Late frost protection – what to retain from the Champagne experience?

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Abstract

With the occurrence of frost, sensitive plants are susceptible to damage. One of the most counter-intuitive impacts of climate change is the increasing frequency of spring frost. Studies have warned of this problem (Inouye, 2008)[1], describing an earlier budburst due to higher temperatures during winter and the last day of frost remaining around the same date. The risk of polar jet stream destabilisation by quick warming has also been mentioned (Molitor *et al.*, 2014)[2]. Since 2016, Western European vineyards have suffered from frost damage almost every year (Rochard *et al.*, 2019)[3].

Frost occurs as either radiative frost or advective frost[4]. Radiative frost is most common during spring and can occur during anticyclonic conditions under clear skies and when wind speeds are low. Cold air will flow to lower altitudes, and an inversion layer will form with negative temperatures at plant height[5].

[1] Inouye, D. W. (2008). Effects of climate change on phenology, frost damage, and floral abundance of montane wildflowers. Ecology, 89(2), 353-362. https://doi.org/ 10.1890/06-2128.1

[2] Molitor, D., Caffarra, A., Sinigoj, P., Pertot, I., Hoffmann, L., & Junk, J. (2014). Late frost damage risk for viticulture under future climate conditions: a case study for the Luxembourgish winegrowing region. *Australian Journal of Grape and Wine Research*, *20*(1), 160-168.

[3] Rochard, J., Monamy, C., Pauthier, B., & Rocque, A. (2019). Stratégie et équipements de prévention vis-à-vis du gel de printemps et de la grêle. Perspectives en lien avec les changements climatiques, projet ADVICLIM. In *BIO Web of Conferences* (Vol. 12, p. 01012). EDP Sciences.

[4] Rochard, J., Monamy, C., Pauthier, B., & Rocque, A. (2019). Stratégie et équipements de prévention vis-à-vis du gel de printemps et de la grêle. Perspectives en lien avec les changements climatiques, projet ADVICLIM. In *BIO Web of Conferences* (Vol. 12, p. 01012). EDP Sciences.

[5] Hu, Y., Asante, E. A., Lu, Y., Mahmood, A., Buttar, N. A., & Yuan, S. (2018). Review of air disturbance technology for plant frost protection. *International Journal of Agricultural and Biological Engineering*, *11*(3), 21-28.

Advective frost is associated with a cold air mass. It is characterised by the presence of wind and generally a low relative humidity. The most dangerous advective frost events will be preceded by rain or snow[6] because of evaporation that will directly decrease temperature of buds. This additional type of frost is often called evaporation frost. Most of the time, dangerous frost events are a combination of both advective and radiative frost. Due to its northern position, the Champagne region is regularly affected by frost (Figure 1) and it therefore has extensive experience in frost protection. Since the end of the 19th century, Champagne winegrowers have tried to fight against frost with different techniques. The "Association Viticole Champenoise", and subsequently the "Comité Champagne", have conducted experiments since the beginning of the 1930's to find protection techniques to combat this scourge[7].

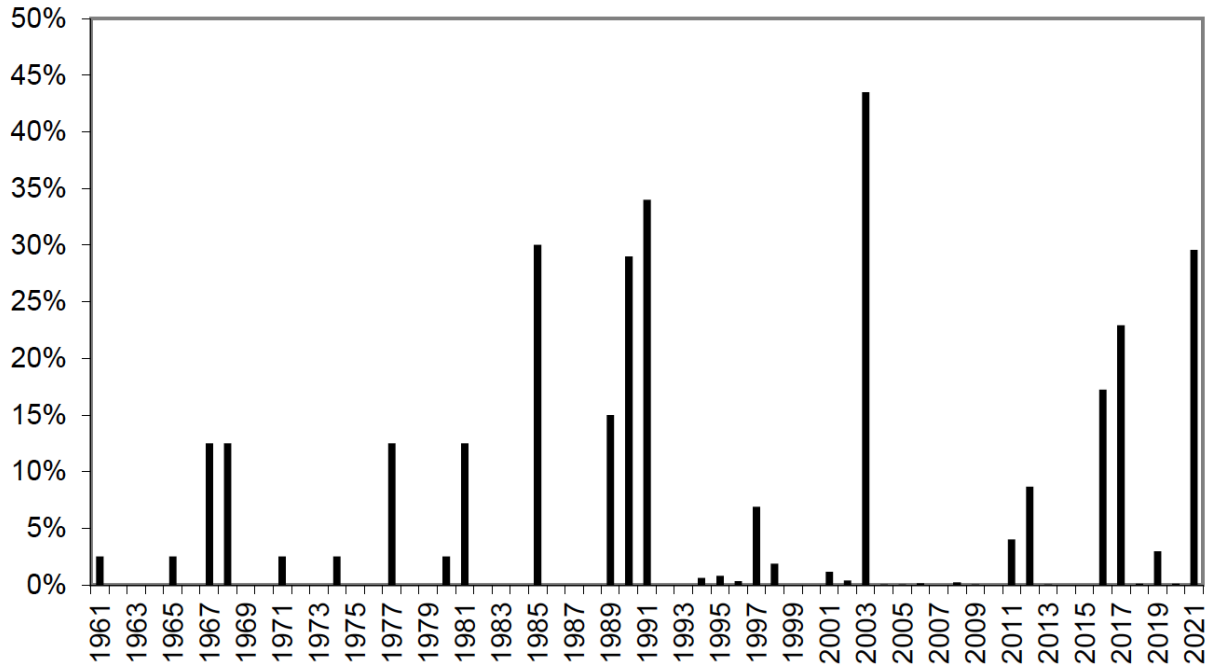


Figure 1. Annual percentage of frozen buds in the Champagne appellation.

Efficiency assessment method

To assess its efficiency, a given technique is monitored from installation to harvest. To record temperatures during a frost, one or several temperature sensors are installed in the vines depending on the technique used. Immediately after a frost event, a bud count is performed to assess the percentage of frozen buds in the control and in the protected modalities of the plots. The fertility of secondary buds depends on the grape variety; therefore, cluster counts are carried out to assess the

[6] Pauthier, B., Debuisson, S., & Descôtes, A. (2018). Comment lutter contre le gel de printemps?. *Le Vigneron champenois*, (3), 51-59.

[7] Pauthier, B., Debuisson, S., & Descôtes, A. (2018). Comment lutter contre le gel de printemps?. *Le Vigneron champenois*, (3), 51-59.

difference between the control and the protected buds. Finally, harvest weights were recorded to determine the impact on the yield.

Investment and usage cost

Not every system protects the same surface area, and the same technique can be sold at different prices depending on the seller. A market study has been carried out for different plot scales.

Sustainability

All the techniques were evaluated by applying a life cycle analysis process to determine which options to choose, replace or keep, in order to decrease the carbon footprint of frost protection.

Results

Passive protection

Passive protection begins before planting with an analysis of vineyard topography. The aim is to mitigate any risks of radiative frost which will mainly impact the lower lying areas. Knowing this, the choice of the grape variety and rootstock is essential to limit the risk of frost. In high-risk areas, it is necessary to choose a grape variety that has late budburst and that is grafted onto a rootstock that does not confer precocity to the scion.

It is also essential to avoid walls, embankments or hedges placed perpendicularly to the slope. This will limit the risk of cold air pooling.

Passive protection can also be ensured by carrying out certain vineyard management practices, such as pruning, growing cover crops or tillage. An experiment on late pruning (November vs March) performed from 1985 to 1993 in Champagne[8] delayed budburst for about 10 to 12 days depending on the variety (Pinot Noir, Chardonnay) and pruning method (Guyot simple, Chablis, Cordon de Royat). In 2021 and 2022, the same experiment was performed on Chardonnay with two dates of pruning (1 November vs 1 April) and two pruning methods (Guyot simple vs Chablis). A mean delay of 11 days was observed on Guyot simple and 8 days on Chablis. Another task linked to pruning is wrapping. For certain pruning methods (Guyot simple, Chablis), leaving the shoots unwrapped can produce a 20 to 30cm gain in height. During a radiative frost this difference can correspond to higher temperatures of 1 °C or even 2 °C at distal bud height[9].

[8] Langellier, F., & Panigai, L. (1999). Lutte contre les gelées de printemps: Nouveaux acquis. *Le Vigneron champenois*, *120*(3), 65-79.

[9] Association Viticole Champenoise. (1991). Les gelées de printemps. Hors série, *Le Vigneron champenois*.

Tillage increases the release of humidity from the soil and the temperature 40 cm above the soil can be 3 °C lower than undisturbed bare ground[10]. Given that humidity increases a bud's sensitivity to frost[11] delaying soil tillage when a frost event is forecast will limit the risk of frost.

Above soil covered by dense and high grass, temperature will be 2 °C lower than above bare ground or short grass[12]. When a frost event is forecast, mowing three to four days before the event can limit the impact of the frost without releasing humidity.

Setting up an individual stock, as Champagne has done since 2007, allows winegrowers to stock a certain amount of wine from one or several previous years for use in subsequent years. It is an effective way of maintaining quality and of buffering yield variation caused by meteorological hazards like hail or frost. Thanks to this solution, the use of frost protection methods has decreased in Champagne, thus reducing any related environmental impacts.

Active Protection

All the techniques mentioned hereafter have been tested for at least five years in Champagne.

When water freezes, energy is released in the form of heat (80 kcal/l). The principle of sprinkler frost protection is therefore to form a "wet" ice layer that is continually freezing and releasing heat into the vine tissues which remain above a lethal temperature. This method is one of the most efficient (protection up to 100 %) but requires great mastery, because starting too late will form an ice layer on the buds with a temperature under the lethal threshold. Increased monitoring is also needed to prevent pipes and sprinklers from freezing if water is directly pumped from the river. If water storage or exploration is needed, the cost can be multiplied by 3 to 4. The carbon footprint of the method is dependent on the water pump technology, but it is low, even with a petrol engine. The main issue with this method is that it requires access to a large amount of water due to its high consumption (40 m^3/h/ha). An environmental evaluation of other factors related to the method, like leaching or erosion, is in progress.

Different types of fuels can be used in burners to produce heat to maintain air temperatures above a lethal level. The efficiency of this technique is dependent on four main factors: calorific value, burner efficiency, wind speed and burner density. For example, 200 fuel oil burners per hectare are required to maintain a non-lethal temperature during a -6 °C frost event with no wind (95 %

[10] Langellier, F., & Panigai, L. (1999). Lutte contre les gelées de printemps: Nouveaux acquis. *Le Vigneron champenois*, *120*(3), 65-79.

[11] Itier, B., Flura, D., Brun, O., Luisetti, J., Gaignard, J. L., Choisy, C., & Lemoine, G. (1991). Analyse de la Gélivité des Bourgeons de Vigne. Expérimentation in situ sur le Vignoble Champenois. *Agronomie*, *11*(3), 169-174.

[12] Association Viticole Champenoise. (1991). Les gelées de printemps. Hors série, *Le Vigneron champenois*.

protection). Most French companies have stopped producing fuel oil burners and only one is still producing gas burners, the cost has therefore exploded since 2017. Other drawbacks related to the method are its very high carbon footprint (400 l/ha/h fuel oil consumption) and the polluting and harmful particles that are released into the air.

The use of candles is based on exactly the same principle as fuel burners. Paraffin is burned to produce heat and maintain air temperature above a non-lethal value. The density of candles needs to be higher than fuel burners because of their lower efficiency. To maintain temperature during a -6 °C frost event with no wind, 500 to 600 candles per hectare would be needed (90 % protection). In April 2022, the cost in France was from 10 to 13 € per candle. Considering that paraffin is derived from petroleum, the carbon footprint is not compatible with sustainable viticulture.

Since 2018, some wood pellets burners have been tested in Champagne. The principle and the efficiency of this technique are the same as for fuel oil burners. The density is also the same, with 200 burners per hectare for a frost with a temperature of about -6 °C (95 % protection). The investment is around 40,000 € per hectare. The pellet consumption is about 1 000 € per night per hectare.

Windmills rely on an inversion layer occurring during a radiative frost. Their efficiency is therefore dependent on the frost type. With a thermal inversion during a radiative frost, warm air can be only a few meters above the ground and within reach of the windmill. The goal is to mix the warm and cool air layers to maintain temperature above the lethal threshold for buds. The mean gain is about 1 °C at a 100 m distance for a fixed windmill. The gain can be enhanced by up to 3 °C with the addition of a burner. The cost is around 45,000 € for a fixed windmill without burner. The carbon footprint is dependent on the energy of the engine. The main problem for windmills is that they do not work if the inversion layer is too high or during an advective frost. The noise can also disturb any neighbours.

PEL-101-GV is an elicitor tested from 2004 to 2013 in Champagne. The principle is to increase the plant resistance to cold using a patented process. The efficiency depends on the phenological stage from zero before one leaf, to 0-50 % after one leaf for a -2.5 °C frost. The cost is about 200 € per application. The carbon footprint is the same as that of any type of spray application.

Electric heating cables have been tested in Champagne from 1992 to 2003. Experimentation with new types of cables restarted in 2017 and is still in progress. The cables are tied close to the shoots which means that in Champagne this type of protection is only possible for Guyot simple and Cordon de Royat pruning methods. The results show an efficiency of around 70 to 90 % for a -4 °C

radiative frost which can decrease to 30 % for a -8 °C advective frost. The cost is between 45,000 € and 100,000 € per hectare, including the price of an electric generator. The main problem with this type of protection is the very important power requirement (at least 200 kW/ha). The carbon footprint is dependent on the power generation method.

Technique	RF Efficiency	AF Efficiency	Cost	Carbon Footprint
Sprinkling	+++	+++	++	+
Fuels burners	+++	++	++/+++	+++
Candles	++	+/++	+++	+++
Pellets burners	+++	++	++	+
Windmills	++	0	+/++	+/++
PEL 101GV	+/0	+/0	+	+
Heating cables	++	+	+++	+/++

Table 1. Efficiency, Cost and Carbon footprint evaluation of the different frost fighting techniques. RF is for Radiative Frost, AF for Advective frost.

Conclusion

The choice of a method to fight frost must be tailored to the local conditions (e.g., topography, microclimate and frost frequency), the economic context (e.g., wine selling price and market trend) and the environmental context (e.g., noise, runoff, emissions and carbon footprint).

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