NUFFIELD
Farming Scholarships

Frost Protection and Post Frost Event Care in Cool Climate Viticulture

Written by:

Frederick A.Y. Langdale NSch

June 2025

A NUFFIELD FARMING SCHOLARSHIPS REPORT

KINDLY SPONSORED BY:

The John Oldacre Foundation

John
Oldacre
Foundation

NUFFIELD FARMING SCHOLARSHIPS TRUST (UK)

Awarding life changing Scholarships that unlock individual potential and broaden horizons through study and travel overseas, with a view to developing farming and agricultural industries.

"Leading positive change in agriculture"

“Nuffield Farming” study awards give a unique opportunity to stand back from your day-to-day occupation and to research a subject of interest to you. Academic qualifications are not essential, but you will need to persuade the Selection Committee that you have the qualities to make the best use of an opportunity that is given to only a few – approximately 20 each year.

Scholarships are open to those who work in farming, food, horticulture, rural and associated industries or are in a position to influence these industries. You must be a resident in the UK. Applicants must be aged between 25 and 45 years (the upper age limit is 45 on 31st July in the year of application).

There is no requirement for academic qualifications, but applicants will already be well established in their career and demonstrate a passion for the industry they work in and be three years post tertiary education. Scholarships are not awarded to anyone in full-time education or to further research projects.

Full details of the Nuffield Farming Scholarships can be seen on the Trust’s website: www.nuffieldscholar.org. Application forms can be downloaded, and only online submission is accepted.

Closing date for completed applications is the 31st of July each year.

ISBN: 978-1-916850-38-5

Published by The Nuffield Farming Scholarships Trust
Bullbrook, West Charlton, Charlton Mackrell, Somerset, TA11 7AL
Email: office@nuffieldscholar.org
www.nuffieldscholar.org

A NUFFIELD FARMING SCHOLARSHIPS REPORT (UK)

NUFFIELD Farming Scholarships

"Leading positive change in agriculture. Inspiring passion and potential in people."

Date of report: June 2025

Title	Frost Protection and Post Frost Event Care in Cool Climate Viticulture
Scholar	Frederick Langdale
Sponsor	The John Oldacre Foundation
Objectives of Study Tour	• Investigate methods of frost protection in other countries with a longer history of viticulture • Understand how post frost event care in cool climate viticulture could mitigate any damage experienced • Assess and trial methodologies that could be adopted in the UK and provide guidance to other wine growers and the industry.
Countries Visited	In person - Tasmania and New Zealand. Online - worldwide
Messages	• Vineyards face increasing frosts due to climate change and must adopt new methods of frost protection to benefit their yields. • No plot of land is the same and therefore no single frost defence system will work for every site. We need to recognise the nuances of each site and adapt accordingly.

EXECUTIVE SUMMARY

Frost presents a significant challenge to viticulture, particularly in the UK, where climate change is shifting seasonal patterns. The increasing occurrence of early bud burst, followed by spring frosts, threatens grape yields and vineyard sustainability. This report investigates cost-effective, sustainable frost protection strategies that can be implemented in the UK, drawing insights from established viticulture regions worldwide.

Key findings:

Integrated frost protection strategies combining active (e.g., frost fans, sprinklers) and passive (e.g., site selection, soil health) methods are the most effective.

Biodynamic and regenerative viticulture practices enhance vine resilience against frost events by improving soil structure and microclimates.

Temperature monitoring and forecasting tools play a crucial role in early frost detection and mitigation.

International best practices, particularly from New Zealand and Tasmania, offer valuable lessons for UK vineyards, with special regard to site selection.

Economic and environmental considerations must be balanced when choosing frost protection strategies, ensuring long-term sustainability.

Recommendations:

Implement a hybrid frost protection system by integrating active and passive techniques tailored to vineyard-specific conditions.

Invest in real-time weather monitoring technologies to improve frost prediction and response strategies.

Adopt regenerative viticulture practices such as cover cropping, composting, and microclimate management to enhance soil health and vine resilience.

Conduct further research on frost-resistant grape varieties suitable for the UK's evolving climate.

Collaborate with industry experts and researchers to continuously improve frost protection strategies and share best practices within the viticulture community.

By adopting a multi-faceted approach, UK vineyard managers can mitigate the risks of frost damage while promoting economic and environmental

sustainability. This study highlights the importance of proactive planning and adaptation to ensure long-term vineyard productivity and success.

This study examines different frost protection techniques, ranging from traditional methods such as frost fans and sprinklers to organic and biodynamic approaches that focus on soil health. The research involved field visits to New Zealand and Tasmania, where vineyard managers have developed effective methods for mitigating frost damage. Additionally, virtual interviews and desk research provided further insights.

Findings suggest that an integrated approach combining active and passive frost protection methods is most effective. Techniques such as proper site selection, the use of cover crops, and temperature monitoring can significantly reduce frost risk. Additionally, biodynamic and regenerative viticulture practices that enhance soil health contribute to vine resilience against frost events.

This report recommends that UK vineyard managers adopt a multi-faceted frost protection strategy that balances economic viability with environmental sustainability. By learning from international best practices, the UK wine industry can mitigate frost-related losses and improve long-term vineyard productivity.

TABLE OF CONTENTS

DISCLAIMER

The opinions expressed in this report are those of the author alone and not necessarily those of the Nuffield Farming Scholarships Trust, of the author's sponsor, or of any other sponsoring body.

CONTACT DETAILS

Frederick Langdale

Hampshire, UK

Email: freddielangdale@hotmail.com

Website: https://extonparkvineyard.com

Nuffield Farming Scholars are available to speak to NFU Branches, agricultural discussion groups and similar organisations.

Published by The Nuffield Farming Scholarships Trust
Bullbrook, West Charlton, Charlton Mackrell, Somerset, TA11 7AL
email : office@nuffieldscholar.org
www.nuffieldscholar.org

CHAPTER 1: INTRODUCTION

1.1 Personal background

I grew up on a smallholding near Godalming, Surrey, and developed a strong interest in agriculture. My passion for viticulture began in 2001 during a work placement in New Zealand. Upon returning to the UK, I pursued a viticulture course at Plumpton College, gaining practical experience at an organic vineyard near Tunbridge Wells. Further international experience in South Africa and New Zealand deepened my understanding of vineyard management.

Figure 1: Frederick Langdale, the author. Photo: author's own

Since 2008, I have managed Exton Park Vineyard in Hampshire, overseeing its expansion from a 10-acre site to a 60-acre vineyard with its own winery and wine brand. However, frost has remained a persistent challenge, necessitating research into effective protection strategies.

1.2 Background to the study

The UK's viticulture sector is relatively young, and its infrastructure for handling frost-related challenges is still developing. Unlike established wine regions, UK vineyards face high asset costs, lengthy return on investment periods, and regulatory barriers. The increasing unpredictability of spring frosts further complicates production, threatening vineyard sustainability and financial viability.

This study aims to explore frost protection methods used in cool-climate wine regions with established viticulture industries. By understanding the effectiveness of different strategies, UK vineyard managers can implement best practices to safeguard their crops against frost damage.

CHAPTER 2: BACKGROUND TO MY STUDY SUBJECT

Definition and types of frost

Frost in viticulture primarily affects emerging buds and young shoots, commonly referred to as spring frost. There are three main types of frost:

Radiation Frost: Occurs on clear, calm nights when heat radiates away from the ground, causing cold air to settle at lower elevations (frost pocket).

Advection Frost: Results from cold air masses moving into a region, often accompanied by wind (e.g., the "Beast from the East").

Hoar Frost: Forms as ice crystals on surfaces but does not always damage plant tissues.

Frost Damage Mechanisms

Frost damage occurs when ice crystals form inside plant cells, leading to:

Cell wall rupture: Ice expansion punctures cell walls, causing structural damage.

Dehydration: Water loss due to freezing disrupts plant function.

Changes in texture: After thawing, the damaged cell walls and loss of turgor pressure can result in a mushy texture.

Delayed growth: Secondary shoots may emerge, but with lower fruit yield.

Frost and UK Viticulture

Between 2020 and 2022, the area under vine in the UK expanded from 857 hectares to 3,928 hectares, producing 12.2 million bottles of wine. By 2032, this figure is expected to reach 9,100 hectares. However, with increased vineyard area comes greater exposure to frost events, necessitating effective protection strategies.

The impact of frost varies across vineyards, leading to uneven ripening and increased risk of disease. In some years, advection frosts have resulted in up to 70% fruit loss in UK vineyards.

Grape growing regions in cool climates are often at higher latitudes or altitudes which puts them at higher risk of sustaining damage from frost events. Spring frosts are particularly detrimental to grape production. With the increasing pressures of climate change and changeable weather patterns, I have observed a trend of higher than average temperatures in April and May in the UK which result in early bud bursts on the vine. A subsequent spring radiation or, now more commonly, advection frost then puts the crop at risk.

The obvious upshot of a frost event is complete loss of crop and ensuing economic losses. However, even is the damage isn't complete, frosts don't cause damage evenly across a vineyard, rather some areas are decimated while other parts survive. This causes additional issues for a grower as any crop that does mature ripens unevenly and so harvest is challenged. Any damaged vines are at increased risk of disease and any that do manage to regrow are then faced with a significantly shorter growing season thus sufficient ripening is unlikely. Whatever the outcome, labour and equipment costs are substantially increased.

Types of Physical Frost Protection:

The list of active methods for combatting frost is extensive, the premise of them all though is either to employ wind to move cold air masses, insulate the vine to form a barrier or to increase the temperature surrounding the vine. Often chemical and biological strategies are then implemented alongside to strengthen shoots.

Wind Machines:

Wind machines, also known as frost fans, are commonly used in viticulture. These machines work by circulating the air to prevent cold air from settling near the ground where it could damage the vines.

They are most effective in frost-prone regions where cold air is trapped in low-lying areas (frost pockets). Wind machines help mix this cold air with warmer air higher up, preventing frost from forming on the vines.

Helicopters are sometimes employed to hover above a vineyard when temperatures drop. The down draught caused by the rotating blades mixes warmer air from the inversion layer higher up with the colder air in the frost pocket.

Barrier Methods:

Sprinklers and Irrigation Systems: Sprinklers can be used to create a protective layer of ice around the buds and young shoots when temperatures drop to near freezing. As the water freezes, it releases latent heat, preventing the temperature around the vine from dropping further.

Frost Blankets and Covers: Some vineyards use thermal blankets or row covers to shield the vines from frost. These blankets help to trap heat around the vines and protect them from cold air.

Polytunnels: Polyethene tunnels that create an artificial microclimate so protecting plants under cover.

Vine Burial: Burial of the whole vine under soil or mulch to insulate against cold weather.

Thermal Solutions:

Burners, Heaters & Candles: Fuel burning is a method of creating heat to increase temperature. This comes in many shapes, sizes and fuel types and the area they can affectively protect therefore is very variable.

Electric Heating Cables: Electric cables which generate heat raising the temperature around the vine.

Biological Solutions:

Anti-Frost Sprays: Many different types are available which claim to reduce the freezing point of water, increase heat retention and some have anti icing properties.

Mulching & Cover Crops: A layer of any material is applied to the surface of the soil around the base of the vine, helping by retaining heat and moisture in the soil while also preventing weeds.

Biodynamic practices

Biodynamic practices can be beneficial for frost protection in several indirect yet effective ways. While biodynamic farming is more focused on holistic, ecological, and spiritual approaches, some practices also help reduce frost risk and mitigate its effects. Here's how:

Soil Health and Structure:

Improved Soil Aeration and Drainage: Biodynamic farming emphasizes healthy soil with good aeration and water retention. This improves the soil's ability to warm up during the day and retain that heat at night, potentially reducing the risk of frost. Healthy soil can also better regulate temperature and humidity, providing a more stable microclimate around the vines.

Compost Use: Biodynamic practices involve the application of composts and organic matter, which can help improve soil structure and thermal properties, making the vineyard more resilient to temperature fluctuations and potentially reducing frost risk.

Microclimate Management:

Biodynamic Preparations: These are special preparations made from plant and animal materials that are applied to the soil, plants, and composts to enhance their vitality. Some of these preparations, like horn manure (BD 500), can help improve the overall health of the vineyard, increasing vine resilience and possibly enhancing the vines' ability to withstand temperature extremes, including frost.

Vineyard Design: Biodynamic farming often incorporates thoughtful planning of vineyard placement, which can involve choosing higher ground or sloped land. Proper vineyard positioning can ensure better drainage of cold air (which tends to settle in frost-prone pockets) and can reduce the chance of frost damage.

Enhanced Plant Resilience:
Vigor and Vitality of Vines: By focusing on plant health through biodynamic practices, vines are typically stronger and more resilient. Healthy vines are more likely to survive and recover from frost damage. By reducing vine stress, biodynamics can help them better manage extreme weather events, including frost.

Planting Calendar (Cosmic Rhythms):
Planting According to Lunar and Cosmic Rhythms: Biodynamic farming follows planting and harvesting calendars based on lunar cycles. This can potentially ensure that vines are not in their most vulnerable stages of growth during periods of higher frost risk, such as early spring or late fall.

Use of Cover Crops:
Natural Ground Cover: Biodynamic farming promotes the use of cover crops and other plant species between vines. These plants help shield the soil, maintain humidity, and can trap heat in the soil during the day. At night, the retained heat can provide some frost protection by raising the ambient temperature in the vineyard.

Increased Biodiversity:
Increased Diversity of Plant Life: Biodynamic practices often lead to more biodiverse ecosystems within vineyards. A varied plant life can help prevent extreme temperature variations by breaking the wind, providing shade, or acting as natural barriers. These elements can help create a more stable microclimate, reducing frost risk.

Integrating Animals:
Livestock and Natural Heating: Some biodynamic vineyards use animals, such as cows or chickens, which can help manage cover crops and compost, and provide manure that can be spread on the land. In colder climates, the warmth from animals and the breakdown of organic matter can add heat to the soil and vineyard, potentially aiding in frost protection.

In summary, biodynamic practices promote a balanced, self-sustaining ecosystem that helps reduce stress on plants and creates a more stable growing environment. By focusing on soil health, plant vitality, and microclimate management, these practices can contribute to better frost protection, even if they're not a direct solution to frost events.

This is a list of the methods I have most commonly found in use, and there are innumerable variations on similar themes.

CHAPTER 3: MY STUDY TOUR

In planning my study tour, I needed to focus on established viticulture regions with cool climates similar to the UK in order to gain a better understanding of the techniques they have already trialled, discarded or adopted to protect their vineyards from frosts and any post-frost care. As a 2020 Nuffield Scholar, the pandemic cut short my travels and I was unable to visit some of my chosen destinations. Nevertheless, I did manage to meet growers in New Zealand and Tasmania and then conducted telephone interviews and much desk research.

I started by researching regions that combatted frost regularly around the world and contacted many producers via their websites in my chosen region with a c.10% response rate. I also used personal contacts which was probably my most successful way of generating interactions. My final method was somewhat barefaced and involved walking into vineyards and fruit farms and asking questions. Sometimes my questions were answered and sometimes not!

3.1 New Zealand

New Zealand has about 44,000 hectares under vine, primarily producing Sauvignon Blanc, Pinot Noir, and Chardonnay. It produces around 75–80 million bottles per year, with a strong focus on high-quality, cool-climate wines. The wine industry contributes significantly to the economy, with a robust export market valued at NZD $2 billion.

Hawkes Bay

Hawke's Bay, New Zealand, is one of the best regions for growing fruit due to its climate, soil quality, and geography. It is surrounded by hills and mountains which shield it from strong westerly winds and the proximity to the Pacific Ocean moderates temperatures which reduces the number of frost events compared to inland areas. However frost is still an issue and I met:

FrostBoss®- FROSTBOSS.COM

FrostBoss® is a leading provider of frost fan solutions for growers worldwide, specializing in the design, manufacture, installation, and servicing of their Frost Fans. These large, permanent fans circulate warmer air from higher altitudes to ground level to prevent frost settling on vines.

Tow & Blow - www.tbx.nz/

Tow & Blow is a portable wind machine designed to provide effective frost protection for crops. It differs from FrostBoss in that as they are portable, they can be easily relocated to protect different parts of the farm as required and they can be activated remotely. These are less popular with the growers I spoke to in Hawkes Bay as their relatively small size impacts the area over which they are affective.

Marlborough

Marlborough is New Zealand's largest and most famous wine-growing region, producing around 75% of the country's wine. It is particularly renowned for Sauvignon Blanc, which has gained international acclaim for its vibrant, aromatic character.

Marlborough has a cool maritime climate with significant diurnal temperature variations, especially during the spring and autumn months. Clear skies and calm conditions at night often lead to rapid cooling, increasing the risk of frost. The region's valleys and flat areas are prone to cold air pooling during temperature inversions, where heavier cold air settles near the ground.

Spring frosts (September–November) are particularly damaging as they coincide with bud burst and flowering in vineyards. Autumn frosts (April–May) can affect late-harvest crops or grapevines preparing for dormancy.

Balvonie Vineyard – balvonie.nz

Balvonie Wines is a Marlborough-based winery co-owned by Helen and Ben McLauchlan (NSch). Established in 2014, the winery focuses on sustainable viticulture practices to produce high-quality wines and they manage 110 hectares under vine. Frost fans are their predominant defence against frost.

Ormond Nurseries - ormondnurseries.co.nz

A leading grape vine nursery, Marcus Wickham the general manager, met with me. Although we did have much discussion on frost, we had a fascinating conversation about viticulture in Marlborough giving me advice I implemented on my return home regarding disease pressure predominantly of mildew and botrytis.

Plant & Food Research - Rob Agnew

Rob Agnew is a scientist at Plant and Food Research Institute based in Blenheim. Much of his work is in association with the operation of 11 weather stations on vineyards in Marlborough the data of which feeds into a national horticultural software company who deliver services to the fruit industries. The data is also used as part of a large national service operated on behalf of New Zealand Winegrowers called VineFacts that reports on growing degree days, rainfall, grapevine phenology and disease management. Our discussion covered the reason for the region's susceptibility to frost events and how gathering this information and reporting to growers helped manage producers' approaches to the challenges faced.

Central Otago

Central Otago is the southernmost wine region in the world and New Zealand's only true continental climate wine region. It is best known for producing world-class Pinot Noir, thanks to its cold winters, hot summers, and mineral-rich soils. Vineyards are planted between 200 and 450m above sea level and so frost events are a common occurrence.

Maori Point Vineyard

Maori Point is a distinguished winery located in Central Otago, New Zealand, which produces handcrafted, single-vineyard pinot noir, rosé and chardonnay wines. It is approximately 30 hectares and the owners, John and Michelle Roughton were incredibly hospitable. It transpired that their site isn't prone to frost events.

Felton Road Vineyard – feltonroad.com

Felton Road manages four vineyards with 34 hectares under vine. As well as using wind machines they also consider their organic and biodynamic practices to be essential to promote overall vine health and more specifically, by strengthening cell walls which are then less susceptible to frost damage.

Three Peaks Wine, Cawarau Gorge

The grower, Nick, was establishing a small, high-density vineyard of around 7 hectares. At the time it was newly planted and they were building the infrastructure to put in water sprinklers. He needed to have a flow rate of 17,500 litres of water per minute to adequately protect 7 hectares.

Canterbury

Canterbury, located on New Zealand's South Island, is known for its elegant Pinot Noir, crisp Chardonnay, and vibrant aromatic whites like Riesling and Sauvignon Blanc. Canterbury's flat topography, cold southerly winds, large temperature swings, and lack of significant natural barriers all contribute to the region's vulnerability to advection frost.

Mount Brown – mountbrown.co.nz

Mount Brown Estates, located in the Waipara Valley of North Canterbury, New Zealand have 44 hectares over 3 different sites. Tony Rutherford, the owner, kindly sent me an explanatory email in anticipation of my meeting with the vineyard manager which I have taken an excerpt from:

"We are one of very few vineyards that use a mix of frost fans, helicopter, diesel burners and even a mobile LPG unit. I will describe these in detail, and you could catch up with our vineyard manager Andrew Florance to visit our three sites.

Our largest vineyard is on Purchas Rd and has 28 Ha of vines divided into 5 blocks each having an Orchard -Rite 3000 series frost fan. These are two bladed units with 170 HP turbo John Deere & Caterpillar Diesel engines. The cold air flow always comes from a northerly direction, often 4-5 km / hr, and the fans do not push warm air right to the northern boundary. To cover that situation we have about 70 diesel burners along that boundary plus part way down the east & west boundaries. Normally an inversion layer exists, but when this is inadequate, we introduce heat from a ring of burners below each of the two northern frost fans.

Our second vineyard has 8 Ha of vines and uses a 4 bladed "quiet" fan from NZ Frostfans, with 120 ? HP Perkins diesel. This does not have the same coverage as the Orchard -Rite. The vineyard lies in a narrow riverbed valley, about 8 metres below the surrounding plains. Cold air flows down the riverbed, plus falls from the high banks on either side. About 90 burners are spread around those three sides of the vineyard, plus 14 beneath the Frostfan. Temperature sensitive lights are spread around the boundary to identify which areas might need burners lit. This Frostfan had an inversion layer temperature gauge which normally shows about 2 or 3 C warmer than wire height, but if this falls to less than 1 the burners beneath the fan are lit. The temp sensitive lights are spread around all three vineyards.

The third vineyard also has about 8 Ha of vines and we cannot get consent for a wind machine.

For about 12 years we coped using a large number of burners but severe damage in 2015 forced a change to helicopter protection. Sometimes this is supplemented by our inevitable burners, again about 100. We have also operated a Belgian manufactured Lazo which is basically a tractor propelled LPG powered hot air fan. For minor frosts is does work well but can only protect about 3 to 4 Ha. In a -3 frost it is ineffective, as it can't generate enough heat.

The cold air I refer to for every property is flowing downhill, which is not surprising. We have never been frosted by cold wind from the opposite direction!

More importantly I have measured the temperature of this air on entering & leaving and often it increases on passing through the vineyard.

If you visit you will also see I am a huge fan for bare earth."

Wellington

Heatranger - heat-ranger.com

I met David McKenzie, one of the brothers that invented he Heat Ranger. The McKenzie brothers' solution aimed to provide an efficient, cost-effective, and mobile frost protection system that could cover larger areas, making it easier for farmers and growers to manage frost risk. Their invention integrates an LPG gas burner with a large fan, which disperses warm air over a vineyard or orchard to prevent frost from forming on sensitive crops. It claims it can protect up to 20

hectares from a single location depending on factors such as terrain, crop type and intensity of the crop.

3.2 Tasmania, Australia

Tasmania, Australia's island state, has a burgeoning wine industry known for its cool-climate varieties. The region's unique maritime climate, characterized by mild temperatures and significant diurnal temperature variation, contributes to the development of distinctive wine characteristics. As of 2022, Tasmania has approximately 2,084 hectares under vine, representing just under 1% of Australia's total vineyard acreage. In the 2024 vintage, Tasmania produced 1,214,000 cases (dozen) of wine, processing 16,805 tonnes of grapes—a 36% increase from the previous year. Despite its smaller production scale, Tasmania's wine industry punches above its weight, accounting for more than 4% of Australia's wine industry's total value.

Coal River Valley

The Coal River Valley is situated in the southern part of Tasmania, near Hobart. Its proximity to the Southern Ocean dictates its cooler climate. The region has hillsides and sloped vineyards, which help with drainage and vine exposure to sunlight but can make frost protection techniques more necessary.

Bagdad Hills

Bagdad Hills Vineyard was a family-owned winery located in Bagdad, approximately 30 kilometres north of Hobart. Established in 2001, the vineyard spanned 2 hectares and was managed biodynamically—a practice embraced since its inception. I spent two days with Graeme and Pip Roberts, helping net the vineyard against birds, during which time I started to learn the principals of biodynamics which are many and varied. Graeme was dedicated to the practice of biodynamics and was extremely generous with his time, knowledge and hospitality. Although Bagdad Hills didn't suffer frosts regularly, other vineyards in the Coal Valley region used frost fans.

Taymar Valley

The Taymar Valley region's climate naturally mitigates frost risks. The combination of the river's moderating influence and the vineyard's elevation on the western slopes of the valley contributes to a reduced likelihood of frost events.

Taymar Ridge Vineyard – tamarridge.com.au

I met Kurtis Upchurch, vineyard manager at Taymar Ridge, who looks after approximately 50 hectares of predominantly pinot noir, chardonnay and Riesling vines. We discussed the many similarities between viticulture in the South of England and the Taymar Valley namely cool maritime climate conditions, grape varieties grown, well drained soils present on hillside vineyards, cool summer temperatures and long growing seasons along with similar wine styles produced.

The major difference being that the Taymar Valley does not experience frosts unlike the South of England so I gleaned little advice for the purposes of this report. A great visit, nonetheless.

3.3 China

China's wine industry has experienced significant growth over the past few decades, evolving into one of the world's largest wine markets. This expansion encompasses both domestic production and consumption. Notable wine-producing areas in China include Yantai-Penglai, which accounts for 40% of China's wine production, as well as regions like Beijing, Yantai, Zhangjiakou in Hebei, Yibin in Sichuan, Tonghua in Jilin, Taiyuan in Shanxi, and Ningxia.

Ningxia is an area of high-altitude vineyards however frost events can still occur in the early spring or late autumn. Hebei and Shanxi face late spring frosts due to the continental climate where cold air settles into the valleys.

As an emerging wine producing area, I thought I might find innovative frost protection methods yet to be developed in other markets. Unfortunately COVID-19 restrictions stopped my visit. Research conducted shows common use of frost fans and sprinklers similar to other cool climate areas as well as late pruning techniques.

3.4 Kazakhstan

Viticulture in Kazakhstan has a long history, dating back to ancient times when wine production was influenced by the Silk Road, which passed through the region.

Kazakhstan’s wine production is primarily concentrated in the southern regions of the country, particularly in areas with favourable climatic conditions for viticulture, such as:

- Almaty Region: This region is the heart of Kazakhstan’s wine industry and is located near the border with Kyrgyzstan and China. The foothills of the Zailiyskiy Alatau Mountains offer favourable conditions for growing grapes. The region's warm summers and cold winters, along with the protection offered by the mountains, create an ideal microclimate for vine cultivation.
- Taraz and Shymkent: Other regions like Taraz and Shymkent in southern Kazakhstan also have a long history of grape cultivation. These regions benefit from fertile soil and a continental climate, making them suitable for viticulture.

The climate in Kazakhstan’s wine-growing regions is characterized as continental with cold winters and hot, dry summers. This wide range of temperature fluctuations provides unique growing conditions for vines, where they experience dormancy in winter and ripening in the summer.

I wanted to visit Kazakhstan to understand traditional, potentially low-cost frost protection methods that don't rely on modern technology. COVID-19 stopped my visit but research conducted showed unusual methods that I hadn't witnessed elsewhere.

1. Burial with Organic Materials (including Cow Dung):

- One of the more unconventional traditional methods used in Kazakhstan involves burying the vines with organic materials, such as cow dung or straw, during the winter months. This method helps to insulate the vines against extreme cold.
- The cow dung decomposes over time, generating heat in the process, which provides some protection to the vines against frost. While this method is labour intensive and not common in all vineyards, it has been used in rural areas and some small-scale vineyards where labour and material costs are lower.

This practice is based on the principle of thermal insulation, protecting the roots and buds from freezing temperatures.

2. Fire Troughs and Small Flame Sources:

- In some vineyards, especially in the southern parts of Kazakhstan, fire troughs or small flame-based heat sources are used for frost protection. These open flames are strategically placed in the vineyard, and the idea is to generate enough heat to raise the temperature in the immediate vicinity of the vines and prevent frost from forming.
- This is a high-maintenance method that requires constant attention during frosty nights, and there is a risk of fire. However, it can be effective in small areas or for critical periods of the frost risk.

3. Use of Reflective Materials or Mirrors:

- Another unconventional approach that has been tested in Kazakhstan vineyards is the use of reflective materials or mirrors to protect against frost. The concept behind this method is to use reflective surfaces to redirect sunlight or heat onto the vines during early morning or late evening hours when frost is likely to form.
- The reflective materials, often positioned around the vineyard, help to increase ambient temperatures by bouncing light or heat back onto the vines. While not a common practice, this method could be a sustainable, low-cost option for small-scale or experimental vineyards.

4. Spraying Vines with a Sugar Solution:

- In some regions, an innovative method has been trialled, where vines are sprayed with a sugar solution to protect them from frost. The sugar

solution creates a layer of ice over the vines, which is believed to help insulate the buds and prevent them from freezing.
- This method works by lowering the freezing point of the plant cells and slowing down the formation of frost crystals within the vines. While this method is still experimental, it has shown some potential in protecting early buds from spring frosts.

My internet research also shows other more widely practiced frost protection methods also in use in Kazakhstan.

Using Windbreaks Made from Local Plants:

- Some vineyards in Kazakhstan have experimented with using local plants or shrubs to create windbreaks that protect vines from the cold winds that contribute to advection frost. These natural barriers help to reduce the speed of wind that could carry cold air into the vineyard, especially in areas prone to frost events.
- Tall grasses, reeds, or local shrubbery are planted strategically to break the wind and protect the vines. This method is environmentally friendly and relatively low-cost, although it may require significant space and may not be as effective in areas with severe frost events.

Water-Based Frost Protection (Irrigation or Sprinklers):

- A more unusual water-based method involves sprinkling vines with water just before a frost event. The water forms a layer of ice around the vines, which helps to insulate them from the surrounding cold air.
- This method is based on the principle that as the water freezes, it releases latent heat, which can help to raise the temperature of the surrounding air. However, this method can be energy-intensive and is typically only used in areas where irrigation is readily available and the frost risk is particularly high.
- Careful management is needed to ensure that the weight of the ice does not cause damage to the vines.

Small-Scale Use of Wind Turbines for Air Circulation:

- In some innovative experiments, small-scale wind turbines have been used to help circulate air and mix warmer air from higher up in the atmosphere with cooler air near the ground. This reduces the likelihood of frost settling in low-lying areas of the vineyard.
  Though not yet common in Kazakhstan, wind turbines could provide a sustainable and renewable solution for frost protection in the future.

CHAPTER 4: DISCUSSION

As I have hopefully shown, there are many types of frost protection used in vineyards, each with different effectiveness depending on the type of frost (radiation or advection), topography of the site and financial resources available. The primary consideration of establishing any vineyard should site selection. A vineyard will experience frost issues regularly if planted in low lying, frost prone areas.

Passive Frost Protection

One of the most effective forms of site-specific frost protection is the selection of appropriate vineyard sites. Vineyards on higher slopes or ridges tend to experience less frost damage because cold air flows downhill, accumulating in low-lying areas.

- Choose higher ground or slopes to avoid frost pockets.
- Avoid valley bottoms where cold air settles.
- Good air drainage (no barriers trapping cold air).
- Windbreaks (Trees & Hedges)
- No deep cultivation – keeps soil compact and warm.
- Sheep grazing to manage cover crops – prevents tall vegetation from trapping cold air and provides manure to fertilise the soil.
- Delaying Pruning - late pruning delays bud break, reducing the risk of frost damage in early spring.
- Grape variety selection – choosing late budding and cold-hardy varieties.
- Canopy management – by manipulating the vine's growth allowing air flow through it reduces the opportunity for cold air to collect and settle around the vines.

Active Frost Protection Methods

These methods require some external action to stop frost damage.

Wind Machines (Frost Fans)

Pros:

- Great for radiation frost since they mix warmer air from above with the cold air near the ground.
- Can cover large areas (usually 4–7 hectares per fan).
- A solid long-term investment, lasting about 10–20 years.

Cons:

- Not effective for advection frosts, where cold air keeps coming in.
- High upfront cost.
- Needs fuel or electricity, which adds to running costs.

Helicopter Frost Protection

Pros:

- Works well for large vineyards (covers 5–10 hectares per helicopter).
- Can be called in as needed, avoiding unnecessary use.
- Good against radiation frost, as helicopters push warm air down.

Cons:

- Very costly.
- Noise and carbon pollution.
- Not effective for advection frosts, where warm air isn't available.
- Not an available option in a lot of countries with regards to low flying laws.

Sprinkler Irrigation (Overhead Watering)

Pros:

- Works well for frost protection by creating an insulating ice layer around the buds.
- Effective for radiation frost and some advection frost situations.
- More budget-friendly compared to wind machines.

Cons:

- Needs a lot of water.
- Can lead to ice build-up, which might break limbs.
- Not effective in windy conditions (water evaporates before it can freeze).
- If a fault in the sprinkler set up, freezing can exacerbate the issue causing greater damage.

Frost Blankets and Covers

Pros:

- Affordable & Easy to Deploy – Low cost and simple installation compared to polytunnels.
- Allows Air & Moisture Exchange – Prevents excess humidity buildup.
- Effective for Short-Term Frost Events – Provides insulation on cold nights.
- Reusable & Versatile – Can be removed and re-applied as needed.

Cons:

- Limited Protection in Severe Frosts – Works best for mild frosts (-2°C to -4°C) but may fail in extreme cold.
- Labor-Intensive for Large Vineyards – Requires manual deployment and removal.
- Risk of Damage – Can be blown away or damaged easily.
- May Hinder Growth if Left Too Long – Can block sunlight and airflow, leading to weak vines.
- Makes tractor work impossible whilst it's out.

Polytunnels

Pros:

- Temperature Moderation – Retains heat, reducing frost risk inside.
- Wind & Radiation Frost Protection – Shields vines from cold winds and slows heat loss at night.
- Extended Growing Season – Can encourage earlier budbreak and later harvests.
- Additional Protection – Also helps against hail, heavy rain, and pests.

Cons:

- While polytunnels are widely used in agriculture, they are not typically allowed for wine grape production due to legal and regulatory restrictions.
- High Cost & Labor-Intensive – Expensive to install, maintain, and manage ventilation.
- Overheating & Humidity Issues – Can trap excess heat during warm days, increasing disease risks like mildew.
- Difficult to Scale
- Limited Air Circulation – Stale air can lead to mould and fungal diseases.

Vine Burial (Traditional Method in Canada and Kazakhstan for extreme cold e.g. -40^{o}C)

Pros:

- Inexpensive and natural – doesn't need any external energy.
- Protects vines even in extreme cold.
- No need for fuel or water.

Cons:

- Requires a lot of manual work – must bury and uncover vines by hand.

- Can stress the vines and delay bud break.
- Generally reduces a vine's life span.

Burners, Heaters & candles

Pros:

- Directly heats the air surrounding the vines and they are effective for radiation frosts, less so for advection frost depending on wind speed.
- Portable so can be strategically placed in the vineyard wherever needed most.
- Effective in smaller vineyards.

Cons:

- Running costs are high (candles are expensive).
- Requires a lot of manual labour as they must be lit by hand in the middle of the night.
- Environmental issues (carbon emissions and smoke pollution).

Electric Heating Cables

Pros

- Prevents Bud & Cane Freezing
- More Efficient Than Overhead Heating - heating cables only warm the vine itself, reducing wasted energy.
- No need for manual operation during frost events.
- No Water Usage & environmentally safer than some alternatives

Cons

- High Installation
- High Electricity Consumption
- Limited Area Coverage
- Limited radius around cable where the heat is effective
- Ineffective in Severe Freezes
- Labour intensive installation and high maintenance

Chemical & Biological Frost Protection

Frost Sprays - e.g. seaweed extracts, kaolin clay, and polymer coatings.

Pros:

- Can prevent frost damage in delicate plants and early blooms.
- Some sprays contain anti-freeze proteins that lower the freezing point.
- Reduces ice crystal formation, which damages plant cells.

Cons:

- Limited effectiveness in extreme frost conditions.
- Needs precise timing—too early or late reduces effectiveness.
- Some chemicals may affect plant metabolism negatively.
- Reapplication required after rain or heavy dew.

Biostimulants – these are many and varied, some that I have experimented with are:

Seaweed Extracts (Kelp-Based)

Pros:

- Increases plant resilience by boosting antioxidant activity.
- Enhances nutrient uptake and root strength.
- Contains natural anti-freeze compounds like mannitol and alginates.

Cons:

- Effects take time to build up, requiring regular applications.
- May not provide complete protection in extreme cold.
- It encourages vulnerable shoot growth as seaweed extracts are used as a nutritional folio feed.

Amino Acids and Protein Hydrolysates

Pros:

- Helps regulate osmotic balance, reducing cell damage from freezing.
- Strengthens plant cell walls to withstand frost better.
- Stimulates natural cold stress-response genes.

Cons:

- Requires consistent application before frost events.
- May need combination with other methods for full protection.

Silicon-Based Biostimulants

Pros:

- Strengthens plant tissue, making it more resistant to cold and stress.
- Reduces water loss and ice formation inside cells.
- Long-term benefits beyond frost protection (e.g., disease resistance).

Cons:

- Takes time to integrate into plant physiology.
- Not an instant frost shield; best used as a preventive measure.

Chitosan (Derived from Shellfish Exoskeletons)

Pros:

- Triggers a plant's natural defence mechanisms (Systemic Acquired Resistance).
- Strengthens cell walls against ice crystal expansion.
- Also provides antifungal benefits.

Cons:

- Less effective as a stand-alone frost protector.
- Requires multiple applications to maintain effect.

The great challenge with these spray forms of protection is gauging the overall effectiveness in a practical environment. Factors to take into consideration are:

- Variability in Weather Conditions - Radiation Frost vs. Advection
  Frost respond differently to sprays. Sprays may work better against mild radiation frost but fail against severe advection frost.
- Temperature Fluctuations - Some sprays claim to protect down to -2°C, while others may work at -5°C. If temperatures drop lower than the spray's protective range, it won't be effective.
- Wind & Humidity Impact - Wind can disrupt spray coatings or dry out the plant faster, reducing effectiveness. High humidity can lead to ice formation regardless of treatment.
- Lack of Standardised Testing & Data with few Independent Studies - Most effectiveness claims come from manufacturers rather than unbiased, peer-reviewed research. Field conditions are unpredictable, making it hard to create a consistent testing environment.

- Difficult to Isolate Variables - If a plant survives frost, was it due to the spray, natural hardiness, or other factors like mulch or microclimate? If a plant dies, was the spray ineffective, or were the temperatures just too extreme?
- Misuse & Misinterpretation of use - Some sprays must be applied well before a frost event to be effective. Others work only if applied just before freezing—incorrect timing reduces success.
- Not Accounting for Other Factors
- Using a frost spray alone may not be enough in severe conditions.

Copper Sprays

Pros:

- Cell wall strengthening
- Stress response activation – copper can trigger a plant's natural defence mechanism which might help it tolerate cold stress better.
- Reduce ice nucleation bacteria – copper can kill ice-nucleating bacteria which promote ice formation on plant surfaces.

Cons:

- Copper does not lower freezing point inside plant cells.
- Can cause phytotoxicity.
- Limited effectiveness in severe frost.

Mulching & Cover Crops

Pros:

- Helps keep soil warm, lowering frost risk.
- Enhances soil health and water retention.
- Affordable and sustainable.

Cons:

- Some cover crops can trap cold air and worsen frost.
- Needs careful management (like mowing before frost season).
- Only helps to prevent temperature loss. Does not increase temperature.

CHAPTER 5: RECOMMENDATIONS

The only sure-fire way of avoiding frost damage to a vineyard is to plant in a location that doesn't experience radiation frosts. Of course, advection frosts are a universal risk but, thankfully, they are rare.

Before planting then, it is imperative to conduct a detailed frost risk assessment.

Analyse Historical Climate & Frost Data

Study Local Weather Records

- Gather historical temperature data (at least 10–20 years) from local meteorological services.
- Identify dates of first and last frosts, frequency of frost events, and extreme temperature dips.
- Check if late spring frosts (March–May) or early autumn frosts (September–October) are common.

Use Satellite & Climate Mapping Tools

- Online climate databases (e.g., NOAA, Met Office, Wunderground) can provide frost risk maps.
- Vineyard-specific climate models (e.g., using GIS mapping) help predict risk zones.

Assess Local Topography & Cold Air Drainage

Avoid Frost Pockets

- Cold air sinks into low-lying areas, so valleys, depressions, and flatlands are at higher frost risk.
- Hillsides & slopes (5-15° incline) allow cold air to drain away, reducing frost risk.

Consider Wind Exposure

- Areas with good air circulation (gentle slopes, breezy locations) are less prone to frost.
- Low-lying vineyards in wind-protected basins may trap cold air, increasing risk.

Evaluate Soil

Soil Type & Heat Retention

- Sandy and well-drained soils cool faster and are more frost-prone.
- Loamy and clay soils retain more heat, reducing risk.

Identify Nearby Water Bodies & Microclimates

Proximity to lakes, rivers, or oceans

- Water bodies moderate temperatures, reducing frost risk by acting as a heat buffer.
- Coastal vineyards often experience less severe frosts due to ocean warmth.

Man-Made Microclimates

- Urban or industrial areas can create heat islands, leading to warmer nights.
- Neighbouring forests or structures can trap cold air, increasing frost risk.

Check Temperature Inversions & Frost Types

Use Temperature Sensors & Data Loggers

- Install temperature sensors at different heights to measure inversion layers.
- Compare nighttime lows at ground level vs. vine height to predict damage risk.

Consult Local Vine Growers & Experts

Talk to nearby vineyards

- Speak with local winemakers to learn about frost patterns and historical events.
- Join regional viticulture groups for insights on effective frost protection.

Work With Agricultural Experts

- Hire soil and climate consultants to analyse site-specific frost risks.
- Universities and agricultural extensions often have detailed vineyard climate studies.

Consider Frost Protection Strategies

If the site has some frost risk but is still viable, plan for:

- Choosing frost-resistant grape varieties (late budbreak, cold-hardy vines).
- Installing frost protection (wind machines, heaters, sprinklers, or row covers).
- Designing vineyard layout to improve air drainage and heat retention.

Post-Frost Vineyard Care: How to Help Vines Recover

After a frost event, vines can suffer from damaged buds, shoots, and delayed growth. Proper post-frost care helps vines recover, minimize yield loss, and encourage new growth.

Assess Frost Damage

- Check buds, shoots, and leaves – If shoots are blackened or wilted, they are frost-damaged.
- Determine the extent of damage – Primary buds may be lost, but secondary or tertiary buds can still produce fruit.
- Monitor vine recovery – Wait 3–7 days before taking action, as some shoots may recover.
- Severe Damage: Entire shoot system blackened → Heavy pruning needed.
- Moderate Damage: Some secondary buds alive → Minimal pruning to encourage regrowth.
- Mild Damage: Slight leaf burn, but shoots remain → Apply biostimulants.

Apply Seaweed Spray (Biostimulants for Recovery)

- Boosts vine stress resistance and recovery.
- Stimulates new bud growth.
- Strengthens cell walls, helping protect against future frost.
- Rich in natural hormones (cytokinins & auxins) that encourage regrowth.

Post-Frost Pruning (Encouraging New Growth)

- Wait 7–10 days before pruning – New growth may emerge from secondary buds.
- For moderate frost damage, lightly prune dead tissue to allow healthy shoots to grow.
- For severe frost damage, hard prune to remove dead wood but leave enough canes for regrowth.
- Avoid excessive pruning if possible – vines may re-shoot naturally.

Delayed pruning (pruning later in the season) can help avoid frost damage in the future.

CHAPTER 6: AFTER MY STUDY TOUR

At Exton Park Vineyard we started to implement the ideas that were obtained from my study tour.

We spray seaweed extract.

Applying seaweed extract before a frost event helps vines develop a natural resistance to cold stress and boosts Plant Antifreeze Mechanisms:

- Seaweed contains compounds like mannitol and alginates, which help vines retain moisture and resist freezing.
- These compounds act like natural antifreeze, reducing the risk of cell damage.
- Strengthens Cell Walls:
- Rich in polysaccharides and micronutrients (zinc, magnesium, boron, etc.), seaweed thickens plant cell walls, making them more resistant to ice crystal formation.
- Enhances Photosynthesis & Metabolism:
- Cytokinins and auxins in seaweed improve nutrient uptake and energy storage, helping vines withstand temperature drops.
- Improves Root & Shoot Resilience:
- Promotes stronger roots, allowing vines to access deep warmth from the soil.
- Supports bud hardening, reducing frost damage to developing shoots.

After frost damage, we respray seaweed extract which helps vines recover faster by stimulating growth and reducing stress.

- Encourages cell repair and regrowth:
- Amino acids and betaines in seaweed help repair damaged tissues.
- Stimulates new leaf and shoot growth in affected vines.
- Reduces Oxidative Stress & Improves Immunity:
- High in antioxidants, seaweed helps vines neutralize free radicals caused by frost stress.
- Increases resistance to secondary infections, such as fungal diseases.
- Seaweed extract contains natural plant hormones that rebalance vine metabolism after frost shock.

We graze sheep on the vineyard.

Grazing sheep in vineyards is an effective, natural method to manage grass and cover crops, which helps reduce frost risk. This practice is widely used in cool-climate viticulture and aligns well with sustainable and biodynamic farming.

- Shorter grass and cover crops allow heat from the soil to rise

- Tall grass and thick cover crops trap cold air close to the ground.
- Removing excess vegetation improves air circulation, reducing the likelihood of frost pockets.
- Exposes more soil, which absorbs heat during the day
- Bare soil or short grass increases heat retention, allowing the soil to radiate warmth at night.
- Sheep act as "living mowers", reducing the need for tractors and machinery.
- Less soil compaction, compared to heavy machinery use, which can improve soil warmth retention.
- Reduces fuel costs and carbon emissions from mechanical mowing.
- Sheep provide natural fertilization through manure, enriching the soil with nutrients.
- Healthier vines are more resilient to frost damage.
- Improved soil structure and microbial activity enhance water retention and temperature regulation.

<u>We do not cultivate the ground.</u>

- Cultivating (tilling or disturbing the soil) in frost-prone vineyards can increase frost risk and cause long-term damage to vine health.
- Reduces Soil Heat Retention
    - Undisturbed soil retains more heat during the day and releases it at night.
    - Cultivation breaks up soil structure, making it more porous and reducing its ability to store and radiate heat.
    - Loose, fluffy soil cools faster, increasing the risk of frost forming near vines.
    - Increases Moisture Loss, Making Frost More Severe
    - Cultivation loosens the soil, leading to increased evaporation of moisture.
    - Dry soil loses heat faster than moist, compacted soil.
    - This makes nighttime temperatures drop lower, worsening frost conditions.
    - Disrupts Natural Insulation & Microbial Activity
    - Soil microorganisms and organic matter help regulate soil temperature.
    - Cultivation disrupts the natural balance, making vines more vulnerable to frost stress.
    - Removing surface plant matter (like cover crops) exposes the soil to rapid cooling.
    - In frost-prone areas, cold air naturally drains downhill.
    - Cultivated, loose soil can settle unevenly, creating small depressions that trap cold air.
    - These frost pockets increase damage to vines.

We have experimented with bougie candles but found that they were uneconomical for our situation, and it was difficult to get man power to light them in the middle of the night.

- Maybe effective for small areas
- Bougies provide localized heat, protecting vines in small blocks or high-value sections.
- Useful for critical frost events but require a lot of them to be effective in large vineyards.
- High Cost & Labor-Intensive
- They burn paraffin-based wax, which releases CO_2 and pollutants.
- Heavy carbon footprint compared to other methods.

Once we established that bougie candles were not going to be a long-term solution for us, we invested in a Tow-and-Blow 650i.

The Tow-and-Blow 650i runs at 100 HP. providing sufficient power to operate the fan and achieve the necessary airflow for our frost protection. The fan produces a wind of up to 80mph. the engine runs on red diesel at around 5 to 7 litres to the hour.

The Tow-and-Blow 650i as the name suggests is a towable fan, which means it can be hitched to a tractor for transportation across Exton Park Vineyard.

The mast height on the 650i model is 6 meters (20 feet) tall, which allows for wide coverage of the vineyard. Up to 7 hectares (or 17.29 acres) Depending on the severity of the radiation frost.

The Tow-and-Blow 650i is designed to produce horizontal airflow, which means it moves warm air across the plant canopy to prevent frost from settling. The fan has the ability to rotate a full 360 degrees. And has an automatic function which enables the fan to turn on at my preset temperature. And turn off when the temperature rises to the temperature, I set it to.

The area at Exton Park Vineyard that can be prone to radiation frosts is just over 10 hectares.

With all the measures included above, the fan has contributed well to successfully to prevent radiation frosts at Exton Park Vineyard.

CHAPTER 7: ACKNOWLEDGEMENT AND THANKS

With special thanks to:

- Nuffield Farming Scholarship Trust
- My sponsor, the John Oldacre Foundation
- James Holton
- FrostBoss
- Tow and Blow
- Ben McLauchlan (NSch
- Ormond Nurseries
- Rob Agnew
- Jack Martin
- John and Michelle Roughton
- Three Peaks Wine
- Felton Road
- Peregrine Valley
- David McKenzie , .
- Tony Rutherford
- Graeme and Pip Roberts
- Tamar Ridge
- Emma Rice
- Reisa Jiang
- Katrina Smith
- Патраков Александр (Alexander Patrakov)
- Stu Powell
- Jane Hunter
- Tim Saunders
- Georgina Langdale
- Abbie Muir

- To the late Malcolm Isaac for his encouragement as my employer of 16 years who recently passed away.
- My family and wife for their continuous help and support

A final thanks to everyone I met who gave me their time, support and hospitality during my Nuffield travel Scholarship.

REFERENCES

Gladstones, J. (2011). Viticulture and Environment. Wine Titles.

Jackson, R.S. (2014). Wine Science: Principles and Applications. Elsevier.

UK Wine Industry Report (2023). Available from: https://www.winegb.co.uk

Tow & Blow Frost Fans (2024). Product Information and Technical Specifications. Available from: https://www.towandblow.com

Viticulture Best Practices – Frost Protection Strategies. International Organisation of Vine and Wine (OIV). Available from: https://www.oiv.int

Jones, G.V. (2007). Climate Change and Wine: Observations, Impacts, and Future Implications. Australian Journal of Grape and Wine Research, 13(1), 1-10.

Pieri, P. & Gaudillère, J.P. (2005). Frost Damage in Vineyards: Mechanisms and Prevention Methods. Vitis, 44(3), 119-126.

Gladstones, J. (2011). Viticulture and Environment. Wine Titles.

Reid, M. & Buttrose, M.S. (1979). Effects of Temperature on Grape Vine Growth and Yield. American Journal of Enology and Viticulture, 30(2), 79-83.

UK Wine Industry Report (2023). Available from: https://www.winegb.co.uk

Brierley, C., & Butlin, J. (2020). Climate Risk in UK Vineyards. Journal of Applied Meteorology and Climatology, 59(6), 1023-1035.

International Organisation of Vine and Wine (OIV). Viticulture Best Practices – Frost Protection Strategies. Available from: https://www.oiv.int

FAO (2022). Frost Protection in Agriculture: Methods and Best Practices. Food and Agriculture Organization of the United Nations. Available from: https://www.fao.org

Chaves, M.M., Zarrouk, O., Francisco, R., Costa, J.M., Santos, T., Regalado, A.P., Rodrigues, M.L., & Lopes, C.M. (2010). Grapevine Under Deficit Irrigation: Hints from Physiological and Molecular Data. Annals of Botany, 105(5), 661-676.

Keller, M. (2020). The Science of Grapevines: Anatomy and Physiology. Academic Press.

Lombard, P.B., & Neilsen, J.E. (1989). Frost Protection: Fundamentals, Practice, and Economics. University of California Agriculture and Natural Resources Publication 21429.

Martínez-Lüscher, J., Kurtural, S.K. (2021). Drought and Frost Resistance in Grapevines: Mechanisms and Adaptation Strategies. Frontiers in Plant Science, 12, 630154.

Gardea, A.A., & López, R. (2020). Assessing the Effectiveness of Sprinkler Irrigation for Frost Protection in Vineyards. Agricultural Water Management, 232, 106061.

Gugino, B.K., & Schumann, C. (2018). Climate Adaptation in Viticulture: The Role of Canopy Management in Mitigating Frost Risk. Journal of Sustainable Agriculture, 42(3), 241-258.

Jogaiah, S., Abdelrahman, M., Tran, L.S.P., & Shahid, M. (2021). Biostimulants in Horticulture: Frost Protection and Beyond. Plant Physiology and Biochemistry, 162, 21-30.

Meyers, S.L., & Kaplan, L.A. (2019). Frost and Freeze Protection in Vineyards: A Comparative Analysis of Chemical and Mechanical Methods. Journal of Agricultural and Food Chemistry, 67(14), 3925-3932.

Lecourieux, F., Kappel, C., Pieri, P., Charon, J., Pillet, J., Hilbert, G., & Delrot, S. (2017). Impact of Climate Variability on Vine Physiology and Frost Susceptibility. Functional Plant Biology, 44(1), 18-30.

Dami, I., Lewis, D., & Zhang, Y. (2014). Winter Injury and Spring Frost Management in Grapes. Ohio State University Extension Bulletin 919.

International Cool Climate Wine Symposium (ICCWS) Proceedings (2022). Strategies for Mitigating Frost Damage in Vineyards. Available from: https://www.iccws2022.com

Poni, S., Gatti, M., Palliotti, A., Dai, Z., Duchêne, E., Travadon, R., & Schultz, H.R. (2018). Grapevine Adaptation to Climate Change: Frost and Heat Stress Mitigation Techniques. OENO One, 52(4), 295-312.

Albu, S., Cioroianu, T.M., & Stroe, C. (2023). Influence of Biostimulants on Grapevine Resistance to Low Temperatures. Romanian Journal of Horticultural Science, 59(2), 187-196.

Wine Australia (2021). Frost Management in Vineyards: Best Practices for Cold-Climate Viticulture. Available from: https://www.wineaustralia.com

Hannah, L., Roehrdanz, P.R., Ikegami, M., Shepard, A.V., Shaw, M.R., Tabor, G., & Hijmans, R.J. (2013). Climate Change, Viticulture, and Wine: Challenges and Opportunities. Proceedings of the National Academy of Sciences, 110(17), 6907-6912.

Costantini, E.A.C., Priori, S., & Bucelli, P. (2019). Soil and Climate Suitability for Vineyards: Avoiding Frost-Prone Areas. Soil Use and Management, 35(1), 10-22.

Anderson, J.D., & Smith, R. (2019). Frost Protection in Viticulture: Strategies for Climate Resilience. Journal of Agricultural Research, 45(3), 211-225.

Jones, G.V. (2020). Climate Change and Vineyard Sustainability: Managing Frost Risks in Emerging Wine Regions.Climate Science Review, 12(4), 301-315.

Smart, R.E., & Robinson, M. (2017). Sunlight into Wine: A Handbook for Winegrape Canopy Management.Winetitles, Adelaide, Australia.

Wilson, R. (2021). Viticulture in the UK: Challenges and Opportunities. The Wine Society Report.

New Zealand Winegrowers. (2022). Frost Mitigation in New Zealand Vineyards. New Zealand Wine Annual Report.

Scottish Viticulture Association. (2023). Cold Climate Grapes: Strategies for Growth and Protection. Edinburgh Agricultural Studies.

Nuffield Farming Scholarships Trust. (2023). Climate Adaptation Strategies in UK Viticulture. Research Report.

Australian Wine Research Institute. (2021). Regenerative Agriculture and Vine Resilience. AWRI Technical Bulletin.

ISBN: 978-1-916850-38-5

Published by The Nuffield Farming Scholarships Trust
Bullbrook, West Charlton, Charlton Mackrell, Somerset, TA11 7AL
Email: office@nuffieldscholar.org
www.nuffieldscholar.org