the latent heat of vaporization ($L \approx 2.501 \times 10^6$ J kg^{-1} at 0 °C), the water vapour flux density is expressed in energy units (i.e. W m^{-2}). Evaporation is important for all frost protection methods involving the use of water. The ratio of the latent heat of vaporization to the latent heat of fusion is 7.5, so considerably more water must be frozen than is vaporized to have a net gain of energy when using sprinklers for frost protection.

It is common for fruit growers to experience problems with spots of damage on the skin of fruit. While this may not damage the fruit to the point where it is completely lost, the spot damage reduces the value of fruit for table consumption. This problem is probably due to water droplets being on the fruit before going into a night with subzero air temperature. For example, if a light rain, fog or irrigation occurs during the day so that the fruit is covered by spots of water, this water will evaporate during the night and the fruit flesh near water droplets can cool as low as the wet-bulb or frost-bulb temperature, which is lower than the air temperature. As a result, damage can occur where there were water droplets on the fruit. If the dew-point temperature is low, damage can occur to sensitive crops, even if the air temperature remains above 0 °C.

Additional resources on energy balance

Readers who want more rigorous and detailed information on energy balance as it relates to frost protection are referred to Rossi *et al.* (2002), Barfield and Gerber (1979) and Kalma *et al.* (1992).

CHAPTER 4

FROST DAMAGE: PHYSIOLOGY AND CRITICAL TEMPERATURES

INTRODUCTION

Low temperature (e.g. chilling and freezing) injury can occur in all plants, but the mechanisms and types of damage vary considerably. Many fruit, vegetable and ornamental crops of tropical origin experience physiological damage when subjected to temperatures below about +12.5 °C, hence well above freezing temperatures. However, damage above 0 °C is chilling injury rather than freeze injury. Freeze injury occurs in all plants due to ice formation. Crop plants that develop in tropical climates, often experience serious frost damage when exposed to temperature slightly below zero, whereas most crops that develop in colder climates often survive with little damage if the freeze event is not too severe. Some exceptions are lettuce, which originated in a temperate climate, but can be damaged at temperatures near 0 °C and some subtropical fruits trees that can withstand temperatures to -5 to -8 °C. Species or varieties exhibit different frost damage at the same temperature and phenological stage, depending on antecedent weather conditions, and their adaptation to cold temperatures prior to a frost night is called "hardening". During cold periods, plants tend to harden against freeze injury, and they lose the hardening after a warm spell. Hardening is most probably related to an increase in solute content of the plant tissue or decreases in ice-nucleation active (INA) bacteria concentrations during cold periods, or a combination. During warm periods, plants exhibit growth, which reduces solute concentration, and INA bacteria concentration increases, which makes the plants less hardy.

Frost damage occurs when ice forms inside the plant tissue and injures the plant cells. It can occur in annuals (grasses and legumes of forage and silage crops; cereals; oil and root crops; horticultural; and ornamental crops) multi-annuals and perennials (deciduous and evergreen fruit trees). Frost damage may have a drastic effect upon the entire plant or affect only a small part of the plant tissue, which reduces yield, or merely product quality.

In this chapter, a short discussion of the mechanisms, types and symptoms of freeze injury is presented. For interested readers, Levitt (1980), Sakai and Larcher (1987) and Li (1989) provide extensive reviews of both freezing and chilling injury. Later in this chapter, a short discussion of hardening, sensitivity, kind-of-damage and critical damage temperatures of important crops are presented.

CELL INJURY

Direct frost damage occurs when ice crystals form inside the protoplasm of cells (intracellular freezing), whereas indirect damage can occur when ice forms inside the plants but outside of the cells (i.e. extracellular freezing). It is not cold temperature but ice formation that actually injures the plants (Westwood, 1978). It is believed that intracellular ice formation causes a "mechanical disruption of the protoplasmic structure" (Levitt, 1980). The extent of damage due to intracellular freezing depends mainly on how fast the temperature drops and to what level it supercools before freezing. There is little or no evidence that the duration of the freezing affects injury. In fact, Levitt (1980) states that freeze injury seems to be independent of time for short periods (e.g. 2–24 hours).

Direct intracellular freeze injury is associated with rapid cooling. For example, Siminovitch, Singh and de la Roche (1978) observed intracellular freezing and cell death when winter rye plants were cooled at 8 °C per minute to -12 °C when the supercooled water froze inside the cells. When plants were cooled to -12 °C over 23 minutes, ice formation was extracellular and the plants fully recovered after thawing. In climate chamber studies to determine critical temperatures, plant cuttings are typically cooled at a rate of between 1.0 and 2.0 °C h^{-1}. This is a slower rate than in the rye plant experiment and a slower rate than some of the rates that often occur in nature. Indeed, Levitt (1980) reports that, in nature, freeze injury results from extracellular ice crystal formation and there is no evidence of intracellular freezing.

Although the evidence is not strong, it seems that the rate of thawing after a freeze is also partially related to the amount of damage. Citrus growers in southern California commonly believe that slowing the warming process after a freeze night can reduce frost damage. In fact, growers justify operating wind machines longer into the morning following a freeze night in order to slow the thawing process. Yoshida and Sakai (1968) suggested that thawing rate will slow the rehydration of cells in plants that experience extracellular freezing and that might reduce the damage due to fast thawing.

Levitt (1980) proposed that cells were gradually killed as a result of growth of the extracellular ice mass. Recall that the saturation vapour pressure is lower over ice than over liquid water. As a result of extracellular ice formation, water will evaporate from the liquid water inside the cells and will pass through the semipermeable cell membranes and deposit on the ice crystals outside of the cells. As water is removed from the cells, the solute concentration increases and reduces the chances of freezing. However, as ice continues to grow, the cells become more desiccated. Typically, in injured plants, the extracellular ice crystals are much larger than the surrounding dead cells, which have collapsed because of desiccation. Therefore, the main cause of frost damage to plants in nature is extracellular ice crystal formation that causes secondary water stress to the surrounding cells. In fact, there is a close relationship between drought-tolerant plants and freeze-tolerant plants.

Note that antitranspirants are often promoted as a method of freeze protection. It is argued that the frost damage occurs because of cell dehydration and the antitranspirants are purported to reduce water loss from the plants and provide freeze protection. However, the cell desiccation results from evaporation of cellular water in response to a vapour pressure gradient caused by extracellular ice formation and not because of transpiration. There is no evidence that antitranspirants reduce desiccation due to extracellular ice crystal formation.

AVOIDANCE, TOLERANCE AND HARDENING

Plants resist low temperatures by avoidance or tolerance. Strategies to avoid low temperatures include:

- snow retention throughout the winter, which protects both the aerial and subterranean parts of the plants (Ventskevich, 1958);
- the biophysical effect of dense canopies, which shield part of the plant from the cold sky;
- bulky organs (e.g. trunks or big fruits) with high heat capacity that lag their temperature behind air temperature, which may save them from damaging temperatures (Turrell and Austin, 1969); and
- artificial frost protection methods, which modify the microclimate of the plants (e.g. foams, covers and fogging).

Tolerance of low temperature can be achieved by:

- avoiding freezing through a decrease of the freezing point or an increase in the degree of supercooling (Burke *et al.*, 1976);
- tolerance of extracellular freezing by reducing the amount of ice formed due to an increase of the concentration of solutes in the protoplasm (Li and Palta, 1978);
- tolerance of a higher degree of desiccation due to the plasmolysis of the protoplasm (Gusta, Burke and Kapoor, 1975); or
- increasing the permeability of the plasma membrane to avoid intracellular freezing (Alden and Hermann, 1971; Levitt, 1980).

The temperature at which freezing occurs can fluctuate considerably depending on to what extent the plants have hardened. However there are plants (e.g. many C_4 plants, palm tree leaves and tomato plants) that have very little or no hardening capacity (Larcher, 1982; Olien, 1967). Hardening involves both mechanisms of avoidance and tolerance of freezing. The accumulation of sugars or sugar alcohols lower the freezing temperature of tissues (e.g. in olive and citrus tree leaves) and supercooling increases in many deciduous and evergreen fruit trees in response to low air temperature. Some cells may harden by increasing the proportion of unsaturated fatty acids of plasma membrane lipids, which would increases membrane stability during desiccation. Since hardening is an active process that depends on assimilate level in the tissues, all conditions that deplete the pool of assimilates in the tissues reduce hardening.

Although cold temperatures cause fruit plants to harden against frost damage, hardiness is quickly lost during a few warm days. The fruit buds will regain hardiness but at a much slower rate than they lose it. This is the basis for the practice of cooling crops with sprinklers during daytime warm periods to reduce temperature and avoid the loss of hardening.

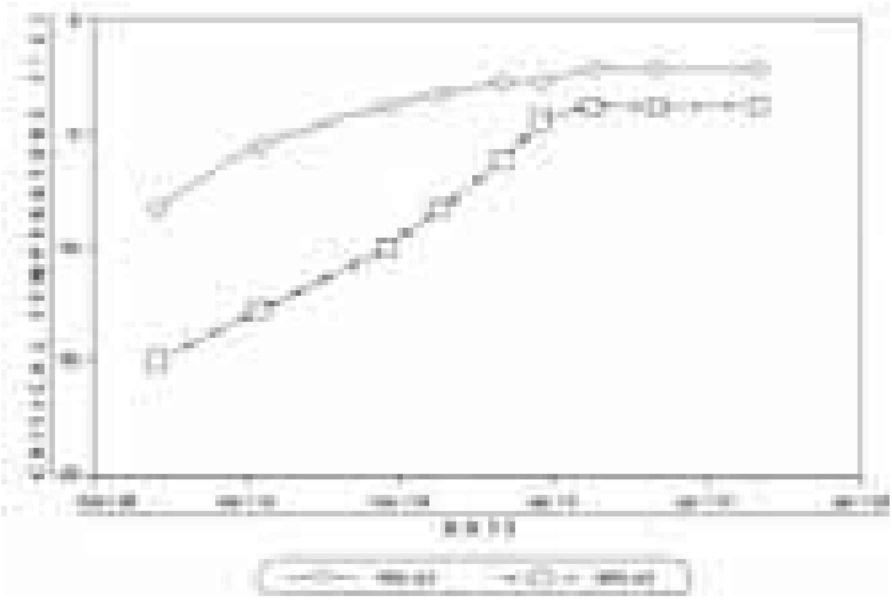
In the past, researchers have attributed fluctuations in freeze sensitivity to physiological changes, but the contribution of INA bacteria to the sensitivity, which might also be a factor to consider, has generally been ignored. For example, a rapid increase in ice-nucleating bacterial concentration might also occur during warm periods. As cold temperatures return, the concentration of bacteria might decline slowly.

PLANT SENSITIVITY

Plants fall into four freeze-sensitivity categories: (1) tender; (2) slightly hardy; (3) moderately hardy; and (4) very hardy (Levitt, 1980). Tender plants are those that have not developed avoidance of intracellular freezing (e.g. mostly tropical plants). Slightly hardy plants include most of the subtropical fruit trees, deciduous trees during certain periods, and fruit and vegetable horticultural [truck] crops that are sensitive to freezing down to about -5 °C. Moderately hardy plants include those that can accumulate sufficient solutes to resist freeze injury to temperatures as low as -10 °C mainly by avoiding dehydration damage, but they are less able to tolerate lower temperatures. Very hardy plants are able to avoid intracellular freezing as well as avoid damage due to cell desiccation.

FIGURE 4.1

Typical 10 percent and 90 percent bud kill temperatures for cherry trees corresponding to average dates observed at the Washington State University, Prosser Research and Extension Centre (Proebsting and Mills, 1978)



Although freeze sensitivity categories give general information about the cold that a plant organ can endure before frost damage occurs, hardening and phenological stage are almost as important. For example, temperature that produces both 10 percent (T_{10}) and 90 percent (T_{90}) bud kill increases as the season progresses from first swelling to post bloom (Figure 4.1). In addition, the temperatures that produce T_{90} bud kill in deciduous trees increases more rapidly and approach the temperatures that produce T_{10} kill.

Wang and Wallace (2003) presented a list of fresh fruits and vegetables by freeze susceptibility categories (Table 4.1.) showing relative sensitivities when exposed to freezing temperatures. Caplan (1988) gave a list of freeze-tolerance groupings for annual flowers (Table 4.2). Table 4.4 provides an extensive list of some of these and other crops.

TABLE 4.1

Susceptibility of fresh fruits and vegetables to freezing injury

MOST SUSCEPTIBLE	MODERATELY SUSCEPTIBLE	LEAST SUSCEPTIBLE
Apricots	Apples	Beets
Asparagus	Broccoli	Brussels sprouts
Avocados	Carrots	Cabbage, mature and savoury
Bananas	Cauliflower	Dates
Beans, snap	Celery	Kale
Berries (except cranberries)	Cranberries	Kohlrabi
Cucumbers	Grapefruit	Parsnips
Eggplant	Grapes	Rutabagas
Lemons	Onion (dry)	Salsify
Lettuce	Oranges	Turnips
Limes	Parsley	
Okra	Pears	
Peaches	Peas	
Peppers, sweet	Radishes	
Plums	Spinach	
Potatoes	Squash, Winter	
Squash, Summer		
Sweet potatoes		
Tomatoes		

SOURCE: Wang and Wallace, 2003.

TABLE 4.2

Categories for freeze hardiness of various annual flowers

HARDY	TOLERANT	TENDER	SENSITIVE
Cornflower	Bells of Ireland (*Moluccella*)	Aster	*Ageratum*
Ornamental cabbage	Blackeyed Susan (*Rudbeckia*)	*Nicotiana*	Balsam
Pansy	*Coreopsis*	Petunia	Begonia
Primrose	Pinks (*Dianthus*)	*Scabiosa*	Cockscomb
Violet	Pot Marigold (*Calendula*)	Statice	*Impatiens*
	Snapdragon	Sweet alyssum	Lobelia
	Stock (*Matthiola incana*)	Verbena	Marigold
	Sweet pea		Moss rose (*Portulaca*)
	Torenia		Periwinkle (*Vinca*)
			Phlox, annual
			Salpiglossis
			Salvia
			Zinnia

SOURCE: Based on Purdue University publication HO-14, as cited by Caplan, 1988.

TYPES OF DAMAGE AND CRITICAL TEMPERATURES

There are numerous studies on critical damage (T_c) temperatures for a variety of crops. These numbers were obtained using a range of methods and one should use caution when attempting to use published critical temperatures to manage starting and stopping temperatures for active protection methods. For example, some researchers have compared long-term commercial damage records with temperature measurements from standard shelters. In some instances, the temperature sensor, shielding, mounting height, etc., are not reported. These factors can affect the results and it is difficult to apply information from one location to another because insufficient information was supplied. Also, there are always microclimate differences, even within a research plot, that can affect results. For example, the authors have observed spatial differences of 1.0 °C or more within a couple of hundred metres in an orchard during a freeze night, measured at the same height above the ground on flat terrain. Therefore, it is somewhat questionable that T_c values from shelter temperatures are universally applicable.

Many researchers have cut small branches from trees and placed them in climate control chambers where the excised branches were cooled to a range of subzero temperatures and the damage was observed. While this process is more standardized than field measurements, the microclimate inside of a climate control chamber is not the same as branches exposed to the sky. For example, one could determine the amount of damage for branches exposed to 30 minutes at a range of temperatures, but within a tree the uncut branches will have a broad range of temperatures. Branches in the upper tree canopy will be exposed to the sky and therefore will probably be colder than air temperature. Conversely, branches embedded in the canopy are likely to be warmer and thus less prone to damage. In deciduous trees before the leaves develop fully, there is usually an inversion from the ground upward, so the coldest air temperatures are near the bottom of the trees. When trees have most of their leaves expanded, however, the minimum temperature, on radiation frost nights, rises to the height where most leaves are. In any case, using temperatures from a weather shelter only provides a rough guideline for expected damage.

In addition to variations of plant part temperatures within a tree and spatially throughout an orchard, vineyard or field, there are also variations in INA bacteria, which are now known to be a factor determining how low plants will supercool. To our knowledge, no researchers have taken into account differences in ice-nucleating bacteria concentrations when evaluating critical temperatures. For example, almond trees are known to have large concentrations of INA bacteria. If one block of an orchard was sprayed with bactericides that reduced the INA bacterial population and another was not sprayed, then the critical temperature for the block with fewer bacteria should have lower critical temperatures. This is another factor that complicates the decision about starting active protection methods. In general, the best approach is to use the published values as a guideline and start and stop protection based on an additional safety factor correction to published T_c values. It is better to err on the high side.

It is important to note that critical temperatures determined in a laboratory are obtained in carefully controlled freezers with slow air movement. The air temperature in the freezer is lowered in small, predetermined steps and held for 20 to 30 minutes or more after each step to allow the buds to come into equilibrium. This practice has given rise to the common misconception that buds have to be at a temperature for 20 to 30 minutes or so before damage will occur. The truth is that for short periods (2 to 24 h) the duration plant tissue is below a particular temperature is less important than how low the temperature goes (Levitt, 1980). Plant tissues cool at a rate dependent on the radiation balance and the temperature difference between the tissue and its environment. Therefore, if the air suddenly drops several degrees the tissue can rapidly cool below critical levels and result in freeze injury. If the plant tissue contains supercooled water, mechanical shock or agitation of the leaves and buds by wind machines or helicopters could initiate ice crystal formation, resulting in damage even if the tissues are above the chamber-determined critical temperature values. However, the chamber values provide guidelines as to when freeze protection measures need to be implemented.

ANNUAL AND BIENNIAL CROPS

Vegetable crop damage symptoms vary widely and can sometimes be confused with biotic damage. Table 4.3 shows a list of frost damage symptoms of some vegetable crops. Species differ greatly in their resistance to frost, but the maximum level of resistance is only attained when environmental conditions allow hardening to take place. Variety is often as important as species in defining resistance to frost, specially when there are winter and spring types. In general, also, there is an inverse relation between earliness of a variety and frost resistance.

Field experiments on critical damage temperatures for fresh fruits and vegetable crops are somewhat limited, but the highest freezing temperatures from studies on fruit and vegetable storage are provided in Table 4.4. Although the critical damage temperatures might be slightly higher than the air temperatures at which damage is expected under field conditions, the information in Table 4.4 can be useful as a guide.

During severe frost events with no snow, the young leaves of grasses and winter cereals seedlings may be damaged, but recovery is possible if the tillering node is not affected. However, if this meristem is damaged, winterkill will occur.

TABLE 4.3

Frost damage symptoms for vegetable crops (Caplan, 1988)

CROP	SYMPTOMS
Artichoke	Epidermis becomes detached and forms whitish to light tan blisters. When blisters are broken, underlying tissue turns brown.
Asparagus	Tip becomes limp and dark and the rest of the spear is water soaked. Thawed spears become mushy.
Beet	External and internal water soaking and sometimes blackening of conductive tissue.
Broccoli	The youngest florets in the centre of the curd are most sensitive to freezing injury. They turn brown and give off strong odour.
Cabbage	Leaves become water soaked, translucent and limp. Upon thawing the epidermis separates.
Carrot	Blistered appearance, jagged length-wise cracks. Interior becomes water soaked and darkens upon thawing.
Cauliflower	Curds turn brown and have a strong off-odour when cooked.
Celery	Leaves and petioles appear wilted and water soaked upon thawing. Petioles freeze more readily than leaves.
Garlic	Thawed cloves appear greyish yellow and water soaked.
Lettuce	Blistering of dead cells of the separated epidermis on outer leaves, and become tan with increased susceptibility to physical damage and decay.
Onion	Thawed bulbs are soft, greyish yellow and water soaked in cross-section. Damage is often limited to individual scales.
Pepper, bell	Dead, water-soaked tissue in part or all of pericarp surface with pitting, shrivelling and decay follow thawing.
Potato	Freezing injury may not be externally evident, but shows as grey or bluish-grey patches beneath the skin. Thawed tubers become soft.
Radish	Thawed tissues appear translucent and the roots soften and shrivel.
Sweet potato	A yellowish-brown discoloration of the vascular ring and a yellowish green, water-soaked appearance of other tissues. Roots soften and become susceptible to decay.
Tomato	Water soaked and soft upon thawing. In partially frozen fruits, the margin between healthy and dead tissue is distinct, especially in green fruits.
Turnip	Small water-soaked spots or pitting on the surface. Injured tissues appear tan or grey and give off an objectionable odour.

TABLE 4.4

The highest freezing temperature for fresh fruits and vegetables

COMMON NAME	SCIENTIFIC NAME	TEMPERATURE (°C)
Acerola; Barbados cherry	*Malpighia glabra*	-1.4
Apple	*Malus pumila*	-1.5
Apricot	*Prunus armeniaca*	-1.1
Artichoke – globe	*Cynara scolymus*	-1.2
Artichoke – Jerusalem	*Helianthus tuberosus*	-2.5
Asian pear, Nashi	*Pyrus serotina; P. pyrifolia*	-1.6
Asparagus, green, white	*Asparagus officinalis*	-0.6
Avocado	*Persea americana*	
cv. Fuerte, Hass		-1.6
cv. Fuchs, Pollock		-0.9
cv. Lula, Booth		-0.9
Banana	*Musa paradisiaca* var. *sapientum*	-0.8
Barbados cherry	*Malpighia glabra*	-1.4
Beans		
Snap; Wax; Green	*Phaseolus vulgaris*	-0.7
Lima beans	*Phaseolus lunatus*	-0.6
Beet, bunched	*Beta vulgaris*	-0.4
Beet, topped		-0.9
Berries		
Blackberries	*Rubus* spp.	-0.8
Blueberries	*Vaccinium corymbosum*	-1.3
Cranberry	*Vaccinium macrocarpon*	-0.9
Dewberry	*Rubus* spp.	-1.3
Elderberry	*Sambucus* spp.	-1.1
Loganberry	*Rubus* spp.	-1.7
Raspberries	*Rubus idaeus*	-0.9
Strawberry	*Fragaria* spp.	-0.8
Broccoli	*Brassica oleracea* var. *italica*	-0.6
Brussels-sprouts	*Brassica oleracea* var. *gemmifera*	-0.8
Cabbage		
Chinese; Napa	*Brassica campestris* var. *pekinensis*	-0.9
Common, early crop	*Brassica oleracea* var. *capitata*	-0.9
Late crop	—"—	-0.9
Cactus pear, prickly pear fruit	*Opuntia* spp.	-1.8
Carambola, Starfruit	*Averrhoa carambola*	-1.2
Carrots, topped	*Daucus carota*	-1.4
Cauliflower	*Brassica oleracea* var. *botrytis*	-0.8
Celeriac	*Apium graveolens* var. *rapaceum*	-0.9

COMMON NAME	SCIENTIFIC NAME		TEMPERATURE (°C)
Celery	*Apium graveolens* var. *dulce*		-0.5
Cherimoya; custard apple	*Annona cherimola*		-2.2
Cherry, sour	*Prunus cerasus*		-1.7
Cherry, sweet	*Prunus avium*		-2.1
Chicory	see *Endive*		
Chilies	see *Pepper*		
Citrus			
Calamondin orange	*Citrus reticulata x Fortunella* spp.		-2.0
California & Arizona, (USA) dry areas			-1.1
Florida (USA), humid areas			-1.1
Lemon	*Citrus limon*		-1.4
Lime, Mexican,	*Citrus aurantifolia;*		-1.6
Orange	*Citrus sinensis*		
California & Arizona (USA), dry areas			-0.8
Florida (USA), humid areas			-0.8
Blood orange			-0.8
Seville; sour	*Citrus aurantium*		-0.8
Pummelo	*Citrus grandis*		-1.6
Tangelo, Minneola	*Citrus reticulata x paradisi*		-0.9
Tangerine	*Citrus reticulata*		-1.1
Chives	*Allium schoenoprasum*		-0.9
Coconut	*Cocos nucifera*		-0.9
Collards, kale	*Brassica oleracea* var. *acephala*		-0.5
Corn, sweet and baby (maize)	*Zea mays*		-0.6
Cucumber, slicing	*Cucumis sativus*		-0.5
Currants	*Ribes* spp.		-1.0
Custard apple	see *Cherimoya*		
Dasheen	see *Taro*		
Date	*Phoenix dactylifera*		-15.7
Dill	*Anethum graveolens*		-0.7
Eggplant	*Solanum melongena*		-0.8
Endive, Escarole	*Cichorium endivia*		-0.1
Fennel	*Foeniculum vulgare*		-1.1
Fig	*Ficus carica*		-2.4
Garlic bulb	*Allium sativum*		-2.0
Gooseberry	*Ribes grossularia*		-1.1
Grape	*Vitis vinifera*	*fruit*	-2.7
		stem	-2.0

COMMON NAME	SCIENTIFIC NAME	TEMPERATURE (°C)
Grape, American	*Vitis labrusca*	-1.4
Horseradish	*Armoracia rusticana*	-1.8
Jujube; Chinese date	*Ziziphus jujuba*	-1.6
Kale	*Brassica oleracea* var. *acephala*	-0.5
Kiwano	see *African horned melon*	
Kiwifruit;	*Actinidia chinensis*	-0.9
Kohlrabi	*Brassica oleracea* var. *gongylodes*	-1.0
Leafy greens		
Cool season	*various genera*	-0.6
Warm season	*various genera*	-0.6
Leek	*Allium porrum*	-0.7
Lettuce	*Lactuca sativa*	-0.2
Longan	*Dimocarpus longan*	-2.4
Loquat	*Eriobotrya japonica*	-1.9
Mango	*Mangifera indica*	-1.4
Melons		
Cantaloupes, netted melons	*Cucurbita melo* var. *reticulatus*	-1.2
Casaba	*Cucurbita melo*	-1.0
Crenshaw	*Cucurbita melo*	-1.1
Honeydew, orange-flesh	*Cucurbita melo*	-1.1
Persian	*Cucurbita melo*	-0.8
Mombin	see *Spondias*	
Mushrooms	*Agaricus,* other *genera*	-0.9
Nashi	see *Asian pear*	
Nectarine	*Prunus persica*	-0.9
Okra	*Abelmoschus esculentus*	-1.8
Olives, fresh	*Olea europea*	-1.4
Onions	*Allium cepa*	
Mature bulbs, dry		-0.8
Green onions		-0.9
Papaya	*Carica papaya*	-0.9
Parsley	*Petroselinum crispum*	-1.1
Parsnip	*Pastinaca sativa*	-0.9
Peach	*Prunus persica*	-0.9
Pear, European	*Pyrus communis*	-1.7
Peas (pod, snow, snap, sugar)	*Pisum sativum*	-0.6
Peppers		
Bell Pepper, Paprika	*Capsicum annuum*	-0.7
Hot peppers, Chiles	*Capsicum annuum* and *C. frutescens*	-0.7
Persimmon, kaki	*Diospyros kaki*	
Fuyu		-2.2
Hachiya		-2.2

COMMON NAME	SCIENTIFIC NAME	TEMPERATURE (°C)
Pineapple	*Ananas comosus*	-1.1
Plantain	*Musa paradisiaca* var. *paradisiaca*	-0.8
Plums and Prunes	*Prunus domestica*	-0.8
Pomegranate	*Punica granatum*	-3.0
Potato, early crop	*Solanum tuberosum*	-0.8
late crop		-0.8
Pumpkin	*Cucurbita maxima*	-0.8
Quince	*Cydonia oblonga*	-2.0
Radish	*Raphanus sativus*	-0.7
Rhubarb	*Rheum rhaponticum*	-0.9
Rutabaga	*Brassica napus* var. *napobrassica*	-1.1
Salsify, vegetable oyster	*Trapopogon porrifolius*	-1.1
Sapotes		
Caimito, star apple	*Chrysophyllum cainito*	-1.2
Canistel, eggfruit	*Pouteria campechiana*	-1.8
Black sapote	*Diospyros ebenaster*	-2.3
White sapote	*Casimiroa edulis*	-2.0
Shallot	*Allium cepa* var. *ascalonicum*	-0.7
Spinach	*Spinacia oleracea*	-0.3
Squash		
Summer (soft rind); courgette	*Cucurbita pepo*	-0.5
Winter (hard rind); calabash	*Cucurbita moschata; C. maxima*	-0.8
Star-apple	see *Sapotes*	
Starfruit	see *Carambola*	
Strawberry	see *Berries*	
Sweet potato, yam [in USA]	*Ipomoea batatas*	-1.3
Tamarind	*Tamarindus indica*	-3.7
Taro, cocoyam,	*Colocasia esculenta*	-0.9
Tomato	*Lycopersicon esculentum*	
mature green		-0.5
firm ripe		-0.5
Turnip root	*Brassica campestris* var. *rapifera*	-1.0
Watercress;	*Lepidium sativum*	-0.3
Watermelon	*Citrullus vulgaris*	-0.4
Witloof chicory (endive)		-0.1
Yam	*Dioscorea* spp.	-1.1

SOURCE: From Whiteman, 1957, as reported in the University of California, Davis, Postharvest web page: http://postharvest.ucdavis.edu/Produce/Storage/prop_a.shtml.
NOTE: Some taxonomic names may have changed since 1957.

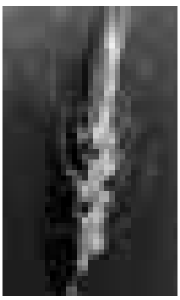
In early and late winter and in early spring, plants may be less hardy, which enhances damage. Snow retention reduces this type of damage (Ventskevich, 1958). Later in the season, during flowering and initial grain growth of cereals, frost damage reduces the number of kernels per spike. The visual result is that a bleached and thinner band forms on the spikes for each frost event, awns become curly, and because the weight of grain is less, spikes are upright near maturity (Figure 4.2).

For cereal crops, the relative resistance to freezing of cereals is (from most resistant): Rye > Bread wheat > Triticale > Barley > Oats and Durum wheat. During the winter, the critical temperatures change in relation to the degree of hardening. However, when hardening is complete, no plant destruction occurs with temperatures that range between -40 to -45 °C for rye, up to above -10 °C for durum wheat (Lecomte, 1989).

Freezing can damage many field crops including annual forage and silage crops, which lose leaf area and hence decrease dry matter production. Table 4.5 shows the critical temperatures for many field crops relative to phenological stages.

FIGURE 4.2

Frost damage to wheat crop



The terminal third of the spike is thinned and the awns are curled (above); and later the spikes remain upright since the grain weight is small (right).

Photos: J P de Melo-Abreu (ISA)

TABLE 4.5

A range of critical damage temperatures (°C) for grain, forage and silage crops

CROP	GERMINATION	FLOWERING	FRUITING
Spring wheat	-9, -10	-1, -2	-2, -4
Oats	-8, -9	-1, -2	-2, -4
Barley	-7, -8	-1, -2	-2, -4
Peas	-7, -8	-2, -3	-3, -4
Lentils	-7, -8	-2, -3	-2, -4
Vetchling	-7, -8	-2, -3	-2, -4
Coriander	-8, -10	-2, -3	-3, -4
Poppies	-7, -10	-2, -3	-2, -3
Kok-saghyz	-8, -10	-3, -4	-3, -4
Lupin	-6, -8	-3, -4	-3, -4
Spring vetch	-6, -7	-3, -4	-2, -4
Beans	-5, -6	-2, -3	-3, -4
Sunflower	-5, -6	-2, -3	-2, -3
Safflower	-4, -6	-2, -3	-3, -4
White mustard	-4, -6	-2, -3	-3, -4
Flax	-5, -7	-2, -3	-2, -4
Hemp	-5, -7	-2, -3	-2, -4
Sugar-beet	-6, -7	-2, -3	–
Fodder-beet	-6, -7	–	–
Carrot	-6, -7	–	–
Turnip	-6, -7	–	–
Cabbage	-5, -7	-2, -3	-6, -9
Soybeans	-3, -4	-2, -3	-2, -3
Italian millet	-3, -4	-1, -2	-2, -3
European yellow lupine	-4, -5	-2, -3	–
Corn [maize]	-2, -3	-1, -2	-2, -3
Millet	-2, -3	-1, -2	-2, -3
Sudan grass	-2, -3	-1, -2	-2, -3
Sorghum	-2, -3	-1, -2	-2, -3
Potato	-2, -3	-1, -2	-1, -2
Rustic tobacco	-2, -3	–	-2, -3
Buckwheat	-1, -2	-1, -2	-0.5, -2
Castor plant	-1, -1.5	-0.5, -1	-2
Cotton	-1, -2	-1, -2	-2, -3
Melons	-0.5, -1	-0.5, -1	-1
Rice	-0.5, -1	-0.5, -1	-0.5, -1
Sesame	-0.5, -1	-0.5, -1	–
Hemp mallow	-0.5, -1	–	–
Peanut	-0.5, -1	–	–
Cucumber	-0.5, -1	–	–
Tomato	0, -1	0, -1	0, -1
Tobacco	0, -1	0, -1	0, -1

SOURCE: After Ventskevich, 1958.

PERENNIAL CROPS

The limits of the natural distribution of many plants including some deciduous fruit trees are related to the minimum temperature at which supercooling can occur (i.e. homogeneous nucleation point), which is near -40 °C. Below the homogeneous nucleation point, freezing is intracellular and lethal (Burke *et al.*, 1976; Weiser *et al.*, 1979; Ikeda, 1982).

FRUIT TREES

Generally, deciduous crop sensitivity to freezing temperature increases from first bloom to small-nut or -fruit stages, and this is when a crop is most likely to be damaged. Sensitivity is also higher when warm weather has preceded a freeze night than if the cold temperatures preceded the freeze. Plants are known to harden against freezing when exposed to cold temperatures over long periods and this hardening is lessened if exposed to warm temperatures. Considerable information on sensitivity of deciduous fruit trees relative to phenological stages are provided on the Washington State University – Prosser Research and Extension Centre WEB site (http://fruit.prosser.wsu.edu/frsttables.htm) and on the Michigan State University – Van Buren County Cooperative Extension Web site: (http://www.msue.msu.edu/vanburen/crittemp.htm). On both Web sites, photographs are provided to display the phenological stages for a variety of crops. Another review on spring frost injury and hardiness is presented in Rodrigo (2000).

Although less common than spring injury, winter frost injury typically affects deciduous fruit trees. In northern production areas, when winters are very severe, bark, woody tissue or buds can freeze. Bark injuries include:

- crotch area injuries, which occur in trees with narrow crotch angles that harden late or sometimes incompletely;
- sunscald injuries on sunny, cold winter days, when clouds then block the sun and cause a rapid cooling towards air temperature that may produce freezing;
- bark splitting, which may occur under very cold conditions; and
- trunk, collar and root injuries that occur when the soil protective effect is insufficient to avoid freezing of those plant parts (Myers, 1988).

Under extreme winter temperatures, or when trees fail to harden-off, woody tissues of branches are damaged (tip dieback) or trunks freeze (blackheart). In blackheart, xylem cells are killed, the wood oxidises, becomes dark and discoloured and the vessels fill with gummy occlusions. Blackheart usually doesn't kill the trees immediately, but opportunistic wood rotting organisms invade the injured trees and reduce productivity and longevity. Dormant winter buds often supercool to very low temperatures (e.g. -25 °C in peach winter buds and -41 °C for buds of azaleas). Winterkill of buds and bark tissues commonly occurs in plants that partially lose hardiness due to relatively warm periods. During spring-time, supercooling capacity gradually reduces as the buds expand and form flowers. Fully open flowers typically have critical temperatures between -1 °C and -3 °C (Burke *et al*., 1976).

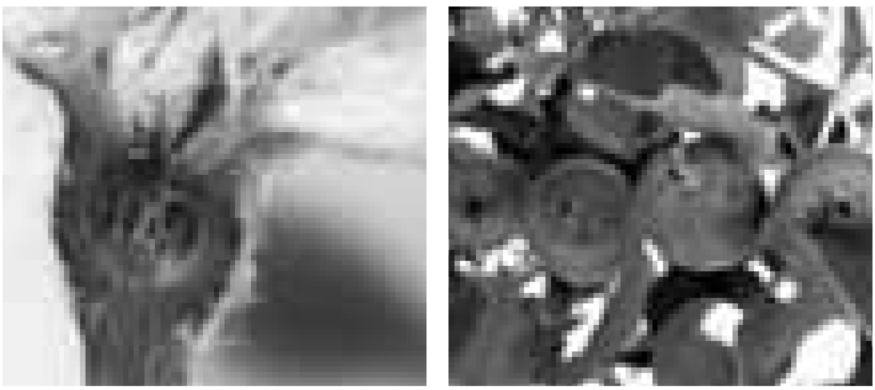
Flowers are often damaged by spring frosts and the symptoms are darkened petals. Usually the flower style is more sensitive than the ovary to frost damage. After fertilization, the seeds are the most sensitive organs. A few days after a freeze event, the proportion of damaged flowers is obvious. When cut with a knife, healthy flowers have light green interior while damaged flowers are brownish (Figure 4.3A).

Seeds are essential for the normal development of most fruits, but some varieties of damaged apples and pears are able to sustain parthenocarpic development to yield misshapen fruits. Stone fruits are more susceptible to seed loss because they have only one or two seeds, while apples and pears are less susceptible, having more seeds.

When fruit experiences freeze injury, a coarse russet tissue grows and covers a portion or even the entire outside of the fruit. Although the damage can originate much earlier, russet rings show after full bloom (Figure 4.3B).

FIGURE 4.3

Frost damage to an apple flower (left); and on small fruits (right) [russet patches near the eyes and rings].



Photos: A. Castro Ribeiro (ESAB, IPB, Portugal)

Table 4.6 lists critical temperatures for almond tree varieties, where some of the data came from field observations using temperatures from standard shelters and some came from excised-branch climate chamber studies. In the table, the full-bloom data for cv. Peerless are somewhat different for the field and chamber data, which illustrates the problem when comparing chamber studies with field observations. According to Hansen's full-bloom data, 25 percent damage would be expected at -2.2 °C, whereas only 1 percent damage was observed at -2.2 °C in the chamber studies. In general, for the same damage level, temperatures from chamber studies tend to be lower than from field studies. Therefore, the critical damage temperatures in the field are likely to be higher and damage could result when critical temperatures from chamber studies are used. If the bud, blossom or small-nut temperatures were measured directly in the field rather than using shelter temperatures, then the critical temperatures should be closer to those observed in the chamber studies. However, measuring bud, blossom or small-nut temperatures is not simple. The main point is that published critical temperatures should not be viewed as absolutely correct, but only as a guideline for making decisions about when to start and stop active protection methods.

TABLE 4.6

Damage expected (%) to some almond varieties at various development stages after 30 minutes below the indicated temperature

VARIETY		STAGE	TEMPERATURE °C							
			-5.6	**-5.0**	**-4.4**	**-3.9**	**-3.3**	**-2.8**	**-2.2**	**-1.7**
Peerless	[F]	Full bloom				100	75	45	25	
		showing pink		100	75	50	25			
Peerless	[C]	full bloom				79	50	14	1	
		petal fall						63	14	3
		nut stage						46	45	9
NePlus Ultra	[F]	full bloom			100	75	50	25		
Mission	[F]	showing pink	100	80	60					
Drake	[F]	full bloom		100	75	50	25			
		showing pink	75	50	25					
Nonpareil	[F]	full bloom	75	60	40	20				
		showing pink	20	10						
Nonpareil	[C]	nut stage						19	14	3
Butte	[C]	nut stage					90	45	27	10

NOTES: [C] indicates tests with excised branches in a freezing chamber (Connell and Snyder, 1988).
[F] indicates results of several years of unpublished field observations by Harry Hansen (retired USA National Weather Service) using a Stevenson screen and fruit frost shelter temperatures.

Table 4.7 contains a listing of the widely used deciduous tree crop critical temperatures corresponding to the main phenological stages (Proebsting and Mills, 1978). While these critical temperatures were developed in chamber studies, they do provide some guidance as to critical temperatures for use in the field. To account for the difference between field and chamber measured critical temperatures, the T_c values to use for management in the field should be slightly higher than those listed in the table.

TABLE 4.7

Critical temperature (T_c; °C) values for several deciduous fruit tree crops

CROP	STAGE	10% KILL	90% KILL
Apples	Silver tip	-11.9	-17.6
	Green tip	-7.5	-15.7
	1/2" green	-5.6	-11.7
	Tight cluster	-3.9	-7.9
	First pink	-2.8	-5.9
	Full pink	-2.7	-4.6
	First bloom	-2.3	-3.9
	Full bloom	-2.9	-4.7
	Post bloom	-1.9	-3.0
Apricots	Tip separates	-4.3	-14.1
	Red calyx	-6.2	-13.8
	First white	-4.9	-10.3
	First bloom	-4.3	-10.1
	Full bloom	-2.9	-6.4
	In shuck	-2.6	-4.7
	Green fruit	-2.3	-3.3
Cherries (Bing)	First swell	-11.1	-17.2
	Side green	-5.8	-13.4
	Green tip	-3.7	-10.3
	Tight cluster	-3.1	-7.9
	Open cluster	-2.7	-6.2
	First white	-2.7	-4.9
	First bloom	-2.8	-4.1
	Full bloom	-2.4	-3.9
	Post bloom	-2.2	-3.6

CROP	STAGE	10% KILL	90% KILL
Peaches (Elberta)	First swell	-7.4	-17.9
	Caylx green	-6.1	-15.7
	Caylx red	-4.8	-14.2
	First pink	-4.1	-9.2
	First bloom	-3.3	-5.9
	Late bloom	-2.7	-4.9
	Post bloom	-2.5	-3.9
Pears (Bartlett)	Scales separate	-8.6	-17.7
	Blossom buds exposed	-7.3	-15.4
	Tight cluster	-5.1	-12.6
	First white	-4.3	-9.4
	Full white	-3.1	-6.4
	First bloom	-3.2	-6.9
	Full bloom	-2.7	-4.9
	Post bloom	-2.7	-4.0
Prunes (Italian)	First swell	-11.1	-17.2
	Side white	-8.9	-16.9
	Tip green	-8.1	-14.8
	Tight cluster	-5.4	-11.7
	First white	-4.0	-7.9
	First bloom	-4.3	-8.2
	Full bloom	-3.1	-6.0
	Post bloom	-2.6	-4.3

The 10 percent kill and 90 percent kill imply that 30 minutes at the indicated temperature is expected to cause 10 percent and 90 percent kill of the plant part affected during the indicated phenological stage.

SOURCE: Proebsting and Mills, 1978

GRAPES AND WINE GRAPES

Grapes and wine grapes are often damaged by spring-time frosts. Since leaves form first, they are more prone to damage, but flowers and small berries are also sometimes damaged. Full recovery is common for leaf damage, but fruit damage can reduce production. The occurrence of early autumn frosts increases susceptibility to fungi attacks (e.g. botrytis). During winter, dormant buds are very rarely damaged, since they can resist temperatures below -10 °C, down to -20 or even -30 °C (Leddet and Dereuddre, 1989). Table 4.8 shows critical temperatures for grapes in relation to developmental stage.

TABLE 4.8

Critical temperature (T_c) values (°C) for grapevines

		?	?
Grape [(1)]	New growth:		-1.1
	Woody vine:	-20.6	–
	French hybrids	-22.2	-23.3
	American		-27.8
		10% kill	90% kill
Grapes (cv. Concord)[(2)]	First swell	-10.6	-19.4
	Late swell	-6.1	-12.2
	Bud burst	-3.9	-8.9
	First leaf	-2.8	-6.1
	Second leaf	-2.2	-5.6
	Third leaf	-2.2	-3.3
	Fourth leaf	-2.2	-2.8

The 10 percent kill and 90 percent kill imply that 30 minutes at the indicated temperature is expected to cause 10 percent and 90 percent kill of the plant part affected during the indicated phenological stage

NOTES: (1) Krewer, 1988. The critical temperature was reported without giving the percentage kill.
(2) www.msue.msu.edu/vanburen/crtmptxt.htm.

OTHER SMALL FRUITS

Blackberries and blueberries are hardy in winter, so frost damage occurs almost exclusively to the flowers and small fruits during spring-time. In contrast, if protective measures are not implemented, strawberries and kiwifruit are damaged in cold winters. First bloom is critically important for strawberry production, so frost damage during that phase is serious. When young, the cambium of young kiwifruit is often damaged by relatively high temperatures in autumn and spring, as well as by frost during cold winters. The first expanded leaves are tender and hence sensitive to damage. Critical temperatures of several small-fruit crops are shown in Table 4.9.

TABLE 4.9

Critical temperature (T_c) values (°C) for several small fruits

CROP	PHENOLOGICAL STAGE		
		?	?
Blackberry[1]	Dormant flower buds		-73.0
	Open flower buds		-2.2
		?	?
Blackberry[1]	Dormant flower buds	-27.2	-28.9
	Open flower buds		-2.2
			90% kill
Blueberry[2]	Swelled flower buds		-6.1
	Individual flowers distinguishable		-3.9
	Flowers distinctly separated, corollas expanded but closed		-2.2
	Fully opened flowers		-0.6
			?
Kiwifruit[3]	Dormant flower buds		-18.0
	Green tip		-3.0
	Leaf veins visible		-2.0
	Expanded leaf		-1.5
	Individual flowers distinguishable		-1.0
			90% kill
Strawberry[2]	Tight bud		-5.6
	Tight with white petals		-2.2
	Full bloom		-0.6
	Immature fruit		-2.2

The 10 percent kill and 90 percent kill imply that 30 minutes at the indicated temperature is expected to cause 10 percent and 90 percent kill of the plant part affected during the indicated phenological stage.

SOURCES: (1) Krewer, 1988. The critical temperature was reported without giving the percentage kill. (2) Powel and Himelrick, 2000. (3) Vaysse and Jourdain, 1992.

CITRUS FRUITS

Most citrus do not have a pronounced and stable dormancy. Growth is only reduced in winter and a spread of 1 to 2 °C in the freezing point of fruits is common between orchards and varieties, and even between trees. As the air temperature drops during the night, the fruit temperature typically lags behind and it is often a few degrees Celsius higher than the air temperature, especially during the evening. The bigger the fruit, the greater the lag between fruit and air temperature. Supercooling plays also a role in the freezing temperature and explains the importance of freezing nuclei concentration and white frost or dew formation on the fruit surface. Also, it is known that the peel has a lower freezing temperature than the flesh inside. Therefore, frost damage can occur inside the fruit without any obvious damage on the outside. Despite all these confounding factors, some critical fruit temperatures for the major citrus crops are presented in Table 4.10.

TABLE 4.10

Critical fruit temperatures (T_c) when citrus fruits, buds or blossoms begin to freeze

CITRUS SPECIES	CRITICAL TEMPERATURE (°C)
Green oranges	-1.9 to -1.4
Half ripe oranges, grapefruit and mandarins	-2.2 to -1.7
Ripe oranges, grapefruit and mandarins	-2.8 to -2.2
Button lemons	-1.4 to -0.8
Tree ripe lemons	-1.4 to -0.8
Green lemons (diameter >12 mm)	-1.9 to -1.4
Lemon buds and blossoms	-2.8

SOURCE: After Puffer and Turrell, 1967.

When air temperature (T_a) drops rapidly following a warm day, citrus fruit temperatures (T_{cf}) lag behind the air temperature drop and the temperature difference (T_{cf} - T_a) is bigger for larger fruit. When protecting small fruit and there is a rapid air temperature drop after sunset, wind machines and heaters should be working when T_a reaches T_c (Table 4.10). For larger fruit, on nights with rapid air temperature drop during the evening, start the wind machines or heaters when T_a is slightly lower than T_c (e.g. when $T_a = T_c - 0.5$ °C). During mild advection frosts or on nights with higher humidity and slower temperature drop, T_{cf} is closer to T_a, so the wind machines or heaters should be working when the $T_a \approx T_c$ (Table 4.10). If the fruit and leaves are wet from rainfall, fog or dew and the wet-bulb temperature (T_w) is expected to fall below T_c during the night, wind machines and heaters should be started as soon as possible in the evening to dry the fruit surfaces before the wet fruit temperature falls below T_c. Otherwise, damage to the peel is likely.

During weather conditions when the air temperature is expected to reach the dew-point (T_d) temperature, which is higher than T_c and the predicted minimum temperature is below T_c, then it is wise to start the wind machines or heaters before T_a falls to T_d and dew or frost begins to condense on the fruit.

On nights following light rainfall or snow or when dew or frost forms on the fruit, damage can occur to the fruit rind even when the shelter temperature is above the critical damage fruit temperature. This occurs because the temperature of the wet part of the fruit can fall to the wet-bulb temperature, due to the removal of sensible heat as the water evaporates. This is the cause of rind spot damage that occurs in some years. This is also true for spot damage on deciduous fruit damage during autumn freezes. The wet-bulb temperature is always between the air and dew-point temperatures and the wet-bulb temperature is lower when the dew-point is low. If the fruit is wet going into a freeze night, protection should be started as early as possible. In these conditions, the objective is to evaporate the water off the fruit before the wet-bulb temperature reaches 0 °C. Using heaters or wind machines before nightfall will help to evaporate water off the plants. However, using wind machines when the fruit is wet after the wet-bulb temperature falls below the critical fruit damage could cause rind injury or worse. Table 4.11 gives the air temperature corresponding to a wet-bulb temperature $T_w = 0$ °C for a range of dew-point temperatures and elevations.

TABLE 4.11

Air temperatures (°C) corresponding to a wet-bulb temperature T_w = 0 °C for a range of dew-point temperatures and elevations

DEW-POINT TEMPERATURE	ELEVATION (METRES ABOVE MEAN SEA LEVEL)			
(°C)	0 m	500 m	1000 m	1500 m
0	0.0	0.0	0.0	0.0
-2	1.2	1.3	1.4	1.5
-4	2.3	2.5	2.6	2.8
-6	3.3	3.5	3.7	3.9
-8	4.1	4.4	4.6	4.9
-10	4.8	5.1	5.4	5.8
-12	5.4	5.8	6.1	6.5
-14	6.0	6.3	6.7	7.1
-16	6.4	6.8	7.2	7.7
-18	6.8	7.2	7.7	8.1

CHAPTER 5

FROST FORECASTING AND MONITORING

VALUE OF FROST FORECASTS

Assessing the value of frost forecasts involves complicated decision analysis, which uses conditional probabilities and economics. Accurate frost forecasting can potentially reduce frost damage because it provides growers with the opportunity to prepare for frost events. This chapter presents and discusses the value of frost forecasting, some frost forecasting models currently in use, and a simple model for on-farm prediction of minimum temperature during a radiation frost.

While decision analysis is used in many fields, applications to frost forecasting are limited. Papers by Banquet, Halter and Conklin (1976) and Katz, Murphy and Winkler (1982) have discussed using decision analysis to evaluate the cost-effectiveness of frost forecasts. Katz, Murphy and Winkler (1982) thoroughly investigated the value of frost forecasting in the Yakima Valley in Washington State, USA. This valley is well known for production of apples and to a lesser extent pears and peaches. The valley is also noted for a problem with frequent freezing during bud break, flowering and small-fruit stages of these crops. The authors used Markov decision processes in a model that structures the problem into identifying possible actions, events and consequences. Crop sensitivity to freezing changes during bud break, bloom and small-fruit stages, so logistic functions that relate crop loss to minimum temperature were derived for each developmental period where the relationship between damage and temperature was known. Then the utility of the frost forecast was evaluated by calculating the conditional standard deviation in minimum forecast using only climate data, current forecasts from the USA National Weather Service and a perfect forecast where the minimum temperature prediction is always correct. The standard deviation is "conditional" because it is based on an assumed level of forecast accuracy.

Based on climate data alone, Katz, Murphy and Winkler (1982) estimated that the conditional standard deviation of the minimum forecast would be 3.6 °C. By definition, the standard deviation is 0 °C for a perfect forecast. Based on forecaster skill in the 1970s, the "current" forecast conditional standard deviation was about 2.1 °C. Therefore, the National Weather Service forecast skill had improved the conditional standard deviation by 48 percent [i.e.] of the difference between using climate data and a perfect forecast. The relative values (i.e. economic value of the forecast divided by the total value of production), expressed in percentages, are shown in Table 5.1. The economic value of the forecast is the additional net value of production resulting from having the forecast. The table shows that increasing the current forecast skill to a perfect forecast would increase the relative values by an additional 18 percent, 15 percent and 23 percent for apples, pears and peaches. Therefore, except for peaches, the economic benefits from further improvements in forecast skill are smaller than comparable past improvements.

TABLE 5.1

Relative value (percent of total production) and total value of production ($ per hectare) for apples cv. Red Delicious, pears cv. Bartlett and peaches cv. Elberta in the Yakima Valley of Washington State (USA) using climatology, 1970s' forecasts from the National Weather Service, and a perfect forecast

FORECAST	APPLES	PEARS	PEACHES
Perfect	52	42	45
Current	34	27	22
Climatology	0	0	0
Total Value	$ 5 802 ha^{-1}	$ 4 586 ha^{-1}	$ 3 064 ha^{-1}

NOTES: Conditional standard deviations about the true minimum temperature were 3.6°C for climatology, 2.1°C for the current forecasts and 0°C for a perfect forecast (after Katz, Murphy and Winkler, 1982).

PREDICTING MINIMUM TEMPERATURES

Predicting when the temperature falls to a critical value is important for starting active frost protection methods. Starting and stopping protection at the proper temperature is important because it avoids losses resulting from starting too late and it saves energy by reducing the operation time of the various methods. While it is beyond the scope of this book to address minimum temperature forecasting with synoptic or mesoscale models, some guidelines are possible on how to forecast minimum temperature during radiation frost conditions, using local data.

Ideally, one would develop a microscale (i.e. local) temperature forecast model using energy balance calculations. This has been thoroughly reviewed by Kalma *et al.* (1992). The main conclusion of their review was that "air temperatures cannot be predicted satisfactorily from surface energy balance considerations alone, even if the difference between surface and air temperatures can be specified accurately". They attribute this inability to difficulties with: (1) measuring turbulent sensible heat flux in the range typical of frost nights; (2) accounting for advection; and (3) spatial variations in surface radiation emissivity. Rather than using the energy balance to study the rate of cooling of the ground surface, Kalma *et al*. (1992) proposed to estimate the rate of cooling of a column of air. However, they recognized that both radiative and turbulent sensible heat fluxes depend on vertical profiles of wind, humidity and temperature, which make the process impractical because of measurement problems.

Kalma *et al*. (1992) discuss the one-dimensional temperature prediction models of Sutherland (1980) and Cellier (1982, 1993). The Sutherland model uses a surface energy balance equation assuming that latent heat contributions are negligible, a soil heat flux model and a sensible heat flux model for the bottom 9.0 m of the atmosphere. The input variables are temperature at 0, 1.5, 3.0 and 9.0 m, soil temperature at 0.1 and 0.5 m depth, wind speed at 10 m and net radiation. This model was reported to forecast within 3 °C 90 percent of the time and 2 °C 82 percent of the time. Ultimately, the model was combined with a statistical model to improve the forecast over Florida, USA.

The Cellier (1982, 1993) temperature model calculates changes in temperature within eight layers up to a height of about 100 m in the atmosphere and down to 1.0 m in the soil. The input variables include mean soil temperature and wind speed and air temperature at 3.0 m height at the time when net radiation becomes negative, the most expected negative net radiation value and the dew-point temperature when the net radiation is at its most negative value. The model was reported to provide realistic surface energy balance estimates during the night, but improvements were needed in the estimation of soil heat transfer and atmospheric exchange coefficients (Kalma *et al*., 1992).

A working, deterministic energy balance model to estimate changes in temperature during frost events is preferable; however, no universally applicable model with easily attainable input variables is currently available. Many empirical models for predicting minimum temperature have been reported (Bagdonas, Georg and Gerber, 1978) and some are known to give reasonably accurate forecasts. For example, the equation from Young (1920) has been widely used by the USA National Weather Service (NWS) with considerable success throughout the western USA. However, Young' equation was not used directly but was calibrated for local conditions to account for the time of year and local conditions. These modifications are site specific and they are not widely published. It is unknown whether similar modifications are used to improve the multitude of prediction formulae that are used in various countries (Bagdonas, Georg and Gerber, 1978). Clearly, accounting for time of the year and local conditions should improve minimum temperature forecasting. In fact, Bagdonas, Georg and Gerber (1978) recommended that a forecast model that uses local meteorological factors and site-specific climate data is likely to give the best results. In addition to forecasting the minimum temperature, it is also useful to predict the temperature trend during a frost night. A model based on the original paper by Allen (1957) was used to develop the frost temperature trend model (FTrend.xls) included with this book. Another more complicated model was presented by Krasovitski, Kimmel, and Amir (1996).

CALIBRATING MESOSCALE TO MICROSCALE FORECASTS

For several decades, NWS Service provided fruit-frost forecasts to growers in regions of the USA with high-value crops sensitive to frost. Since the NWS forecasters have more experience forecasting and more and better facilities, they can provide more accurate predictions than a grower can make a day or two in advance of a frost. However, in the late 1980s, these services were dropped from the weather service and growers had to either employ private forecasters or develop their own methods to predict minimum temperatures for their crops.

When the fruit-frost service was operating, weather service meteorologists would forecast for key stations within a region and growers would develop correction factors to predict minimum temperatures in their crops. Generally, the corrections consisted of adding or subtracting a correction to the key station forecast. For example, a grower might subtract 0.5 °C from a key station forecast for a crop located in a low spot. In some cases, growers would use spreadsheets or statistical computer application programs to determine regression equations with the key station minimum temperatures as the independent and minimum temperatures in their crop as the dependent variable.

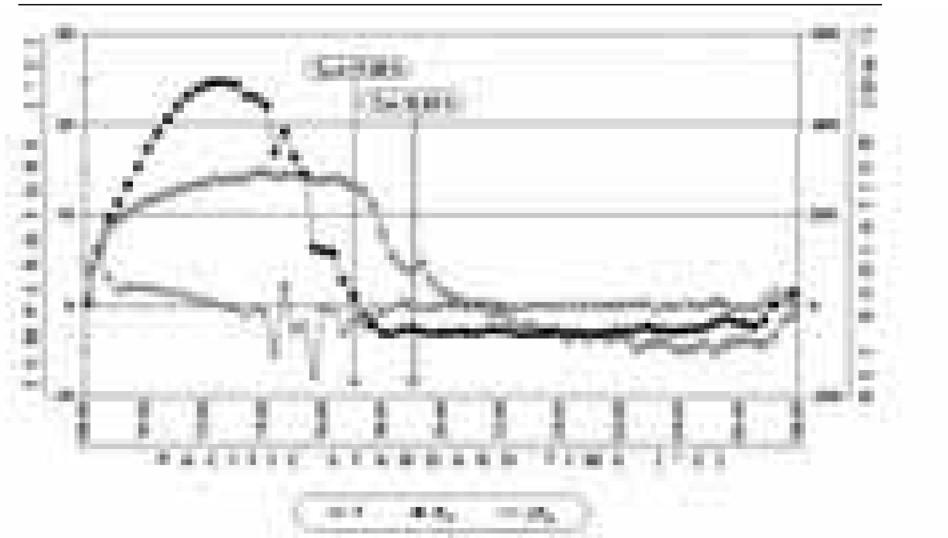
After the NWS fruit-frost forecasting service ended, large growers and those with serious frost problems would employ private weather forecast services to provide site-specific minimum temperature predictions. In many cases, groups of farmers would cooperate and hire a private forecaster to continue forecasting for the key stations used by the NWS. Then their correction factors could still be used to predict minimum temperatures in their crops. Although using correction factors and key stations for site-specific frost predictions is helpful for two- to three-day planning and management, the direct use of data collected in or near the crop is likely to give better predictions during a particular frost night. A method to develop local forecasts is presented in the next section.

A SIMPLE MINIMUM TEMPERATURE FORECAST MODEL

A simple, empirical forecast model (FFST.xls), which can easily be calibrated for local conditions, is included with this book. The model, which is based on the method of Allen (1957), uses historical records of air and dew-point temperature at two hours past sunset and the observed minimum temperature during clear sky, calm, frost nights to develop the regression coefficients needed to accurately predict the minimum temperature during a particular period of the year. Two hours past sunset is the starting time (t_0) for the model. This time corresponds to when the net radiation has reached its most negative value (Figure 5.1). Assuming there is little or no cloud cover or fog during the night, the net radiation changes little from time t_0 until sunrise the next morning. On a night with intermittent cloud cover or fog or variable wind speed, the model may predict a temperature that is lower than observed. The model may predict too high a minimum temperature if a cold front passes or if there is cold air drainage.

FIGURE 5.1

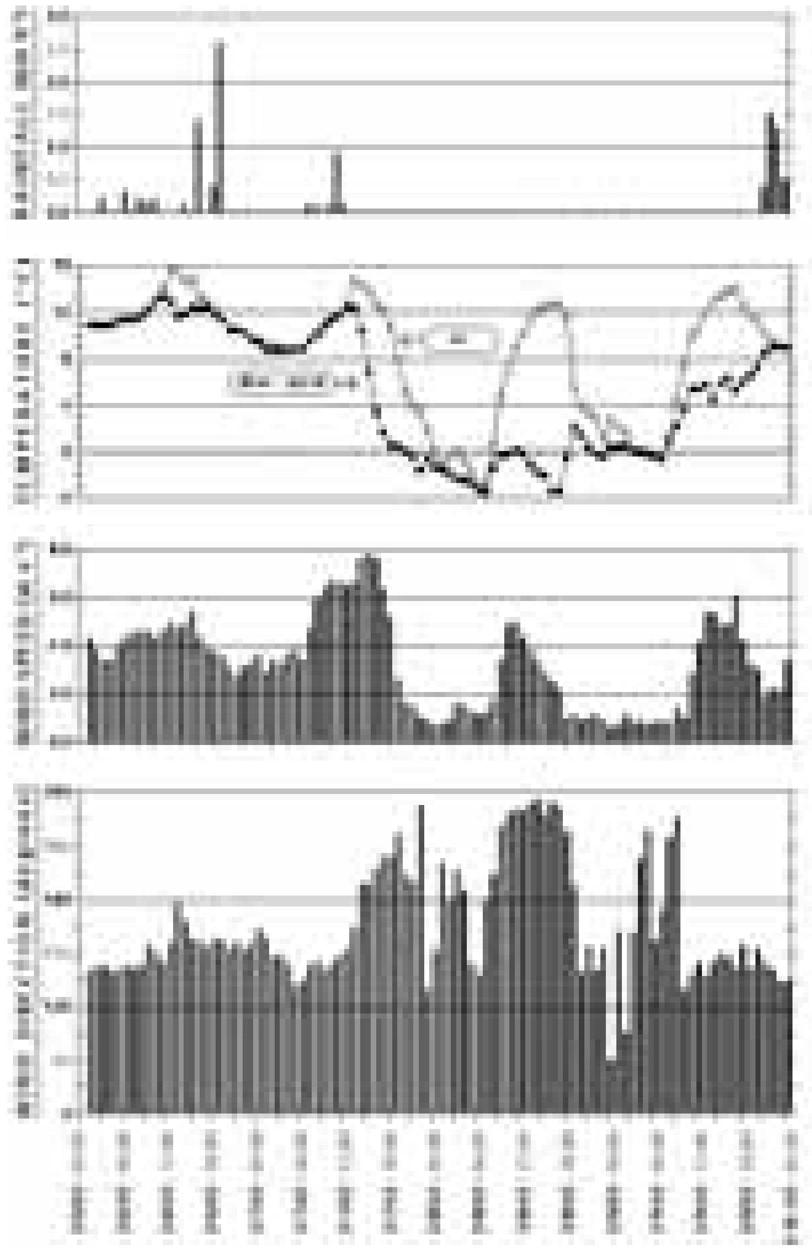
Air temperature at 2.0 m height, net radiation and change in net radiation using 20-minute-interval data collected during a frost night (28 February – 1 March 2002) in a walnut orchard near Ladoga, California (USA)



Key: T_{ss} = Time of sunset. T_O = 2 hours after sunset.

FIGURE 5.2

Sample weather data during an advection frost near Zamora, California (USA), in March 2002. Sunset was at about 1942 h. Dates are given in USA notation (mm/dd/yy)



For use in the FFST.xls application program, select data only from radiation frost nights. Avoid including nights with wind speeds greater than 2.0 m s^{-1} and nights with cloud cover or fog. For example, Figure 5.2 illustrates the data selection problem. On 6 March, there were rainy windy conditions, which continued until near noon on 7 March. Then the rain stopped, but the wind changed from a south to a west-northwest wind and the wind speed was high until about 2100 h. A sharp drop in dew-point temperature is typical of the passage of a cold front. Sunset occurred at about 1742 h, so the wind speed was high for more than three hours past sunset. Net radiation was not measured at this site, so information on cloud cover is unknown. However, intermittent cloud cover often follows a cold front. At two hours past sunset, the air and dew-point temperatures were 5.1 °C and 0.0 °C and the wind speed had just dropped from 2.6 to 1.6 m s^{-1}. There was still a large drop in temperature after this point, which is not characteristic of a radiation frost. Based on this weather data, the weather conditions on 7–8 March were too windy in the evening and they are not typical of a radiation frost. On 8–9 March, the air and dew-point temperatures were 3.9 °C and 1.4 °C at two hours past sunset and the wind speed dropped earlier in the evening (i.e. near sunset). There was no evidence of cold air advection, so the data from 8–9 March can be input into the FFST.xls application program to determine a forecast model. Note that one can use data from nights when the minimum air temperature does not fall below 0 °C as long as the night had clear skies and calm or little wind.

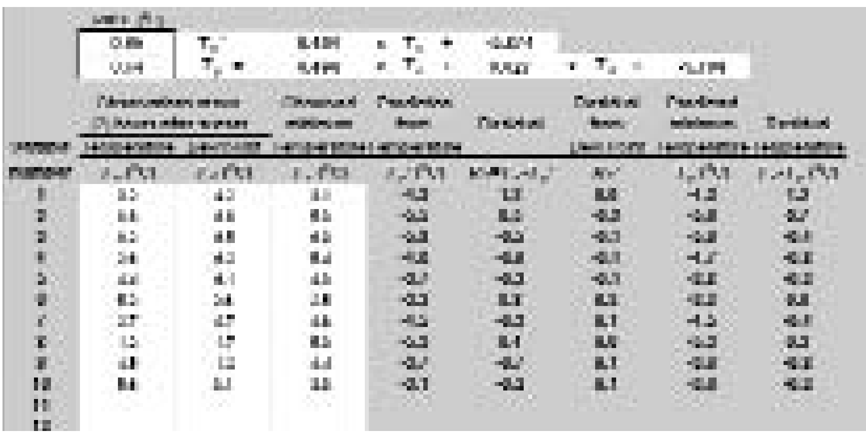
The FFST.xls application program is written in MS Excel for easy input and for graphic as well as tabular output. For as many as 50 nights, the air and dew-point temperature at two hours past sunset are input along with the observed minimum temperature the following morning. A sample input screen with 10 days of input data is shown in Figure 5.3.

In Figure 5.3, the input data were used to determine a linear regression of the observed minimum (T_n) versus the air temperature at two hours past sunset (T_0), and the results are shown in the “Prediction from Temperature (T_p')” column. The output equation for $T_p' = b_1 \times T_0 + a_1$ is shown at the top of the page. To the left of the equation, the root mean square error (RMSE) is shown. This statistic is similar to a standard deviation in that it is a measure of closeness of the predicted and observed values. In Figure 5.3, the RMSE is 0.65 °C for the formula based on the two hours past sunset temperature only. This implies that one deviation about the 1:1 line is approximately 0.65 °C, and two deviations about the 1:1 line would be about 1.3 °C. Assuming that the variation of the RMSE is about the same as a standard deviation, this means that the variation about the 1:1 line would be less than 1.3 °C about 85 percent of the time. After calculating T_p', the residuals ($R_1 = T_n - T_p'$) are calculated and displayed. Then, a linear regression of R_1 versus the dew-point temperature (T_d) is computed and the predicted residual (R_1') values are shown. If $T_p' = b_1 \times T_0 + a_1$ and $R_1' = b_2 \times T_d + a_2$, then the forecast minimum temperature is given by: $T_p = T_p'+R_1' = b_1 \times T_0 + b_2 \times T_d + (a_1+a_2)$. In the Excel program, the output equation $T_p = b_1T_o + b_2T_d + a_3$, where $a_3 = a_1 + a_2$, is displayed at the top of the input-calculation table for easy viewing. Again, the RMSE comparing observed and predicted minimum temperatures is shown to the left of the equation. In this particular data set, the RMSE values were nearly identical for both prediction equations, so there was no apparent advantage from including the dew-point temperature to predict the minimum temperature with this data set. However, including the dew-point temperature in the model will typically improve the prediction.

The FFST.xls program also plots the predicted versus observed temperatures for both the temperature only model (Figure 5.4) and for the temperature and dew-point prediction model (not shown).

FIGURE 5.3

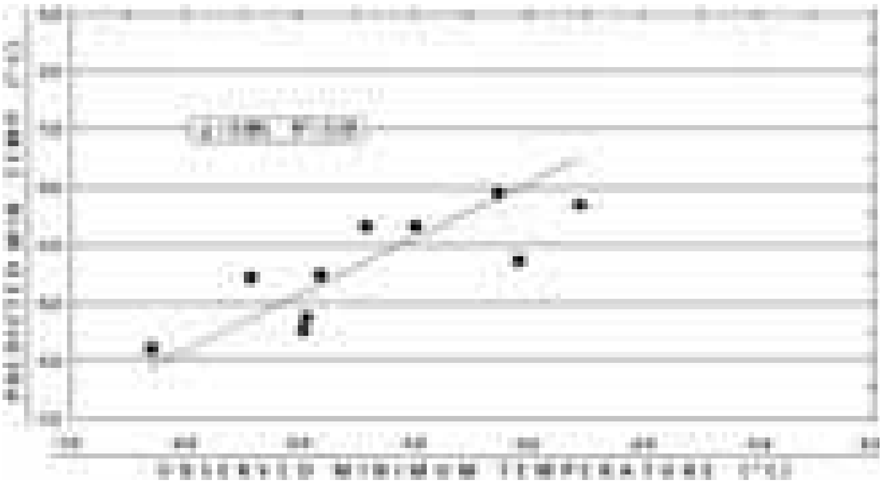
Sample input and calculations for the FFST.xls application program for predicting minimum temperature (T_p)



The data are from the December 1990 and 1998 frosts in the citrus growing region of Lindcove, California (USA).

FIGURE 5.4

Predicted versus observed minimum temperature from the data in Figure 5.3, using only the temperature data from two hours past sunset



A SIMPLE TEMPERATURE TREND FORECAST MODEL

In addition to predicting the minimum temperature, it is useful to have the temperature trend during the night to help determine when protection methods should be started and stopped. Knowing temperature trend during the night helps growers to foresee when active methods should be initiated during the night. The FTrend.xls model estimates temperature trends from two hours past sunset until sunrise the following morning. Sunset and sunrise are determined from the input latitude, longitude and date. The program uses an empirical temperature trend model to predict how the temperature will change during the night. This model uses a square root function to predict the air temperature from two hours after sunset (i.e. time t_0) until reaching the predicted minimum temperature (T_p) at sunrise (i.e. time t_p) the next morning. In addition to the air temperature, the application calculates the change in wet-bulb temperature based on temperature trend and initial dew-point temperature.

The FTrend.xls application contains the worksheets “Title”, “Help”, “Input”, “Plot”, “Wet-bulb” and “Forecast”. The Title and Help worksheets provide information on the developers and instructions on how to use the program. The Input worksheet is used to input temperature data and to display the results of the trend calculations. The Wet-bulb worksheet is used to calculate the air temperature corresponding to the air and dew-point temperature at a given elevation. It is used to help determine the air temperature to stop sprinklers following a frost night. The Forecast worksheet is used to calculate an estimate of the minimum temperature at sunrise the next morning using an input of the air and dew-point temperatures measured at two hours past sunset. In the following sections, these worksheets and their functions will be discussed.

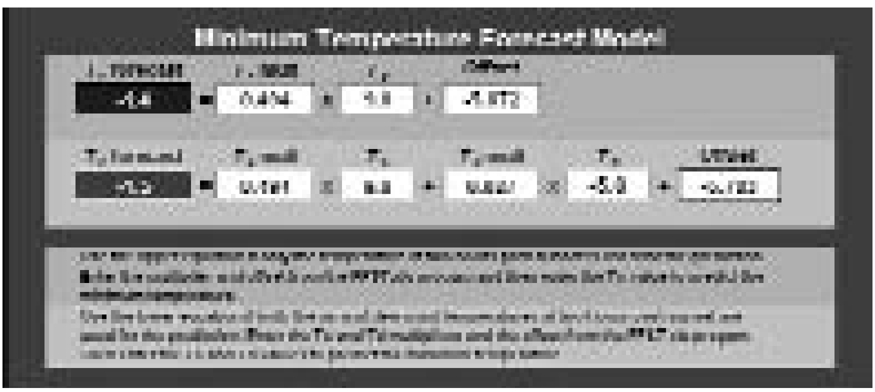
FORECAST WORKSHEET

A forecast of the sunrise temperature is needed for the FTrend.xls application. That forecast can come from a weather forecast service or from the model developed in the FFST.xls program. If a forecast service is used, then the “Forecast” worksheet in the FTrend.xls program is unnecessary. If the minimum temperature forecast comes from the FFST.xls program, then the “Forecast” worksheet in FTrend.xls is used to make the calculation.

Figure 5.5 shows a sample data entry for the “Forecast” worksheet. First the regression coefficients from either the $T_p' = b_1 \times T_0 + a_1$ or the $T_p = b_1T_o + b_2T_d + a_3$ equations are input into the appropriate cells in the Forecast worksheet (e.g. $b_1 = 0.494$, $b_2 = 0.027$, $a_1 = -5.872$ and $a_3 = -5.783$ in Figure 5.5). The two equations in the Forecast worksheet are completely independent and data can be entered in either one or both to forecast the minimum temperature. In Figure 5.5, the air temperature at two hours past sunset $T_0 = 9.0$ °C was entered in the upper equation and the forecast was $T_p = -1.4$ °C. The air and dew-point temperatures input into the lower equation were $T_0 = 9.0$ °C and $T_d = -5.0$ °C and the resulting prediction was $T_p = -1.5$ °C.

FIGURE 5.5

Sample minimum temperature forecast coefficient and temperature entry in the “Forecast” worksheet of the FTrend.xls application program

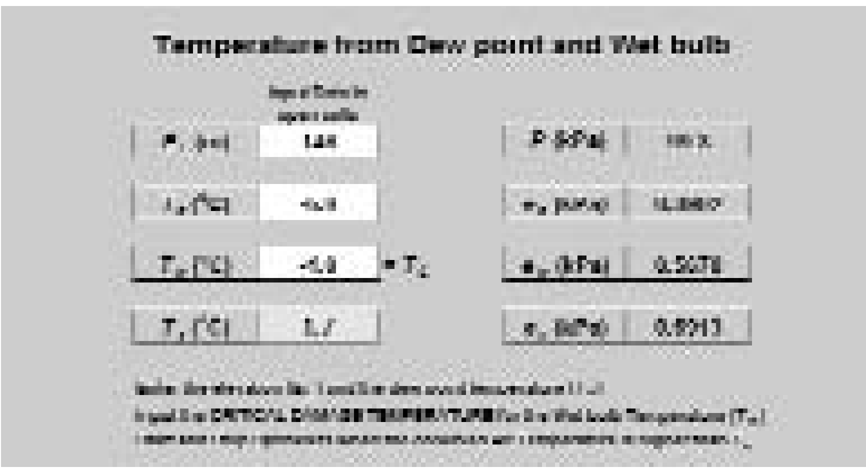


WET-BULB WORKSHEET

The worksheet Wet-bulb in the FTrend.xls application is for determining the air temperature corresponding to an input value for wet-bulb and dew-point temperature at a specified elevation. This is used to help determine when to start and stop the use of sprinklers for frost protection. A sample of the Wet-bulb worksheet is shown in Figure 5.6. In the example, the elevation was entered as E_L = 146 m above mean sea level. If the critical damage temperature for the protected crop is T_c = -1.0 °C, then T_w = -1.0 is input as shown in Figure 5.6. Recall that the critical temperature will vary depending on the crop, variety, phenological stage and hardening. In Figure 5.6, the value T_d = -6.0 °C was input for the dew-point temperature. After the elevation, wet-bulb and dew-point temperatures are entered, the program calculates the corresponding air temperature. When using sprinklers for frost protection, they should be started and stopped when the air temperature measured upwind from the protected crop is higher than the air temperature shown in the Wet-bulb worksheet. The Wet-bulb workshe*et al*so calculates the barometric pressure as a function of the elevation and the saturation vapour pressures at the dew-point (e_d), wet-bulb (e_w) and air temperatures (e_s). Note that the actual water vapour pressure (e) is equal to e_d.

FIGURE 5.6

Sample data entry and calculations from the Wet-bulb worksheet of the FTrend.xls application program



INPUT WORKSHEET

Predicting air temperature trend

The "Input" worksheet is used to enter the air temperature (T_0) at two hours past sunset and the predicted minimum temperature (T_p) the next morning (Figure 5.7). The latitude, longitude, elevation and local time meridian are entered into the Input worksheet to determine day length, the local standard time and constants that depend on the elevation. Enter positive latitude for the Northern (°N) and negative latitude for the Southern (°S) Hemisphere. Enter positive longitude for locations west of Greenwich (°W) and negative longitude for locations east of Greenwich (°E). Input the elevation in metres above mean sea level. The temperature trend during the night is calculated using a square root function and the results are displayed in the Input worksheet (Figure 5.7) and are plotted in the Plot chart (Figure 5.8) of the FTrend.xls application. A critical temperature $T_c = 1.5$ °C was entered in this case.

FIGURE 5.7

Sample of the "Input" worksheet of the FTrend.xls application with the air temperature at two hours past sunset when $T_0 = 4.4$ °C and the predicted minimum temperature $T_p = -4.0$ °C

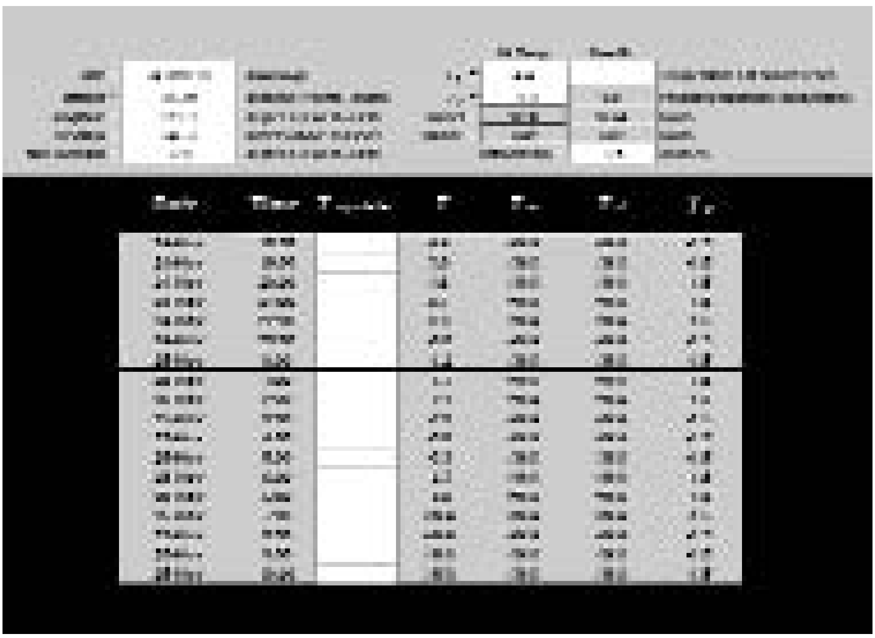
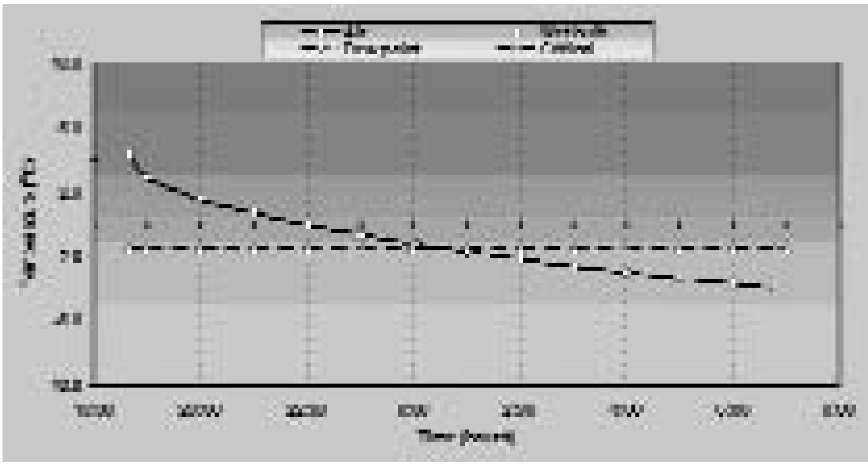


FIGURE 5.8

Sample plot resulting from data entry into the "Input" worksheet of the FTrendl.xls application, using the data shown in Figure 5.7



Predicting wet-bulb temperature trend

If the dew-point temperature at two hours past sunset is also entered into the Input worksheet, then the application will calculate the change in wet-bulb and dew-point temperature as well as air temperature. A sample of the Input worksheet with T_d = -2.8 °C is shown in Figure 5.9 and the plot is shown in Figure 5.10. The dew-point temperature is fixed at the input value during the night unless the air temperature drops below the input dew-point (Figure 5.10). Then the dew-point temperature falls with the air temperature to the predicted minimum temperature. For example, the air and dew-point both fell from T = -2.8 °C, when the air reached the dew-point temperature, to T_p = -4.0 °C at sunrise (Figure 5.10). This commonly occurs on nights when the air becomes saturated during the night.

The wet-bulb temperature curve in the FTrend.xls application is used to estimate when sprinklers need to be started for frost protection. For example, the wet-bulb temperature falls to the critical damage temperature T_c = -1.5 °C at 2300 h in Figure 5.10. In this situation, the sprinklers should be started prior to 2300 h before the wet-bulb temperature (T_w) falls below T_c = -1.5 °C. Assuming that the latitude, longitude and date are input correctly, the temperature trend plots go from two hours past sunset to sunrise (e.g. 1838 h to 0705 h in Figure 5.10).

FIGURE 5.9

A sample of the Input worksheet of the FTrend.xls application program with the additional entry of the dew-point temperature (T_d) at two hours past sunset

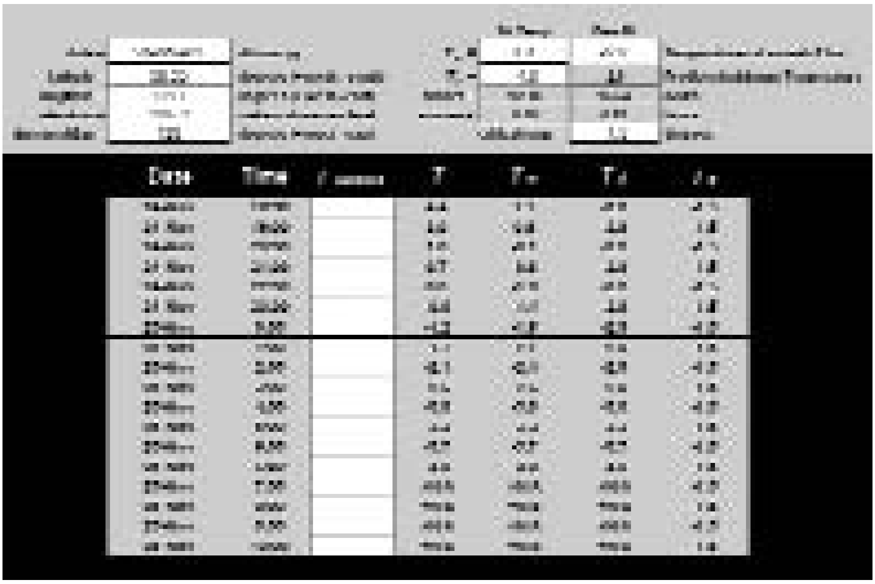
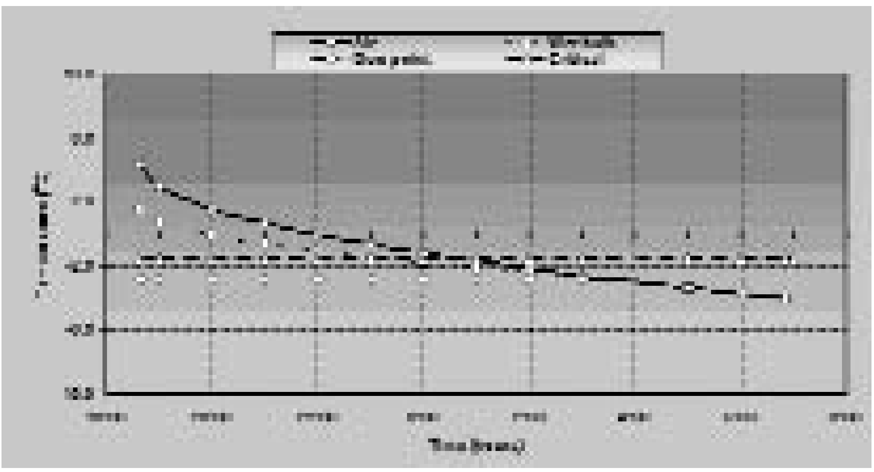


FIGURE 5.10

Sample plot resulting from data entry into the "Input" worksheet of the FTrendl.xls application using data from Figure 5.9 with a dew-point temperature of T_d = -2.8 °C at two hours past sunset



Deciding whether to start sprinklers

The Plot chart of the FTrend.xls application is also useful to help decide if the sprinkler should be used or not. For growers without soil waterlogging problems, shortage of water or concerns about cost, it is best to start the sprinklers when the wet-bulb temperature approaches either 0 °C or the critical damage temperature, depending on the value of the crop and concern about losses. However, for growers who are concerned about these problems, using the FTrend.xls application will help to determine when to start the sprinklers to minimize damage, waterlogging, energy usage and loss of water supply.

When using under-plant microsprinklers, the starting temperature is less important than for other sprinkler systems because mainly the ground and not the plants are wetted. When first started, there may be a small short-term temperature drop as the sprayed water evaporates; however, if the application rate is sufficient, the temperature should recover quickly. With under-plant microsprinklers, one can start when the air temperature approaches 0 °C, without too much risk. The same applies to conventional under-plant sprinkler systems that do not wet the lower branches of the trees. If the under-plant sprinklers do wet the lower branches, then the same starting criteria should be used as for over-plant sprinklers.

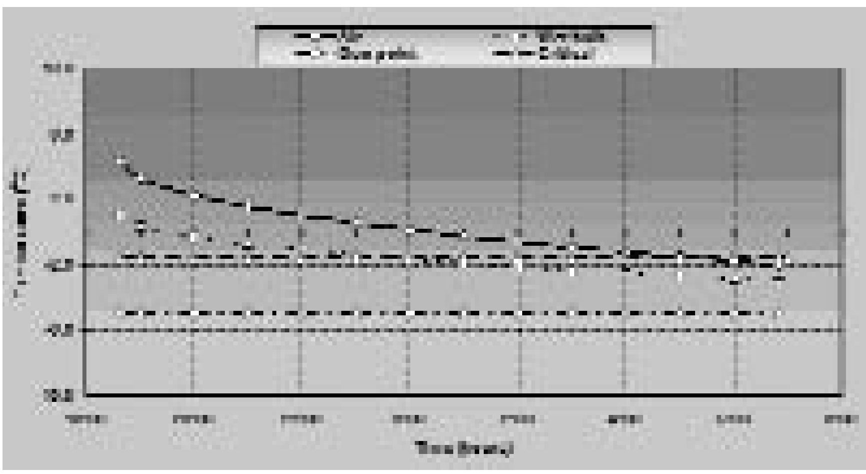
Over-plant sprinklers should be started so that they are all operating when the wet-bulb temperature approaches the critical damage temperature (T_c). However, note that the published critical damage temperatures are not always correct, so selecting a T_c slightly higher (e.g. by 0.5 °C) than the published value might be advisable. The choice depends on the risk one is willing to accept. If the minimum temperature (T_p) is forecast to be more than 1.0 °C lower than T_c, it is generally advisable to start the sprinklers as the wet-bulb temperature approaches T_c using the FTrend.xls program, as previously described. The problem arises when T_p is forecast to be near T_c. Even if T_p is slightly higher than T_c, it is possible for the equation to be incorrect on any given night depending on the local conditions. For example, the T_p forecast equation could work well for years and then it might fail completely on one night due to strange conditions on that night (e.g. often it is related to infrequent cold air drainage). This has happened to professional fruit-frost meteorologists in California and it is not so uncommon. However, in most cases, the prediction equations should work well. This is a good reason for close temperature monitoring during a frost night.

When T_p is forecast to be near T_c, the decision whether to protect and when to protect depends on the dew-point temperature. If the dew-point temperature is low, then it is often advisable to start the sprinklers before T_w falls below T_c. This is illustrated in Figure 5.11, where T_p = -2.0 °C and T_d = -5.0 °C were input. Although T_p is only slightly lower than T_c, because T_d is low, T_w falls to T_c before midnight. Consequently, the decision whether or not to use the sprinklers must be made before midnight. In this example, the sprinklers would need to run for more than seven hours. If the sprinklers are not started, there is a good chance that the air temperature will fall slightly below T_c for about two hours. Depending on accuracy of the forecast, hardening of the crop, etc., the crop would probably experience some damage. However, if the forecast is low or T_c is set too high, there might be little or no damage. This makes the sprinkler starting decision difficult. Again, it depends on the amount of risk the grower wants to accept and if there are problems with waterlogging, water shortage, or cost. However, if the sprinklers are used for this example, they should be started before midnight.

Figure 5.12 shows a temperature trend plot with the input dew-point temperature T_d = T_p= -2.0. In this case, T_p is below T_c and protection may be needed. However, because the dew-point temperature is relatively high, the grower can wait until later in the night to decide whether or not to protect. If sprinklers are used, the grower should start them at about 0400 h, so they would run for slightly more than three hours. If the sprinklers are operated correctly, it is unlikely that damage would result from the moderate frost on the night

FIGURE 5.11

Temperature trend plot using data from Figure 5.9, but with the predicted minimum temperature T_p = -2.0 °C and the dew-point temperature T_d = -5.0 °C

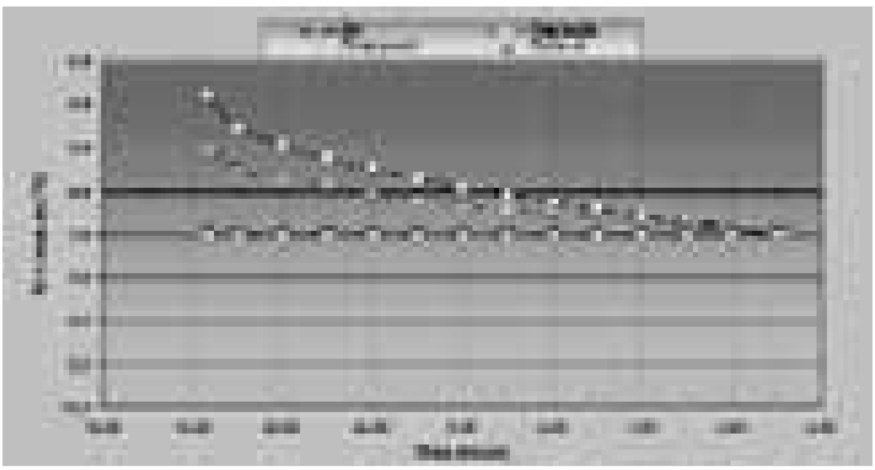


depicted in Figure 5.12. If the sprinklers are not used, it is uncertain if there would be damage or how much would occur. Again, it depends on the forecast and other physical and economic factors. Also, some crops that abort fruit or nuts (e.g. apple trees), can lose buds, flowers, fruit or nuts to freeze injury, yet overall production may not be greatly affected. For other crops that lose production due to loss of any buds, flowers, nuts or fruits (e.g. almond trees), damage should be avoided and less risk taken. Another big decision is related to whether or not the conditions are too severe for the sprinkler application rate to provide adequate protection. This is discussed in the chapter on active frost protection.

Sprinklers can be stopped after sunrise when the wet-bulb temperature again rises above the critical damage temperature. The temperature increase after sunrise depends on many factors and it is nearly impossible to accurately forecast. To determine when to stop the sprinklers, one should measure the wet-bulb temperature or the dew-point temperature upwind from the protected crop, and then use the Wet-bulb worksheet in the FTrend.xls application program to calculate the minimum air temperature for stopping the sprinklers. Enter the elevation, dew-point temperature and the wet-bulb temperature equal to the critical damage temperature (i.e. $T_w = T_c$). The sprinklers can be stopped if the sun is up and shining on the crop and the air temperature is higher than the air

FIGURE 5.12

Temperature trend plot using data from Figure 5.9, but with the dew-point temperature T_d = -2.0 °C and predicted minimum temperature T_p = -2.0 °C



temperature calculated in the Wet-bulb worksheet. To be absolutely safe, input 0 °C for the wet-bulb temperature and stop the sprinklers when the sun is shining and the air temperature measured upwind from the protected field is higher than the calculated air temperature from the Wet-bulb worksheet.

Updating with current temperature observations

Another feature of the FTrend.xls program is that the temperature trend can be updated during the night with observed temperatures. For example, if it were cloudy between 2000 and 2200h during the night described in Figure 5.9 and the temperature at 2200 h was measured as T = 1.0 °C rather than the 0.0 °C as predicted in Figure 5.9, then T = 1.0 °C is entered for 2200 h in the T_{update} column (Figure 5.13) and all of the subsequent temperatures are shifted upward to account for the update (Figure 5.14). The predicted minimum temperature and the wet-bulb temperature trend from 2200 h until sunrise were both increased. The change in the wet-bulb temperature trend is significant in that the time when the wet-bulb temperature intersects the critical damage temperature was shifted from 2300 h to 0100 h. Therefore, starting sprinklers for frost protection could be delayed by about two hours. This illustrates the importance of monitoring temperatures and updating the FTrend.xls application model during the night.

FIGURE 5.13

A sample of the Input worksheet of the FTrend.xls application program with the 2200 h air temperature updated to Tupdate = 1.0 °C

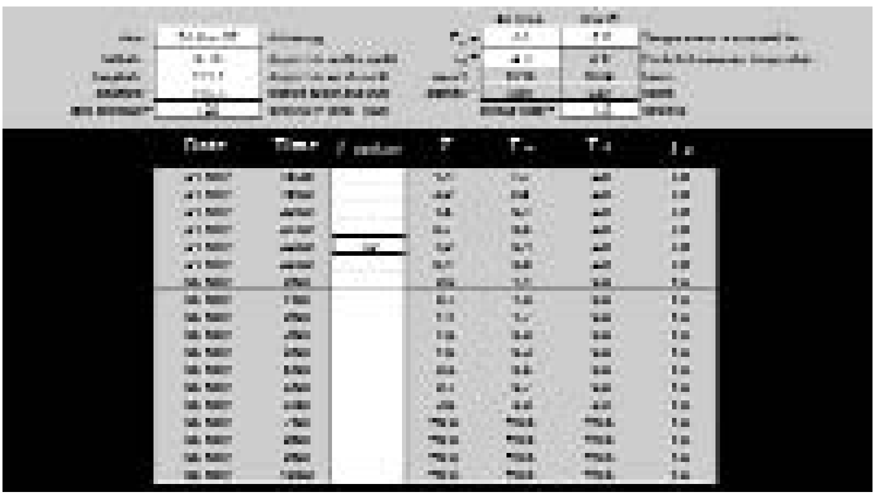
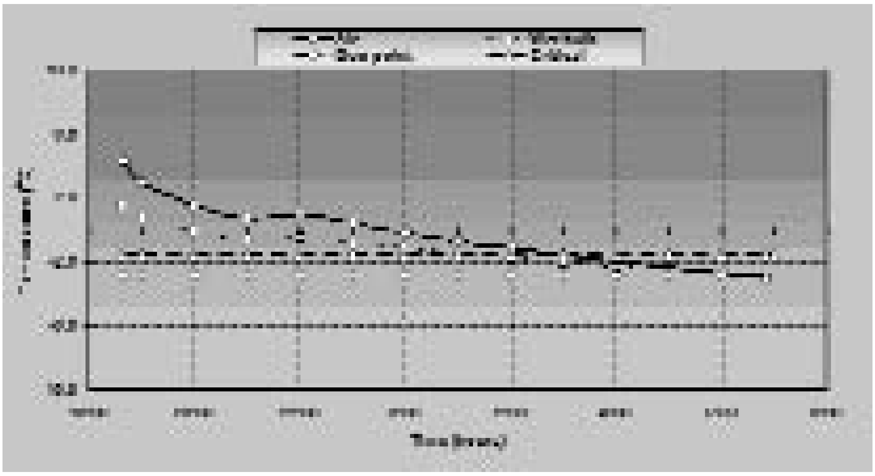


FIGURE 5.14

A sample of the Plot chart from the FTrend.xls worksheet using the input data from Figure 5.12 with the measured air temperature updated at 2200 h



Documentation of the FTrend.xls application

The air temperature trend calculation uses a square root function from two hours after sunset (i.e. time t_0) until sunrise (i.e. time t_p) the next morning. First a calibration factor b' is calculated from the predicted minimum temperature (T_p) and the temperature at time t_0 (T_0) as:

$$b' = \frac{T_p - T_0}{\sqrt{h}} \qquad \text{Eq. 5.1}$$

where h is the time (hours) between t_0 and t_p (e.g. h = (24 - t_0) + t_p). The temperature (T_i) at any time t_i hours after t_0 is estimated as:

$$T_i = T_0 + b' \sqrt{t_i} \ \ ^\circ C \qquad \text{Eq. 5.2}$$

If only the T_0 and T_p temperature data are inputted, then the FTrend.xls application calculates only the temperature trend. However, if the dew-point temperature at two hours past sunset (T_d) is also input, the application calculates the wet-bulb temperature between t_0 and t_p as well. During the night, the dew-point is fixed at the initial value T_d unless the temperature trend falls below T_d.

When the air temperature trend is less than T_d, the dew-point temperature is set equal to the air temperature. The wet-bulb temperature is calculated as a function of the corresponding air and dew-point temperatures and the barometric pressure, which is estimated from the elevation.

The wet-bulb (T_w) temperature is calculated from the dew-point (T_d) and air temperature (T_a) in °C as:

$$T_w = T_a - \left(\frac{e_s - e_d}{\Delta + \gamma} \right) \quad °C \qquad \text{Eq. 5.3}$$

where e_s and e_d are the saturation vapour pressures (kPa) at the air and dew-point temperature, Δ is the slope of the saturation vapour pressure curve at the air temperature (T_a) in °C:

$$\Delta = \frac{4098\, e_s}{(T_a + 237.3)^2} \quad kPa\, °C^{-1} \qquad \text{Eq. 5.4}$$

and γ is approximately equal to the psychrometric constant.

$$\gamma = 0.00163 \frac{P_b}{\lambda} \quad kPa\, °C^{-1} \qquad \text{Eq. 5.5}$$

where P_b is the barometric pressure in kPa and λ is the latent heat of vaporization:

$$\lambda = 2.501 - 2.361 \times 10^{-3}\, T_a \quad MJ\, kg^{-1} \qquad \text{Eq. 5.6}$$

where T_a is the air temperature in °C. Note that γ from Equation 3.6 will give similar results to using Equations 5.5 and 5.6.

Alarms and monitoring weather during a frost night

Although forecasting temperature trends during frost nights is important for identifying approximately if and when protection is needed, a good temperature monitoring program may be more important. The basic essentials include a frost alarm to wake you in time to start any protection methods before damage occurs and a network of temperature stations throughout the crop. Frost alarms are commercially available from a variety of sources. The cost of an alarm depends on its features. Some alarms have cables with temperature sensors that can be placed outside of your home in a standard shelter while the alarm is inside where the alarm bell can wake you. There are also alarms that can call you on the telephone or that use infrared or radio signals to communicate from a remote station back to your home to operate an alarm. However, as the frost alarm becomes more sophisticated, so the cost goes up.

Commonly, frost damage percentages are based on the plant tissue being exposed to half-an-hour below a critical temperature, whereas air temperatures are measured in a standard (or fruit frost) shelter at a height of 1.5 m. Perry (1994) recommends that thermometers should be placed at the lowest height where protection is desired. Perry (1994) also cautioned that sensors should be set where they will not be directly affected by protection methods (e.g. radiation from heaters). The general recommendation was to place the thermometers lower in short, dense crops and higher in taller, sparse crops. The idea is to have the sheltered air temperature reading as close as possible to the plant temperature that is being protected.

In reality the temperature of a leaf, bud, or small fruit or nut is likely to be lower than the shelter temperature. Similar to the boundary layer over a cropped surface, there is also a boundary layer over micro surfaces (e.g. leaves, buds, fruit or nuts). Due to long-wave radiation losses, exposed leaves, buds, flowers, etc. will typically be colder than air temperature during a frost night. Sensible heat diffuses from the air to the colder surface through the boundary layer, but the diffusion rate is insufficient to replace radiational heat losses. As a result, sensible heat content of the plant tissues and air near the surface causes temperatures to fall and leads to an inversion condition over the plant tissues. The depth of this micro-scale boundary layer and the gradient of sensible heat help to determine how fast sensible heat transfers to the surface.

The importance of a microscale boundary layer can be illustrated by considering what happens to your skin in a hot environment (e.g. in a dry sauna). If you stand in a "dry" sauna and do not move, you will feel hot because the ambient temperature is higher than your skin temperature. Sensible heat transfers from the ambient air through the small boundary layer to your skin mainly by diffusion. However, if you start to exercise (e.g. do callisthenics), you will quickly get much hotter. This happens because your exercising will ventilate the skin and reduce the thickness of the boundary layer, which enhances sensible heat transfer to the colder surface (i.e. to your skin). The energy balance of a leaf, bud, fruit or nut is similar. Increasing ventilation (e.g. higher wind speed) will reduce the thickness of the boundary layer and enhance sensible heat transfer. During a frost night, the plant parts tend to be colder than the air, so a higher wind speed will warm the plants to nearly as high as the ambient temperature. If the ambient air temperature is sufficiently high, then little or no damage may occur.

Some problems arise from using shelter air temperature (T_a) for critical damage temperature (T_c). Plant temperature can be quite different from air temperature depending on net radiation, exposure to the sky, and ground, leaf and ventilation (wind) conditions. Critical damage temperatures are often determined by placing excised branches in a cold chamber. In the chamber, the temperature is slowly lowered and held below a specific temperature for 30 minutes and later the branch is evaluated for the percentage damage to the buds, blossoms, fruit or nuts. There is no easy solution for comparing published T_c values with what really happens during a frost night. In practice, one should only use T_c values as a guideline and recall that the temperature of exposed branches is likely to be below temperature measured in a shelter.

Knowing the relationship between the temperature of sensitive plant tissues and shelter temperature will help with protection decisions. For example, it is well known that citrus leaves freeze at about -5.8 °C (Powell and Himelrick, 2000). However, measuring leaf temperature is labour intensive and not widely practiced. Therefore, estimating leaf temperature from shelter temperature is desirable. In addition to citrus, the relationship between leaf temperature and shelter temperature is unavailable for bud, blossom, small-fruit and small-nut stages of most stone fruit and small-fruit crops (Powell and Himelrick, 2000).

Supercooling of plant parts makes identification of critical temperatures difficult. For example, citrus has relatively low concentrations of ice-nucleating bacteria, and this might explain why the T_c for citrus leaves was consistently found to be about -5.8 °C. In many deciduous crops, identifying a clear critical temperature is more difficult because super-cooling varies with the concentration of ice-nucleating bacteria.

The presence of water on plant surfaces will also affect frost damage. Powell and Himelrick (2000) noted that dry plant surfaces freeze at lower air temperature than wet surfaces. They mentioned work in California that showed that wet citrus fruit cooled more rapidly than dry fruit during frost events. At the same air temperature, wet fruit is colder than dry fruit because the water evaporates and removes sensible heat. The wet fruit can cool to the wet-bulb temperature, which is always less than or equal to the air temperature. Spots of water on the peel of citrus fruit going into a frost night can result in spot damage because the peel under the water spots can cool to the wet-bulb temperature while the dry parts of the fruit are warmer. Similar damage can occur to the peel of other fruits if wet going into a frost night. Consequently, it is unadvisable to wet plants before a frost night unless sprinklers will be used during the night.