EIP-AGRI Focus Group
Protecting fruit production from frost damage

STARTING PAPER

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Section 1: Introduction

Scope of the EIP AGRI Focus Group

The EIP-AGRI Focus Groups collect and summarise knowledge on best practices in a specific field, listing problems as well as opportunities. They take stock of the state of play in research and practice and highlight possible solutions to the problems identified. Based on this, the Focus Groups suggest and prioritise innovative actions. They identify ideas for applied research and for testing solutions in the field, involving farmers, advisers, the industry and other stakeholders, and propose ways to disseminate good practices. Focus Group results provide new and useful ideas to solve practical problems and start new Operational Groups or research projects.

This discussion paper serves as input to prepare the first meeting of the Focus Group (FG) on Protecting fruit production from frost damage**.**

For that purpose, the document aims to:

- Establish a common understanding about the scope of the Focus Group and its objectives and to provide a preliminary outline of existing knowledge to be discussed with the Focus Group experts.
- Identify key questions for discussion at the first meeting taking into account the scope of the Focus Group
- Make first suggestions on topics that could be elaborated by Focus Group members in the meeting *(the group should be deciding what will be the subjects in the mini papers)*

In relation to fruit production, there are a number of existing active and passive frost protection methods (data, tools, knowledge and technologies) available to farmers, researchers and planners to cope with a variety of weather and climate-related problems. However, choosing the protection method which is the most cost-effective depends on local risk of frost as well as other factors. This Focus Group will look at examples of good practices and technologies and how these can be transferred to other situations to benefit the wider sector, paying special attention to approaches related to mitigation and adaptation to climate change. It will also look at opportunities and barriers, identify knowledge gaps, and propose areas for future research.

The overarching **QUESTION** of the Focus Group is: **How to protect fruit from frost damage?**
In order to answer this, the Focus Group is expected to carry out the following tasks:

- Assess existing methods and tools and how they can be used to better anticipate and take action to protect fruit against frost; identify good practices and success
- Stories from various European areas, specifically taking into account farmers' and advisers' experiences.
- Compare different management practices and tools considering the feasibility and cost-effectiveness at individual farm level or through collective approaches; identifying the opportunities (such as knowledge requirements, crucial partnerships) and technical/economic barriers that can hinder their uptake or development.
- Identify how these practices may be transferred to other conditions (e.g. location, model or type of production). Consider the role played by advisory systems.
- Identify innovative approaches combining scientific and practical knowledge with new business models.
- Identify further research needs from practice and possible gaps in technical knowledge.
- Suggest innovative solutions and provide ideas for Operational Groups and other innovative projects.

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Frost protection: necessity and scope

Despite global warming (Fig. 1), frost damage in the growing season may even increase if the weather is bringing forward the start of vegetation at a faster rate than the date of last spring frost. There are more economic losses to frost damage than to any weather-related phenomenon (Snyder & De Melo-Abreu, 2005). In the European Union fruit and vegetable sector is particularly affected by frost. For example, in 2017, frost damage to fruits and vineyards attained record high proportions.

Frost damage occurs when freezing temperatures are lower than critical damage temperatures of the plant tissues. Climate and microclimate drive minimum temperatures and plant frost-resistance depends upon the constitution of the plant and other factors. The plants tend to get less resistant as the season progresses or growing conditions are favorable. On the contrary, their resistance increases when subjected to less favorable growing conditions. Environmental conditions may be natural or result from anthropic intervention. Many of the processes involved are well known, especially those related to the physical environment, and qualitative responses of plant tissues. Knowledge gaps include some aspects of quantitative responses, variability and inheritance of frost resistance, nature of frost damage at the cellular and molecular levels, and the importance and mechanisms of ice nucleation.

Frost protection methods that are currently used are essentially the same that were used in the last decades of the 20th century. Most of these methods are protective (site selection; managing cold air drainage; plant selection; proper pruning; plant covers and screens, soil operations for heat conductivity enhancement; planting date for annual crops; bacteria control, chemicals). Long standing active methods include heaters, sprinklers, foggers, wind machines, helicopters, foams and combination methods (Fig. 2).

But the existing methods have their limitations and/or are costly and in the search for improvements, new methods have been proposed: For example upward-blowing wind machines (SIS system) or horizontal hot-air blowers (towed by the tractor or static) (Fig. 3). Furthermore, management difficulties have drawn the development of new tools, namely models and specific software.

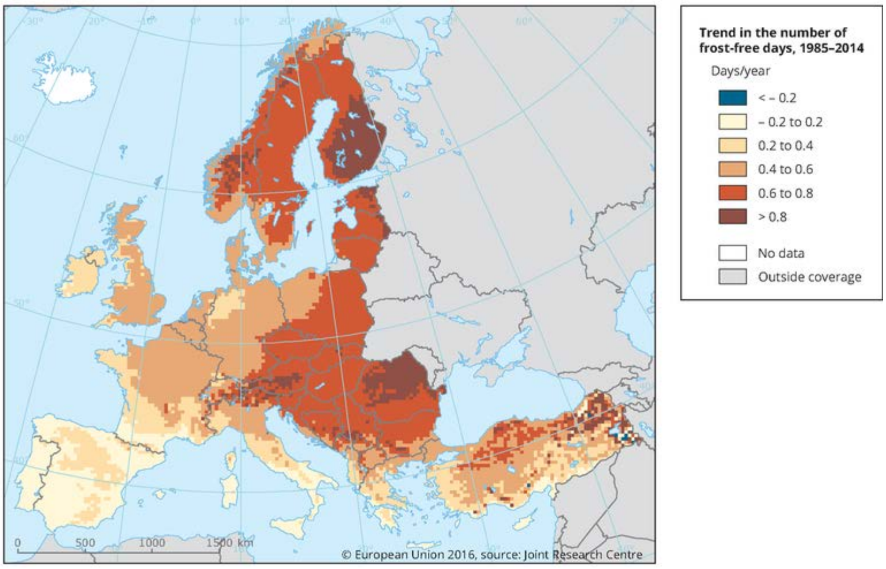

Fig. 1. Trend in the number of frost-free days (1985-2014) in Europe.

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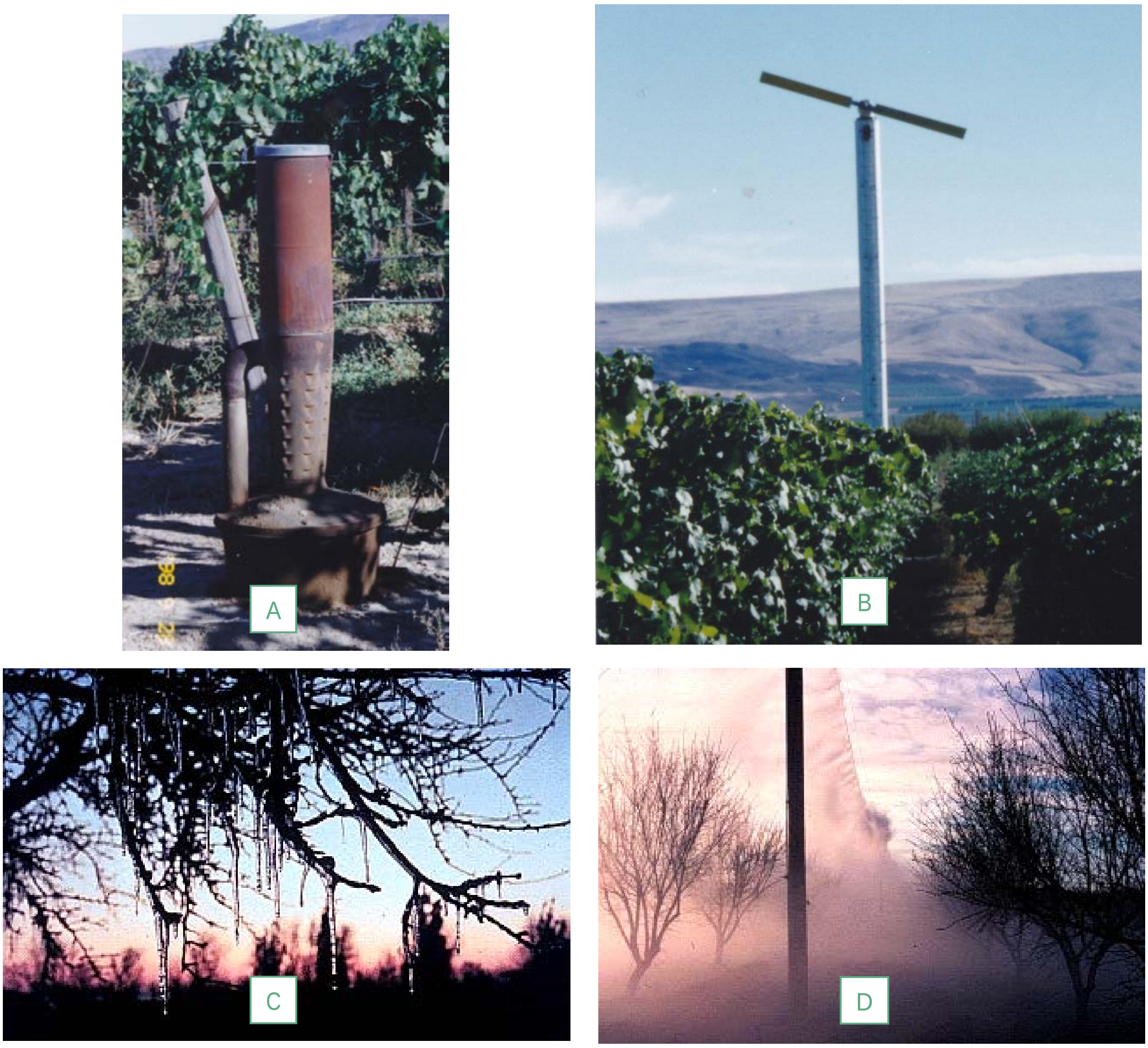

Fig. 2. Active methods: (A) Heaters. (B) Wind machines. (C) Ice formed after sprinkling (photo: R.L. Snyder). (D) Foggers (photo: R.L. Snyder).

Fig. 3. (A) Upward-blowing wind machines (SIS system). (B) Horizontal hot-air blowers towed by a tractor (photo: R.L. Snyder)

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Section 2: Essentials of methods of frost protection, risk and economics

There is a huge amount of background information that is necessary to understand all aspects of frost protection. Here, we will name the methods available and present the highlights of their applicability and performance. Additionally, in Appendix I, there is a slightly wider approach, and in the FAO book (Snyder & De Melo-Abreu, 2005) there is a rather exhaustive review of the methods of frost protection, risk analysis, and economics.

In general, methods for protecting crops again frost can be grouped into two main categories:

- Passive protection, which includes methods that are implemented before a frost night to help avoid the need for active protection.
- Active protection methods, which are implemented just before or during a frost event.

Table 1. Overall classification of frost protection methods

Passive protection: *Implemented well before frost event*	**Active protection** *Implemented just before or during frost event*
site selection	heaters
managing cold air drainage	wind machines
plant selection	helicopters
canopy trees	sprinklers
plant nutritional management	surface irrigation
proper pruning	foam insulation
plant covers	combinations of methods that are done during a frost night to mitigate the effects of sub-zero temperatures.
avoiding soil cultivation	mobile heaters
Irrigation	vertical flow wind machines
removing cover crops	plant cover
soil covers	
trunk painting and wraps	
bacteria control	
chemicals	
planting date for annual crops.	

But how to choose within this wide range of systems? Which is the most effective, at a rational cost for each crop and/or site?
In principle passive methods have the advantage of being inexpensive -or low cost- and, often, may have cumulative effects among them and/or in combination with active methods. Moreover, they should be implemented whenever frost is a recurrent problem. Active methods are usually more difficult to manage, e.g for correct timing, and always intensive in capital and running costs, due to high energy usage and installation costs.

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In line with this, table 2 provides a classification of anti-frost methods according to their overall effectiveness for the different types of fruit productions. This refers to physical effectiveness, since economic efficiency depends on the value of the crop, which is highly variable and therefore unpredictable.

Table 2. Estimated levels of protection conferred by frost protection methods (Snyder & De Melo-Abreu, 2005):

** → significant, in general < 1 ºC*
*** → good, generally 1-3 ºC*
**** → very good, generally < 3-7 ºC*
? → reduced or contradictory information
NA → in general, not applied for this type of crop, due to effectiveness or economic reasons.

Method (Specifics of each method in Annex I)	Pome & stone fruits	Grapes	Citrus	Small fruits	Comments
Site selection; managing cold air drainage; plant selection	***	***	***	***	When factors/conditions are favourable
Canopy trees	**	**	**	**	Also used to protect coffee crop
Plant nutrition management	*	*	*	*	More protection possible in the case of delaying sensitive stages
Proper pruning	**	**	NA	variable	Small fruits: depends upon the specific crop and training system
Avoiding soil cultivation, irrigation, removing cover crops	*	*	*	*/**	Small fruits: depends upon the specific crop and training system
Trunk painting and wraps	***	***	***	***	Applied to allow recovery, but unprotected organs are damaged
Bacteria control	*/**	*/**	*/**	*/**	Limited information
Chemicals	*/**	*/**	*/NA	?	Bactericides/ growth regulators
Heaters	***	***	***	***	If proper dimensioned are very effective, but extremely expensive in the open-field
Wind machines, helicopters	**	**	**	**	If strong inversions are developed
Sprinklers; foam insulation; plant covers	***	***	**	***	Sprinklers: Very effective (keep organs around 0ºC, but ice weight may be a problem). Citrus and other evergreen fruit trees are often damaged by ice weight.
Surface irrigation	**	**	**	**	Flooding is often even more effective
Combination of (active) methods	variable	variable	variable	variable	Depends on the methods involved. Usually is used to increase protection of one method in isolation
Mobile heaters, vertical blowers	?	?	?	?	Limited experience and contradictory reports, but most probably do not work under most conditions

However, despite this wide range of methods, information and experience available, fruit growers keep facing damages due to frost episodes. Practical problems when choosing or applying the methods, or uncertainties due to the numerous conditions and factors to consider (crops and site), might make an effective method to fail.

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Thus, from the farmers perspective, amongst many others, some of these key elements to consider, playing a role in the effective protection of fruits against frost, might be:

SELECTION OF THE METHOD(S) – Is complex due to the number of factors and variables to consider. There is a physical side and a biological side to this problem. Climate is the fundamental factor, but microclimate of the plots must be known. Tridimensional aspects of the site impact on microclimate due to elevation, relief, slope and aspect. Besides, lower atmosphere, soil and vegetation variables have also a significant effect on energy budget and, therefore, on the value and distribution of temperature.

On the other hand, the biological side determines the plant/tissue resistance. But plant resistance is species/variety specific, depends on the phase of the plant, and its recent environment (not only temperature). Better recent growing conditions, generally, imply reduced resistance.

Finally, other constraints need to be taken into consideration (e.g., smoke of heater, noise of wind machines and blowers, and water availability for irrigation). The evaluation of active methods is site specific and requires inputs of climate, capital and running costs, and critical damage temperatures. Choice is difficult as many factors have to be taken into account. However today there are some tools that bring some support. For example, the program FrostEcon (companion CD of Snyder & De Melo-Abreu, 2005) computes the revenue obtained in each of the methods selected and without protection and their probability distribution.

ACTIVE METHODS DIMENSIONING – Dimensioning of the system (no. of heaters, rate of water application, power and distribution of wind machines and blowers, etc.) depends upon energy budget and its components under projected. But the probability distributions of these variables are difficult to ascertain, moreover under global change scenarios.

ACTIVE METHODS MANAGEMENT – Management of active methods rely on accurate and precise climatic data to decide, for example, when the system should start operating or regulate intensity of the work of the devices. Therefore, microclimate data by weather stations must be collected and treated, and temperature predictions yielded. Additionally, warnings or automated turning on/off of the protection system are desired.

AIDS AND SUPPORT FOR FARMERS – Farmer needs to be well informed about specifics of the site, crop and protection methods, so as to effectively protect the production. Therefore, professional management, support and advice is welcome and needed. However, to get independent (vs commercial) advice might be an issue, especially in case of methods with high technical requirements.

DECISION SUPPORT SYSTEMS (DSS) – As any other complex system, frost protection methods require management of accurate and prompt information, to take right and timely decisions, and this could be supported by DSSs. However, the use of DSS by farmers for protecting crops against frost is quite low. Availability, effectiveness or tailoring of features are some aspects that might hinder the use of DSSs

Section 3: Discussion questions

- From the fruit production perspective, do you think that frost is a major problem in your region/country? And in EU?
- According to your experience/perception, is frost risk likely to increase in the foreseeable future?
- What have been the practical difficulties that you encountered in the use of passive methods? And what about active methods?
- Can you indicate examples of methods of protection that you have immediate knowledge of and did not protect the crop? Why was not working? Was the problem avoidable?
- In the use of active methods, how was done the prediction and monitoring of temperature and humidity time-course in advance and during the night of frost?
- Did you ever use or feel the need to use computer applications in order to manage frost protection methods?

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- Were you ever in contact with a novel approach that supposedly protects against frost? Which? Do you think that it is effective or not?
- Do you have any ideas for improvement of frost protection methods?
- Do you agree with the levels of effectiveness attributed to the methods present in Table 2?
- Has it been easy for you get specialized information about frost protection methods?
- The future: Where future innovations are likely to occur?
    - New materials?
    - Climate change effects on severity and frequency of frosts?
    - What may be the evolution of DSSs?

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Appendix I: Summary of Methods of frost protection

Introduction

These notes present information on important aspects of frost protection methods without complicated equations or concepts. More detailed information is given in the FAO books:

- Snyder & De Melo-Abreu, 2005. Frost Protection: fundamentals, practice, and economics, Vol. I. FAO, United Nations, Rome. This volume details the technical aspects of frost protection. http://www.fao.org/docrep/008/y7223e/y7223e00.htm
- Snyder, De Melo-Abreu & Matulich, 2005. Frost Protection: fundamentals, practice, and economics, Vol. II. FAO, United Nations, Rome. This volume details the risk and economical aspects of frost protection. http://www.fao.org/docrep/008/y7231e/y7231e00.htm

References are not generally included in these notes to reduce its size and to simplify reading.
In the companion CD of the book there are programs that handle many of the calculations, simulations and analysis that are instrumental for the application of frost methods.

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 mild 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.

Critical temperature values are given for some deciduous tree crops and grapevines (Fig. A.1). Blackberries and blueberries are more hardy then grapes especially when buds are in the dormant phase. Kiwifruit and strawberries are less hardy then grapes. Citrus are very sensitive to frost.
T_{10} and T_{90} values are provided, where T_{10} and T_{90} are the temperatures where 10% and 90% 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.

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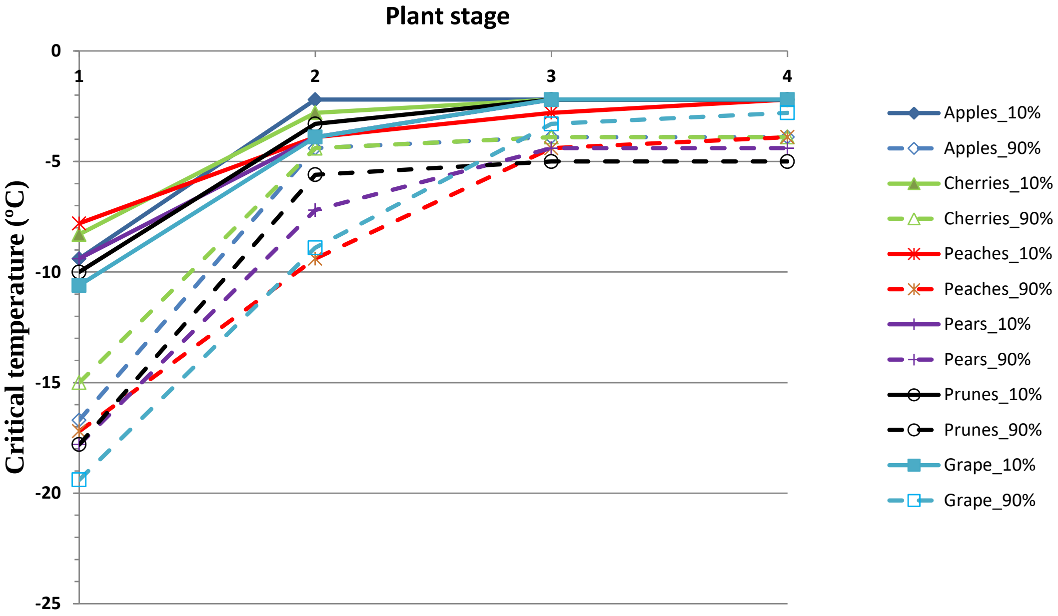

Fig. A.1. Critical damage temperature in relation to developmental stage of some fruit trees and grapes. Stage 1: onset of bud activity (e.g., first swell); Stage 2: bud burst; Stage 3: bloom or 1st leaf for grapes; Stage 4: post-bloom or 4 leaf for grapes.

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. 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.

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;
- chemicals; and
- planting date for annual crops.

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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. 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.

Cold air is denser than warm air, so it flows downhill and accumulates in low spots much like water in a flood. 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.

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.

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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

Higher canopies intercept the radiation form the surface and the lower canopies under them, thus conferring appreciable frost protection. 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.

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.

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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.

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.

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. 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% water in the late autumn when the air temperature is above 10 °C will reduce this problem. White paint, insulation and other wraps (e.g. fibreglass or polyurethane foam) are known to improve hardiness against frost damage in peach trees.

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.

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Chemicals

Many chemicals have been available allegedly lower critical temperature (Tc) of crops.

Products that reduce the number of bacteria (bactericides), such as copper sulphate solutions sprayed over the canopies, are likely to have some positive effect, because they contribute to supercooling (see bacteria control). Growth regulators that delay blooming that occurs in the spring are technically beneficial because frost risk decreases rapidly as spring progresses.

Most other type of products that are sprayed over the canopies are appointed by their manufacturers to be effective in frost protection. However, there is conflicting evidence that these commercially available cryoprotectants and antitranspirants work[1]. Finally, those products that are essentially solutes, which lower the freezing point of water outside the plant organs are likely not effective, and may even be disadvantageous.

Active protection

Active protection methods include

- heaters;
- wind machines;
- helicopters;
- sprinklers;
- surface irrigation;
- foam insulation; and
- combinations of methods that are done during a frost night to mitigate the effects of subzero temperatures.
- new solutions that there is no evidence that they to work

The cost of each method varies depending on local availability and prices. 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.

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. To achieve the best efficiency, increase the number of heaters and decrease the temperature of the heaters. However, this is often difficult

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to accomplish because of equipment costs, labour, etc. 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.

Heater distribution should be relatively uniform with more heaters in the borders, especially upwind, and in low cold spots. Heaters are expensive to operate, so they are commonly used in combination with wind machines or as border heat in combination with sprinklers.

Note that isolated small orchards require more heaters than large orchards or those surrounded by other protected orchards.

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.

Wind machines

Wind machines alone generally use only 5% to 10% of the fuel consumed by a fuel-oil heater protection system. However, the initial investment is high (e.g. about 30 000 € 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.

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.

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.

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 lead to severe damage.

Sprinklers

The energy consumption of sprinklers is about 10% of 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.

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Protection against frost with sprinklers can be performed in different ways. The conventional system is to use over-plant sprinklers or under-plant sprinklers, however further variants are also in use, trying to improve the efficiency or overcoming some of the limits of the traditional methods. That's the case of microsprinklers, trickle-drip (low-volume) irrigation or conventional sprinklers over covered crops, under-tree or with heated water.

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. 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.

Sprinkler distribution uniformity is important to avoid inadequate coverage, which might result in damage. 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.

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.

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% 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.

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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.

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.

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. 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 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, 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.

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. For deciduous trees, the water should run under the trees where the warmed air will transfer upwards to warm buds, flowers, fruit or nuts. 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.

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.

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. While the warmed air near the surface will naturally transfer throughout the crop, operating wind machines with the sprinklers will enhance heat and water vapour transfer. Typically, growers start the lower cost sprinklers first and then turn on the wind machines if more protection is needed.

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).

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.

New solutions under test

Mobile Heaters

A mobile heater is commercially available as a method for frost protection; however, scientific evaluations of the machine are not favourable. The mobile heater uses four 45-kg propane tanks to supply the fuel for the heater, which mounts on the back of a tractor. The heater uses a centrifugal fan to blow the heated air horizontally and perpendicular to the tractor direction as it moves up and down the rows.

The main problem of this machine is that the amount of heat is too small to stop cooling and hot air may even increase losses due to buoyancy.

Vertical flow wind machines

The use horizontal fans to produce vertical upward flow and to pull down the warm air aloft has been investigated. However, these fans generally work poorly because mechanical turbulence mixing with the trees

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reduces the area affected by the ventilation. Also, the high wind speed near the base of the tower can damage horticultural and ornamental crops.

Wind machines that blow vertically upwards are commercially available and there has been some testing of the machines. The idea is that the fan will pull in cold dense air near the ground and blow it upwards where it can mix with warmer air aloft. Testing has shown that this method has a temporary positive effect on temperatures near the fan; however, the extent of influence and duration of the effect is small.

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.

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.

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