eip-agri
AGRICULTURE & INNOVATION

EIP-AGRI Focus Group
Protecting fruit production from frost damage

FINAL REPORT
NOVEMBER 2019

funded by European Commission

Table of contents

funded by European Commission

1. Executive summary

This report presents the results of the **EIP-AGRI Focus Group (FG) on `Protecting fruit production from frost damage`**. In the European Union, the fruit and vegetable sector is particularly affected by frost and, despite global warming, the risk of frost damage in the growing season may increase. Frost damage occurs when freezing temperatures are lower than critical damage temperatures of the plant tissues.

The frost protection methods that are currently used by fruit producers are essentially the same that were used in the last decades of the 20th century. Despite the wide range of methods available, farmers in Europe keep facing serious challenges when fighting frost. In addition, the few relatively new systems or materials that were introduced have not been fully tested yet, nor are they generally adopted by fruit growers.

This Focus Group gathered 20 experts and a coordinating expert, supported by a facilitation team from DG AGRI and the EIP-AGRI Service Point (**Annex A**). The experts are researchers, farmers, advisers, representatives of the industry, or NGOs. The work of the Focus Group started in June 2018 and the report was delivered in November 2019.

Discussions were framed by a **starting paper** written by the coordinating expert, partly based on a survey circulated to the group's members before the first meeting. The current methods of frost protection for each group of fruit crops and grapes were briefly introduced, and special attention was given to the barriers and challenges of these practices, methods and technologies. Subsequently, there was a discussion on the strategies, tools and actions that could improve the performance of the practices that are already effective, and that could address the failure factors of some of the methods / technologies that have potential to be effective. In line with this discussion, some specific topics and questions were further developed by the group in short documents called 'minipapers', which reflect the main ideas and concerns that emerged from the discussions (**Annex B**).

The discussions resulted in sets of good practices, success factors and failure factors for selected passive and active methods of frost protection. These are all summarised in chapter 5 and **Annex C**, with additional methods to provide a complete overview. The main ideas behind these results are as follows:

- Knowledge of the microclimate in frost nights is very important, both for passive and active methods. Particularly important is knowledge about the flows of cold dense air and the strength of the inversions. This requires measurements of physical variables such as minimum temperatures and wind speed in different parts of the orchards.
- Knowledge of phenology (accurate models of plant growth and development) is essential for both groups of methods, because critical frost damage temperatures change with the stage of the plant.
- For active protection methods, timing and monitoring of environmental variables are essential. These can only be achieved when real-time temperature, humidity and, in some cases, wind speed and direction are measured in the orchard on various spots. Profile measurements of temperature are also important.
- Species/cultivars and/or rootstocks that are resistant to frost save energy, work and money.
- The application of chemicals that could make the plants avoid or resist frost would also be practical.
- Overhead sprinkling is currently the most affordable type of protection for many crops, but it is not perfect. It can be improved, notably to save water.

The work that was done for the minipapers and during the discussions in the second Focus Group meeting allowed the experts to formulate a selection of research needs coming from practice, and a number of ideas for EIP-AGRI Operational Groups (OGs).

funded by European Commission

The main research need that was identified, was to study and compare the effectiveness of methods under different conditions. The next four in the ranking are:

- the need to add more biology to the models,
- creating a database to refine the prediction of frost damage,
- developing a reliable monitoring and alarm system
- creating better phenological models

The list of ideas for Operational Groups includes the demand for a decision support system (DSS) to select the frost protection method that is most suited under local conditions, and to evaluate frost risks. The creation of such a DSS would allow farmers and advisers to successfully deal with the complexities of frost protection. Other ideas followed: selecting the most effective chemicals to be applied in frost protection, installing a monitoring and alarm network, creating a frost information database and a hand device to measure frost damage.

EIP-AGRI Focus Group experts

2. Introduction

Despite global warming, the risk of frost damage in the growing season may even increase if the weather is bringing forward the start of vegetation growth, or the frequency of episodes of late spring frost increases. There are more economic losses due to frost damage than to any other weather-related phenomenon (Snyder & De Melo-Abreu, 2005[a]). In the European Union, the fruit and vegetable sector is particularly affected by frost, and in 2017, for example, proportions of frost damage to fruits and vineyards reached a record high (EC, 2017; EC, 2018).

Frost damage occurs when freezing temperatures are lower than critical damage temperatures of the plant tissues. Many of the processes involved are well known, especially those related to the physical environment, and qualitative responses of plant tissues. Knowledge gaps include quantitative responses, variability and inheritance of frost resistance, the nature of frost damage at cellular and molecular levels, and the importance and mechanisms of ice nucleation.

Frost protection methods are classified as active or passive. Most methods are passive (protective) and are implemented well in advance of the frost events. Other methods are active and are implemented just before or during the frost event. A few active methods have recently been proposed, but their efficacy is not established.

The objectives of the Focus Group (FG) were:

- Summarise the theme of the FG, with emphasis on good practices.
- Identify the methods of protection that are very likely to have a potential for reducing frost damage. When possible, attribute a range for the positive effect.
- Identify problems in the application of frost protection methods and take notice of the suggestions on how to circumvent them.
- Discuss the information and simulation tools available to assist growers on frost protection activities and cost-effectiveness assessment.
- Identify most relevant knowledge gaps and suggest new lines of applied research.
- Analyse the impact of global climate change on the incidence of frost damage in fruit production and on frost protection.
- Suggest innovative avenues that may result in modifications of existing or new-effective frost protection methods and contribute to future work of OGs.
- Dissemination plan of results and elaboration of Focus Group Final Report

3. Focus Group composition and description of the process

The EIP-AGRI Focus Group (FG) consisted of a team of 20 experts with different types of experience, practical, advisory, and research, coming from different EU regions (**Annex A: Members of the Focus Group**). They have jointly worked for a year and a half, meeting twice during this period. To support the organising team in terms of content, José Paulo de Melo e Abreu was appointed as coordinating expert to write a starting paper, to facilitate the technical discussions in the groups, and to assist in reporting tasks. The **starting paper**, prepared at the beginning of the process, helped to establish a common understanding about the purpose of the Focus Group. Together with contributions from the experts, collected through an online questionnaire, this starting paper provided a background on frost-related physical and biological processes. It also presented the state of play in frost protection methods, and identified key questions for discussion at the first meeting.

The objectives of the first meeting (Warsaw and Grójec area, Poland, 27-28 June 2018) were to reach a common understanding of the Focus Group tasks, as described in the Focus Group call, and to organise the Focus Group work. Discussions in this first meeting focused on challenges when protecting fruit from frost, and good practices and sources of innovation to overcome these challenges. Following the discussions, the group selected a number of topics that would be dealt with in greater depth through the so-called minipapers. These minipapers are very solution-oriented documents, that further explore key questions related to frost damage strategies and their limitations. All minipapers have been prepared by the Focus Group members, in the period between the two meetings. The minipapers cover the following topics (**Annex B**):

- Active frost protection systems
- Assessing costs and benefits of frost protection measures in fruit production
- Affordable real-time online frost detection data
- Use of chemicals to help plants tackle frost damage
- Phenology models and critical stages

The first meeting included a field trip with two visits that illustrated farm practices to protect fruit crops against frost and control frost damage. The visits illustrated both the farmer and the cooperative perspective and enriched the discussion on the effectiveness of methods to deal with frost damage.

The objective of the second Focus Group meeting (Brussels and Sint-Truiden, Belgium, 27-28 November 2018) was to reach a common understanding on innovation and research needs from practice. During this meeting, experts also proposed ideas for Operational Groups and other innovative initiatives. The group also addressed follow-up steps and dissemination activities after the publication of the final report. The field trip of this second meeting included three visits that illustrated some aspects of frost protection from the farmer's perspective, with the support of innovative solutions provided by research (e.g. techniques of targeted overhead sprinkling).

funded by European Commission

4. State of play

Frost damage occurs when freezing temperatures are lower than critical damage temperatures of plant tissues. Climate and microclimate determine minimum temperatures, and the frost resistance of a plant depends on its constitution and on other factors. Plants tend to become less resistant as the phenological stage advances (e.g. blooming and fruit stages, especially small-nut are the most critical). For a given stage, favourable growing conditions lower the resistance of plant organs to frost. On the other hand, this resistance increases when plants face less favourable growing conditions. Environmental conditions may be natural or they may result from human intervention. Many of the processes involved are well known, especially those related to the physical environment and to qualitative responses of plant tissues. However, there are still some knowledge gaps, for example regarding some aspects of quantitative responses, variability and inheritance of frost resistance, the nature of frost damage at cellular and molecular levels, the importance and mechanisms of ice nucleation, and accurate weather prediction models at local scale.

The frost protection methods that are currently used are essentially the same as those that were used in the last decades of the 20th century. Most of these methods are passive (protective), such as for example site selection, managing cold air drainage, plant selection, proper pruning, plant covers and screens, soil operations for heat conductivity enhancement, bacteria control or the use of chemicals. Long-standing active methods include heaters, sprinklers, foggers, wind machines, helicopters, foams, and combinations of these methods, all of them activated during the episodes of frost on the fields.

Despite this wide range of existing methods, frost is still a challenge for most growers. All these classical methods have several limitations, especially concerning management, and/or they are costly. However, more recently, a few methods have been proposed: upward-blowing wind machines (known as the SIS system) or horizontal hot air blowers (towed by a tractor, or static). In addition, the management difficulties of innovative and traditional methods have led to the development of new tools, especially (economic, phenological, weather) models and specific software to support decisions.

a. Framing the key issues

Crop sensitivity and critical temperatures

Frost damage to crops does not result from cold temperature but mainly from extracellular (i.e. not inside the cells) ice formation inside the plant tissue. This draws water out, dehydrating and causing injury to the cells. Following periods of mild cold, plants tend to harden against freeze injury, and they lose the hardening after a warm spell. A combination of these and other factors determines the temperature at which ice forms inside the plant tissue and when damage occurs. The amount of frost injury increases as the temperature falls. The temperature corresponding to a specific level of damage is called a “critical temperature” or “critical damage temperature”, and this is given the symbol T_c (Sakai & Larcher, 1987). The T_c values for deciduous orchards and vineyards vary with the phenological stage (Snyder & De Melo-Abreu, 2005[a]), and they also depend on the species. For example blackberries and blueberries are hardier than grapes, especially when buds are in the dormant phase, and grapes are more resistant to frost than kiwifruit or strawberries. On the other hand, citrus are very sensitive to frost.

Critical temperature values are given for some deciduous tree crops and grapevines in **Fig. 1** and **Minipaper 5**. The values 10 and 90% indicated in the legend of Figure 1 refer to values T_{10} and T_{90}. 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 small 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.

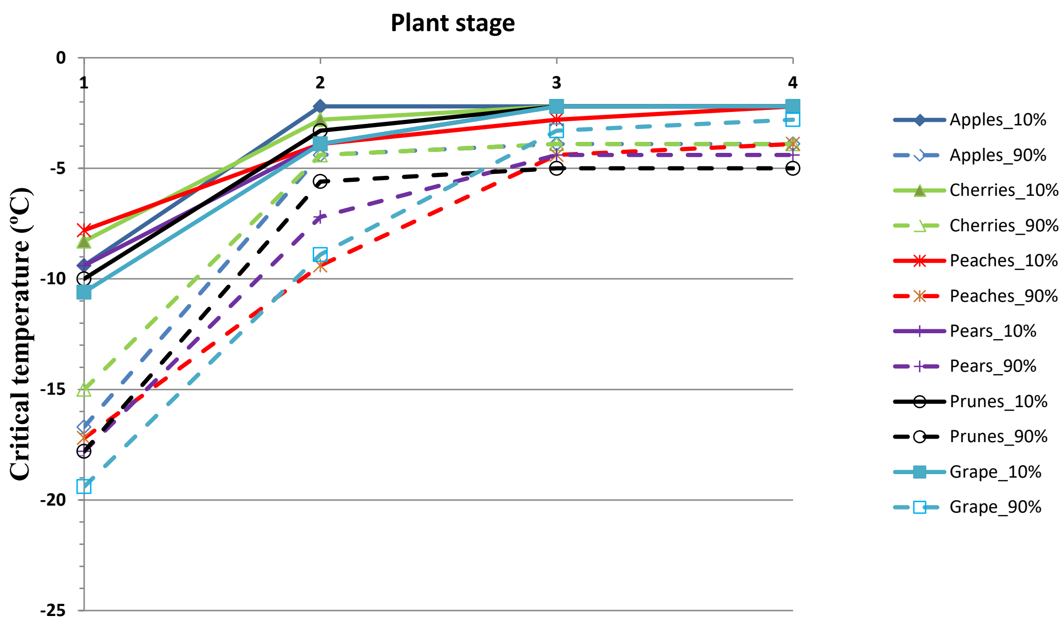

Fig. 1. Critical damage temperature in relation to developmental stage of some fruit trees and grapes. Stage 1: onset of bud activity (e.g. first swell); Stage 2: bud burst; Stage 3: bloom or first leaf for grapes; Stage 4: post-bloom or fourth leaf for grapes. Source data from Snyder & De Melo-Abreu, 2005a.

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 the temperatures of sensitive plant tissues, and these temperatures 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 (De Melo-Abreu, 1985).

Frost protection methods

There are many methods of frost protection and many are physically very effective. The existing methods may be classified as passive (protective or indirect) and active (direct) (Bagdonas *et al.* 1978; Snyder & De Melo-Abreu, 2005[a]). Passive protection includes methods that are implemented well in advance of the frost events to help avoid the need for active protection. Active protection methods are implemented just before or during a frost event (**Table 1**). For more detailed information about these methods see the **starting paper** and **Annex C**, and Bagdonas *et al.*, 1978; Evans, 2000; Powell & Himelrick, 2000; De Melo-Abreu, 2018.

Table 1. Classification of frost methods (Based on Snyder & De Melo-Abreu, 2005[a])

Passive protection: *Implemented well before frost event*	**Active protection** *Implemented just before or during frost event*
site selection (avoiding the frost-prone areas and spots)	heaters
managing cold air drainage (e.g. stop or divert cold air drainage away from the crop; remove downslope obstacles to its drainage)	wind machines (mix the air inversion layer that forms during radiation frost nights, thus increasing air temperature near the surface)
plant selection and planting date (e.g. opting for later budbreak varieties or rootstock)	helicopters (same type of effect as wind machines)
canopy trees (shade trees over fruit plants; very common for tropical crops such as coffee)	sprinklers (e.g. overhead sprinkling brings water to the system that, upon freezing, liberates the latent heat of fusion that is used by the canopy to maintain its temperature)
plant nutrition management (e.g. avoid excessive nitrogen fertiliser application and related growth at the end of the season)	surface irrigation (liberation of latent heat of fusion into the air modulates temperature)
proper training and pruning (e.g. raising the height of fruits and double-pruning)	mobile and rotating hot air blowers
plant covers (e.g. use of natural or artificial materials such as plastics or nets to reduce loss of heat and radiation from the plants)	upward vertical-flow air blowers (purportedly, successively projects the lower layer of air upwards, thus allowing the next warmer layer to replace it)
keeping surface heat conduction high (e.g. expulse still-isolating air from the soil and cover crop)	combinations of methods
trunk painting and wraps (painting trunks white lowers temperature and delays budbreak; wraps reduce the heat flow from the trunk to the air)	
bacteria control (some bacteria function as ice nucleators[1]; the reduction of their numbers favours super-cooling)	
chemicals (some delay budbreak, others may have a cryoprotectant effect, i.e. they prevent the freezing of tissues, avoiding cell damage)	

[1] The ice formation process is mostly initiated by the presence of ice nucleation active (INA) bacteria. After forming, the ice then propagates inside the plants into the plant tissues. Non-ice nucleation active (NINA) bacteria compete with INA bacteria and, when applied, may reduce the concentration of these bacteria. Antibiotics and copper compounds applications can also reduce the concentration of INA bacteria.

Energy consumption, costs and cost-effectiveness of frost protection methods

The amount of energy required for each system of frost protection is an important factor when analysing the economic performance of different methods.

In general, passive methods need little or no input of external energy. Often they rely upon the energy available in the environment, needing little work to manage the energy fluxes to the benefit of the plants. Other methods use the genetic variability and knowledge of plant responses and physiology to have plants that are not damaged in cold environments. On the other hand, active methods demand high inputs of energy, either stored in fossil fuels (solid, liquid or gaseous) or electricity.

An estimate of the amounts of energy necessary for active protection in a fictitious apple growing location was made with the programme FrostEcon (Snyder & De Melo-Abreu, 2005[b]) (Fig. 2). Results show that horizontal hot air blowers (H-Blowers) needed less energy than all the other methods, and for example sprinklers and fans need about 10% of the energy necessary to run heaters.

This cost-benefit analysis (CBA) computes total expected costs (fixed and variable) of each option and compares these with total expected benefits. There are very few recent studies in the EU that assess the costs and benefits of frost protection methods in fruit production. Minipaper 2 discusses, among other things, the methodologies that can be used for such studies. Annex C includes a qualitative evaluation of the level of installation and operational costs of some of the methods.

Ideally, these studies should be complemented with a computer tool that allows the adaptation to other conditions, which is not a simple matter. Up to now, to our knowledge, FrostEcon (Snyder & De Melo-Abreu, 2005[b]) is the most comprehensive computer programme tailored for comparison of frost protection methods. This program computes the number of frost events, their duration, frost damage, costs of protection with any method and the risk and probability of losses or gains (see also Minipaper 2).

Figure 3 shows the result in FrostEcon of the calculation of the total costs (€/ha) of some protection methods, using estimates of costs associated with that type of protection in a fictitious apple growing location.

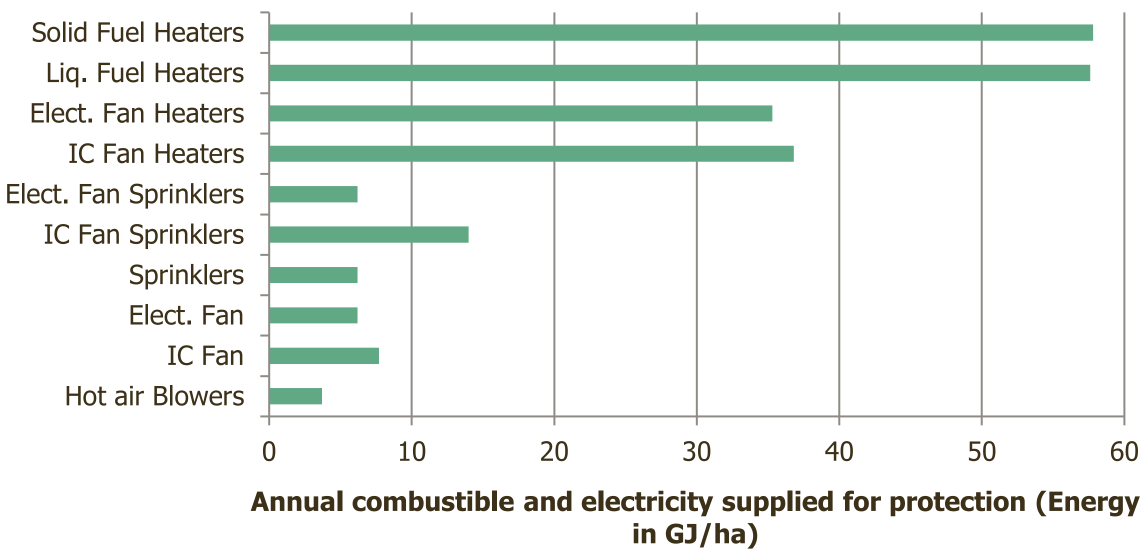

Fig. 2. Estimated annual energy necessary to run some active methods of frost protection in a fictitious location characterised in the program FrostEcon (Snyder & De Melo-Abreu, 2005b).

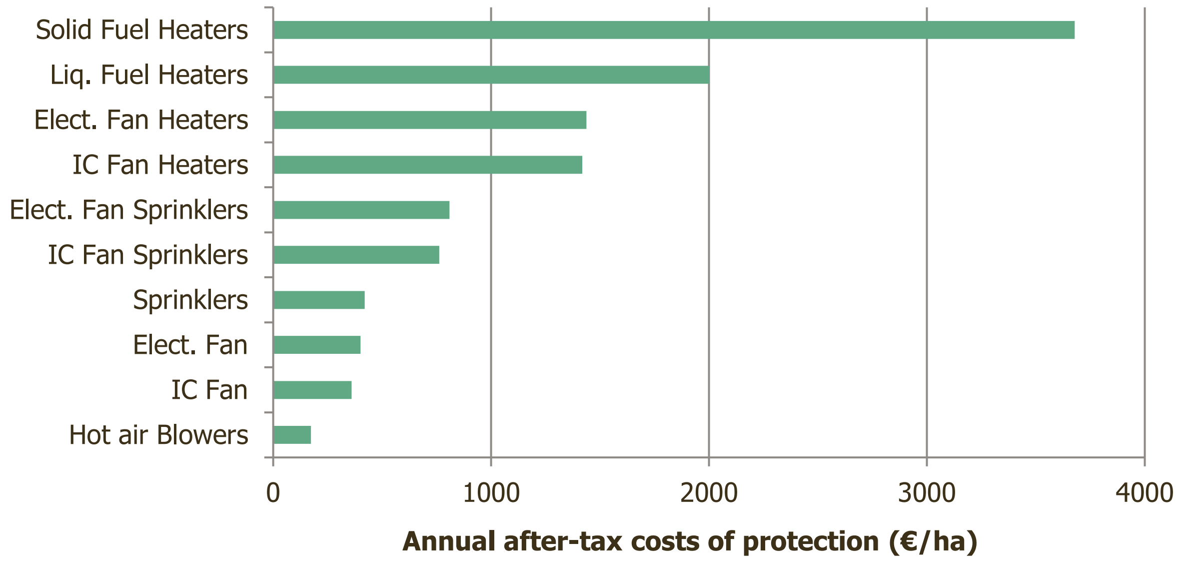

Fig. 3. Estimation of annual after-tax costs of protection to run some active methods in a fictitious location characterised in program FrostEcon (Snyder & De Melo-Abreu, 2005b). The prices and costs are estimates for 2018

b. Success and failure factors

For a given crop, the probability of occurrence of frost damage depends on the probability of temperature to be lower than the critical damage temperature (Tc). Hence, climatic, phenological and Tc information are crucial for the prediction of this probability. Whenever frost protection is contemplated, the optimal protection conferred by each method also needs to be known.

- Temperature and other weather elements are generally available from meteorological services or weather station(s) placed in the orchards. However, the microclimate may be significantly different from the climate determined in a nearby climate station, due to topographic factors (e.g. slope and aspect, and distance to the valley floor), soil colour and conductivity, orientation of the lines of trees, and soil cover.
- Tc depends on phenological stage and level of hardening. Therefore, phenological stage must be somehow simulated, through competent models, which are not yet available for all crops.

All these needs for information about the site, plant and management, and the requirements and specificities of the different methods available, make effective protection of a fruit crop very difficult and challenging.

The Focus Group has discussed the success and failure factors that make a difference at the time when these methods are implemented. In the table presented in Annex C, for the sake of completeness, we present those contributions along with equivalent notices for most of the methods that were left out of the core of the FG discussions.

A general overview of the results of the discussions reveals that, concerning **active methods**, the main barriers are the high installation costs or difficulties to effectively operate the systems. Those make heaters, helicopters, heat candles or wind machines affordable only in case of high levels of production or very valuable end products, combined with proper and local weather forecasts, so as to better decide when to start using the method.

For example, in the case of vineyards, heat candles are common in some areas (e.g. in France), as the high price of the product compensates for costs and labour requirements, but there are many associated difficulties. The fast lightning of the candles at the right time, and the problems in stabilising the candles when placing them on tilted surfaces seem to be the main issues.

Sprinklers and under-plant irrigation are clearly some of the most used and popular methods to fight frost. However, they also face some issues related to water availability and requirements. For example, water scarcity in periods of drought, but also to cases where the frost occurs several days in a row. This is because it is not recommended (and/or possible due to the high water consumption) to make use of this method for several consecutive days.

The discussions on **passive methods**, focused on site specifics, cultivars and varieties (resistance, blooming time, robust cultivars vs market preferences) and pruning (when, how intensive it should be, etc.). In general, these methods are theoretically effective, but come with many other side effects affecting the plants (e.g. reducing growth and/or fruit production). Therefore, more information and support are needed to efficiently use them. The case is similar for chemical methods, including some new products, which have not yet been studied well.

For example, in the case of grapes, it was mentioned that minimal pruning is not very widely used yet but that it has some advantages, like less labour costs for pruning and more chances that some of the buds will survive the frost event. However, this comes with a disadvantage, which is the smaller size of grapes. This is not a problem for wine grapes but it is not feasible for table grape growers.

Optimal performance of a given method of protection is achieved by implementing the best practices for the method and under the circumstances, and this is a complex matter. However, some guidelines may be given to support the strategic and tactical decisions of fruit growers. These guidelines may constitute a basis for a **Decision Support System (DSS)** that is likely to be the best way to deal with such complexity.

funded by European Commission

5. What can we do? Recommendations for better frost protection in the future

After the Focus Group discussed success and failure factors associated with existing methods, some ideas for possible improvement of these methods emerged. Some of these seek to improve current practices; other ideas imply the systematic gathering of information or the construction of new tools for current methods. Finally, other ideas represented research needs that may well be taken up by newly formed EIP-AGRI Operational Groups. **Five minipapers** were written with the purpose of dealing with some of the main themes from these ideas in greater detail.

In general, the Focus Group recognised that, in the past 50 years, very few new methods have been invented. The new developments are mainly related to new materials and equipment solutions. Some of the `new` methods are in fact modifications of old ones. For example, horizontal hot air blowers, that are now commercially available after introducing substantial improvements, were first promoted in the early 1960s (Ballard and Proebsting, 1978). It was further recognised that the reduced acceptance of some of the methods was related to knowledge gaps in certain aspects of the protection systems or their environment, to deficient monitoring of the relevant environmental variables in frost nights, to difficulty in managing the systems during protection, and to lack of orientation on the viability and selection of the most appropriate method. Both the efficacy of the system to protect the crops and the cost-effectiveness of the protection need to be considered when selecting frost protection systems.

The discussion yielded a number of sets of good practices for selected passive and active methods. All of these are summarised in the next subsections and in **Annex C**, along with similar items for the remaining methods that did not receive as much attention in the discussions. The main ideas conveyed were:

- Knowledge of the microclimate during frost nights is very important for both passive and active methods, mainly the flows of cold dense air and the strength of the inversions. This requires measurements of physical variables such as minimum temperatures and wind speed in different parts of the orchards.
- Knowledge of phenology (accurate models of plant growth and development) is essential for both groups of methods, because critical frost damage temperatures change with the stage of the plant.
- In active protection, timing and monitoring of environmental variables are essential. These can only be achieved when real-time temperature, humidity and, in some cases, wind speed and direction are measured in the orchard on various spots. Profile measurements of temperature are also important.
- Species/cultivar and/or rootstock resistant to frost save energy, work and money.
- The application of some chemical that could make the plants avoid or resist frost would also be practical.
- Overhead sprinkling confers about the best affordable protection for many crops, but it is not perfect. It can be improved, namely to save water.

a. Reduced use of water in above crown sprinkling

From all the existing techniques, above crown sprinkling of water during frost is the only method that offers effective protection until -7°C, but it also suffers from several constraints. For example, the high demand of water makes this method not viable in some areas, the low accuracy of some sprinkler systems, the inefficacy under windy conditions, installation costs or the higher risk of occurrence of some diseases associated with humid conditions.

Thus, apart from its ability to fully protect fruit flowers against severe frost damage, the above crown sprinkling system also has several drawbacks, with low sustainability (e.g. due to high water use) as one of the most negative points.

Reducing the water consumption (up to 50%) by using in-row or low-volume sprinklers needs further testing and improving (e.g. the wind sensitivity of these systems remains a problem). This would greatly lower the

funded by European Commission

environmental impact of the above crown sprinkler system (Jorgensen et al., 1996). Combined with very accurate, real-time monitoring of temperature (and relative humidity) changes, additional saving on water consumption is possible by using a lower water pressure at mild freezing temperatures (until -2 °C).

Minipaper 1 collects some examples on technologies, such as in-row micro-sprinklers, already in use that manage to importantly reduce the water consumption.

Naandanjain Flipper system used in vineyards has been successfully applied in Belgium in pome fruit. It delivers water in the tree row and not on the grass strip. Approximately 15 m^3/ha/h water is used, which is more than 50% less water than with conventional sprinkling systems. The system is a bit more sensitive to wind than regular sprinklers and can be used under a hail net or any other cover system.

Netafim Pulsar™ with StripNet™ head is a tube with air bag and special valve that gives several pulses per minute. It has a 12 l/h overflow and gives a 3.8 mm/h spray intensity in the weaving belt. This sprinkling system represents an additional 40% saving of water. Excel-wobblers use about 20-30% less water, and give a very even droplet distribution due to a bigger and more even droplet size than standard sprinklers. They are more energy-efficient, since they use less pressure.

Nevertheless, a thorough comparison of less water-consuming sprinklers under frost conditions is needed since multiple water saving sprinklers exist, but it is not clear which are suitable for frost protection.

b. Affordable real-time online frost detection data

Several methods have been identified to protect plants against frost. However, for the success of any endeavour, the availability of accurate information is crucial. So, farmers urgently need the following information before activating a frost protection system:

- Weather forecast
- Accurate real-time information about temperature and other parameters in their fruit orchards

In general, farmers have only one weather station at one location, with temperature measurement at standard height (1.25 m to 2 m), which is clearly not enough for an accurate frost forecast. Adding more sensors at different heights to one station and/or adding more stations increases the representation of the measurements over an entire orchard. Adding more of these expensive fully equipped weather stations solely for monitoring frost is an expensive investment. One solution is not to buy more of these expensive weather stations, but

funded by European Commission

instead to have more individual (smaller) measuring devices that only register temperature and relative humidity. So, what are the requirements and needs of a reliable and affordable frost detection system?

The ideal frost detection system offers a number of crucial functionalities, each of which are described in Minipaper 3. The total solution should come at a reasonable price for an average fruit farmer. The ideal solution is simple, affordable, reliable, accurate, real-time and online.

Affordable real-time online frost detection data for farmers in frost-prone regions

- ✓ Data recorded: Measuring temperature and air humidity (RH, dew point or wet-bulb temperature) in multiple locations within the area of the endangered crop is most important.
- ✓ Affordability: Multiple measurements are required on several heights and locations in one orchard. Modern digital monitoring devices provide an affordable alternative to the classic weather stations when a flexible combination of sensors is required. These sensors need a high accuracy and resolution and the device needs a reliable internet connection, such as GPRS or 3G/4G.
- ✓ Real-time measurements and notifications: Measurements should be transmitted in real time, giving the user information about the past few minutes, not hours. When the bandwidth of the network is limited, one possible solution is to only send the data when a certain threshold is crossed. Warnings to the owner could be sent by SMS or email.
- ✓ Decision support: A decision support system (DSS) is helpful to integrate different kinds of information sources, in order to give farmers the most accurate information possible. Different solutions for this aspect are on the market.

Temperature inversion[2]: In order to decide whether inversion can be exploited, it is crucial to first measure temperature at different heights. The type of frost (radiation vs advection) will determine the quality of the inversion layer.

In order to improve accuracy, a kind of 'citizen science' approach was implemented in Austria for the forecast of scab: farmers have a Web App on their smart mobile device, through which they can add the actual situation in their orchard: e.g. "leaves are wet" even though the forecast tool reports that the "leaves are dry" (https://obstwarndienst.lko.at/1251/Schorf). The forecast is then adapted to the real situation and the plant health situation is re-calculated and therefore better approaches reality. Similar to this, for frost warnings it might be useful to think about possible additions by the customer.

c. Phenology knowledge (and models)

The degree of frost damage depends on the stage of the plant as well as on weather conditions. As the phenological stage is crucial for the plant's susceptibility to frost, it is important to understand the physiology of the plant and the influencing factors for budbreak and bloom. In addition to the plant stage, the critical temperature for the plant depends on various factors, which – to some extent – can be influenced by the farmer. In order to predict the risk of frost in time, phenological models can be helpful to predict plant development.

The understanding of physiological processes in plants that are related to spring frost can help farmers to better estimate the risk of frost damage. It can help them take – as far as possible – correspondent measures. Minipaper 5 provides some further information on specific methods and practices that farmers can apply to

[2] Temperature inversion happens when temperature increases with height, when a layer of cool air at the surface is overlain by a layer of warmer air.

funded by European Commission

deal with phenology. Even so, farmers should be cautious, as these models provide only theoretical estimations, and do not consider all factors influencing phenology.

Chilling and forcing heat models have been combined to predict budbreak or bloom in fruit crops. For pome fruit, stone fruit and nuts, several models are available. These are mainly focused on predicting only bloom dates. For example, for grapevines mainly two approaches are used: the Growing Degree Days model (GDD) and the Grapevine Flowering Veraison model (GFV). These models provide reasonably good estimations for bloom (GDD also for budbreak) under temperate and in cool climates. However, in warm and Mediterranean regions, the estimated dates are too early (up to 2 weeks) to use the general formulation of the models or the same values. In the GDD model, reference values for warm regions are available. These improve the accuracy of the estimates, but the expected error can still be too high. A summary of some phenological models adjusted for European conditions to estimate bloom in nuts, stone and pome fruit trees is presented in **Minipaper 5**.

For all crops, the following points can be summed up:

- Phenology and development of plants follow inner stimuli (i.e. phytohormones) and outer conditions (i.e. temperature, day length). Perennial plants are therefore distinctly affected by unusual weather conditions due to climate change. Especially warm conditions at the end of dormancy (early spring) can result in early budbreak or bloom, and end in high risk situations for spring frost.
- Stress avoidance in general enhances the capability of plants to cope with unfavourable conditions.
- Susceptibility of plants to spring frost depends on the phenological stage. Date of budbreak or bloom can be influenced by the choice of species or cultivar, the rootstock-variety combination and site selection.
- Nutrition state influences the degree of frost damage. Especially a balanced supply ofnitrogen and potassium is vital. Oversupply with nitrogen should be avoided, as it enhances susceptibility to frost.
- If components used (rootstock/scion) are taken from different climatic zones, a strong rootstock influence is usually observed. For instance, peach cultivars grafted on *Prunus mandshurica* is known to be delayed by 7-10 days in flowering/fruit ripening time. Therefore it is possible to find and use a 'delaying rootstock' to better cope with early spring frost. However, side effects such as increased incompatibility of grafts should be considered. Furthermore, it is not applicable for early cultivars.
- Phenological models are not complete enough to be used in decision support systems (DSS), as they usually only estimate bloom (sometimes including budbreak).

d. Use of chemicals in frost protection: methods and initial recommendations

Although some chemicals are already used in growing practice, their effects are not well understood in many cases. Pros and cons of interesting methods, side effects, costs, difficulties, etc. are discussed in **Minipaper 4**.

In general, two main approaches are discussed:

- Treatments to delay bloom or budburst
- Treatments to help the plant cope with frost

Delaying bloom or budburst is an indirect and preventive method, which must be realised before the risk of frost can be estimated. Depending on the timing of the delay and the moment of spring frost, the delay can be sufficient to avoid or reduce damage on cultures. Otherwise, active protecting methods are required in addition.

Delaying is judged a very promising method, especially for sensitive species with short dormancy phases (apricots, sweet cherries or grapevine). However, the attained delay might not be effective enough (depending on situation and timing of spring frost) and active protecting methods may still be required. Regarding possible methods for fruit trees, only little information is available. The effect of substances that enhance frost resistance of plants is estimated to be rather limited – and consequently not sufficient for severe or long-lasting spring frost events. Therefore, the risk of damages in spite of (costly) measures is too high.

funded by European Commission

Methods already tested in field trials and practice are:

- GA3 saves the harvest in some pear cultivars (which may help to regulate bloom and vegetative growth). However, inferior fruit quality – as in the natural parthenocarpic behaviour – must be taken into account. The pronounced effect is evident only with respect to parthenocarpic fruits.
- Applications of Prohexadione-Ca (Regalis), potentially combined with GA4+7, as post-treatment reduce yield losses on apples.
- Sprayings with Gibberellin GA4+7 are used either as pre-treatment or post-treatment on apples and pears to reduce frost sensitivity or damage, respectively. Effects on fruit quality are to be expected at higher doses.
- Rape oil for delaying budbreak of grapevines is judged a hopeful method, but cultivar-specific reactions and other uncertainties still need to be investigated.

For all mentioned methods, it has to be considered that attained effects and unwanted side effects highly depend on various inner (e.g. cultivar, vigour) and outer factors (e.g. conditions at/after application). Also the timing of applications is vital for success.

e. Assessing costs and benefits of frost protection methods in fruit production

The choice of frost protection method is a complex decision. Orchard managers have to consider climatic conditions and risks, technical feasibility and effectiveness, and economic aspects. In general, active methods are more expensive than passive methods, although there might be indirect costs of passive methods that should not be ignored, e.g. increased risk of soil erosion when planting tree rows downward the slope to facilitate cold air drainage.

Frost risk management decisions are difficult to make, because they require considering long planning horizons, accounting for various fixed and variable costs, and estimating parameters that are not precisely known. Current and future frost risk, bloom times, frost damage levels and price responses in the event of widespread frost damage are among the critical variables that should be considered but whose precise values are usually unknown.

Decision analysis based on probabilistic simulation is a commonly used approach to risk management in many fields. It can account for risk and uncertainty, and it can help growers objectively quantify their frost challenges and select appropriate ways forward. To date, such methods are rarely applied by orchard managers, because many are unfamiliar with these approaches, and tools to support them are not readily available. Research and extension should try to assist growers in bridging these methodological gaps, so that they can be optimally equipped for choosing frost protection strategies that fully account for the frost risk profile of their particular location.

Minipaper 2 discusses, among other things, the methodologies that can be used to undertake such studies. Ideally, these studies should also provide a computer tool to allow adaptation to other conditions.

The approach to decision making involves the following steps:

- Identifying frost protection measures that are effective and technically feasible on the given site and for a given crop
- Identifying costs and benefits
- Calculating net benefits

Dealing with uncertainty

A key challenge for decision making about investment in frost protection measures is to deal with uncertainty. Different approaches for assessing uncertainty are possible.

funded by European Commission

A commonly applied technique in risk assessment is the so-called **Monte Carlo simulation**, which can be carried out with EXCEL or other calculation software. The basic principle is to identify those variables of the cost-benefit calculation that cannot be predicted with certainty, i.e. that are stochastic. Instead of estimating one mean value, a probability distribution of possible values is specified. As an example, minimum, maximum and most likely values are defined for stochastic factors in the calculations (see also Table 3), dependent on the specific conditions on the farm and according to the growers' own perceptions. In the Monte Carlo simulation, the simulation tool repeats the cost-benefit calculations many times, e.g. 10 000 times. In these calculations, the values for each of the specified variables are drawn randomly from previously defined ranges of possible values. Hence the result of each of the calculations is the combination of different possible values, showing a possible outcome of net benefits. The distribution of possible outcomes can now be further analysed: How broad is the range of possible outcomes? What is the share of simulation results with negative net benefits? Based on these indicators, the different technologies can be compared against each other and against a reference situation without frost protection.

Table 3: Stochastic factors of the benefit-cost analysis of frost protection measures

Factor	Example	Data source
Potential yield without frost in a given year, site and variety	Range of yield levels, minimum and maximum yield per ha	Regional fruit production statistics, experimental stations and yield trials, on-farm records of yields
Yield in case of frost event without protection	Range of yield levels, minimum and maximum yield per ha	Regional experimental stations and yield trials, on-farm records of yields
Saved yield / prevented losses for each frost protection measure under consideration	Technical efficiency, range of the share of yield that is saved.	Technical reports, experimental stations
Frequency of frost events with potential yield losses	Minimum and maximum number of years with frost events during lifetime of the orchard	Historical weather data, records of regional flowering dates
Output price in year with frost event	Minimum, maximum and most likely price of output	Price statistics, trends

f. Other recommendations

The starting paper and its references include many recommendations, success and failure factors that were not thoroughly discussed by the Focus Group but that are, nevertheless, useful for frost protection. Annex C summarises some other important aspects that could not be fully discussed.

funded by European Commission

6. Research needs from practice

Following a broad discussion, the Focus Group prioritised a set of research needs from practice, considering the following as the most important.

a. Studying and comparing the effectiveness of methods under different conditions

Most of the studies that are conducted to evaluate the effectiveness of frost protection methods only test one method in one location/environment. This reduces the potential to use the conclusions of such studies to select one method, within a number of alternatives, in another location. The same reasoning may be used for a specific solution in a given location/environment.

Therefore, it would be useful to have the same method(s) or solution(s) tested in different locations/environments with careful determination of the phenological stage of the crop at the time of the frost (see below). For example, conducting comparison tests of the effectiveness of different chemicals used for frost protection (enhancing frost resistance, delaying budbreak or bloom) under different field conditions.

b. Adding more biology to models

Conducting studies to find and validate easily detectable physiological markers for phenological stages to be able to make the models more precise.

c. Establishing a database on potential yields for different species/varieties and critical temperatures on species/variety level

The idea is to create a database with potential yields and frost damage related to actual temperatures in as many locations as possible. This information could be used to determine critical damage temperatures and allow validation of frost damage models.

d. Developing a reliable monitoring and alarm system that relies both on surface and profile information of temperature, humidity and wind speed

Measuring temperature at different heights (0-30 m) (and RH, wind) to be able to come up with a precise, reliable warning system to start, for example, sprinkling at the right time.

e. Studying the different behaviours and phenology of cultivars under varying climate conditions

Conducting studies on the behaviour of cultivars in avoidance, resistance or other frost-related survival mechanisms of plants. Phenological stage studies and reliable simulation models are crucial in cultivar evaluation.

Annex D provides the full list of research needs prioritised by the experts.

funded by European Commission

7. Ideas for Operational Groups

The Focus Group developed five ideas for EIP-AGRI Operational Groups

a. A local-scale decision support system for selecting methods of protection or for assessing frost risks in fruit production

In general, it is difficult for farmers to find reliable and local information to properly determine the risk of frost, and also to decide which method is better, for a particular case, to protect fruit orchards from frost. Therefore, the objective will be to allow the farmer to select appropriate and local frost risk strategies.

The idea of this OG is to develop a tool that locally assesses frost risk and indicates to the growers when there is risk of frost and what protection method is more suitable. The tool will be preferably an application but could be any other type of resource that provides advice.

The results and information will be relevant for several stakeholders such as agronomists, farmers, advisers, scientists or managing authorities.

The tasks to develop the tool will start by gathering all background information needed for a complete risk assessment of frost. This includes meteorological services, data about water volumes and availability, etc.

Furthermore, the growers will need to provide their inputs, for example what they have (location of orchards, anti-frost systems installed, crops, etc.) but also informing and cooperating for demonstrations on new technologies that they would like to try.

As various inputs for information are needed, the actors involved in this OG will be farmers, advisers, scientists, meteorological services, administration, suppliers, etc.

b. Field experiments to try different frost protective agents (chemicals)

Currently there are several products available of which the effect and functionality is questionable and/or can have unwanted or negative side effects. Additionally, there are several factors such as phenology, weather or treatment dose, which might influence their effectiveness.

Therefore, the objective is to compare some of the available frost protective agents, under different conditions or doses, to determine the optimal conditions for their performance. Based on these trials, a set of recommendations for proper use of these chemical frost protection agents will be formulated.

The tasks for the OG will be first to compile a shortlist of protection agents to test. Then to design the protocol for the trials under controlled and field conditions, so as to assess frost damage. Duration of the test will be for at least two years. Final step will be to develop the guidelines on proper application of the agents.

Participants in the OG will be growers, practical research centres and suppliers of the chemicals to be tested.

c. Establishing and optimising a T/RH (wind) sensor network in a fruit growing region

The issue to be tackled by the OG is that the individual frost warning systems at grower's level are not standardised and they are not comparable or reliable. The objective of the project will be to establish a reliable and on-site measuring and warning system in a location, benefiting growers, advisers and researchers.

Tasks will be to screen and select sensors, data collectors and transfer systems, install and start measuring (independent from the frost situation) at the most critical sites, so as to calibrate and adjust the system.

funded by European Commission

The actors needed for the project will be growers and advisers, sensor and technology suppliers, researchers and meteorologists.

d. Frost Research Effective Database (FRED)

The objective is to contribute to better prevention of frost damages at local level, increasing the effectiveness of the methods to protect the orchards. The objective is to set up the Operational Group with a specific group of growers.

The concrete results of the OG will be open base protocols and information, for local frost risk estimation and assessment.

The idea can be developed through 6 steps:

1. Gather – historical – meteorological data of the area,
2. Set up a network of meteorological stations to record local meteorological data,
3. Collect and analyse the data locally (open platform to share), to model the risk prediction and map risk areas,
4. Gather information and real experiences related to frost in the area (recognition of each problem),
5. Full implementation of the system to each member of the OG,
6. Real testing and feedback phase to improve the system.

Actors involved will be farmers, advisers, local and national authorities, and agricultural chambers and non-profit organisations, if existing, and related to growers. These will be necessary actors, but also potential beneficiaries of the results.

Then researchers (stations, meteorological data, agricultural) and companies for providing equipment are also needed in the project.

e. Hand device to measure frost damage

The objective is to measure the actual freezing temperature causing damage – in flowers –, establishing the limit temperature below which there might be damage and below which the protective measures should be activated. This is based on the measurement of ice nucleation temperature of flowers and could help to develop, improve or even validate predictive models used for assessing and determining frost risk. The result for the end user will be a device determining the exact plant organ temperature at which damage occurs, helping them to decide when it is needed to protect the fruit.

The device will determine the temperature at which ice crystallises in the flowers. Consequently, the measured damaging temperature will be possible to use for the precise and reliable frost warning systems/decision support systems. The task of the Operational Group will be double: a) to develop a reliable model, based on research and field trials, to determine the principles to deduce the limit temperature, and b) to develop and optimise the temperature measurement procedure and device.

The actors involved in these OGs will be mainly researchers, growers and technical companies. Farmers and advisers will benefit from the results as it will develop a system that provides information on when and where the damage can happen.

funded by European Commission

f. Other recommendations, including improving take-up

The role of passive methods cannot be over-emphasised, due to its importance.

The 3-D modelling of the flow of cold air could be very important to the methods "site selection" and "managing cold air drainage". This involves GIS-based modelling and extensive research for the validation of the model. This type of model could be integrated in a decision support system that would include those methods.

The method "plant selection" involves many aspects, and some of them belong to the domain of a more fundamental type of research. There is enough variability of frost resistance characteristics in most species to allow successful crop improvement. There is nothing more effective than to have a frost-resistant cultivar that can be installed in the frosty spots. Studies of 'plant x site x management' interaction could identify cultivars that are more appropriate for a given environment. The influence of rootstocks on the plant response is a fundamental part of such studies.

The experts of this FG have an important role in the impact of the work that is produced. They may be active agents in the constitution of OGs in their own countries.

The FG members will also contribute to the dissemination of the recommendations and ideas produced by the group. All media are important to improve the acceptance of frost protection methods and technologies.

funded by European Commission

8. References

Bagdonas, A., Georg, J.C. & Gerber, J.F. 1978. Techniques of frost prediction and methods of frost and cold protection. World Meteorological Organization Technical Note, No. 157. Geneva, Switzerland. 160p.

Ballard, J.K. & Proebsting, E.L. 1978. Frost and frost control in Washington orchards. Washington State University Extension Bulletin, No. 634. Pullman, Washington. 27p.

De Melo-Abreu, J.P. 1985. As Geadas, Conceitos, Génese, Danos e Métodos de Protecção. ISA, UTL. Lisboa. 219 pp.(in Portuguese).

De Melo-Abreu, J.P. 2018. Agrometeorologia. Aplicação da Meteorologia para Maximizar a Produção Agrícola. Agrobook. Lisboa. 360 pp. .(in Portuguese)

EC, 2017. Extreme weather pushes EU wine harvest to historical low in 2017. News (4 October 2017), European Comission, EU. Available: https://ec.europa.eu/info/news.

EC, 2018. Apple Dashboard. Agricultural markets: dashboards and Tariff Rate Quotas (TRQs). Available: https://ec.europa.eu/agriculture/dashboards_en.

Evans, R.G. 2000. Frost protection in orchards and vineyards. (available at: http://www.bsyse.prosser.wsu.edu/report/frost.html).

Jorgensen, G., Escalera, B.M., Wineman, D.R., Striegler, R.K., Zoldoske, D. & Krauter, C. 1996. Microsprinkler frost protection in vineyards. California State University at Fresno, CATI Publication #960803.

Powell, A.A. & Himelrick, D.G. 2000. Principles of freeze protection for fruit crops. Alabama Cooperative Extension System, ANR 1057B. (Also available at http://www.aces.edu).

Sakai, A. & Larcher, W. 1987. Frost survival of plants. New York NY: Springer-Verlag. 321p.

Snyder & De Melo-Abreu, 2005[a]. Frost Protection: fundamentals, practice, and economics, Vol. I. FAO, United Nations, Rome. This volume details the technical aspects of frost protection.

Snyder, De Melo-Abreu & Matulich, 2005[b]. Frost Protection: fundamentals, practice, and economics, Vol. II. FAO, United Nations, Rome. This volume details the risk and economical aspects of frost protection.

Annex A. Members of the Focus Group

Name of the expert	Profession	Country
Jean-Marc Audergon	Researcher	France
Alois Bilavcik	Researcher	Czech Republic
Anna Brugner	Adviser	Austria
Lopo Carvalho	Adviser (farmer)	Portugal
Roman Chaloupka	Working at an NGO	Czech Republic
Sabrina Dreisiebner-Lanz	Researcher	Austria
Hildegard Garming	Researcher	Germany
Maciej Gąstoł	Researcher	Poland
Jerneja Jakopic	Researcher	Slovenia
Jean-François Larrieu	Adviser	France
Kieran Lavelle	Adviser	Ireland
Eike Luedeling	Researcher	Germany
Susan McCallum	Researcher	United Kingdom
Carlos Miranda	Researcher	Spain
Serge Remy	Researcher	Belgium
Jonathan Sercu	Industry	Belgium
Andrej Soršak	Adviser	Slovenia
Branislav Šebo	Farmer	Slovakia
Chiara Vicini	Researcher	Italy
Krystian Zawiliński	Farmer	Poland

Facilitation team

José Paulo Mourão de Melo e Abreu	Coordinating expert	Portugal
Beatriz Guimarey Fernández	Task manager	Spain
Liisa Kübarsepp	Back-up manager	Estonia

You can contact Focus Group members through the online EIP-AGRI Network.
Only registered users can access this area. If you already have an account, you can log in here
If you want to become part of the EIP-AGRI Network, please register to the website through this link

funded by European Commission

Annex B. Minipapers on prioritised topics

Minipaper	Title	Contributors
MP 1	Frost protection by overhead sprinkling	Serge Remy (Coord.), José Lopo Carvalho, Jerneja Jakopič, Jean-François Larrieu, Andrej Soršak, Anna Brugner
MP 2	Assessing costs and benefits of frost protection measures in fruit production	Hildegard Garming (Coord.) Eike Lüdeling
MP 3	Affordable real-time online frost detection data	Jonathan Sercu (Coord.), Kieran Lavelle, Lopo Carvalho, Serge Remy, Sabrina Dreisiebner-Lanz, Chiara Vicini, Anna Brugner, Jean-Marc Audergon
MP 4	Use of chemicals to help plants tackle frost damages	Sabrina Dreisiebner-Lanz (Coord.), Alois Bilavcik, Roman Chaloupka, Maciej Gąstoł, Susan McCallum, Carlos Miranda
MP 5	Phenology and critical temperatures	Carlos Miranda (Coord.), Alois Bilavcik, Roman Chaloupka, Sabrina Dreisiebner-Lanz, Maciej Gąstoł, Eike Luedeling, Susan McCallum

funded by European Commission

Annex C. Good practices, success and failure factors

Based on De Melo-Abreu, 1985, 2018; Snyder & De Melo-Abreu, 2005[a,b] and Focus Group expert opinions.

PASSIVE METHODS					
METHOD/ VARIANT	**ESSENTIALS OF THE METHOD**	**APPLICABI-LITY**	**SUCCESS FACTORS**	**FAILURE FACTORS**	**ECONOMIC ASPECTS**
Site selection	Look for a suitable climatic zone for the crop. Avoid locations around which cold air forms, drains down the slopes and ponds.	Should be the main concern for implantation of frost-sensitive crops.	Reliable climatic data. Proper knowledge of crop characteristics and management. Predict the flow of air in the landscape. Gentle, uniform slopes are usually better since cold air does not accumulate. Slopes are, often, many degrees warmer during frost nights. For deciduous trees, northern facing slopes have later phenological development and will be less likely to be injured by both winter and spring frosts. Southern facing slopes are usually warmer and better for evergreens.	Disregard of any of these concerns may have irremediable consequences. Lack of availability of suitable sites.	Implantation of a permanent crop in a bad location may bring total or partial loss of the investment.
Managing cold air drainage	Divert the flow of cold air away from your crop under cooling conditions. Remove leeward obstacles to the passage of draining cold air.	Sometimes it is feasible. A few rows of trees may be effective and may provide several degrees of protection.	Study the night flow of air (e.g, use smoke bombs). Remove windward sources of cold air formation.	Deficient knowledge of the flow of air.	Costs effective in many situations due to direct and indirect benefits (e.g., income from the wood of the trees, windbreak effects).
Plant selection **(plant date)**	Use of more appropriate species/cultivar, hardier plants, later flowering, better rootstocks.	Very important for implantation of frost-sensitive crops.	Proper knowledge of the characteristics of the genetic material, and rootstock effects.	Lack of knowledge of these aspects. No delaying rootstocks available.	Affordable

funded by European Commission

Canopy trees	Intercropping frost-resistant-higher trees with shorter-sensitive trees. Results in higher downward radiant flux during the night.	Very efficient and absolutely necessary under many circumstances. Shade trees over coffee plants are used in many regions (e.g. Brazil).	Necessary to find the right combination, to avoid adverse effects due to plant biology or management.	Incompatibilities, shading, sanitary problems, management difficulties.	Positive under some circumstances.
Plant nutrition manageme nt	N oversupply increases growth and frost susceptibility	Important to withhold N fertilisation and water to fruit trees in late summer, because trees need to harden before cold weather occurs in autumn/winter.	Right timing	Since hardening is an active process, poor nutrition may be detrimental.	Positive, if any.
Proper training and pruning	- Pruning stimulates growth. - Double pruning reserves resource wood for production following a damaging frost. - High forms of training subtract fruits/grapes from colder temperatures near the ground.	Late pruning, double pruning and high forms of training are used in many parts of the world, mainly in grapevines. May reduce very much the likelihood of frost damage.	Right timing	Adverse weather conditions just before bud burst may excessively delay pruning operations.	Labour costs increase
Plant covers	The covers are warmer than the sky: more downward radiant flux.	Adequate materials may result up to 5ºC of protection.	Place the covers around the plants, so that air movement is restrained. Remove the covers as soon as possible in order to avoid sanitary problems.	Some films are not effective. Black plastic is less effective than clear plastic. Condensation inside the covers and excessive heat during the day may be detrimental.	Rather expensive for field crops
Keeping surface heat conduction high	Still air has a very low conductivity, hence refrain soil cultivation just before a frost event. Keep soil moist to minimise the content of still air (water is	During the night heat may flow to the surface and slow down night cooling if the surface is conductive.	Should be implemented well before the frost period in order to allow heat to be stored in the soil.	Inappropriate timing.	Good cost-benefit ratio

funded by European Commission

	more conductive). Removing cover crops that trap air.	This method may confer up to 2º C of protection.	Timing is important. If implemented too late little heat is stored in the soil. Moist soil is beneficial, but saturated soil has lower conductivity and is likely to lose heat through evaporation.		
Trunk painting and wraps	- Autumn application of diluted water-based latex white paint avoids or reduces trunk damage due to dehardening. Wraps applied at the same time may replace the paint. - White-painting may also delay the onset of growth in spring. - 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.	- Is used in cold continental climates for trunk protection. It saves the trunk and allows regeneration of the trees. - Wrapping young citrus tree trunks with water bags was reported to give even better protection than fibreglass or polyurethane foam.	- Apply paint only if the air temperature is above 10º C. Complete painting by mid-afternoon to allow adequate time for drying. The faster the paint dries, the less chance there is of damage occurring. – Trunks should be wrapped from the ground surface to as high as possible.	Insulation that absorbs water brings diseases. When bud unions are too near the ground there is potential for disease problems.	Good trunk wraps are expensive, and placement and removal (after 2-3 years) consume labour. Soil banking is effective, material is free, but is labour-intensive.
Bacterial control	- The ice formation process is mostly initiated by presence of INA bacteria. After forming, it then propagates inside the plants into the plant tissues. NINA bacteria compete with INA bacteria and, when applied, may reduce the concentration of these bacteria. - Antibiotics and copper compounds applications can also reduce the	Application of NINA bacteria or use of antibiotics has not been widely used. Copper compounds are used frequently (e.g. potato crops in Portugal).			Copper compounds are used also for fungal control. Hence, their cost is only partly attributable to frost protection.

	concentration of INA bacteria.				
Chemicals	Besides copper compounds that have bacterial control action, there are some chemicals that are retardants of crop growth and other chemicals that are cryoprotectants and antitranspirants that allegedly reduce the Tc of the crops directly.	There is conflicting evidence that commercially available cryoprotectants and antitranspirants work.			No installation costs, and operational costs are low.
ACTIVE METHODS					
METHOD/ VARIANT	**ESSENTIALS OF THE METHOD**	**APPLICABILITY**	**SUCCESS FACTORS**	**FAILURE FACTORS**	**ECONOMIC ASPECTS**
Heaters	Open-fire heaters and candles provide sensible heat to replace energy losses. Additionally, stack heaters provide a high fraction of radiant energy that is absorbed by the plants. Heaters use liquid, solid or gas fuels. Smoke has no effect, since the smoke particles are too small to absorb terrestrial radiation.	Heaters are still in use in some countries where fuel is cheap, or where high revenue crops are grown. If the number of heaters and burning rate are adequate, they are effective.	To be used under strong-inversion radiation-frost conditions. Stack heaters provide some protection even under wind frosts. Much more efficient if there are many small fires than if the fires are few and big, due to chimney effect.	Wind frosts or katabatic wind drifting away heat from the crop. Weak or no temperature inversion. Insufficient number of heaters or inappropriate distribution in the field.	Very high operational costs. For most situations it is unaffordable.
Wind machines (classical)	Under radiation frost conditions, temperature inversions develop. Classical wind machines 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.	Only effective if a strong inversion is present. It is used extensively whenever frost protection needed is less than about 2º C. Usually used in permanent crops (e.g. fruit trees, grapevines) but may be used essentially with any crop. Area covered is 4–6 ha.	Microclimate must be studied before possible installation of the machines. The strength of the inversions must be measured in a few days. Ideal placement of the fan depends upon the air flow in frost nights.	Deficient control of the time to start and stop protection. Minimum temperatures that are likely to occur should not be more than 2º C lower than the critical damage temperature. Inversion must be present.	Installation costs high, but operational costs are moderate. Auto-starting systems are also available.

funded by European Commission

	Typically, the height of this axis of the fans is about 10–11 m, and they rotate at about 590–600 rpm. There are also wind machines with four-blade fans. May be powered by fuel oil, gas or electricity . Power is typically 65–143 kW, but is higher in some models (e.g., 143 kW). Their operation results in the mixing of the lower layers and concomitant air temperature at plant level increases.		Not operate with wind speed above 8 km/h or when supercooled fog occurs.	Make sure that the noise generated by the machine is within the tolerance of the neighbours and compatible with current laws.	
Wind machines **(variants)**	Some variants of the classical-stationary wind machine have lower towers, higher fan rotation speed, and are portable.	The underlying principles of the variants of the classical-stationary model are the same. However, if i) the height of the tower is lower, the access to higher layers of warm air is restricted; ii) if the power is lower, the area covered by the flow of air is reduced; and iii) higher rotations of the propeller are less efficient.	For portable wind machines that have lower height and power, the protection conferred and area of coverage is smaller. Hence, more machines should be used. Make sure there is a temperature inversion.	The considerations on classical wind machines, concerning the presence of the inversion and noise apply to these machines.	Installation costs high, but operational costs are moderate.
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.	It is used in some countries/regions where helicopters are available. Estimated coverage area by a single helicopter varies between 22 and 44 ha.	Monitoring of temperatures in the canopy in many places is fundamental and the colder spots need to emit signals to the pilot of the helicopter. Recommendations on pass frequency vary between 30 to 60 minutes,	If control of temperature is not appropriate serious damage occurs.	Operational costs are unaffordable for most growers.

			depending on weather conditions.		
Sprinklers **(overhead, classical)**	The water conveys some sensible heat and, much more significantly, upon freezing over the plant organs, the latent heat of fusion is released and made available to plants (and air). While liquid water wets the ice that is formed over the plant surface, temperature remains around 0 ºC. At the same time, part of this heat is lost to evaporation, mainly if the air is rather dry and there is wind. Special sprinklers are necessary to avoid that they stop rotating as ice forms on them. The rate of application depends on weather conditions, microclimate and characteristics of the canopy.	When the plants are able to tolerate the weight of the ice and enough water is applied, this method may convey protection down to -7 ºC. Water must be available in quantity and quality for all the frost events. Widely used in developed countries for many species (e.g. pome fruits, blueberries, strawberries). Is not used with most stone fruit and some citrus trees, since they are prone to limb breakage and loss of scaffolds.	The starting time for this method should be related to wet-bulb temperature, not air temperature. Stopping should occur after the ice has melted. Rates of application need to be calculated taking into account all factors. For some species, the training and pruning need to be adapted to the method, so the trees are able to support the weight of the ice that forms. It is necessary to have a backup water pump, for the event of failure of the main pump.	Deficient control of the wet-bulb temperature may cause the systems to start too late. Wind and blockage of the rotation of the sprinklers may cause damages. Severe damage can occur if the sprinkler system fails. The weight of the ice that forms may break limbs and loss of scaffolds in trees of some species. Root disease can be a problem in poorly drained soils and/or sensitive species.	Installation costs are high, but energy consumption and operational costs are relatively small.
Targeted overhead sprinklers	Targeted sprinklers spray the water directly on to the plants, with minimal amounts of water falling between plant rows.	Method variant that has not been widely used, but some growers use these systems and are very happy with them.	The application rate is reduced in relation to soil coverage. Filtering system must be very efficient and the water quality needs to be high. Should not be used in microclimates where there is katabatic wind.	Wind, bad water quality or inefficient filtering are frequent failure factors.	Installation costs are high. Energy consumption and water use are reduced to a minimum. Operational costs are relatively small.
Sprinklers over	Sprinkling over covered crops in greenhouses and	Method variant that has not been widely	Water quality, namely the absence of substances that	Salt and other precipitates may	Affordable for many protected crops.

funded by European Commission

covered crops	frames provides considerable protection. The principles are similar to other sprinkling systems.	used, but is fully efficient. Water consumption is high.	may deposit over the covers is essential. Structure must support the weight of the frost.	reduce transparency of the covers. Structures and covers may collapse with the weight of the ice.	Installation costs are high and operational costs low.
Under-tree conventional sprinklers and micro-sprinklers	Same principles as overhead sprinkling apply. With micro-sprinklers water is applied under the trees only, which reduces protection but there is less water consumption.	Under-tree sprinklers are commonly used for frost protection of deciduous tree crops in regions where the minimum temperatures are not too low. Microsprinklers are also used, because they are sometimes replacing the sprinkler for irrigation.	Fewer above-ground sanitary problems than overhead sprinkling. Fewer soil and root problems than overhead sprinkling.		Since the system is used mainly for irrigation, the costs attributable to the installation costs are inexistent and operational costs are low.
Trickle-drip irrigation	These are low-volume irrigation systems. There is a wide variety of system components and application rates.	Most of the time their effectiveness is low, due to the principles involved and insufficient amount of latent heat released.	In general should not be relied upon.	Evaporation may even result in negative effect of this variant.	
Surface irrigation	Flood irrigation relies mainly on the transfer of the sensible heat of water, while furrow irrigation relies mainly upon the release of the latent heat of fusion.	- Flood irrigation is used in low-lying crops when large amounts of water are available. May confer full protection if enough water is used. - Furrow irrigation is only effective for low-lying crops and uses less water than flood irrigation. - Both methods are commonly used.	- Application rate must be calculated taking in consideration the distinct underlying principles of the systems. - For deciduous plants, furrows should be positioned under the trees for ascending heat to warm the plants. It should be started early enough to ensure that the water reaches the end of the field before air temperature falls below the critical temperature.	Water availability, prediction of frost, inappropriate control of starting time, little effect for tall trees are common failure factors.	Low installation and operational costs, if water is low-cost or free.

funded by European Commission

Combination methods	Some combinations are possible and may be used: under-plant sprinklers and wind machines, surface irrigation and wind machines, heaters and wind machines, sprinklers and heaters.	Except for surface irrigation combined with heaters, which has been widely used, the other combinations have been rarely (if ever) used by growers. Combination methods are an ultimate recourse for locations and circumstances where, among the viable methods, one method in isolation is insufficient to avoid frost damage.	Choose the right combination for your location, crop and circumstances. Control of temperature and timing are essential. Sometimes, one method is implemented and the other is only started if necessary. For example, you may start wind machines first, and the heaters are lit if the temperature continues to fall.	Management of these methods is more difficult and requires monitoring of temperature trend during the night. Wind is incompatible for some of these combinations	Costs are generally high, and depend upon the costs of the methods that are combined.
Mobile and rotating hot air blowers	Hot air is projected horizontally. The constructer claims that the heating effect is not what confers the protection. The mechanism involved allegedly relies on phase changes.	No controlled scientific experiments support their effectiveness, as far as we know.			Installation costs are high and operational costs are low. Energy consumption is low.
Upward vertical-flow air blowers	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.			Installation costs are high and operational costs are low. Energy consumption is low.

Annex D. List of research needs

Ranking	Research need
1	Studying and comparing the effectiveness of methods under different conditions
2	Adding more biology to models
3/4	Establishing a database on potential yields for different species/varieties and critical temperatures on species/variety level
3/4	Develop a reliable monitoring and alarm system that relies both on surface and profile information of temperature, humidity and wind speed
5	Studying the different behaviours and phenology of cultivars under varying climate conditions
6/9	Testing below-ground sprinkling (in combination with hot air machines) for stone fruit
6/9	App (tool) for assessing frost protection measures considering risk (simulation tool) Related to need for database for potential yield/loss in different conditions
6/9	Study the use of oils to delay flowering in other fruits besides vine (also combinations of different oils), for example stonefruit and berries • In general only used for vine because needs to be applied well in advance to flowering in order to delay budbreak, but in case of other crops that would mean quite low temperatures that do not enable applying oil (damages on plants are to be expected) • Also the timing of oil application depending on the phenophase (when to use) • Use of different oils (also combination of oils)
6/9	Need to collect existing data on phenological stages ("merge bubbles") The objective is to gather and connect all the different investigations scattered all over Europe about phenological stages

funded by European Commission

The European Innovation Partnership 'Agricultural Productivity and Sustainability' (EIP-AGRI) is one of five EIPs launched by the European Commission to promote rapid modernisation by stepping up innovation efforts.

The **EIP-AGRI** aims to catalyse the innovation process in the **agricultural and forestry sectors** by bringing **research and practice closer together** – in research and innovation projects as well as through the EIP-AGRI network.

EIPs aim to streamline, simplify and better coordinate existing instruments and initiatives and complement them with actions where necessary. Two specific funding sources are particularly important for the EIP-AGRI:

- ✓ the EU Research and Innovation framework, Horizon 2020,
- ✓ the EU Rural Development Policy.

An EIP AGRI Focus Group* is one of several different building blocks of the EIP-AGRI network, which is funded under the EU Rural Development policy. Working on a narrowly defined issue, Focus Groups temporarily bring together around 20 experts (such as farmers, advisers, researchers, up- and downstream businesses and NGOs) to map and develop solutions within their field.

The concrete objectives of a Focus Group are:

- ✓ to take stock of the state of play of practice and research in its field, listing problems and opportunities;
- ✓ to identify needs from practice and propose directions for further research;
- ✓ to propose priorities for innovative actions by suggesting potential projects for Operational Groups working under Rural Development or other project formats to test solutions and opportunities, including ways to disseminate the practical knowledge gathered.

Results are normally published in a report within 12-18 months of the launch of a given Focus Group.

Experts are selected based on an open call for interest. Each expert is appointed based on his or her personal knowledge and experience in the particular field and therefore does not represent an organisation or a Member State.

eip-agri

AGRICULTURE & INNOVATION

funded by European Commission

Join the EIP-AGRI network & register via www.eip-agri.eu

servicepoint@eip-agri.eu | +32 2 543 73 48 | Koning Albert II laan 15 | Conscience Building | 1210 Brussels | Belgium