AgriEngineering

Review

Agricultural Engineering Technologies in the Control of Frost Damage in Permanent Plantations

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Abstract: The occurrence of late spring frosts due to climate change causes great damage to plantation production worldwide. The main objective of the paper is to provide a comprehensive overview of the problem and to outline effective protective measures against late spring frosts. The nature of frost depends on regional, altitudinal, and geographic differences, but they all share a common problem: they remove heat, resulting in the freezing of new plant growth and flowers. Tissue freezing is affected by critical temperatures and the frost type, intensity, and duration. Protection against late spring frosts can be broadly divided into three categories: active, passive, and chemical measures. In the field of agricultural engineering, various techniques have been thoroughly researched, and their effectiveness has been confirmed by research. These include various sprinkler systems, different heating devices, and large-diameter fans. Conclusive findings are being made on the performance of these systems in sub-zero temperatures and their cost-effectiveness. Climate change increases the importance of protecting permanent crops from late spring frosts and requires advances in agricultural technology to meet changing production demands and challenges.

Keywords: climate change; critical temperatures; fans; fogging; heat loss; heaters; prediction models; radiation; spring frost; sprinkling

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1. Introduction

The main topic at the beginning of this paper is to define the word "frost" and what it refers to. There are many different meanings of this term in the literature, and the FAO interpretation is explained as [1]: The formation of ice crystals on surfaces, known as "frost," can result either from the freezing of dew or from a phase transition from vapour to ice. In addition to this explanation, the term is widely used in agriculture as a meteorological event when crops suffer frost damage. In the literature, the meteorological term for frost is used when the temperature in a weather shelter (1.25 to 2 m above a grass floor, facing north) falls to or below 0 °C. The agricultural term frost refers to the occurrence of temperatures at or below 0 °C on plant tissue when frost problems and damage begin.

Some plants and cultivars are resistant to lower temperatures, while others exhibit varying degrees of resistance to frost intensity, whether it is higher or lower (frost duration). All of these factors depend on the supercooling factors of the cell cytoplasm, the concentration of the amino acid proline, genetic factors, etc. As a result, some parts of certain plants may freeze at temperatures as high as −0.7 °C, while others can withstand much lower temperatures, down to −4.0 °C [1]. Finally, the occurrence of frosts must coincide with the most vulnerable plant stages of budding and flowering in order to cause significant economic damage, which is usually the case in March and April (especially in April in the Northern Hemisphere), in temperate climate areas where most plantation production takes place. In this case, it is called late spring frost.

At low temperatures, plant tissue is destroyed by the formation of ice crystals inside the cell [2]. Depending on the duration of the frost and the phenophase of the plant, the resistance of the plant to negative temperatures increases. Late spring frosts usually occur in April in temperate climates, but this period can extend from late March to early May, when many plant species begin their development or are already in full development. Therefore, it is necessary to know the microclimate to avoid plantation planting in areas where spring frosts are expected, and each farmer must choose the most appropriate method of agricultural engineering, depending on their capabilities, efficiency, and profitability [3].

Based on the above and the climate changes explained in Section 2, it is impossible in today's agriculture not to pay attention to protecting permanent crops from late spring frosts. Apart from some rare chemical methods and passive protection measures, only the use of measures and methods from the field of agricultural engineering can provide answers and solutions to minimize the damage caused by late spring frosts [4]. Given the rising economic damage caused by frost each year, it is essential for every farmer to have effective and efficient control solutions in place. The term "active protection measures" mainly falls in the field of agricultural engineering, and only these measures can protect plantations to a large extent. Active measures that use agricultural machinery are explained in Section 6.3.

It is evident from the global scientific literature and recent studies that late spring frosts are worsening due to climate change. Consequently, frost-related damages are escalating, placing additional stress on agricultural production. Therefore, this paper plays a crucial role in elucidating the issue comprehensively and outlining effective protective measures against late spring frosts.

This scientific review paper was written because of its great importance to agricultural production of permanent plantations and the ever-present threat of major damage from late spring frosts due to accelerated climate change. This paper was designed to first provide an introduction to the title of the paper, then describe the causes of late spring frosts and their types. It then describes the importance of the critical temperature for tissue damage and models for frost prediction. The main part of this paper describes general methods for preventing damage from late spring frost, focusing on measures in the field of agricultural engineering. This is also the main objective of this paper, as there are very few review reports in the global scientific community on the effectiveness of agricultural mechanization measures to reduce frost damage. At the end of this article, important economic issues related to frost protection systems and the author's conclusions from all literature references are listed.

The references (80) used for this scientific review are mainly from the largest scientific databases, where original scientific papers (54) and reviews (7) on the subject of this paper can be found, namely: WOSCC (Web of Science Core Collection)—42 articles; SCOPUS—10 articles; CAB Abstract—3 articles; and International Proceedings Papers—6 articles. In addition to the published scientific research, this paper cited four personal communications from university professors and agricultural experts and five reports from major world organizations (FAO, UN, and EU Commission). This paper also cited one university textbook, one undergraduate thesis, and one Google Scholar object. From other internet sources, five pages from the government or agriculture departments of different states and two other open-source internet pages were cited. Regarding the publication period, the references can be divided into four publication classes: until 2000–5 references; from 2000 to 2010–23 references; from 2010 to 2020–29 references; and the latest from 2020 to today (2023) references.

2. Climate Change and the Occurrence of Late Spring Frost

At the end of the last century and the beginning of this century, planet Earth began to warm sharply due to increased CO_2 emissions into the atmosphere [5–7], and as a result, occurrences of extreme weather events have become increasingly frequent. For example, in the eastern part of Croatia (regional city of Osijek—φ 45°32′ N; λ 18°44′ E), the occurrence of late spring frosts in the multi-year average (1899–2021) is 7 days in March and 2 days in April [8]. However, in the last fifteen years, this average has increased to 8–9 days in March and 4–5 days in April. This may be due to a higher potential for advection frost (which occurs when a large amount of cold air remains in an area for a long period of time), to which eastern Croatia is exposed due to its proximity to the Russian plate, as well as to large amounts of cold air entering the Pannonian Plain during atmospheric pressure instabilities in April. From the above (considering only the occurrence of frost), it can be concluded that the climate is changing rapidly, and the occurrence of temperature extremes is increasing.

US researchers from Illinois [9] reached a similar conclusion, stating that they used a long-term temperature record (1889–1992) to assess whether the frequency of frost damage had increased recently. Their main conclusion was that in the long-term record, frost conditions prevailed in 10 of 124 years, but the annual probability of frost damage (deciduous forest) increased significantly, from 0.03 between 1889 and 1979 to 0.21 between 1980 and 2012.

The authors of [10] reported that in southern Germany, frost damage to apple trees will increase by up to 10% compared to today with a 2 °C warming. They also pointed out that milder winters can cause fruit trees to bloom earlier, increasing the likelihood that frost days will occur after flowering. The total number of frost days will also decrease. A study of flowering time was conducted by Hajkova et al. [11], who (based on multi-year data: 1924–2012) examined changes in cherry flowering. The beginning of flowering and the end of flowering shifted to an earlier date (up to −13.9 and −8.1 days, respectively), and the flowering period lengthened (up to 4.1 days) over the entire period studied.

A rather extensive survey of 27 fruit species with over 5000 phenological observations was conducted in over 1000 locations in Europe [12]. The experts agree that a temperature increase in late winter or early spring can lead to what is known as a "false spring," characterized by an early start to growth, followed by cold spells that cause further frost damage. Fruit species that are very sensitive to climatic changes due to their earlier flowering tend to be at increased risk of frost damage. Geographically, marine and coastal regions in Europe are increasingly exposed to an increase in frost frequency, particularly these late spring frosts, which can have serious economic and ecological repercussions. In contrast to this conclusion, scientists from the United States [13] found that in California, the risk of frost exposure due to climate change decreased, with an average reduction of 63% predicted by the mid-21st century. The main permanent crops, almond and orange, will experience 50–75% less frost, while avocado will experience 75% less frost hours. In this case, climate warming will result in a savings of more than 600 million hL and $4.2 million in electricity costs for pumping water per year (a frost protection method with sprinkler irrigation). It is anticipated that the agricultural water demand will increase, and insect pressure will also increase during the growing season. Climate change will have an overall negative impact on agriculture.

The best conclusion for the occurrence of late spring frosts and climate change is provided by a paper that examined the number of days with minimum temperatures <0 °C in the Northern Hemisphere at latitudes above 30° N [14]. They concluded that climate change will reduce the frequency of frost episodes, lengthen the growing season, and may even result in additional frost days during the growing season. Data from 1982 to 2012 show that ~43% of the hemisphere (mainly in Europe) experienced a significant increase in frost days, mainly in spring. In general, in places where the growing season is longer, the frost period is also longer. As a result of climate change, there are fewer frost days overall, but late spring frosts still occur more frequently in many places. This statement is also supported by scientists from Austria [15]. Their study in southeastern Styria shows that meteorological blocking events (stable high-pressure systems) are partly responsible for cold spells in spring and that the onset of flowering will shift to early April by the end of the 21st century (the model predicts a mean flowering advance of -1.6 ± 0.9 days per decade).

Greek scientists explained [16] that climate change will affect the phenological stages of the vines, with changes in the composition of grapes and wine, yields, and expansion to areas previously unsuitable for grape growing. Future climate changes with warming and water shortage will lead to the loss of viticulture in the Mediterranean and other regions, while in Central and Northern Europe, warming may favour viticulture. Table 1 shows the summary of the specified properties.

Table 1. Summary of frost observation from different research countries.

Country of Study	Frost Observation	Bud/Flowering Observation	Time Period
Croatia	7 times in March 3 times in April 8–9 times in March 4–5 days in April		1899–2021 2008–2023
USA, Illinois	Frost damage probability = 0.03 Frost damage probability = 0.21		1889–1979 1980–2012
Germany (south)	Frost damage to apple trees will increase by up to 10% compared to today with a 2 °C warming		2006–2015
Czech Republic		Flowering period shifted to an earlier date: 13.9 to 8.1 days	1924–2012
Europe (1000 locations)	Frequent cold spells overlapping with budding/flowering	Higher winter and early spring temperature = “false spring”	1950–2013
USA, California	Frost exposure decreased by 63%	50–75% less frost hours for almond, avocado, and orange	to 2050
Austria	Stable high-pressure systems are causing cold spells in spring	Flowering shifted to early April.—1.6 ± 0.9 days per decade.	The end of 21st century
Northern hemisphere (30° N)	~43% of the hemisphere (mainly in Europe) = significant increase in frost days, mainly in spring	Lengthening of the growing season	1982–2012

3. Different Types of Frost

Due to climate change, different geographic locations, different elevations, and different locations of permanent plantings may experience different forms of late spring frosts. As temperature extremes become more pronounced, each frost has its own duration and intensity, as described in the literature. Pfammatter [17] states that three types of frost generally occur: (a) Advection frost—freezing occurs when a large amount of cold air remains in an area for a long period of time; (b) Evaporation frost—freezing due to water evaporation, which can easily lower the temperature of young plant parts and cause damage. An increase in relative humidity and a decrease in air temperature can lead to the occurrence of “evaporative ice”; (c) Radiation frost—freezing occurs when the ground behaves like a dark body and loses heat through radiation on clear and calm nights. Warm air rises, cold air sinks, and freezing occurs. Cittadini et al. [18] stated that due to the frequent occurrence of frosts, it is critical to evaluate the risk of frost damage when planning new orchards and choosing the design and construction of frost protection systems. Figure 1 shows the occurrence of late spring frosts.

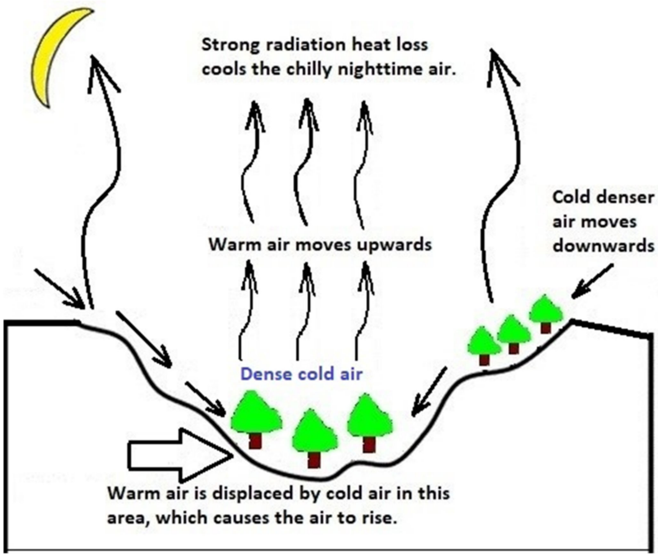

Figure 1. Occurrence of late spring frosts.

The literature [1,2,19–21] indicates that there are ultimately only two critical forms of frost: Radiation frost and advective frosts. In this literature, radiative frost is described as an evening heat loss to the sky of the heat stored in the ground during the day, i.e., during the night/evening hours, there is a radiative heat loss from the ground to the sky. In this way, a temperature inversion occurs between higher and lower parts of the plantations. Radiation frosts occur more frequently and severely in inland regions, and relative humidity is an important factor in the severity of the frost and the critical temperature. A further subdivision of radiation frost [2,20] is: black frost (when the humidity is low and the dew point is below 0 °C, frost occurs without ice forming on exposed surfaces) and white frost (when the humidity is high, dew forms on the ground above 0 °C until the dew freezes into a layer of ice on exposed surfaces). Advective frost is explained similarly to [16]—this frost is the result of moving cold air masses displacing warm air from plantations. This type of frost is very dangerous, and very little can be done to protect plants during an advective frost.

New Zealand scientists [20] divide frost into several categories: ground frost, screen frost, hoarfrost, black frost, radiation frost, and advection frost. They explained that ground frost occurs when dew freezes (grass temperature −1 °C or less), and screen frost occurs when the air temperature in a weather shelter (1.3 m above the ground) is 0 °C or less. Hoar frost can occur when the air temperature is below freezing and ice crystals form and grow on surfaces by sublimation. From all of the literature on frost, it can be concluded that radiation frost is the most common type of late spring frost, and it occurs in most cases around the world, so this type of frost is described mathematically by many scientists. It is precisely against this type of frost that all agricultural engineering measures and methods for suppressing and minimizing damage refer to since this type of frost is the most relatively easy to control.

Depending on their surface temperature and a surface property called emissivity, all surfaces radiate [22,23]. The Stefan–Bolzmann law (1) shows the emission intensity:

$$I = \varepsilon\,\sigma\,T^4\,\left(\mathrm{Wm}^2\right), \tag{1}$$

where:

ε—emissivity (1.0 for most natural surfaces),

σ—Stefan's constant (5.67×10^{-8} W m^2 − °C^4),

and the wavelength (λ_{max}) of the peak of the radiant spectrum is given by Wien's Law (2):

$$\lambda_{\text{max.}} = \frac{2897}{T}(\mu\text{m}), \tag{2}$$

where:

$\lambda_{max.}$—maximal wavelength,

T—absolute temperature (K).

Terrestrial surfaces radiate at about 10 °C (283.2 K) in the infrared, λ_{max} = 10.2 µm, I = 364.7 W m^2, and the sky at about −15 °C (258.2 K), λ_{max} = 11.2 µm, I = 252.0 W m^2. In this case, the loss is 112.7 W m^2, and on cloudy nights, the heat loss is about 10 W m^2 [22]. Thus, due to the differences between the ground and the air, the ground absorbs heat by radiation and then cools in this way.

Based on the above physical law, it is easy to determine the frost risk based on the current day conditions. The simplest method to estimate the "next morning grass minimum temperature" is to take the maximum cooling rate and measure the weather conditions at 3:00 p.m. using Equation (3) [24]:

$$T_g = \frac{1}{3}\left(T + \frac{T_d}{2}\right) - c, \tag{3}$$

where:

T_g—forecast grass minimum temperature (°C),

T—dry bulb temperature (°C),

T_d—dew point temperature (°C),

c—constant (8—May, September, and October; 9—June and August).

If we talk about serious real measurements, the best data are presented by scientists from Italy with measurements in the Po Valley [25], where they measured radiometric (radiation) and ground heat flux. They used a sonic anemometer and a radiometer at their anemological and radiometric station to analyse the solar and far-infrared radiation balance separately. In addition to all of these measurements, an experimental balloon was also launched each night for vertical temperature measurement. This is a great example of real-time in situ measurements of radiative heat losses.

4. Critical Temperatures for Tissue Injuries

Critical temperatures (*Tc*) for tissue injury can be described as the lowest temperatures that a tissue can sustain for 30 min or less without injury [20]. Thus, this does not mean that plants will immediately begin to freeze and that cold temperatures at 0 °C will cause injury. Each plant, cultivar, or species can develop different sensitivities to different critical temperatures that cause tissue damage depending on a whole range of internal and external factors. These factors can be different dew point and surface humidity, type of frost, frost duration, frost intensity, environmental conditions before frost, growth stage and bud development, bud and flower temperature, etc. [1]. Critical temperatures are often referred to as the T-50 temperature [26], which is the lethal temperature that causes 50% or more bud dieback. In the literature, critical temperatures are often referred to as T_{10} and T_{90} [27] or T_{10}, T_{50}, and T_{90} [28]. These values represent temperatures at which 10%, 50%, and 90%, respectively, of marketable crop production is likely to be damaged. Critical temperatures ($T_{10,90}$) vary during different stages of plant development, and generally, both temperatures increase after bud development begins. For example, in apple trees, the T_{90} temperature during winter is −20 °C, but during the bud development and flowering stages, this temperature is −1.7 °C to −2.5 °C. The critical temperature values for some permanent plants are shown in Figure 2 (Stage 1—onset of bud activity; Stage 2—bud burst; Stage 3—blooming/first leaf for grapes; Stage 4—after blooming/fourth leaf for grapes [1]).

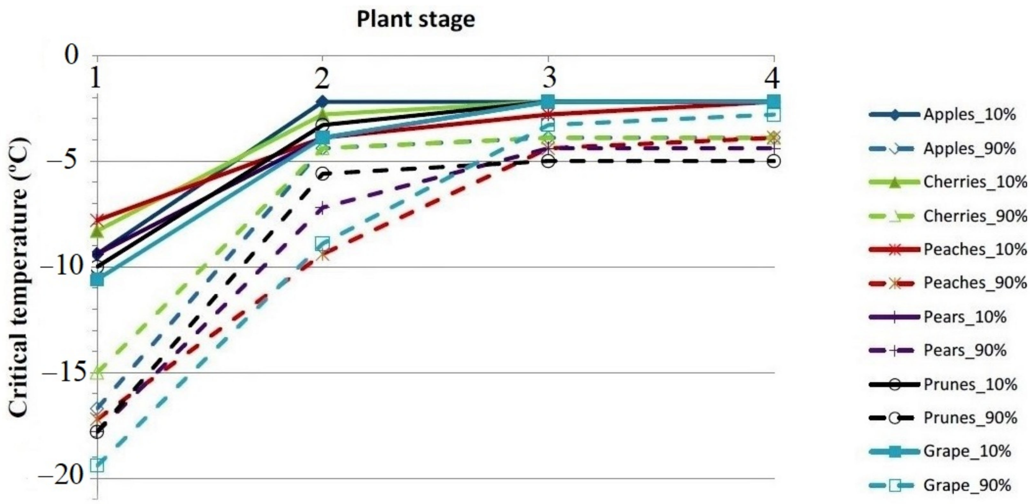

Figure 2. Critical temperatures in relation to the developmental stage of some fruit trees and grapes [1].

There are a few papers reporting the damage caused by late spring frost, and one of them reports major damage to lemon and other citrus trees in the Murcia region of Spain [29]. Scientists there observed spring frosts five times from 2010 to 2012 and studied the damage to different parts of the plants from a critical temperature of −3 °C. The measured T_{min} ranged from −2.88 to −4.51 °C, and the frost duration was between 8 and 11 h. From the above measured temperatures and critical temperature, as well as the influence of frost intensity (frost duration), it can be concluded that severe damage was recorded on most plant parts. Of course, this report is an example of exceptional temperature extremes in the mentioned region, and local farmers were surprised by the weather changes and were not prepared for the use of active frost protection measures, so this type of report is rare. A basic list of critical temperatures for different plant species and phenological stages is shown in Table 2.

Table 2. An overview of critical temperatures for different fruit species (°C).

Crop	Phenological Stages	10% Kill	90% Kill
Apples	Silver tip	−11.9	−17.6
	Tight cluster	−3.9	−7.9
	First bloom	−2.3	−4.7
	Post bloom	−1.9	−3.0
Apricots	Tip separates	−4.3	−14.1
	First bloom	−4.3	−10.1
	Full bloom	−2.9	−4.7
	Green fruit	−2.3	−3.3
Pears	Scales separate	−8.6	−17.7
	First bloom	−3.2	−6.9
	Post bloom	−2.5	−3.9
Prunes	First swell	−11.1	−17.2
	Tip green	−8.1	−14.8
	First bloom	−4.3	−6.9
	Post bloom	−2.7	−4.0
Grape	First swell	−10.6	−19.4
	Bud burst	−3.9	−8.9
	First leaf	−2.8	−6.1
	Fourth leaf	−2.2	−2.8
Citrus fruit	Green oranges Green lemons	−1.4	−1.9

Table 2 shows that for most widely grown plantation crops, the critical temperature is between −2 and −4 °C, while the first 10% kill scenarios for apples can start at −1.9 °C. Citrus trees are very sensitive to low temperatures, where damage begins at −1.4 °C.

Knowing the critical temperatures for each stage of development is extremely important because active measures should be taken to protect against damage just before these temperatures occur. The introduction, explanation, and use of "AgriEngineering" measures (active measures) are the main part of this paper (explained in the special chapter), as they are of critical importance in protecting permanent plantations from late spring frosts.

5. Prediction and Monitoring of Late Spring Frosts

5.1. Temperature—Phenological Models

Many scientists have developed various models, simulations, and statistical representations for predicting and monitoring late spring frosts over years, locations, and climate zones. Some of the models developed are quite accurate, while others are not, but their main function is accomplished: To warn growers of the occurrence of frost in a narrow growing area. The development of these models has significantly reduced frost damage, and many farmers realized the great potential of early warnings so that they could plan and organize frost protection measures in time. Very importantly, due to the long-term models, farmers also recognized the more frequent occurrence and greater intensity of frosts, so they made investments in agricultural machinery with various active protection methods in the field of agricultural engineering.

One of these models is used by Australian scientists for apples and pears in Tatura and Yarra Valley [30]. They use two models: TT (Thermal Time—assuming that only the spring temperature determines flowering timing, with warmer temperatures driving the process) and SC-G (Sequential Chill-Growth—which considers the sequential and independent effects of winter cold followed by spring warmth). In the second model, winter temperatures are important in modelling the process to delay flowering. Local interpretations of +1, +2, and +3 °C for global mean temperature were used to generate climate projections. Using 13 historical and projected daily datasets, which were also used for phenological assessments, the frost frequency was calculated from the daily minimum temperatures (<0 °C). The TT model results showed that progressive warming shifts flowering to September (Southern Hemisphere) and that the frost frequency decreases at +1 and +2 °C projections, while it is without risk at +3 °C. The SC-G model showed that warming initially leads to earlier flowering, and flowering remains within the range of historical observations with further warming, while frost conditions remain unchanged, indicating an initial increase in risk (+1 °C), but the risk decreases with further warming (+2 °C).

A similar approach to local weather information was used by American scientists in South Georgia for blueberry and peach production [31]. Their main objective was to study local weather forecasting and evaluate the Advanced Research Weather Research and Forecasting (WRF-ARW) model for episodic frost events with an automated environmental monitoring network. Air, wet bulb, and dew point temperatures, as well as wind speed and direction, were compared. The results of these simulations demonstrated the applicability and accuracy of frost warnings for both advective and radiative frost scenarios. The accuracy of the minimum temperature prediction was over 90%.

French scientists reported that in the world-famous wine-growing areas of Champagne, the main factors associated with the occurrence of radiation frost are low wind speed, clear sky, and topographic factors, so they developed the Digital Elevation Model [32]. With this model, they mapped the frost-hazardous areas for the entire region using data measured over five seasons and for about 20 weather stations. Similar results for the main French wine-growing regions of Alsace, Burgundy, and Champagne were presented by Sgubin, G. et al. [33]. They noted that it is unclear whether the strong occurrence of frost across France in 2016–2017 is due to climate change, and therefore they assessed the frost risk for French vineyards in the 21st century by analysing temperature projections from eight climate models and their statistical regional downscaling. The day of the year and the typical time of bud break of nine grapevine varieties, as predicted by three different phenological models, determines their behaviour when frost occurs. The main conclusion of this paper was that the probability of frost in the projected area will increase significantly in the 21st century for two of the three phenological models. Quite different from these conclusions and for the Luxembourg area (100 to 200 km from Champagne and Burgundy), scientists have created a model based on phenological phases for grape budding and ensemble-based projections of future air temperature [34]. They noted that their model projections show that the incidence of spring frost damage will decrease in the Luxembourg winegrowing region, but without completely ruling it out for the near (2021–2050) or distant future (2069–2098). This example indeed shows how much the occurrence of frost is regionally conditioned by a whole range of environmental, topographical, and territorial factors already listed.

Scientists from South America (Patagonia) studied the effects of late spring frost at several sites with different sweet cherry cultivars. Because of the lack of historical weather data, they used a theoretical–empirical approach in their model. When the minimum temperature falls below the lethal temperature established for the phenological stage expected at that time, frost damage is assumed to occur on that day of the season. This model uses active measures to reduce frost damage, so this study is fairly unique in that it includes model predictions and the use of agriengineering measures in one place. Thus, this type of quantitative analysis can help farmers make decisions about the required investment and operating costs for frost protection equipment based on the potential impact of a particular control system on average yields and yield stability. It can also guide the prioritization of research questions to fill knowledge gaps related to frost risk assessments [18].

Long-term models for the Swiss Rhone Valley (Sion and Aigle) [35] suggest that late frost risk could increase or decrease in the near future depending on the location and climate change projections. While for reference the risk is higher at a warmer site (Sion) than at a cooler site (Aigle), for the 2021–2050 period, small changes in phenology (days with daily minimum temperatures below 0 °C) and frost risk (days with temperatures below 0 °C) result in a slight decrease in frost risk at the warmer site but an increase at the cooler site. Another long-term model called UniChill was developed by Leoneli, L. et al. [36] for European viticulture. The results showed a general earlier occurrence of bud break and flowering with particular significance for northeastern Europe. In the western regions, late varieties were more affected by warmer temperatures than very early and early varieties. In terms of future scenarios, the frequency of frost events at bud break (T_{min} < 0 °C) varied greatly across Europe, with a significant decrease in western regions (such as Spain and the United Kingdom) and an increase in central Europe (such as Germany). The results of this research indicate that the distribution of grapevine varieties in Europe will change in a warmer climate due to frost episodes rather than flowering stress. So, this paper confirms the research from Greek scientists [16].

The most recent study evaluating spring frosts under future climate change using a phenological modelling approach was conducted by Ru et al. [37]. They investigated the variation of apple phenophases and frost risk on the Loess Plateau (China) with phenology models driven by Global Climate Models (GCMs) and two emission scenarios (SSP2-RCP 4.5 and SSP5-RCP 8.5) for two time periods (2050 and 2090). The results showed that bud break and fruit set are expected to be advanced to different degrees in apples, but the advance is decreasing (budburst 0.04–0.14 d y^{-1}, fruit set 0.12–0.22 d y^{-1}). They also noted that frost frequency will decrease by 0.09–0.36 d under both emission scenarios, but frost intensity will increase by 0.004–0.008 °C d^{-1}. The scientists also confirmed that frost in future periods and changes in frequency show regional differences. A similar study was conducted by Drepper et al. [38], in which a calibrated phenological model was applied to a regional European climate model for the RCP 4.5 and RCP 8.5 scenarios to determine the timing of flowering and associated frost events (<−2 °C). The results showed that flowering in the current pear growing area in Belgium started on average 7.5 (10.8) days earlier under the RCP 4.5 (8.5) scenario, and the last frost occurred on average 12.8 (17.9) days earlier in 2019–2068 compared to 1971–2018. At the end of their study, they concluded that climate change does not lead to more frequent frosts in this area, and therefore, production shifting is not recommended. An overview of all mentioned models is shown in Table 3.

Table 3. An overview of temperature—phenological models for frost prediction.

Country of Study	Model	Properties	Description
Australia	TT—Thermal time	Spring temperatures determine flowering	Flowering shifted to September (South Hemisphere). Frost frequency decreases at +1 and +2 °C projections, while it is without risk at +3 °C.
	SC-G—Sequential chill growth	Winter and spring temperatures determine flowering	Flowering remains within the range of historical observations with further warming. Frost conditions remain unchanged, indicating an initial increase in risk (+1 °C), but risk decreases with further warming (+2 °C).
USA, South Georgia	WFR-ARW Adv. Res. Weather and Forecasting	Air, wet bulb, dew point temperatures, wind speed and direction	Applicability and accuracy of frost warnings for both advective and radiative frost scenarios. The accuracy of the minimum temperature prediction was over 90%.
France	Digital Elevation Model	Mapping of frost hazardous areas	Probability of frost in the projected area will increase significantly in the 21st century for two of the three phenological models.
Argentina	Theoretical–empirical model	Using active measures to reduce frost damage	Quantitative analysis of farmers' decisions about required investment and operating costs for frost protection equipment.
Switzerland	Sion and Aigle model	Location and elevation importance for frost risk	Long-term prediction (2021–2050) for changes of phenology and frost risk.
Europe	UniChill	Future suitability for grape growing	Decrease in frost events in western regions (Spain and United Kingdom) and an increase in central Europe (Germany)
China	GCM—Global Climate Models	Prediction of bud breaking and flowering	Earlier apple flowering (2050–2090) by 0.04–0.14 d y^{-1} for budburst and 0.12–0.22 d y^{-1} for fruit set. Frost frequency will decrease by 0.09–0.36 d, but frost intensity will increase by 0.004–0.008 °C d^{-1}.
Belgium	Climate model for RCP 4.5 and RCP 8.5 scenarios	Prediction of flowering time	Earlier pear flowering started on average 7.5 (10.8) days earlier under the RCP 4.5 (8.5) scenarios. Frost occurrence on average 12.8 (17.9) days earlier in 2019–2068 compared to 1971–2018.

5.2. Machine Learning Models

With the development of global technology, especially computer technology and artificial intelligence, models for frost forecasting based on machine learning and neural networks have been developed recently. In principle, these models are very accurate and can predict with high confidence the occurrence of frost up to 24 h in the future, i.e., they are more accurate than classical temperature phenological models. Their common feature is that they provide a prediction for a narrow area, but machine learning models are transferable to other areas.

One of these models was developed by Talsma et al. [39]. They stated that they developed point-scale frost forecasts for the Alcalde, New Mexico (USA) area using machine learning algorithms. For training the machine learning model, they use 10 years of historical data with hourly resolution from the Natural Resource Conservation Service weather station. Many important weather data, such as temperature (average, maximum, and minimum), wind speed and direction, average dew point, average precipitation, ground temperature, etc., were used for training the machine learning model. From all of the above parameters, it was determined that ground temperature is a key factor for long-term prediction (>24 h), while other factors provide most of the information for shorter-term predictions. Two neural network configurations were created for the model: a convolutional long-term short-term memory (CNN) neural network and a fully connected neural network (DNN). A set of neural nodes with weighted values that change according to the performance of the model, and the signals or connections between the nodes, are the building blocks of neural network models. The model was projected for frost forecasting at lead times ranging from 6 to 48 h. The main result of this research was a fairly high accuracy of the 6 h forecast for predicting minimum temperatures (RMSE of the 6 h forecast = 1.53–1.72 °C). Machine learning methods are also used in the model of Ding et al. [40]. In this case, instead of creating a new model, the accuracy of each standard model was increased using machine learning methods, so the paper proposed causal ensemble modelling to compensate for the performance of standard temperature models. The data for this study came from Japan, from a vineyard on Hokkaido Island.

A machine learning model was also used in South Korea [41] for frost classification and agricultural environment optimization. Random forest and support vector machine models were trained using data from the National Meteorological Administration and an automated system for frost observation for March in the last 10 years (2008–2017). Both models showed good classification performance, and the models successfully classified 117 out of 139 frost cases from the automated station and 35 out of 37 orchard camera observations. From this, it can be seen that a model with machine learning is very accurate and can find applications in orchard farming.

Argentine researchers have described an IoT frost prediction system based on machine learning [42]. Past readings from temperature and humidity sensors were used to train machine learning algorithms to predict future temperatures. This work differs from other machine learning research in that it assumes that ambient thermodynamic conditions are informative for prediction, so for this model and for each site, information about sensor readings from all other sites were included in the training, with the most relevant ones selected autonomously (depending on the algorithm). Considering the scarcity of frost events, the data were augmented with the synthetic minority oversampling technique (SMOTE). In this way, prediction errors are reduced, and model performance is increased. The IoT-based frost prediction system is shown in Figure 3.

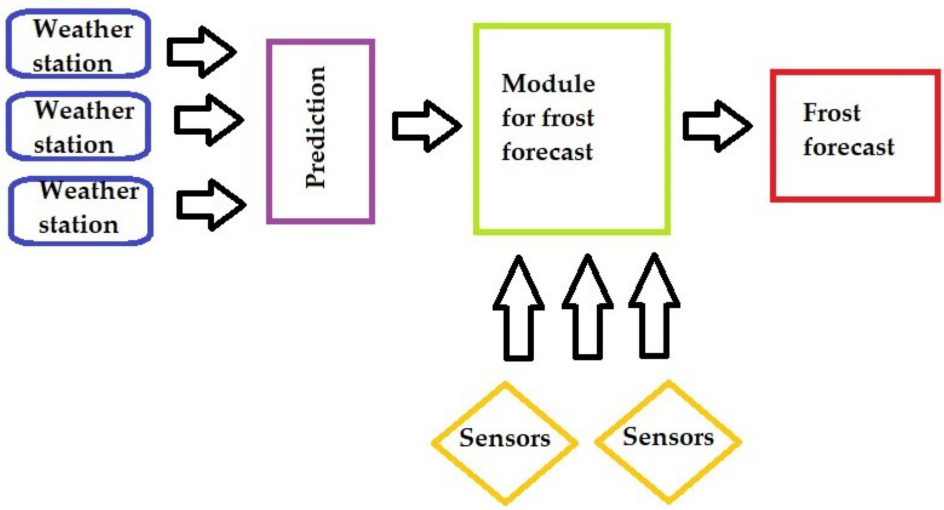

Figure 3. IoT-based frost prediction system.

5.3. Satellites, Sensors, Thermal Cameras, and Drones in Frost Prediction

The use of satellites, in particular the Sentinel-2 mission, for assessing damage and plant recovery time was investigated through satellite remote sensing during the 2017 frost events in northern Italy [43]. Conventional methods for determining frost damage are labour-intensive, costly, and generally focused on small areas, so this was the first time this method was used in this area of agriculture. The results showed for the first time that frost damage can affect the spectral reflectance of medium-resolution photographs. In addition, the ability of various vegetation indicators to calculate recovery times was investigated. Certain spectral regions and vegetation indices were able to detect frost damage because they had lower reflectance, namely: Red Edge 7 (−16.67), NIR (−16.55%), EVI (−16.59%), MTVI1 (−5.77%), and CARI (−5.26%).

A rather simple and interesting example of the use of sensors for frost prediction is presented in the study of Marković et al. [44]. They placed several sensors to measure temperature in an orchard. The sensors had a wireless option for data transmission via GPRS to the server WEB, where the data were stored for further analysis. The main component of the mobile measurement station was a digital controller that controlled the operation of the mobile measurement station through commands written in a simple Python script. With this system, farmers can monitor the weather conditions in their plantations at any time via cell phones and prepare for the occurrence of late spring frost.

Another step toward the use of modern technologies for frost management was presented with a heating technology using unmanned aerial vehicles (UAV—drones) with thermal and RGB cameras in apple trees [45]. Table 4 shows the main specifications of the hardware components used in the study. They used UAVs with thermal cameras for temperature monitoring and an RGB camera to characterize plant growth stage variability.

Table 4. Key specifications of the hardware components [45].

Hardware	Model	Specifications
UAV (DJI Ltd., Shenzhen, China)	DJI Matrice 600 Pro (with TB47S batteries)	6 kg payload, 16 to 32 min hovering time, ±0.5 m vertical and ±1.5 m horizontal hovering accuracy
Thermal camera	DJI Zenmuse XT2 (with a 19 mm lens)	−25 to 135 °C scene range, 7.5 to 13.5 µm spectral range, 32° × 26° FOV, 640 × 512 resolution
RGB camera	DJI Zenmuse Z30	30 × optical zoom, 63.7° × 38.52° wide-end FOV, 2.3° × 1.29° tele-end FOV, 1920 × 1080 resolution

The thermal image stitching algorithm was developed to produce georeferenced orchard temperature maps that achieved sub-centimetre resolution of thermal images within 30 s. Six growth stages of apple flower buds of different sizes were classified using YOLOv4 classifiers trained on 5040 RGB photos; the best model had a mAP of 71.57% for the test dataset of 360 images. The main feature of this research is the generation of thermal maps to simulate orchard requirements during frost events.

6. Methods and Measures for Damage Control of Late Spring Frosts

Authors [1–4,46] divided protection from late spring frosts into three areas: (a) passive protection—selection of the site for planting; avoidance of fieldwork until the danger of frost has passed; care of soil without weeds, whose transpiration lowers the soil temperature; selection of varieties with later flowering and selection advice in this direction; and searching for varieties resistant to low temperatures; (b) active protection—covering plants with various materials, use of smoke and fog with combustion and fogging devices, use of various sprinkling systems, direct heating with various types of stoves, creating air flow through large fans, and heating by infrared radiation; and (c) chemical protection based on the use of hormones to slow down flowering and vegetation. In practice, among all forms of frost protection, three active methods are most commonly used: light sprinkling, direct heating, and the generation of air currents by large fans. In the following, only these active measures are considered the most effective protection methods. Figure 4 shows the flower injuries from late spring frost.

Figure 4. Flower injuries from late spring frost.

6.1. Passive Measures

The term passive protection measures against frost is understood to mean those preliminary actions and measures that will protect the trees/plantation from possible frosts without directly affecting the frost if it occurs. Heat is concentrated during the night near the ground, where plant parts are most susceptible to frost, so covering is the simplest protective measure. Plants can be protected by covering them with straw, peat, cardboard, cloth, or chemical products such as porous foam, plastic wrap, or artificial snow. The problem with this method is that it is only suitable for small cultivated areas. It gives good results when temperatures are not below −3 °C. It works by preventing radiation [3]. Fuller et al. [47] studied the application of hydrophobic particles and acrylic polymer as frost protection. In frost tests, applying a film of hydrophobic particles resulted in less damage, while the acrylic polymer resulted in equal or greater damage compared to control plants.

Another technique, in which plants are covered with a layer of sugar straw, was developed at the University of Perugia, Italy [48]. The organic layer of sugar straw prevents frost damage and protects the young shoots of the vines very well. This research also found that this cotton candy coating technique is very ecological, considering the carbon footprint compared to the traditional technique of burning oak wood to prevent damage from late spring frosts.

The location of a permanent plantation [1,19,49] is very important because of frost protection and the physical properties of the air. Cold air is denser than warm air and flows downhill, where it settles in the micro/macro valleys (Figure 1). The tops of hills are also cold and should be avoided. Therefore, the best place for planting is the slopes, where the cold air flows downhill and the radiation frost risk is not high. It is better to plant on north-facing slopes to avoid earlier flowering and reduce soil warming (less radiation frost). In this regard, many scientists have conducted research on the location, elevation, and topography of plantings [49,50].

Another very important characteristic of passive protection is the water content of the soil [1,46]. It is a rule that when the soil is dry, there are more air spaces that hinder heat transfer and storage. Thus, thermal conductivity and heat transport depend on the water content of the soil. With the regular diurnal cycle, heat movement takes place in the layer up to 0.3 m below the ground. In dry years, therefore, it is good passive frost protection to irrigate the soil near field capacity, because when the soil is wet, heat transfer and storage are better in the upper soil layer, so more heat is stored during the day and can be released at night.

Many of the permanent plantings have grass cover and mulch between the rows. In terms of late spring frosts, this feature is very important because this ground cover and mulch reflect sunlight off the surface and less energy is stored in the soil. Vegetative mulches generally reduce heat transfer to the soil, making crops more susceptible to frost. In orchards, minimal surface temperature differences of up to 2 °C have been found between bare soil and 5 cm tall grass [1,46]. Other passive methods of frost protection include avoiding soil cultivation, plant selection, plant nutrition management, proper pruning, painting the trunk, setting up barriers, etc. For example, Poni et al. [51] showed in their review that pruning performed not later than when two to three unfolded leaves are borne on apical shoots would delay budbreak by ~15 to 20 days (and in this way, prevent the overlapping of flowering and the appearance of frost), while the yield would only be mildly affected.

The positive aspect of passive measures to protect against late spring frosts is that they do not require much energy or money and can help protect against evaporative frosts and weaker forms of radiation frosts. For radiation frosts of longer duration and greater intensity, as well as advection frosts, these measures are completely ineffective.

6.2. Chemical Measures

Chemical protection of plants against the effects of frost involves two different principles: Spraying to delay flowering until a certain stage of development and spraying the canopy and roots during frost to prevent damage. Some of these measures can be classified as passive, since they are carried out in the autumn before the onset of frost, while others involve affecting the plants just before the announcement of frost to reduce the effects of frost and repair damage, so they could be classified as active methods. The following types of chemicals are in use: (a) antitranspirants used to spray the leaves, creating a layer that reduces transpiration and thus increases the temperature of the plant (they are sprayed 24 h before the occurrence of frost); (b) chemicals that generate heat—these preparations are sprayed on the leaves and the tree and generate some heat, since this substance releases heat when in contact with water; (c) frost-resistant chemicals that replace up to 50% of the water in the plant cells, reducing the possibility of freezing (they can be poured around the plant as a water solution 40 to 30 days before the expected first frost, or sprayed on the plants for 48 to 24 h); and (d) minerals—additives for root development strengthen the plant's resistance to cold (they are applied in late fall) [52].

There are different types of preparations used for the treatment of fruit trees, such as patented products whose aim is to induce the plants themselves to produce antifreeze proteins, antifreeze amino acids that allow the plant to better withstand cold and hot temperature shocks, or the application of antifreeze proteins themselves [53]. Recently, with the increase in frost days, new chemical agents are being used daily for foliage application. A comprehensive list of these substances is presented in the study of Drepper et al. [54].

Delaying flowering and budburst using chemical measures can successfully protect plants from late spring frosts, but the chemicals must be applied before the frost threat can be assessed. Otherwise, if delayed flowering overlaps with the occurrence of spring frost, additional active protective measures are needed. For very sensitive species with short dormancy (apricots, sweet cherries, and grapevines), delay is promising, but in some cases the delay achieved is not sufficient. Accordingly, the effectiveness of chemicals designed to increase the frost resistance of plants seems to be rather modest. Therefore, they may not provide sufficient protection against severe or prolonged spring frosts. As a result, the risk of possible damage remains unacceptably high, even with costly protective measures.

6.3. Active measures—Agriengineering Technologies

6.3.1. Protection by Smoking of Permanent Crops

Smoking is the oldest and cheapest protection against frost. The smoke cloud prevents heat emission and thus mitigates the cooling of the soil air layers [52]. Burning should be done in such a way that there is no intense flame but a large amount of smoke, which should spread throughout the plantation. This is not the best example of ecology, but in very difficult conditions, it can be a great help. This method does not raise the temperature but prevents it from dropping further. It is not a particularly safe method, but it can prevent the temperature from dropping by 2 °C [3]. Materials that produce dense smoke (manure, sawdust, or wet straw mixed with leaves) are burned in the plantation. For this method to be successful, about 50 fires per hectare are required. With this method, it is possible to protect the orchard from weaker frosts down to −4 °C. Anti-hail nets, if already installed, can also be very helpful in protecting plantings from late spring frosts by smoking. By using these nets, the smoke remains within the plantings and between the plants themselves for a period of time, prolonging the effectiveness of this protection method. Also, the big problem of this method, apart from the ecological footprint, is the rapid disappearance of smoke in plantations under conditions of low air pressure (therefore, this method is extremely unreliable) [4]. Figure 5 shows the smoking of permanent crops.

Figure 5. Smoking of a permanent crop.

6.3.2. Protection of Permanent Crops by Raining (Sprinkling)

Protection is based on the physical phenomenon that heat is released when water freezes (80 cal/L gr of water). The released heat keeps the soil temperature above 0 °C. Frost protection starts when the temperature drops below 0 °C and continues until the air temperature rises above 0 °C, i.e., until all of the ice on the trees of the plantation has melted [52]. In this method, the ice actually becomes an insulator between the plant parts and the ambient temperature below 0 °C. The release of heat by the freezing of the water droplets prevents the temperature in the thin layer of air between the vegetative organs and the ice cover formed on the plant from falling below −0.3 °C. To avoid possible damage, irrigation should continue even after the temperature has risen above zero until the ice formed on the plants has completely melted. This avoids sudden melting of the ice and cooling of the plant, since the same amount of heat is consumed during melting that was released during freezing. The droplets formed should be very fine and of small diameter so that the ice forms evenly on the plant parts and no damage is caused by breaking the branches. A small amount of water can cause the plants to freeze because not enough heat is released, while a large amount can cause damage because an abnormally large mass of ice forms, resulting in branch breakage [4]. Examples of rain protection show that effective prevention of freezing down to −6 °C is achieved in apples and pears with a water volume of 2.4 mm h^{-1}, or 24 m^3 h^{-1} per hectare. Damage from breaking branches due to a large ice mass was observed at a water volume of 3.2 mm h^{-1} [3].

Sprinkler rotation rate, wind speed, and dew point temperature all affect the application rate required for overplant sprinkling. The evaporation rate increases with wind speed and decreases with decreasing dew point temperatures, so wind speed and dew point temperatures are critical. Sprinkler rotation rates are critical because the temperature of wet areas of a plant first increases as water freezes and releases latent heat as sensible heat and then decreases to a level approaching that of a wet bulb due to evaporation before another water pulse occurs [46]. This case is shown with a precipitation rate of 2.8 mm h^{-1} at a wind speed of 6.9 m s^{-1}. The red line is for a 120 s rotation, the blue line is for a 60 s rotation, and the grey line is for a 30 s rotation of sprinkler. (Figure 6).

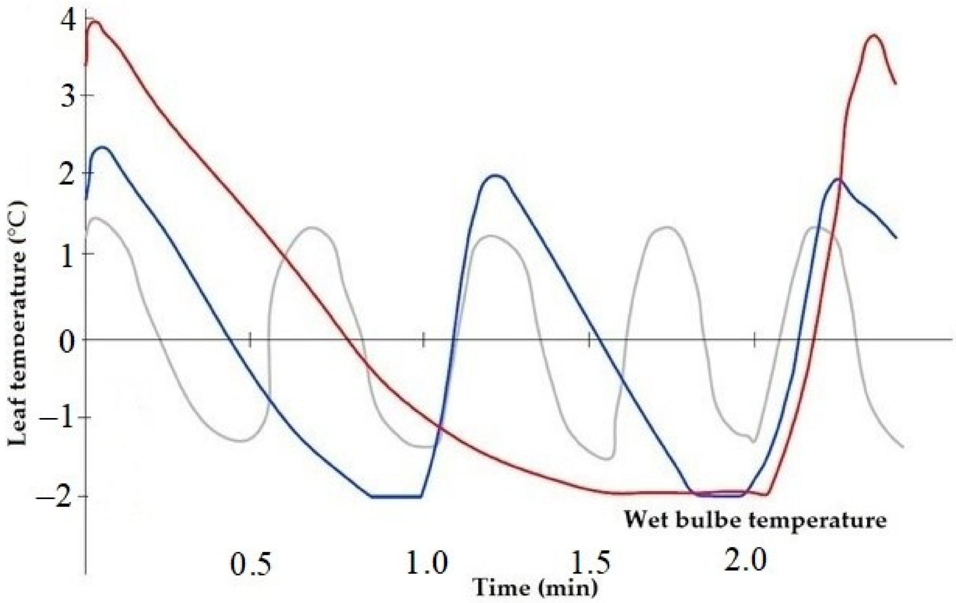

Figure 6. Main properties of sprinkler exploitation.

Considering the amount of water needed for protection, the water sources are mostly reservoirs. Centrifugal pumps with high flow rates and an operating pressure of 6–8 bar (depending on the terrain configuration) are used. An indicator of the success of frost protection is the appearance of the ice on the plants—if the ice is transparent, the protection has succeeded well. If the ice takes on a milky colour, it means that the plants have begun to freeze (Figure 7). The main characteristics of this protection method are high efficiency, but also high-water consumption (usually the protection lasts 10 h) [52].

Ultimately, the sprinkling methods are very effective; that is, they can protect the plantations when frost occurs with greater intensity and duration, but they require high investment for installation and greater amounts of water for protection.

Perry [55] states in his paper that rain sheltering has significant benefits in addition to certain risks. Operating costs are lower because water is much cheaper than oil and gas. Irrigation systems are convenient to operate because they are controlled from a central enclosure with a pump. The same author notes that a rain screen has a multipurpose function; it is used for drought prevention, heat suppression, fertilizer application, and most likely, pesticide protection. Figure 8 shows a method of preventing late spring frosts through over plant traditional sprinkling (a) and sprinklers (b).

Figure 7. Successful protection by rain (**left**) and unsuccessful protection (**right**).

(**a**) (**b**)

Figure 8. Over plant traditional sprinkling (**a**) and sprinklers (**b**).

Many authors [1,19,21,27,28] divided this agriengineering measure into different arrangements of sprinklers:over plant traditional sprinklers, targeted over plant sprinklers, sprinklers over covered crops, under tree sprinklers, under plant microsprinklers, trickle drip irrigation, and under plant sprinklers with heated water. Figure 9 shows an under tree microsprinklers system (a) and microsprinklers (b).

Snyder [46] suggest that when sprinklers are used, protection must begin when the wet bulb temperature is above the critical damage temperature, e.g., if the dew point temperature is −5 °C and the critical temperature is −1.1 °C, then sprinklers should be started when the air temperature is above 1.1 °C. Of course, the sprinklers should not be turned off until the bulb temperature exceeds 0 °C. Minton et al. [21] stated that microsprinkles for frost protection should consume about one-third of the amount of water used by overhead sprinklers. They also emphasize that microsprinklers should apply water only on the vines and not the entire field, including the areas between the vines. Pulsating microsprinklers also require less water pressure than standard overhead sprinklers because they can build pressure in a chamber within the sprinkler and apply water in a pulsating manner, rather than requiring constant pressure for a constant flow. Microsprinklers, when used properly, can protect vines at temperatures as low as −3.33 °C. Regarding the droplet size of the sprinklers, Loder [20] stated that the droplet size should be such that larger droplets are preferred to reduce the chilling effect at the beginning. However, practical experience indicates that fine droplets are advantageous because of better area uniformity.

(**a**) (**b**)

Figure 9. Under tree microsprinkling (**a**) and microsprinklers (**b**).

Evans [28] stated that an over-tree frost protection system is the best and most effective system (it can protect down to −7 °C [26] or up to 6 °C [2]), and its purpose is threefold: irrigation, frost protection, and evaporative cooling to reduce colour and scald (in apples). The protective effect of protection from over-tree sprinkling depends only on the amount (mass) of water applied, so this system is not really the best for young trees and trees with weak trunks and branches. The same author stated that the protective effect of under-tree irrigation systems depends on both the amount (mass) of water applied and the temperature of the water applied, which is limited by the strength of thermal inversion.

Any sprinkler system for frost protection should be computer monitored and controlled, with monitoring of weather data and the decision to put the system into operation. This type of automated system is presented by Koc et al. [56]. They implemented cycled over-tree sprinkling system in 1 acre of dwarf Jonagold apple trees. The control map was based on monitoring weather factors (air temperature, wind speed, and relative humidity) and bud temperatures calculated with on and off times that switched the valve. This type of monitoring reduced water use by about 72% during the three freeze events compared to continuous water application using the same system. The orchard energy balance was used to determine the sprinkler rate. To calculate the energy released when water freezes, the energy lost to radiation, convection, and evaporation must first be calculated. The minimum application rates, the specified minimum on-time or maximum off-time, and the actual sprinkler application rate were used to calculate the intermittent cycle. The energy required to make up for these losses is then converted to a sprinkling rate. The simplified Equation (4) of this phenomenon is [57]:

$$q_s = \frac{T_{sH_2O} - T_\infty}{R_{cond.} + \frac{1}{\frac{1}{R_{conv.}} + \frac{1}{R_{rad.}} + \frac{1}{R_{evap.}}}}, \quad (4)$$

where:

q—heat transfer (W),

s—aggregate state: solid (ice),

T—temperature (°C),

R—thermal resistor (°C W^{-1}),

T_{∞}—air temperature (°C),
cond.—conduction heat transfer,
conv.—convection heat transfer,
rad.—radiation heat transfer,
evap.—evaporation.

Anconelli et al. [58] studied the efficiency of microsprinklers under trees and sprinklers over trees in an artificial environment. They found that altering the microclimate at ground level was effective in reducing damage from late spring frosts. Researchers used different volumes of water to increase the air temperature in the canopy layer and optimize the amount of circulating water. Different water outflows for different types of sprinklers were used to achieve an energy balance with different droplet diameters. When the temperature was above 3 °C, there were no differences between sprinkler types in terms of frost occurrence, but when the temperature dropped below −3 °C, microsprinklers showed better performance. It was also found that, under the same temperature conditions, microsprinklers with a higher water outflow (65 L ha^{-1}) performed better than those with a lower outflow (45 L ha^{-1}).

To protect two orchards (oranges and peaches) covering several areas, another study on the over-tree sprinkler system was conducted in southern Iran [59]. In this work, software-implemented energy balancing was also used to determine the water application rate. The Authors explained the energy balance through this equation (5):

$$I = \frac{2[(h_r + h_c)(T_c - T_1) + L_E]}{L_I}, \tag{5}$$

where:

h_r and h_c—radiative and convective heat transfer coefficients (W m^{-2} °C^{-1}),
T_c—critical temperature (°C),
T_1—plant part temperature (°C),
L_E—difference in latent heat loss (W m^2),
L_I—latent heat of fusion (J kg^{-1}),
2—two sides of the plant,
I—application rate (mm s^{-1}).

T_1 is a function of wind speed (U) and relative humidity (RH); for example: when $U > 3.93$ m s^{-1} or RH > 91%, then $T_1 = T_a$, where T_a is temperature in °C. T_1 is taken as the blossom and fruit temperature for the peach and orange orchard.

The mentioned system was used in three frost events, and the main conclusion was that the system successfully kept the temperatures above the critical value of −4 °C. This success is reflected in the data determining the killed flowers after the frost, where the results show a percentage of 12% killed flowers in the sprinkler blocks, while the control blocks had 41.5% killed flowers. In addition, calculations showed that the amount of water could be reduced by 54% if variable amounts of water were used.

The Australian Department of Water, Land, and Biodiversity Conservation in its report [60] showed the number of "start-ups" for automated sprinkling systems in south-eastern Australia (Coonawarra) for 24 viticulture research areas during the period from 1999 to 2003. The number of days with a temperature less than 2 °C that started the systems were in a range of 4 (1999) to 10 (2003) events. It is obvious that the number of frost days is increasing, and therefore, a recommendation for the application rate required for cold protection at different temperatures of the grape tissue and wind speeds is given in Table 5.

A fairly recent study was presented by Yauri et al. [61] on machine learning to predict irrigation demand from historical data. In this case, sprinkler irrigation of frost-prone crops was performed using an automated system with machine learning techniques and predictive models to reduce frost damage.

Table 5. Sprinkler rate (mm h^{-1}) for over-tree sprinklers necessary for vineyard protection.

Tissue Temperature (°C)	Wind Speed (km h^{-1})				
	0–1.5	**3–6.5**	**8–13**	**15–22**	**29–32**
−3	0.25	0.25	0.36	0.50	1.00
−4	0.25	0.40	0.75	1.00	2.00
−5	0.30	0.60	1.25	1.50	3.00
−6	0.35	0.70	1.40	1.80	3.65
−7	0.40	0.75	1.50	2.00	4.00

6.3.3. Protection of Permanent Crops by Direct Heating

Direct heating is one of the effective methods of frost protection. It is based on heating the air and thus, the sensitive parts of the plant. By burning various materials, heat is generated, and the temperature is kept above 0 °C. Heating is achieved by stoves that radiate heat and heaters with fans that provide protection and warmth by the flow of heated air. The heated air rises to the temperature protection layer at a height of 5–20 m and expands. As a substitute for the heated air rising from the side, cold air meets it, which also warms up and rises even higher. This creates air circulation that warms the plantation and protects the plants from freezing. Heating is more economical when the weather is calm; otherwise, the warm air is quickly removed, and new quantities of warm air are needed, i.e., higher fuel consumption. Examples of protection by direct heating with stoves showed that one stove can effectively protect about 40 m^2. However, more detailed studies showed that 83,736 J h^{-1} per 100 m^2 are required for frost protection down to a temperature of −5 °C. This amount of heat is achieved by burning 3 L of fuel oil or 6 kg of coke in calm weather, while it is 50% higher in strong winds [4]. A portable stove is shown in Figure 10.

Figure 10. Using a portable stove for direct heating.

Another type of direct heating uses a mobile heat generator (Frostbuster), where the working principle lies in the successful mixing of the air below and above the inversion layer. Burning propane generates heat that fans distribute throughout the plantation and reduces frost damage. The amount of heat decreases rapidly with the distance from the source, so it is necessary to restore the amount of heat, which is the limiting factor of this machine, because the machine must return to its original position within a certain time. The heated air from the heater expands, becomes lighter, and rises vertically, and the air turbulence improves the heat transfer to the plantation. A Frostbuster (Figure 11) consists of a burner that burns gas from industrial or domestic cylinders and a fan that distributes the heated air over the plantation (540 o min^{-1}, min. 40 kW of a tractor). The maximum spread of the hot air is 150 m (working width on both sides). The gas consumption is 30–45 kg h^{-1}, and the warm air coming out of the machine has a temperature of 80–100 °C, while the temperature at a distance of one meter from the machine is about 20 °C. Before using this machine, the directions of movement must be marked, and the distance between the passes must not exceed 140 m (usually 70–60 m) [4].

Figure 11. Mobile heat generator—Frostbuster.

The advantages of using a Frostbuster compared to other methods of frost protection are: the relatively low purchase price of the machine (cultivation area up to 10 ha), low application costs, low maintenance costs, harmless to the environment, less incidence of diseases compared to rain protection, easy to apply, and very reliable in use [62].

To prevent possible frost damage, many agricultural growers use StopGEL anti-frost candles. They very quickly and efficiently raise the temperature in the plantation, warming the plantation or areas where vegetables are grown. The candle burns for about 8 h in normal use. The large surface area of the candle ensures maximum heat radiation. The StopGEL candle is easy to handle and store and is lit with a gas lighter [52]. The number of candles needed per hectare depends on the temperature predictions, e.g., if a temperature of −2 °C is expected, about 200 candles are needed for protection. Or, if a temperature of −6 to −7 °C is predicted, then 400–500 candles will be needed. A StopGEL candle is lit with a gas lighter for at least 5–7 s at the highest intensity. After lighting the candle, it is advisable to check the intensity of burning after 10–15 min. If the flame is too weak (flame height 2–5 cm), it is recommended to light it again so that the flame reaches a height of 15–30 cm. Extinguishing a StopGEL candle is very simple: it is sufficient to put the lid on the bucket. Another concept for heating orchards was proposed by Atam and Arteconi [63]. They presented a heating method based on electric heaters and green energy-based systems with electricity from photovoltaic solar cells. They presented a conceptual framework in which photovoltaic cells could be used for frost prevention in apricot orchards.

A rather new and successful approach to the issue of warming permanent plantations was presented in New Zealand [64]. Their research was based on soil cover in the root zone with a solar water heating quilt. This involves filling plastic quilts with water and placing them in direct contact with the soil. This principle improves solar collection and soil heat storage, resulting in a temperature increase of up to 1 °C in the air and up to 3 °C in the soil. They state that solar quilts can collect 2528 MJ (3.95 MJ m^{-2}) compared to 1832 MJ (2.862 MJ m^{-2}) in bare soil, releasing 32% more heat. It follows that this type of heating could result in a heat release of about 3500 MJ per hectare (typical frost conditions).

The idea of heating permanent crops with microwaves has been implemented in Canada with a prototype system in vineyards [65]. The system uses low-power microwave emitters located on 7 m high towers. These microwaves alter the energy balance in the vineyard and slow night time cooling. The microwaves heat the moisture in the vine shoots, causing the water molecules to vibrate, and as the molecules vibrate, the shoots heat up. This principle is in the prototype phase, and it is not yet clear what impact it will have on vineyard biology.

The new generation of orchard heaters was presented in a paper by Evans [66], which presented six years of research to develop more efficient and effective orchard heaters. In that paper, a portable, self-regulating, horizontal pulse-jet motor (burner) was presented. A description of all components was given, and the authors stated that this device uses high-velocity combustion stream air ejection technology to mix the air and produce a temperature rise of 2 to 5 °C above ambient. The special design of this device produces pressure fluctuations without combustion irregularities, with maximization of these amplitudes for high exhaust jet velocities for deep penetration into the orchard. Figure 12 shows a schematic diagram of a pulse-jet combustor.

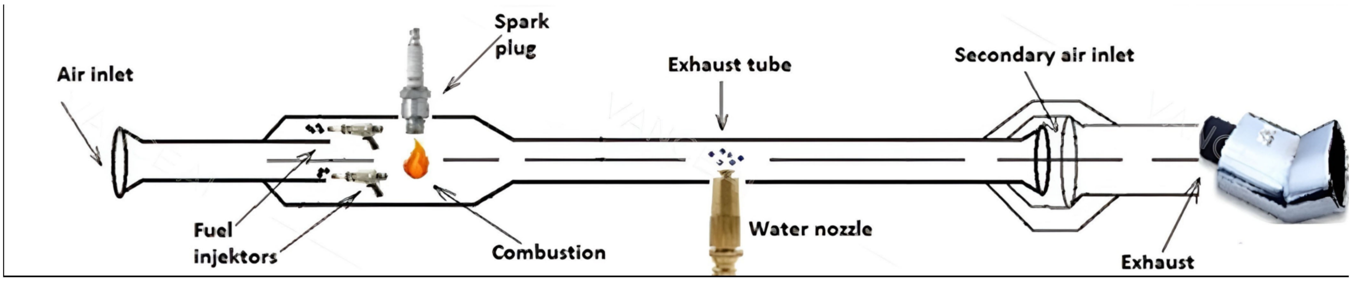

Figure 12. Schematic of a pulse-jet combustor.

The same authors have continued their research and are now testing a pulse-jet burner under operating conditions [67]. When burning 3 l of diesel fuel or 4.7 L of liquid propane, an optimum thermal output of about 110 MJ h^{-1} is achieved. The main results indicate that in comparison to typical orchard heaters, advanced impulse jet heaters have thermal efficiencies on the order of 65–75% compared to 10–15% for typical orchard heaters.

Methods of protecting permanent plantings with various heating systems can achieve protection in frosts of lesser intensity and duration. Problems can occur with frosts of −3 to −4 °C and with increased surrounding wind. In addition, the cost of burning fossil fuels can be relatively high.

6.3.4. Large Diameter Fans

This protection method is based on intensive mixing of the air layers, preventing greater radiation and temperature inversion. Fans driven by electric motors (Figure 13) with a power of 65–75 kW are placed on supports higher than the plantation—one fan is required for every 4 to 4.5 ha. During fan operation, a certain temperature drop of 1 to 2 °C is prevented so that dew and frost do not occur during their operation [4].

The warmer air in the temperature inversion is mixed with the cooler air at the surface by the fans, which provide a nearly horizontal airflow. The fans usually consist of a steel tower with two large, rotating blades (about 3 m in diameter) that sit on a shaft inclined at an angle of about 7° from horizontal to the tower. The height of the fan is about 10–11 m, and the speed is 590 to 600 revolutions per minute. Fans are not recommended when winds in the area are greater than 2.5 m s^{-1} or when there is fog, which can cause severe damage to the fans if the blades freeze [4].

Battany [68] discussed the performance of modern updraft fans compared to conventional fans in his research. To address this hypothesis, experiments were conducted on 12 freezing nights in the spring of 2010 and 2011 in a commercial vineyard using two fans: an updraft fan and a single conventional fan. In particular, at 1.1 m above the vine, the conventional fan regularly resulted in larger and statistically significant temperature increases. Based on the summary relationships between temperature changes, a conventional fan is expected to increase temperatures at vineyard height by 1.6 °C under reverse gradient conditions of 0.2 °C m^{-1}, while upward-blowing wind machines would have no net effect under the same inversion conditions. Smoke tracing of the air stream generated by upward-blowing wind machines showed that the air jet extended to a height of 25 m before gradually descending toward the ground. These results indicate that in the context of this study, the performance of such low-power (6.3 kW) upward-blowing wind machines is relatively low compared to their conventional counterparts.

Figure 13. Fans for protection from spring frost.

Considering the increasingly demanding environmental conditions, Chinese scientists [69] have developed an improved fan impeller in their research. The new fan impeller was designed using the principles of reverse engineering and CFD simulations. The main features of the impeller are the shape of the blade cross-section, the installation angle, the sweep angle, the hub ratio, and the number of blades. After the technical part, field tests were conducted to determine how well the airflow disturbances worked. The best fan performance was obtained with a Ø 2400 mm with a single arc cross-section, an installation angle of 15°, a sweep angle of 87°, a hub ratio of 0.3, and four blades. The required power of the fan was 1.363 kW. According to the field tests, the maximum airflow velocity was 12 m in front of the fan, and the highest probability (71.7%) indicating an improvement in airflow stability was when the airflow velocity was above 3.0 m s^{-1} within 30 min. A hypothetical wind tunnel established to conduct CFD simulations under different combinations of the impeller parameters is show in Figure 14.

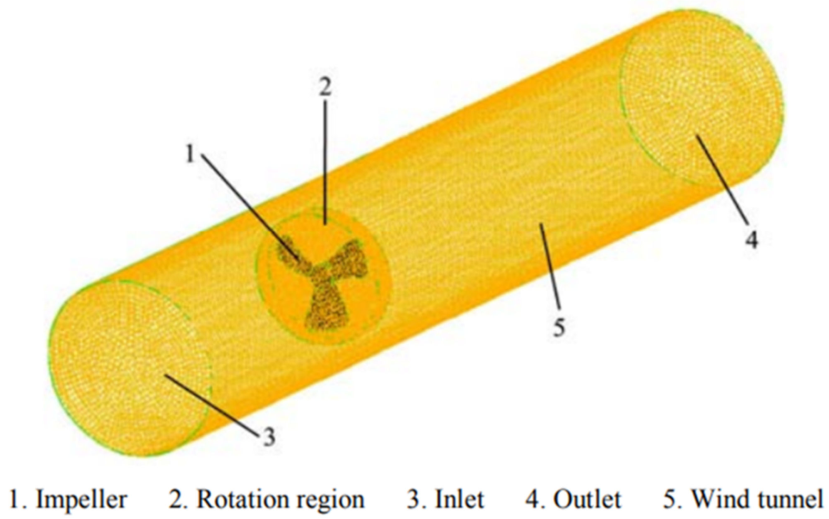

Figure 14. Wind tunnel for CFD simulation [69].

Another Chinese study presented LoRa [70] (low-power long-range) wireless communication technology composed of meteorological monitoring units, a gateway, a server, and defrosting equipment units. The authors gave an overall presentation of the monitoring and control units, the power module, and the meteorological monitoring unit. To combat frost damage, fans on a high vertical tower and an automatic smoke generator are used, so this can be considered a combined method of frost protection [1].

Israeli scientists [71] studied frost damage to avocado trees for the first time using horizontal wind machines (HWM) oriented parallel and across the rows. The minimum temperature in the plantation was −3.16 °C, which is far below the critical temperature. When the fans were oriented parallel, the air temperature depended on the distance from the fans and increased up to 2.4 °C. They measured the avocado yield per tree at 20, 50, and 100 m from the fans as an indicator of frost damage. With a parallel orientation, the yield was 42.76, 30.87, and 20.46 kg tree^{-1} (only 2.77 kg at 125 m), which is decisive evidence that the yield was lower the farther away from the fan. A transverse orientation reduced bud damage to inflorescences at these distances to 6.25 and 43.75%, respectively, as the air temperature was higher only at 20 and 50 m elevations. This study showed that in terms of fan orientation, one system is sufficient to protect the area of 0.6–1 ha in avocado trees.

Interesting research results come from a Portuguese scientist [72] who installed a wind machine with a diameter of 5.4 m with a double-bladed fan mounted on a 10.5 m high steel tower in an apple orchard. Measurements were made on 11 spring frost nights (in two years) with light winds (0.58–1.92 ms^{-1}) and clear skies, resulting in a radiation loss of 2.67 ± 0.38 MJ m^{-2} and a ground heat flux density between −38.0 and −43.1 W m^{-2}. The minimum temperature at 1.5 m averaged −2.6 °C with a range of −0.7° to −4.2 °C. The main conclusions of this study showed that the air temperature increased immediately after the fans were turned on, when the temperature inversion occurred. Between 1.5 and 15 m elevation, fan operation caused a 0.3 °C increase in air temperature for every 1 °C increase in temperature inversion, and the fans reduced flower damage by 60% in the first year and 27% in the second year.

Another approach for starting an inversion temperature due to radiation heat losses is presented by Yazdanpanah [73] with the system SIS (selected inverter sink). This ground fan drains the coldest air from the plantation and expels it upward to warmer elevations, where it disperses. They tested this system in a 20 ha almond orchard, and the average increase in air temperature in the different plots ranged from 0.5 to 2.8 °C. The larger temperature gradients at 100–300 m from the SIS were a maximum of 0.8 °C per 100 m, so multiple SIS systems are needed for longer distances and larger plantings.

Temperature inversion due to radiative heat loss can also be initiated by newer modern means, such as unmanned helicopters [74]. Field experiments were conducted to determine the appropriate flight parameters for an unmanned helicopter designed to protect tea plantations from frost. The most favourable combination of flight parameters was determined to be a flight altitude of 4.0 m, a flight speed of 6.0 m per second, and a flight interval of 20 min. The application of these parameters during the flight resulted in a 1.6 °C increase in the air temperature around the tea canopy, while the strength of the thermal inversion in the background was measured to be 3.8 °C.

The use of various types of fans to protect against late spring frosts can be very successful when radiation frosts of lesser intensity and duration occur. Problems can arise with the appearance of weaker surrounding winds and the appearance of advection frosts. An overview of most of the methods based on air disturbance technology by using different wind machines is presented by Yongguang et al. [75]. An overview of active protection measures is shown in Table 6.

Table 6. An overview of active protection measures.

Method	Principle	Applicability	Positive	Negative
Smoking	A subdued fire on a low-burning material produces a lot of smoke (manure, sawdust, or wet straw mixed with leaves)	Smaller, less intensive Plantations. Relatively effective on lower intensity radiation frosts.	Provides a high fraction of radiant energy that is absorbed by the plants. Relatively low costs.	Smoke particles are too small to absorb terrestrial radiation. The surrounding wind carries the smoke away from the plantations, as well as low air pressure. Ecology is questionable.
Over-tree sprinkling	Heat is released when water freezes (80 cal/L gram of water). The ice actually becomes an insulator between the plant parts and the ambient temperature below 0 °C.	Frost protection down to −7 °C. Start and stop are dependent on the ice properties.	For any type of radiative and evaporation frost. Partially effective for advection frosts.	High installation costs. Severe damage can occur if the sprinkler system fails. The weight of the ice that forms may break limbs and cause the loss of scaffolds in trees of some species.
Under-tree microsprinkling	Same principles as overhead sprinkling apply. Water under trees = less water consumption.	Effective on any form of radiation and evaporation frost. For any plantation size.		The possibility of subcooling plant parts. The ice is likely to cool more than if the water is concentrated in a smaller area.
Direct heating—stationary stoves; mobile generators	Combustion of fossil fuels, whose radiation energy is spread horizontally across the plantation	Effective on any form of radiation and evaporation frost. For smaller and medium-size plantations.	High amount of radiant energy that is absorbed by the plants. Effective for radiative and evaporation frosts.	Installation costs are high. Energy consumption is low. Area coverage is limited.
Large diameter fans	Classic wind axial fans consist of a steel tower with large rotating blades (3–6 m in diameter). Axis tilted up to 7° to the plantation.	Area coverage is from 4–6 ha. Ideal placement of the fan depends upon the airflow on frost nights.	For stronger radiative frosts. Mixing of great amounts of the air. Auto-starting systems connected with a weather station.	Minimum temperatures that are likely to occur should not be more than 2 °C lower than the critical damage temperature. Installation costs are high, but operational costs are moderate.

Table 6. *Cont.*

Method	Principle	Applicability	Positive	Negative
Upward fans	Wind machines that blow vertically upwards. The fan will pull in cold, dense air near the ground and blow it upwards, where it can mix with warmer air.	Area coverage is smaller than for the classical fans (1–2 ha). Relatively effective on lower-intensity radiative frosts.	Low energy consumption. Relatively effective for lower-intensity radiative frosts.	Only a temporary, positive effect near the fan. Installation costs are high.
Unmanned helicopters	Move warm air from aloft in a temperature inversion to the colder surface.	The area coverage depends on the helicopter size, weight, and weather conditions.	Operational costs are unaffordable for most growers.	Recommendations on pass frequency vary between 30 to 60 min. If the control of temperature is not appropriate, serious damage occurs.

7. Economic Issues—Frost Protection System Costs

Late spring frosts due to the aforementioned climate change have and will continue to cause more and more damage to agricultural production, especially to most permanent plantations when flowering coincides with low spring temperatures. Thus, many authors note that economic losses from freezing in the U.S. are the greatest among all-weather hazards. In the past, some events in Florida wiped out all citrus production and caused billions of dollars in costs. In California, frost caused damage to fruit trees over an area of 450,000 ha, amounting to about 500 million dollars [1]. Another observation in terms of cost damage comes from the Australian Bureau of Statistics [19], which found that frost damage in Australian viticulture amounts to more than 33 million dollars each year. In Croatia, the Ministry of Agriculture pays out damages from spring frosts to agricultural producers each year (about 3 million euros for 2021) [76]. Large economic losses are also repeatedly observed in other sensitive permanent crops worldwide, and economic losses are expected to increase. If we compare these monetary amounts with the costs of installing a frost protection system, we will come to the realization that frost protection should not pose major problems.

A fairly good overview of system costs and energy consumption for active agriengineering measures is given in the literature by Snyder [77] and the European Commission [27]. Figure 15 shows the annual energy required to operate most of the agriengineering methods in the FrostEcon program.

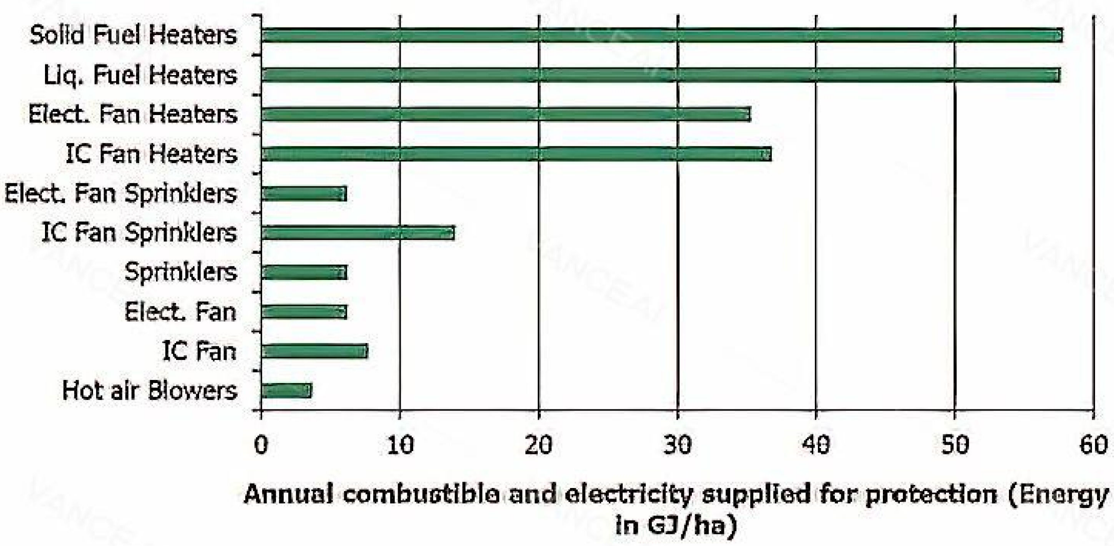

Figure 15. Annual energy necessary to run some agriengineering measures of frost protection [77].

It is clear from Figure 15 that the largest energy consumers are fossil fuel heaters (solid and liquid, close to 60 GJ ha^{-1} spent energy), followed by measures that consume electricity, and the lowest energy consumers are hot air blowers and internal combustion blowers (IC) (Figure 12). The same authors have an annual estimate of protection costs for the same active measures, as described in Figure 15. Prices and costs are estimated for 2018. Figure 16 shows the results of the FrostEcon calculation of total costs (€ ha^{-1}) for a fictitious apple growing site.

Figure 16 also shows that the level of costs is closely related to high energy consumption, so that even in this case, the highest costs are obtained with organic fuel combustion methods (solid and liquid fuel heaters).

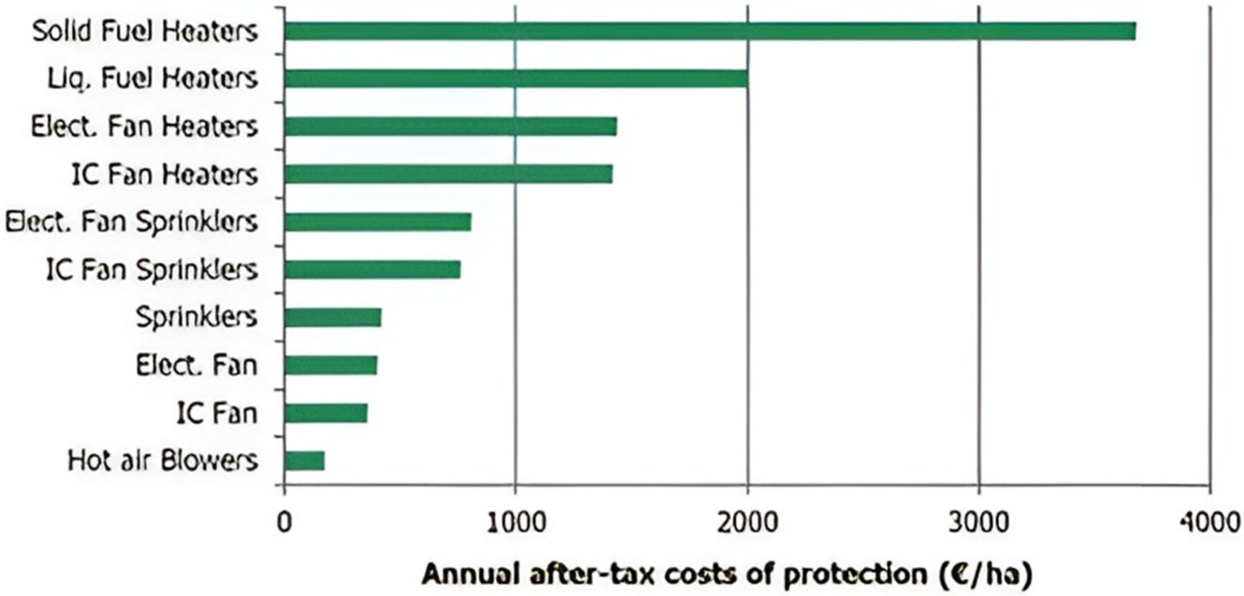

Figure 16. Estimation of annual costs for some of the agriengineering frost protection measures [77].

Another cost projection for a frost protection system is presented by Evans [28]. It is stated that the cost of a wind machine per 10–12 acres (4.4–4.8 ha) is 1500–1800 US dollars, for over-tree and under-tree sprinklers 900–1200 US dollars, under-tree sprinklers 1000–1500 US dollars, for oil heaters 400–450 US dollars, and for propane pressure heaters 2500–4000 US dollars. For accurate modelling and simulation of temperature dynamics, i.e., for calculating the minimum energy required for the optimal design of an energy system for active frost prevention, Atam, E. et al. [78] used thermofluid modelling of large-scale orchards. According to this model, each system must generate a sufficient amount of energy to raise the temperature in the plantation and reduce frost damage. Evans, R.G. [28] states this calculation in his paper, so we need to know the right energy consumption and the right process cost for the right method cost. It states that condensation/evaporation of water at 0 °C gives 9000 BTU/US gallon (2.637 kW/3.785 L), diesel burning releases 142,800 BTU/US gallon (41.84 kW/3.785 L), and propane burning releases 4,284,000 BTU/US gallon (1255.21 kW/3.785 L).

A good example of calculating investment in protection systems as a function of frost frequency is provided by Poling [2]. He calculated the average net yields of vineyards with different probabilities of frost damage. The estimated cost of installing and using a wind machine in a 4 ha vineyard was: initial equipment cost of $28,000, total annual cost of $726/ha, operating cost per hour of $5.36, and labour cost of $25.94/h. Another prediction was the probability of a 50% crop loss, which means a loss of $6609/ha (price per t = $1400). The last prediction is that a wind machine will work 40 h per year. Table 7 shows this calculation.

Table 7. Average net returns of vineyards with different probabilities of frost damage [2].

Probability of Frost Damage (%)	10 Year Average Net Returns ($ ha^{-1})		Difference in Average Net Returns	
	Vineyard with Wind Machine	Vineyard without Wind Machine	$ ha^{-1}	$/4 ha Vineyard
0	1984	2711	−726	−7264
10	1928	2068	−140	−1410
20	1872	1426	446	4463
30	1838	783	1033	10,327
40	1760	141	1619	16,191
50	1704	−502	2206	22,055
60	1648	−1144	2792	27,919
70	1592	−1786	3378	33,783
80	1536	−2318	3965	39,647
90	1480	3071	4551	45,511
100	1424	−3714	5137	51,375

From Table 7 it is clear that in case of a 50% frost occurrence, the savings, i.e., a bigger profit, will be up to 22 thousand US dollars. In years with 100% damage, the profit will be 51,375 US dollars. The same author, in the second edition [79], gave an overview of the operating costs of implementing protection against late spring frosts for other protection methods. He indicated that the cost of helicopter service as a protection method is $825–$1600 per h (available only in Virginia, USA). Burning 40 heaters per acre would cost $100 per h (diesel price of $2.5 per gallon, USA 2007; €2.28/3.75 L = €0.6 L^{-1}). Comparing this price with the diesel price in Croatia in 2023, it is clear that the price in Croatia is 25% higher (agricultural blue diesel = €0.81 L^{-1}) [80].

8. Conclusions

Clearly, climate change is causing frequent spring instability in the atmosphere, and global warming is increasing winter temperatures, causing premature flowering in most species in permanent plantations in temperate latitudes. By combining these two factors into one event at the same time, we get an extremely increased possibility of damage from late spring frosts. The frequency, intensity, and duration of frost events have increased, resulting in increased frost damage throughout the world over the past 10 to 15 years. The nature of frost occurrence varies by location, elevation, and geographic position, but one problem is common to all: heat loss from young plant shoots and flowers. As heat loss occurs, the temperature drops, leading to the freezing of plant tissue. Freezing of tissue depends on the critical temperatures and the type of frost, its intensity, and duration.

Faced with the aforementioned problem, more and more scientists began to study the problem and develop more perfect models for predicting late spring frosts. As a result, nowadays, there are different prediction models in all major agricultural areas, and modern machine learning methods, drones, sensors, and satellites are increasingly used.

Currently, science can offer several solutions to late frost damage control through passive, chemical, and active measures. According to good agricultural practice, every farmer should implement passive measures in their plantings to reduce or even prevent frost damage. Passive measures are implemented throughout the year, and even today, it is hard to imagine agricultural production without them. Chemical measures are not as prevalent as they have not shown much effectiveness, with the exception of the application of antifreeze proteins. Active measures, or as we called them in this paper, agriengineering measures (because they are in their essence measures under the aegis of agricultural machinery, i.e., agricultural engineering), are the only very effective measures against most types of frost that occur. Active measures are called active because of the investment of labour, money, energy, and knowledge. Every farmer should ask some very important questions at the beginning of the investment cycle and planting:

- Will the active measures provide the level of frost protection needed?

- What type of frost is most likely to occur, and how will it be affected by active measures?
- Is this system reliable, i.e., should this investment protect most of the plantation?

Most of the questions posed are answered in this paper, with the exception of system efficiency and reliability. Passive measures (site selection, soil condition, and soil covering, etc.) should protect any planting at low evapotranspiration and radiation frost, at low minus temperatures down to −1 °C. Below this temperature, passive protection measures are completely ineffective. At temperatures between 0 and −2.0 to −2.5 °C, all active measures should provide 100% protection to all plantations. At temperatures below −2.5 °C and without wind, only wind machines show some inefficiency with 20–25% damage. Real problems occur at temperatures below −2.5 °C and with winds of 3–4 m s^{-1}, and then only systems with sprinkling show full effectiveness and all types of heaters show limited effectiveness. So, all active measures are effective in reducing damage at relatively high intensity and duration of radiative and evaporative frost, but when it comes to the issue of advection frost, unfortunately, all methods become useless except methods involving sprinkling, which show limited effectiveness.

The profitability of the system depends, of course, on the size of the plantation and the ideas and wishes of the owners. In the case of large plantations (over 8–10 ha), some of the active measures must be installed because large plantations require high investment costs so that the plantation is relatively protected during severe frost, and the investment pays off with large, high-quality yields. The best solution for this case is any form of sprinkling system, as well as large fan systems. For a medium-size plantation area (3–8 ha), some active measures should be selected and applied. These can be measures with vertical fan towers, combustion heaters, or even 3–4 mobile heaters per plantation (Frostbusters). In these cases, under-tree microsprinkling systems can amortize the investment. For smaller plantations, less than 3 ha, Frostbusters, static heaters, and StopGel candles are really good solutions. From the mentioned statements, some main ideas can be summarized:

- Climate change causes early budbreak and early flowering, which overlap with late spring and cause much damage.
- Many forecasting models have been developed for predicting frost events.
- Protection from frost damage relies on three main areas: passive, active, and chemical measures.
- Active frost protection measures are most effective, depending on which method is used.
- The investment in each method should depend on the frost frequency and intensity, as well as the size of the plantings and the expected yields.

In this paper, all methods of protecting permanent crops from late spring frosts were presented, and the most commonly used methods were examined in detail. In the end, it can be concluded that there are many modern methods for protecting plantings, but farmers mostly use the methods that are most accessible and acceptable in price. In the small plantations across Europe, in most cases, simpler methods of protection without great effect are used, but recently, many of these plantations have been equipped with various systems using air flow heaters and fans. The above facts are the response of modern agricultural production to climate change and the adaptation of producers to the increased risks. Therefore, in the future, any form of intensive fruit and wine production is unthinkable without the use of modern agricultural engineering to protect permanent plantations from late spring frosts.

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