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American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2022.22011
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Review Article

Facing Spring Frost Damage in Grapevine: Recent Developments and the Role of Delayed Winter Pruning – A Review.

Stefano Poni,[1]* Paolo Sabbatini,[2] and Alberto Palliotti[3]

Author affiliations: [1]Dipartimento di Scienze delle Produzioni Vegetali Sostenibili, Università Cattolica del Sacro Cuore, Piacenza, Italy; [2]Department of Horticulture, Michigan State University, East Lansing, MI, United States; [3]Dipartimento di Scienze Agrarie, Alimentari e Ambientali, Università di Perugia, Perugia, Italy.

*Corresponding author: (stefano.poni@unicatt.it, tel:+330523599271)

Acknowledgments: The authors wish to thank Tenute Ruffino (Tuscany) and in particular Maurizio Bogoni and Barmpa Despoina Maria for allowing vineyard access and performing data collection.

Manuscript submitted Feb 9, 2022, revised April 13, 2022, accepted May 17, 2022

Abstract: In this review, we briefly discuss factors conducive to an increased spring frost risk in viticulture and provide updates on vine susceptibility to frost events and damage assessment. The core of the review, though, deals with a physiological oriented tool of prevention of the frost damage consisting in a delayed winter pruning (i.e. executed at or beyond the "wool" bud stage) aimed at postponing bud burst. The exploited principle is related to the inherent acrotony of the grapevine which would "sacrifice" the already developing apical shoots to an incurring frost, while basal nodes will be preserved as being still dormant. A survey conducted on 21 published papers confirms tha, final pruning performed not later than 2-3 unfolded leaves borne on apical shoots would achieve a bud burst delay of about 15-20 days, while yield is

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mildly affected. At times, such a delay can carry on until harvest, thus postponing fruit maturity into a cooler period of the year. Most recommended late winter pruning protocols envisage a two-step intervention. In spurred cordons, a mechanical pre-cut aimed at shortening canes at 7-8 nodes while also performing wood shredding, can be made anytime during the dormant season. Thereafter a final hand spur shortening is made at the suitable developing stage of the apical shoots. In a cane-pruned vine, previous year fruiting cane(s) can be removed any time in winter while selecting at least two canes that must be kept vertical and longer that the required spacing-dictated length. Shortening of the two canes along with horizontal positioning should take place no later than the 2-3 unfolded leaves borne on the apical end of last seasons shoots.

Key words: acrotony, bud burst, climate change, cold injury, ripening, yield

Introduction

Earlier phenology and the compression of the growing cycle in grapevines because of global warming have been widely reported (Jones et al. 2005, Van Leeuwen et al. 2019, Santos et al. 2020, Venios et al. 2020). Additionally, predictions are for longer growing seasons (Santos et al. 2020, Webb et al. 2012). Taken together, these scenarios justify the increasing need for cultural techniques that, especially in warm/hot regions, can delay key phenological stages and fruit ripening into a cooler period. Another characteristic of climate change is that the frequency and severity of weather extremes are increasing (Aghakouchak et al. 2020). Weather is “extreme” when unusually violent in nature or abnormal in its frequency of occurrence or length. According to EAA (2021), weather and climate-related extreme events encompass meteorological events (storms), hydrological events (floods, mass movements) and climatological events (heatwaves, cold waves, droughts and forest or orchard fires). In Europe, the increase of extreme events causing relevant production loss has been estimated at about

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60% over the past three decades. Ranking European countries for the number of crop failures related to extreme events (1980-2019) reports France at the top with 23,491 (50% of insured losses), Italy following with 20,735 (5% of insured losses), and Spain third with 14.679 (26% of insured losses) (COM 2021, EAA 2021). Within such context, a puzzling interaction exists between global warming and grapevine susceptibility to spring frost damage. It might be difficult to explain why, as also reported in Muffler et al. (2016) and Zohner et al. (2020), that despite a warming trend related to climate change and a steady decrease in the number of freezing days in Italy (ISPRA 2020), late spring frost is heavily impacting crop production causing significant economic losses (COM 2021, Cicogna and Tonello 2017). The warming trend has indeed been beneficial causing longer and warmer growing seasons, but has not reduced the risk of frost. In fact, frost events are not decreasing at an inverse rate with that of warming in several viticulture regions of the world (Shultze et al. 2016, De Rosa et al. 2021, Dinu et al. 2021). Bud burst is occurring earlier on average in several varieties and locations, but frost still occurs at approximately the same rate up until the frost-free date (Schultze et al. 2016). Severity and extent of a late frost damage is dependent upon several factors (e.g. altitude, flat vs sloped sites, distance of the vine from the ground, presence of windbreaks or physical barriers, proximity to and size of bodies of water, type of floor management, etc.). However, the increase of frost risk is primarily due to earlier bud burst which widens the time frame within which the probability of incurring freezing temperatures is greater (Kartschall et al. 2015) and to the fact that the frost event might also match with more advanced phenology thus increasing the risk of severe damage. Typically, in warm/hot growing areas having an average growing season temperature (April to October in the NE) varying from 17 to 24 °C (Jones et al. 2005) any frost event occurring round mid-April would easily find vegetative growth at already 5-6 expanded leaves, a phenological stage when the vine is very susceptible

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to frost damage. According to Webb et al. 2012, every degree (°C) of warming would cause a bud burst advancement of about 7-10 days, thus greatly increasing chances of frost injury. Dramatic frost events occurred 2017, 2020 and 2021 primarily in Italy, France, Germany, and Austria (COM 2021). Similar disruptive frost events happened in the eastern US: 2014 (polar vortex), 2007 (Easter freeze), 2010 (Mother's Day freeze), and 2012 (Killer frost); which accounted for an average of $250 million per year (nearly half of total market value) in insurance payments for crop loss to grape and fruit growers (www.rma.usda.gov).

These weather challenges have generated an interest toward innovative solutions for damage prevention or minimization (e.g. selective extraction of coldest air (Arias et al. 2010), usage of hydrophobic particle film and acrylic polymers (Fuller et al. 2003), electrical heating cables (Lamb 2009), vegetal oil application (Centinari et al. 2018, Herrera et al. 2018, Wang and Dami 2020). Such relatively recent approaches are often coupled with other methods of frost protection in vineyards involving wind machines, air heaters and sprinklers (Jones 2006, Davenport et al. 2008). Coverage of these methods is beyond the scope of this review and the focus will primarily be on the technique of heavily delaying winter pruning which delays bud burst and subsequent vine phenological stages until fruit ripening, thus generating a physiological approach to frost protection.

Incidence of spring frost damage in a climate change scenario

Incidence of spring frost damage in a climate change scenario is a complex relationship between a series of superimposing phenomena, including thermal length of the growing season (Trnka et al. 2011), number of frost-free days (FFD, defined as annual number of days with a minimum daily temperature above 0°C), and the advancement of the growing season triggered by the warming effect (Lavalle et al. 2009, Leolini et al. 2018). Several studies have reported a lengthening of the period between the occurrence of the last spring frost and the first autumn

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frost (Schwartz et al. 2006, Schultze and Sabbatini 2019). This has occurred in recent decades in several areas in Europe and the US and more generally in the Northern Hemisphere. However, across all of Europe, the delay in the end of the season (8.2 days in the period 1992–2008) was more significant than the advanced start of the season (3.2 days over the same time period) (Jeong et al. 2011). A somewhat related effect is a general and clear increasing length of the frost-free period in Europe between 1985 and 2014 (Figure 1). The trend is not uniformly spread over Europe though, and the highest rates of change (an extension of the frost-free period by more than 0.8 days per year) were recorded in eastern and northern Europe (EASAC 2013). An interesting regression analysis between time (1974-2008) and number of FFD reported in Lavalle et al. 2009 for four different regions/countries in Europe shows a different pattern depending upon regions. In Denmark and the highlands of the UK, a significant positive linear regression was observed with a FFD increase of about 65 and 90 days over a 35-year span, respectively, whereas in Extremadura (Spain) and Thessalia (Greece), a negative linear regression was found with a FFD reduction of about 50 and 24 days, respectively. Likely, in areas where a significant decrease in the length of the frost-free period occurred, like in southern Europe, plants are more at risk from frost damage due to delay in the last winter-spring frost (Lavalle et al. 2009). In the eastern US similar trends are also reported. Interannual variability of early season temperatures have led to large increases in frost occurrence from year to year (Schultze et al. 2016). Subfreezing temperatures occurred frequently in the months of March, April, and May. For example, the spring frosts of 2010 reduced juice grape production by 60% (Schultze et al. 2014). An abnormally warm early spring followed by a return to climate normal devastated the entire fruit crop in 2012. The spring was 3.7°C warmer than the previous thirty-year average throughout the area, featuring days as much as 20°C warmer than their climatological average (Schultze et al. 2016). Many grape growing regions

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reported accelerated phenological development only to experience devastating frosts in early April across the country. According to the United States Department of Agriculture (USDA), crop losses that year were as high as 95% for tart cherries, and 75% and 40% percent for juice and wine grapes, respectively.

The pivotal factor coming into play is how global warming is impacting the advancement of the growing season in fruit trees and grapevines. Chmielewski et al. (2004) have reported a bloom advancement of 2.3 days/10 years in several fruit trees, 2.0 days/10 years in cherry and 2.2 days/10 years in apple trees. In the grapevine, the advancement of phenology is likely one of the most consistent trends supported by historical data and projection analysis. Bud burst advancement over several decades in grape varieties grown in different environments can vary between 7 and 14 days. The advancement is driven by the increase of growing season mean temperature as +1°C advances bud burst by about 7-10 days, thus greatly increasing chances of frost injury (Fraga et al. 2012, Webb et al. 2012, Van Leeuwen et al. 2019, Santos et al. 2020, Bernáth et al. 2021, Droulia and Charalampopoulos 2021).

The general expectation is that an advanced bud burst may expose vines more frequently to spring frost, mostly because the extreme event will occur at a more advanced stage of shoot growth development when the organ is most susceptible to freezing (Fuller and Telli 1999). However, several climatological analyses carried out in different European locations to estimate spring frost risk under a warming scenario reported controversial results. The comprehensive chapter published by Kovatz et al. (2014) on impacts, adaptation and vulnerability related to climate change in Europe, when addressing the item of projected changes in climate extremes, states a general *high confidence* concerning several phenomena: a) changes in temperature extremes (toward increased number of warm days, warm nights, and heat waves); increases in extreme precipitation in Northern Europe (all seasons) and

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Continental Europe (all seasons except summer); and c) in extreme sea level events. Any other change is defined as *medium* or *low confidence* and some, like cold waves and spring frost risk projection, are not even listed. Uncertainty related to projections for spring frost risks in *Vitis vinifera* L. seems to be confirmed in several other more specific studies. Kartschall et al. (2015) calculated phenological changes and forecast frost risk for the cultivar Riesling grown in Germany using historical data (1901 to 2019) and a projected time span (2011 to 2100) under two climatic change scenarios (RCP8.5 and RCP2.6). An acceleration of all main phenology phases was found from the late 1980s, whereas projection for the period 2031-2060 modeled an acceleration of 11 ± 3 days under the RCP8.5 scenario. Within the same scenario, frost risk is expected to slightly increase over the next decades. Assessment of late frost damage risk in the French regions of Alsace, Champagne, and Burgundy throughout the twenty-first century was made using three different phenological models predicting either statistical occurrence of the last frost day and the characteristic bud burst date (Sgubin et al. 2018). Outputs showed that probability of late frost is expected to significantly increase for two out of three models, whereas the third model gave somewhat opposite results. For southwest England the risk of late spring frosts increases under many future climate projections extending until 2099 due to advancement in the timing of bud burst (Mosedale et al. 2015). However, estimates of frost risk were highly sensitive to the choice of the phenological model. A case study referred to the Swiss Rhone Valley (Sion and Aigle locations) employing 12 phenological models projected over 2021-2050 concluded that frost risk might increase or decrease depending upon location and climate change projections (Meier et al. 2018). To add even more variability to the above picture, a study conducted in Luxembourg (Molitor et al. 2014) reported that the frequency of spring frost damage in the Luxembourgish winegrowing region will decrease, but not disappear in the near (2021–2050) or far future (2069–2098) projections. The most comprehensive

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survey on changes in weather extremes for Italy has been carried out by ISPRA (2013) for the period 1961-2012. The study reported significant trends in the mean decrease of number of freezing days (-11 on average) especially from 1990. Despite this apparent decrease, several grapevine districts in Italy were hit in 2017, 2020, and 2021 by severe late spring frost events. The damage registered in Italy in 2017 and 2021 were quite variable. Moving north to south through the country, vineyards reported damages varying from 20-100%; and loss of the potential crop was estimated at about 20-25% in Lombardy, 20-30% in Emilia Romagna, 20-25% in Tuscany, and 25-35% in Puglia (Atzeni 2017). Indeed, heterogeneity in viticultural traits of Italy play a pivotal role in damage variability. These include a) wide range of cultivars showing a large variation in bud burst dates, b) different growing meso-climates which might enhance or limit susceptibility to late frost, and c) large diversity in training systems showing different susceptibility to damage mostly due to varying distance of the fruiting area from the ground. Summarizing the examples provided above, late spring frosts are a significant risk to grape production in frost-prone viticultural regions. The increase in air temperature due to climate change is likely to advance grape bud burst and exacerbate last frost events and consequent damage in the spring.

An update about grapevine spring frost susceptibility and assessment

Physiological mechanisms and methods: Physiology of the cold hardiness of the grapevine across several bud burst stages (Table 1) has been extensively reported in the literature and results are used to assess and interpret vineyard damages (Howell and Wolpert 1978, Johnson and Howell 1981, Wolpert and Howell 1986, Moncur et al. 1989, Fuller and Telli 1999). Working on Madeleine Angevine and Siegrebbe cultivars grown in the UK, Fuller and Telli (1999) showed that bud burst is accompanied by a linear increase in water content in the bud during the initial developmental stages up until *wool buds* (BBCH 05). Freezing tests, enclosing vines in chambers with progressive cooling to a minimum temperature of -4.5 °C, recorded large changes in water content of the buds from dormant (BBCH 00, water content about 40%) and *green pointing buds* (BBCH 07, water content about 83%). Bud freezing was linearly correlated with bud water content and at the mean exotherm temperature of -3.5 °C scored a damage of 10-20% until the stage BBCH 03 defined as *end of bud swelling; buds swollen, but not green* (Lorenz et al. 1995) then the damage was scored at about 80% for the BBCH 05 stage. Conclusion from Fuller and Telli (1999) was that temperature at which buds froze was not influenced by the cultivar or the acclimation treatment. This is consistent with research reported on Pinot noir where the bud development stage did not influence ice nucleation temperature (Luisetti et al. 1991).

According to Hamed et al. (2000), endogenous freezing assessed using infrared thermography on two grapevine varieties reported that freezing initiated in the cane then travelled into the buds at a speed of 0.47 cm s^{-1}. Ferguson et al. (2014) have provided extensive calibration of a model for dormant bud cold hardiness and bud break prediction in 23 *Vitis* genotypes. Most notably, budbreak occurred earlier in hardier genotypes, consistent with more rapid de-acclimation of genotypes originating from colder climates. As a paradox, conclusion was that these genotypes more vulnerable to spring frost in warmer environments.

As young developing leaves are known to be more susceptible to frost due to their higher water content (Fuller and Telli 1999) hypothesis was made that they can function as a better proxy for cultivar phenotyping against frost tolerance. Degree of frost resistance in young leaves of fifteen grape cultivars was assessed (Sun et al. 2019) showing that the super cooling point was not suitable for comparing frost resistance; instead, the most effective parameters for discrimination were T2 (freezing point) and t2 (time when temperature raises from T1, the super-cooling point, to T2). Based on such analysis, the most frost resistant varieties

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were Muscat Hamburg and Frontenac; Summer Black had an intermediate resistance; and the remaining ones were categorized as low resistant.

Another challenge in determining the frost resistance of plant tissues is choosing the method of air temperature measurement that best represents the actual temperature of the plant organ. In a commentary, Grace (2006) pointed out that plant and organ temperature is a complex interaction of absorbed radiation, wind speed, wetness, and organ shape that provide shelter or stimulate significant turbulence. However, buds are *dry* structures and incapable of an effective transpiration cooling; thus at night, when the radiant energy balance is negative (long wave energy streaming from the bud to the sky), the buds are colder than the atmosphere and the magnitude of such a difference is a strong function of wind speed (Michaletz and Johnson 2006). The issue of representativeness of air temperature measures for true organ temperature has been addressed in budding leaves of the grapevine, apricot flowers, and unripe pear fruits (Litschmann and Středa 2019). For young grapevine leaves, the highest deviations were found between the surface temperature measured with an infrared thermometer sensor and a traditional sheltered thermometer (Stevenson screen type); the latter invariably showed higher nighttime temperatures by 0.4-0.8 °C on average, with a peak of 1.5°C. Conversely, both a wet bulb thermometer (unsheltered thermometer covered with a wet cloth) and a simple unsheltered thermometer were closer to the actual organ temperature with one important distinction. While the unsheltered thermometer provided the best relationship with the temperature of the plant tissue under any condition, the wet bulb readings were affected by the relative humidity (RH) of the air. When RH registered lower than 65-70%, temperature values at night were several degrees lower than bud surface temperature. Thus, when a wet bulb type

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was used to activate a frost protection device (e.g. sprinkler irrigation), the warning could occur prematurely.

Cultural factors. Sun et al. (2018) investigated the role that soil temperature can play in regulating the response of grapevine leaves to frost. In a pot experiment where roots of Merlot seedlings were kept either in warm (~ 20°C) or cold (~ 0°C) soil and then subjected to frost treatment, severe damage to the young leaves occurred with cold soil, whereas a warm soil led to reduced frost injury. A non-targeted metabolomic analysis showed that, in the warm treatment, pathways related to citrate cycle as well as glycine, serine, and threonine were enhanced. This outcome seems to be paving the way to further applied research to understand if root distribution in soil volumes marked by different temperatures could significantly impact vine frost susceptibility. While soil/root temperature is indeed affected by a number of factors (e.g. lithological features, soil texture, water holding capacity, color, organic matter content) it is also known that root depth is quite responsive to under trellis floor management (Centinari et al. 2016, Klodd et al. 2016). Any practice which might favor a shallower root system due to an undisturbed soil surface (e.g. mulching, herbicides) might help mitigate consequences of a frost event (Guerra and Steenwerth 2011). Moreover, clean cultivated soil absorbs and then re-radiates more heat, providing frost risk mitigation.

However, any condition that will favor in spring soil warming hence root metabolism is also expected to lead to a more advanced bud burst increasing the risk of frost damage, in that potentially counteracting beneficial effects discussed above. Though, such hypothesis is still uncertain: work done on potted Shiraz grapevines exposed to two different soil temperatures (13 °C and 23 °C) showed no effects on the time of bud burst, anthesis and the number of flowers per inflorescence (Field et al. 2020).

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New digital technologies: The recent efforts in precision viticulture (Matese and Di Gennaro 2015, Ozdemir et al. 2017, Giovos et al. 2021) have also provided interesting approaches to monitor and detect spring frost damage in vineyards by remote sensing. Some vegetation indices (VI) such as Red-Edge 7, NIR, EVI, MTVI1 and CARI calculated from medium resolution Sentinel-2 acquired data, proved to be effective in estimating lower light reflectance in pergola trained vineyards after severe frost damage when compared to undamaged vineyards (Cogato et al. 2020). Moreover, the same VI bands provided evidence of recovery to full canopy size about 40 days after the frost event. It is indeed encouraging that, likely due to the frequent revisit time of Sentinel-2 constellation, generating robust time-series for spatial and temporal analyses can be used to assess the impact of late frost in vineyards. Indeed, the pergola trellis type, forming an almost horizontal continuous green cover, likely facilitates performance of indices calculated from low or medium spatial resolutions. However, robustness of this method will require either association with yield or grape quality data as well as extension to vertically shoot positioned trellises showing a typical discontinuous green cover.

An even broader application is a practical remote sensing monitoring framework for late frost damage in wine grapes based on *in-situ* measurements and multi-source satellite data (Li et al. 2021). This framework provides estimates of the daily minimum air temperature (T_{min}) with the spatial resolution of 100 m and was tested to map the severe late frost damages that occurred in April 2020 in northwest China. About 41% of the vineyards suffered severe frost damage, and the total affected area was about 16.381 ha. The results of late frost damage obtained by estimating the T_{min} agreed with the statistics of the Agricultural Meteorological Disaster Department. Using high spatial resolution analyses of minimum night-time temperatures to explore the impact of current and future frost risk is another active research field. Multivariate Adaptive Regression Splines (MARS) were used to model high resolution (30 m grid) minimum temperatures in the Yarra Valley wine region in southeastern Australia (Gobbett et al. 2020). Modelling the accuracy for prediction of minimum night temperature records was good ($R^2 = 0.68$) whereas all the future climate scenarios project down-elevation movement of the frost line of between 10 m and 30 m depending on scenarios. A similar approach has been used by Webb et al. (2018), who in a study on viticulture suitability in Tasmania, wanted to identify land areas prone to damaging spring and late season frost. The main outcomes were that risk classifications for the -1°C threshold were appropriate for this study and that classifications of suitable, moderately suitable, and unsuitable defined as to <1 frost every 10 years (<10%), >1/10 to 1 frost every 2 years (10–50%), and >1 frost every 2 years (>50%) for temperature values ≤−1°C was found to correlate with viticulture suitability and in agreement with grower expectations.

Technical protocols for application of delayed winter pruning

Using late winter pruning, close to or after the time of normal bud burst, to postpone vegetative growth commencement is not either a brand new or revolutionary concept in viticulture. Quite old work from Pouget (1966) and subsequently from Wample (1994) had already clarified main traits of temperature driven dormancy breaking mechanisms in the grapevine bud (Pouget 1966) and that different mid-winter pruning dates, albeit spanning from November until March (Northern Hemisphere) were ineffective at altering bud burst response (Wample 1994). According to the literature search provided in the present review paper, pioneer studies hypothesizing that a purposely delayed winter pruning could have achieved a consistent bud burst delay to be used as a prevention tool in areas at high risk of spring frost were those by Friend and Trough (2007) and by Friend et al. (2011). Afterwards, several other

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papers have followed to cover still unknown or poorly studied characteristics of the technique and among them: i) seasonal variation in canopy physiology and efficiency; ii) impact on yield components and return crop next year; iii) chances that the initial growing cycle postponement can carry until ripening and iv) consequence on grape composition and wine styles. Before addressing these topics, the two following sub-paragraphs will describe current best practice when a delayed winter pruning is going to be applied on either spur pruned or cane pruned vines.

Spur pruning

As shown in Figure 2A, once other conditions are similar (e.g. distance of the productive cane or cordon from the soil, bud load per meter of canopy length, etc.) susceptibility to spring frost damage of spur-pruned cordon vines is usually higher than that observed in a cane-pruned system (Figure 2B). The reason is related to the different pruning cuts, where the short spur with the typical *two-count node* will have a reduced level of acrotony compared to a long cane with 8-10 buds; and consequently, will have uniform sprouting which is more conducive to severe frost damage (Daskalakis and Biniari 2019, Ezzili and Bejaoui 2001, Intrieri and Poni 2000, Lavee and May 1997). In a situation like the one in Figure 2A, any residual crop to be harvested in the current season is left to the degree of fruitfulness of any shoot from either latent, base, and secondary buds which is known to be much lower than the primary buds.

The working protocol applied in most of the studies performed to assess the effectiveness of highly delayed winter pruning strategies in spur-pruned cordons is shown in Figure 3. The operation can be performed in two steps or just in a single passage. The two-step procedure envisages a mechanical pre-pruning that might be executed anytime in the dormant season using an over-row rotating disk machine that, differently from a cutter bar machine, is able to easily avoid posts and rigid obstacles along the row while the cutting distance from the cordon

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is regulated to leave not less than 7-8 nodes per cane (Figure 3A). Moreover, pruning machines employing rotating disks can perform an on-the-go cane chopping and shredding, greatly facilitating any subsequent hand operation. Thereafter, final shortening to the required spur length (Figure 3B) is quickly performed by hand when, on average, 2-3 unfolded leaves are formed on the apical buds of the canes. Depending upon vine vigor, lateral canes might be present on the apical portion of last season's shoots. While their vigor is expected not to be very high as the mechanical pre-pruning removes most of the apical nodes and, with them, vigorous laterals developed after shoot trimming the previous season, their presence exert some control on the development of the subtending nodes (Pellegrino et al. 2020). Therefore, they should be the main target to observe when visual scouting is performed after bud burst to assess if the 2-3 unfolded leaf stage has been reached.

Based on working time needed to manage a fully or partially mechanized VSP trellis (Intrieri and Poni 1995) combining winter mechanical pre-pruning with a late hand finishing will lead to an estimated number of working hours of about 50-60/ha (10-15 hours for the mechanical hedging and 40-45 for the subsequent follow up depending upon cane number per vine and degree of residual cane detachment) which seems to be even lower that the workload needed to manage one-step hand pruning in VSPs of comparable vigor (70-90 hours/ha).

Cane pruning

Due to factors related to the apical dominance exerted by apical buds on a horizontally positioned cane (Intrieri and Poni 2000), susceptibility to late frost damage of cane-pruned vines is usually milder than that recorded on spur-pruned cordon training systems. The staggered bud burst occurring along horizontal canes (Figure 2B) allows basal and median nodes to be at a delayed growth stage when the freezing event takes place, limiting damage. However, applying a delayed winter pruning on a long cane training system (e.g. Guyot,

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Pendelbogen) is slightly more cumbersome and risky than acting on a spur-pruned training system with a permanent cordon. If the successful two-stage pruning previously described for a spur cordon needs to be replicated, then a cane-pruned system should receive a preliminary pruning adjustment in the winter (i.e. past year fruiting cane separated from the 1-2 canes selected for renewal) and the final pruning will then pertain to the selected cane(s). However, this approach was tested on cane-pruned Pinot noir grapevines and resulted in mild effects on vine phenology and overall vine performance (Gatti et al. 2018). Conversely, when all pruning operations were postponed at a stage of about 2-3 unfolded leaves on the distal portion of the unpruned canes, a delay in bud burst of 18 days (data pooled over three years) was obtained when compared to the standard winter pruning. However, the one-time pruning method is unlikely to be favored by growers for a number of reasons: i) postponing and performing in one step the quite complex cane pruning method will necessitate access to skilled hand labor within a narrow time window; ii) an intervention made on the whole canopy when bud burst has already initiated on the apical part of the canes will unavoidably slow down the operational times and potentially damage the swollen buds or initially developed shoots; and iii) a psychological barrier might exist against the idea of operating so late in a still untouched canopy. Therefore, a good compromise needs to be found between the one-step and two-step procedures giving preference to the latter. In lack of previous on-site experiences, a reasonable starting point is the one proposed in Figure 4 where, upon the first passage (A) a past-year cane is removed and at least two vertical long canes are retained. Final pruning (B, B') will consist of shortening the two canes to the length that will allow them to maintain mostly dormant nodes (B) and simultaneously fill the spacing on the wire (B'). Although specific research on the subject is still missing, chances to induce a significant bud burst delay on median and basal nodes to be retained, are maximized if: i) retained canes are as close to vertical as possible, as

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this position enhances the effects of acrotony; and ii) retained canes are longer than the ones retained for production, dictated by the intra-row vine spacing. When such requirements are overlooked, probabilities to induce a bud burst delay decrease significantly. For example, when short shoot trimming is performed during the growing season, optimal cane length is often non available at the time of cane selection during winter pruning, and this might strongly interfere with technique effectiveness. Although figure 2B suggests that the horizontal cane positioning still obey to the principle of acrotony, indeed the inhibition towards the basal buds is weaker and late pruning efficacy undermined. Trought et al. (2011) investigated the effects of different cane-pruning dates on Sauvignon blanc with the last treatment being performed just prior to bud burst, therefore without any active vegetation under course. Nevertheless, the last pruning dates did postpone bud burst by about 5 days when compared to the winter pruning dates, a delay that was recovered by the time of bloom.

Effects of delayed winter pruning on seasonal phenology and vine performance

Bud burst response

Published research, arranged according to country, cultivar, pruning type and timing, bud burst time, yield response and ripening delay as compared to standard winter pruning are summarized in Table 2. A literature review was performed to identify works published in peer-reviewed scientific journals and conference proceedings that focused on the topic of late winter pruning on the grapevine. Main criteria for data curation were the inclusion of research that within the definition of *late pruning* there was at least one treatment where pruning was applied not earlier than the swollen bud stage. Out of 21 published papers referring to an array of cultivars and wine regions, mostly focusing on spur pruning, late winter pruning was carried out anywhere between the two extremes of swollen buds and 7-8 unfolded leaves.

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It is hypothesized that the delay in basal bud development associated with delayed pruning is related to correlative inhibition, as suppression of the growth of the basal nodes occurs when longer canes with additional buds are left at pruning time (Howell and Wolpert 1978). This phenomenon is the expression of shoots growing basipetally along a grapevine cane and becoming stronger with increasing cane length and position tending to become vertical (Bangerth 1989, Lavee and May 1997). These principles find a robust confirmation from the list of the reviewed works as, when compared to a control pruning performed at full vine dormancy, any *late* winter pruning has generated a bud burst delay varying from 5 to 56 days (Table 2). Such delays in vine growth greatly increase chances to avoid or limit frost damage: the wider the time window between control and late pruned treatments, the higher the probability that a frost event occurring within this period might hit the already developing apical shoots while the basal nodes are still dormant (Figure 5). It is noteworthy that the contribution by Petrie et al. (2017) is the only one to refer to a sprawling canopy, and while many of the canes remained in a horizontal position, few of the basal buds had burst when the delayed pruning occurred. Indeed, shifting from a warm to a cool climate, the impact of the delayed bud burst can be different and, for instance, it could also result in a significantly delayed ripening. This calls for more work to be carried out in such regions, especially to check if and how the recovery mechanisms which, in a warm climate, often allows progressive depletion of the initial delay (Gatti et al., 2016) come also into play.

The inherent difficulty of these studies is that data validation which might be provided by occurrence of a significant frost event within the trial duration is, for obvious reasons, truly unpredictable. However, such a situation occurred in the two-year trial on Lemberger (Persico et al. 2021) where, in 2019, a freezing event occurred on 29 April, when the phenological stage of the control averaged between E-L 3 and 4, *woolly buds* and *green leaf tips visible*,

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respectively. In 2019, late-pruned vines (1 May) had 61% greater yield than control vines, reflecting differences in shoot freeze damage between the two treatments. Moreover, final grape quality was not affected. Another suitable example where effects of late winter pruning in the presence of a significant frost event is reported in Friend at al. (2011) when, in their Chardonnay trial in New Zealand, on 25-26 September 2000, a radiation frost occurred with minimum night temperature reaching -1.7°C, causing damage to a portion of the developing buds which was then quantified at 33% killed primary shoots. Conversely, in the late pruning treatments, killing of the primary shoots was limited to no more than 3%. Then albeit on a more observational basis in a mature Sangiovese vineyard in Tuscany, Barmpa et al. (2021) verified effectiveness of late pruning over a severe frost event which occurred between 6-8 April 2021 (Figure 6). Cane shortening to required spur length was performed on 22-23 April also including an intermediate treatment where, after the mechanical pre-pruning done previous December, cane trimming was quickly performed in January 2021 to retain only one cane per spur. With a frost damage of about 90% primary shoots killed leading to a final cluster number and yield of 7.6 and 1.51 kg per vine, the recommended two-step late pruning maintained at harvest 15.2 clusters and 3.10 kg/vine, whereas the three-step approach led to 11.5 clusters and 2.34 kg/vine (Barmpa et al. 2021).

Yield response

The yield response to the phenological stage at which winter pruning is performed seems quite straightforward: a low to moderate yield limitation is found when pruning time does not trespass the 2-3 unfolded leaves, whereas pruning performed at a much later stage can very severely impair yield reaching >50% reduction as compared to standard pruning (Frioni et al. 2016, Gatti et al. 2016, Petrie et al. 2017, Silvestroni et al. 2018, Allegro et al. 2019). Hypothesis of increasing yield limitation occurring with later interventions has been first

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tackled in Gatti et al. (2016) where the latest treatment (>7-8 unfolded leaves) caused a 92% yield reduction related to a very low cluster number. The mechanism involved is hypothesized as a severe source limitation imposed with the very late pruning causing carbon starvation to the developing inflorescences which in large majority would deviate into a tendril differentiation (Yang and Hori 1979). The same paper also suggests that on a 1 m spur-pruned cordon with a 8-10 node bud load, to avoid a major yield limitation, removed leaf area per vine should not exceed 0.2-0.3 m^2.

Reading through case studies reported in Table 2 suggests that although a cultivar-dependent yield reduction is an important factor to consider, a distinct outlier is the work by Friend and Trought (2007) who found in a Merlot vineyard sited in New Zealand a spectacular yield increase for a winter pruning delayed until the development of about 5 cm long shoots (~ 2 unfolded leaves). While in literature we have some evidence that a progressive shift of winter pruning towards a time closer to bud burst is conducive to a slight yield increase (Coombe 1964), results reported by Friend and Trought (2007) highlight a quite special case as it envisages in the latest pruning a significant increase in the proportion of large, seeded berries and a drastic reduction in smaller and shot berries. This study was conducted on the east coast of New Zealand where sudden changes in temperature (10 °C change in the space of 20 mins), even as late as Nov/Dec (flowering time) are possible favoring the setting of a high fraction of seedless lightweight berries. Conversely, remaining cases where yield showed sometimes a remarkable increase vs the standard winter pruning (Friend et al. 2011, Barmpa et al. 2021, Persico et al. 2021) all pertain to a late frost event occurring before the hand finishing was performed. Not surprisingly, in all cases, such yield preservation occurred without impacting fruit quality at harvest.

Carrying delay until harvest?

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Chances to carry postponement of the growth and development cycle of the grapevines obtained with late winter pruning until harvest is primarily a function of the magnitude of the delay in spring shoot development which, as previously shown, may vary from a few days (Buesa et al. 2021) to more than 50 days (Zheng et al. 2017, Silvestroni et al. 2018, Allegro et al. 2019). Such a large variation in the postponement of the start of bud burst is related to several factors including: i) the phenological stage, hence advancement of growth, when the pruning is performed (usually the later the pruning the larger the bud burst delay); ii) seasonal conditions characterizing the post-pruning phase and differences in crop level which might hinder late season growth; and iii) length and position of the unpruned canes which might affect the number of burst nodes at the time of pruning as well as the amount of removed leaf area.

Among those papers reporting analytical assessment of key phenological stages following delayed winter pruning (Gatti et al. 2016, Frioni et al. 2016, Gatti et al, 2018, Silvestroni et al. 2018), except for Petrie et al. (2017) likely due to the specific canopy type utilized in the experiment (sprawl), a general erosion during the season of the maximum delay registered at bud burst is quite clear. Physiological bases underlying this behavior are not easy to disentangle as the matter of discussion is about a canopy starting to develop over a month later than usual where leaf formation, growth, and senescence as well as all stages of berry development take place under different environmental conditions and the dynamic of the source-to-sink balance is deeply altered.

Methodologically speaking, due to the complexity of the interactions involved, following the seasonal canopy changes upon a severely delayed winter pruning vs standard winter pruning is of utmost difficulty. However, Gatti et al. (2016), working on potted vines, undertook the challenge and, using a whole-canopy gas exchange system (Poni et al. 2014)

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tracked, from bud burst until almost leaf shedding, the net CO_2 exchange rate (NCER) of canopies subjected to either late (2-3 unfolded leaves hereafter shortened as LWP) or very late (7-8 unfolded leaves) winter pruning as compared to standard winter pruning (SWP). LWP achieved a 17-day delay in bud burst that was progressively filled along the season and harvest threshold set at a total soluble solids (TSS) of 20 °Brix was reached 3 days before SWP. Three main mechanisms contributed to such efficient compensation: i) higher canopy efficiency as shorter time needed to reach maximum NCER/leaf area (22 days vs 34 in SWP); ii) highest maximum NCER/leaf area (+37% as compared to SWP); and iii) higher NCER/leaf area rates from veraison to end of season. As a result, seasonal cumulated carbon in LWP was 17% higher than SWP. In most cases though, a significant delay in grape maturity was maintained either as an estimated number of days needed to reach the same maturity level of the control vines or, in case of a single harvest date, as ripening variables statistically differed among the imposed pruning dates. A quite frequent trait within the overall delayed ripening was that technological maturity assessed as sugar-to-acid ratio almost invariably confirmed slower sugar accumulation paralleled with better acid retention and improved phenolic maturity as a consequence of retarded winter pruning.

To name a few of the most significant outcomes, Allegro et al. (2020) reported in Merlot that late winter pruning carried out at three unfolded leaves secured at harvest higher TA and anthocyanins-to-sugar ratios than standard pruning. Similarly, Petrie et al., 2017 for pruning performed on Shiraz and Cabernet Sauvignon between E-L 2 and E-L 15 found an increased anthocyanin: TSS ratio for a sugar concentration higher than 13.5 Baumé. Palliotti et al (2017) and Silvestroni et al (2018) working on Sangiovese and Gatti et al. (2018) focusing on cane-pruned Pinot noir arrived at the consistent common scenario of a significantly delayed technological maturity at harvest (i.e. lower TSS and higher TA), unaffected total anthocyanins and improved phenolics. An even more consistent outcome is shared by Frioni et al. (2016), Moran et al. (2017) and Zheng et al. (2017) who, despite working under largely different conditions and cultivars, found that delayed sugar accumulation was associated with an increase of total anthocyanins and phenolics at harvest.

The above results link to the decoupling of anthocyanins and sugar accumulation that is a main challenge under a global warming scenario; especially in warm/hot regions, rate of sugar accumulation should be reduced while accumulation of phenolic components should remain quite insensitive or even be improved. Late winter pruning enters with full right into the array of techniques which have been already addressed and validated for such challenges (Sadras et al. 2012, Sadras and Moran 2012, Palliotti et al. 2014, Poni et al. 2018, 2020, Gutiérrez-Gamboa et al. 2021). However, an explanation for this decoupling potential of a late winter pruning technique needs to be provided. Based on evidence that anthocyanin synthesis and degradation is, respectively, inhibited and enhanced at berry temperature exceeding 35°C (Mori et al. 2007); the most likely hypothesis is that once the delayed pruning can shift onset of veraison into a cooler period, berry pigmentation is consequently enhanced. Recent work conducted on Shiraz (Moran et al. 2019, 2021) on the interaction between timing of winter pruning and elevated temperature has led to the conclusion that late pruning maintained the anthocyanin-to-sugar ratio, which decreased with heating in two seasons and, most importantly, wine color density, concentration of anthocyanins and phenolics correlated negatively with daily mean temperature in a short window (2 weeks) immediately after veraison. Other effects cannot be ruled out though. In a trial on Merlot, Allegro et al (2020) found that late winter pruning treatments significantly increased the skin-to-pulp ratio at harvest; if cell skin formation takes place within 4-5 weeks after flowering (Coombe and McCarthy 2000) the process can benefit from a higher rate of cell division allowed by the

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postponement of the first stage of berry growth into a warmer period. However, the proposed mechanisms seem to have some important deviation such as that reported in Petrie et al. (2017) where the latest winter pruning applied on Shiraz at E-L 15 and on Cabernet Sauvignon at E-L 11, despite a significant yield reduction, did not result, in the highest anthocyanins: TSS ratio. Thus, the decoupling effect of the late winter pruning strategy risks being spoiled when a very late timing of intervention (i.e. later than 3-4 unfolded leaves) leads to a prolonged source limitation and carbon deficit (Gatti et al. 2016) which might ultimately impair color accumulation. As reported in Bobeica et al. (2015) and, more recently in Zhu et al. (2019) using Sangiovese and Cabernet Sauvignon vines, a reduced leaf area-to-yield ratio (i.e. 0.33 m^2/kg in source-limited vines vs. 1.15 m^2/kg in control vines) decreased total anthocyanin concentration by 84.3% as compared to the non-source-limited control, whereas it decreased sugar concentration only by 27.1%.

It is of any evidence that the sugar/color decoupling issue assumes quite different traits in a cool climate viticulture where the most desirable outcome is having the largest bud burst delay which will not severely curtail yield and impede achievement of the desirable ripening. However, some light can also be shed onto such scenario: while previous work conducted in cool climate regions (Dami and Beam 2004, Loseke et al. 2015, Wang and Dami 2020) already demonstrated that the use of bud-break delaying products caused no effects on grape composition at harvest and on wine chemistry provided that cycle postponement did not exceed 10-14 days, when a similar delay was induced through late winter pruning (Persico et al. 2021) wine chemistry was not affected as well as carbohydrate storage or bud free tolerance in the following dormant season.

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Conclusions and future directions

More advanced grapevine phenology observed on a worldwide basis has consistently led to an aggravation of damage and related economic losses due to spring frost events in viticulture. Such worsening is not quite related to an increase in the frequency of the freezing events, but rather to the more advanced bud and shoot growth stage which significantly increase the probability to incur severe damage. These events also show a fairly new trait in that they might easily occur in *warm* areas which, traditionally, have been almost exempted from such fatality (i.e. several wine districts in Central and Southern Italy).

The above scenario has increased the overall concern about late frost damage and has stimulated some new approaches for prevention and damage mitigation. In this review we have concentrated our efforts on a “physiological based” solution consisting of a moderately delayed winter pruning. The principle is both simple and effective. Extra apical buds are retained on canes before final shortening to the pruning length required by the training system. Published research suggests that, to avoid a significant yield decrease, the late pruning should be done when apical shoot development does not exceed the 2-3 unfolded leaves, i.e. about 5 cm in length. At the same time, this intervention might postpone bud burst by 15-20 days in the basal or subtending nodes, therefore greatly increasing the likelihood of avoiding or limiting frost consequences. Indeed, the technique implies adjustments especially in terms of the winter pruning calendar as well as training of the working crew. In vineyards of medium to large size and where the postponement of the winter pruning task does not seem realistic, an alternative strategy would be to identify, based on experience and historical weather data, areas at higher risk of spring frost, and concentrate efforts on those. In spur pruning cordons, mechanical pre-pruning executed in winter with an over-row disk machine followed by a rather fast manual shortening to required spur length is mostly recommended.

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Future directions of the presented technique must be part of a broader strategy aimed at improving risk assessment and prevention of damage due to spring frost in vineyards. A desirable development would be to carry out additional work in cool climate areas to balance the knowledge gap nowadays existing towards work done in warm/hot regions. On a more operational basis, the best compromise between limitations imposed by the short time window for hand finishing and the need to carry out the technique on a fairly high surface still needs fine tuning. Indeed, while spur pruning seems more suited than cane pruning, a quite advanced frontier would be figuring out a single mechanical late intervention performing a short pruning in a previously untouched canopy.

The same future directions, though, should strategically include the delayed winter pruning approach into an action plan which should be applied, pre and post planting, in vineyards deemed at high risk for frost damage. The same strategy will have to take into account and incorporate the followings: i) reconsider at planting and during vine training choices related to cordon and clusters distance from the ground; ii) adapt floor management to maximize heat absorption during the day and re-radiate more heat during the night and early morning hours; iii) update current anti-frost irrigation systems using micro-dripper mounted on top of each post and able to nebulize water on a narrow strip along the row where organs to be protected are located.

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Table 1 Critical temperatures of Pinot noir and Concord at different phenological stages. CT is the temperature at which plant tissues are damaged and expressed as CT50, corresponding to 50% level of damage.

	Pinot noir*		**Concord****
Phenological stage	No injury	CT_{50}	CT_{50}
Bud swell	-1.0	-3.4	-3.5
Bud burst	-1.0	-2.2	-3.1
1-leaf (unfolded) stage	-1.0	-2.0	-
2-leaf (unfolded) stage	-1.0	-1.7	-
4-leaf (unfolded) stage	-0.6	-1.2	-

*Sugar D, Gold R, Lombard P. Gardea A. 2003. Strategies for frost protection. In Oregon Viticulture. E.W. Hellman (Ed.) Oregon State University Press. Corvallis, Oregon.

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Table 2 Synoptic information from research papers on the impact of late winter pruning (LWP) strategies on growth, yield and fruit quality of grapevine. C = control.

Country/cultivar	Pruning type/growing condition	Stage of LWP[a]	Effects on bud burst	Yield response [b]	Ripening delay[c]	Reference
Italy/Pinot noir	Cane/field	~ 10 cm	9-23 day delay	-35%	< TSS, pH, > TA, tartrate, malate, phenolics	Gatti et al. (2018)
Australia/Cabernet S. and Shiraz	Spur/field	2/3 and 7/8 unfolded	~ 25 day delay	-10 and -55%	3 weeks – Shiraz; 2 weeks Cabernet S.	Petrie et al. (2017)
Italy/Sangiovese	Spur/field	10 and 20 cm	24-29 day delay	-22 and -43%	< TSS, pH, > TA, phenolics	Palliotti et al. (2017)
Australia/Shiraz	Spur/field	2/3 unfolded	14-28 day delay	not reported	> anthocyanins, phenolics, wine fruit profile, body intensity	Moran et al. (2018)
Italy/Sangiovese	Spur/field	4/5 unfolded	N/A	-55%	< TSS; > TA, anthocyanins, phenolics	Frioni et al. (2016)
Australia/shiraz	Spur/field	2/3 unfolded	14-28 day delay	unchanged	< TSS; > anthocyanins and phenolics	Moran et al (2017)
Spain/Maturana tinta	Spur/field	Visible inflorescences	10-54 day delay	unchanged	< TSS; > TA, anthocyanins, phenolics	Zheng et al. (2017)
New Zealand/Merlot	Spur/field	~ 5 cm	24-56 day delay	+63 to 93%	< TSS; > TA,	Friend and Trought (2007)
Italy/Sangiovese	Spur/potted	2/3 and 6/8 unfolded	17 and 31 day delay	-28% and -92%	> TSS; anthocyanins and phenolics	Gatti et al. (2016)
Italy/Sangiovese	Spur/field	3/4 and 7/8 unfolded	30-47 day delay	-34% and – 62%	3 to 9 days delay for TSS of 20 °Brix	Silvestroni et al. (2018)
Italy/Merlot	Spur/field	3/4 and 7/8 unfolded	24-56 day delay	-40% and -71%	<TSS, pH; > TA	Allegro et al. (2020)
Spain/Bobal and Tempranillo	Spur/field	BBCH 6-9	15-20 day delay	-10%	> TA:TSS and > anthocyanins-to-TSS ratio	Buesa et al. (2021)
Brasil/Chardonnay	Spur/field	7, 14 and 21 days after C pruning (25 August)	N/A	0 to -58%	Variable according to pruning time	Brighenti at al. (2017)
USA/ Lemberger and Riesling	Spur/field	EL = 7-9d	10-11 day delay	+61% to +36%	Negligible	Persico et al. (2021)
Italy/Pinot noir	Spur/field	2/3 unfolded	11 day delay	-5% to -47%	< TSS; > TA,	Frioni et al. (2018)
Argentina/Malbec	Spur/field	2-3 unfolded and 8 unfolded	15-29 day delay	-17% and -16%	Mild effects	Morgani et al.(2022)

New Zealand/Chardonnay	Spur/field	21 and 41 days after C pruning (25 July)	N/A	+38%	N/A	Friend et al. (2011)
Australia/Cabernet S.	Spur/field	48 days after C pruning (5 July)	~5 day delay	N/A	< TSS	Martin and Dunn (2011)
Australia/Zante Currant	Spur/field	~ 5cm	N/A	Reduced 1st season; unchanged 2nd season	N/A	El-Zeftawi and West (1970)
US/Perlette	Spur/field	1, 2 and 3 weeks post budbreak	N/A	Reduced	N/A	Jensen and Dokoozlian (1991)
Italy/Sangiovese	Spur/field	2-3 unfolded leaves	~15-20 day delay	+53 and +100%	Unchanged	Despoina et al. (2021)

[a] LWP = Late Winter Pruning, reported as length (cm) or number of unfolded leaves or phenological stage recorded on apical nodes of non-pruned or pre-pruned canes. When indicators are missing, the data are expressed as number of days after control (C) winter pruning.

[b] Reported as variation (%) from the standard winter pruning (control).

[c] Reported as number of days to reach the level of fruit maturity of the control treatment or variables showing significant delays and or changes vs control.

[d] Eichhorn-Lorenz scale. 7 = first leaf separated from shoot stem; 9 = two-to-three leaves separated.

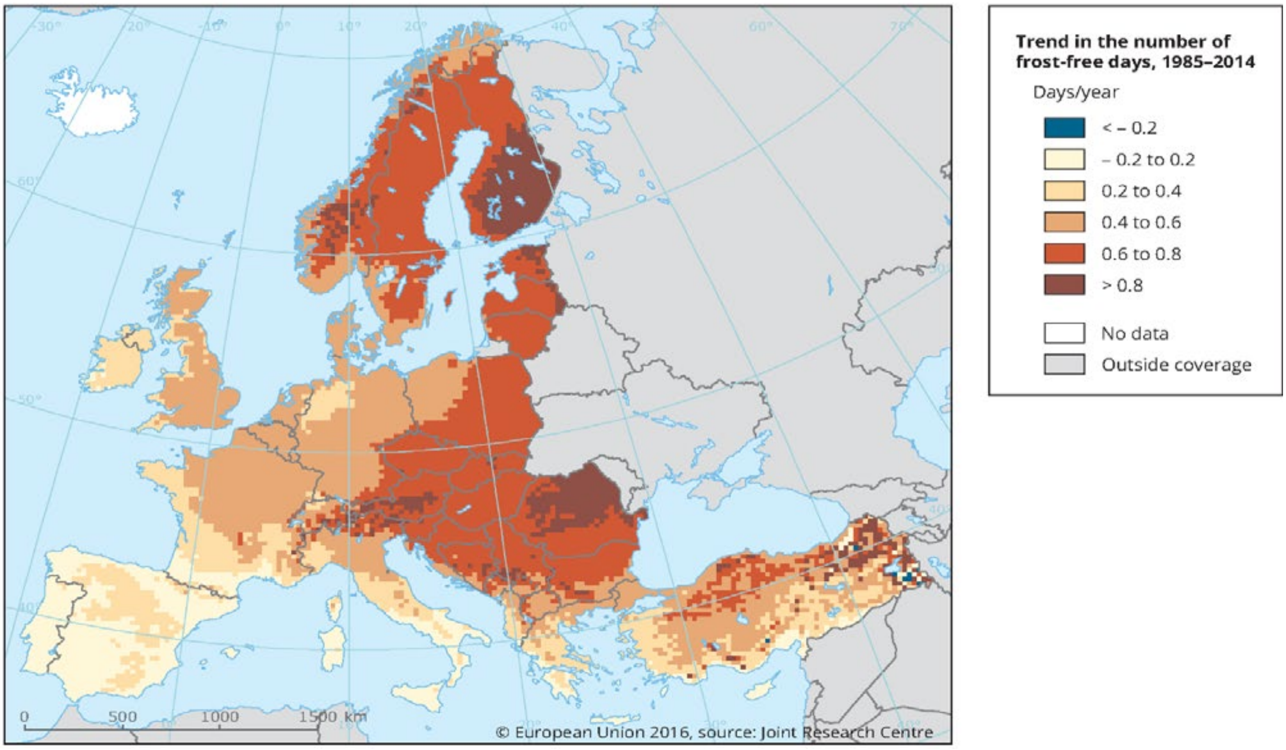

Figure 1 Annual rate of change of frost-free days representing the trend coefficient for long-term changes in the annual number of days with a minimum daily temperature above 0 °C. For example, a value of 1 indicates that the number of frost-free days has increased on average by 1 day per year in last 30 years (period 1985-2014). The analysis is based on the JRC-MARS gridded meteorological data at 25 km resolution. Data source: http://agri4cast.jrc.ec.europa.eu/DataPortal/Index.aspx?o=d in https://www.eea.europa.eu/data-and-maps/figures/rate-of-change-of-frost-1.

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Figure 2 Close view of a spurred cordon (A) and a cane pruned Sauvignon Blanc vine (B) after a very severe frost event in Central Italy (spring 2017). Notably, shoots produced on the spurs reported 100% mortality (A), whereas in the cane pruned system, only apical shoots were killed whereas the first 4-5 basal nodes, as being still dormant, avoided the freezing injury.

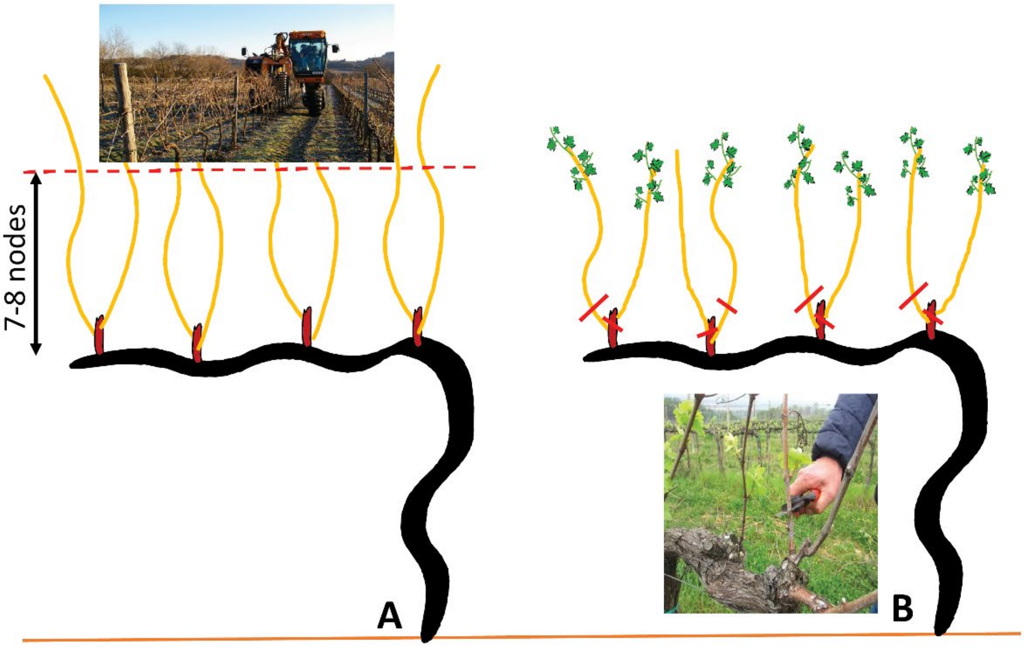

Figure 3 Diagram of the two pruning steps recommended for delayed winter pruning in a spur pruning cordon. In (A) mechanical pre-pruning is performed anytime during the dormant the season to leave 7-8 node canes and concurrently performing wood shredding. In (B), at the optimal stage of 2-3 unfolded leaves developed in the apical part of the pre-pruned canes, manual shortening to the desired spur length is executed.

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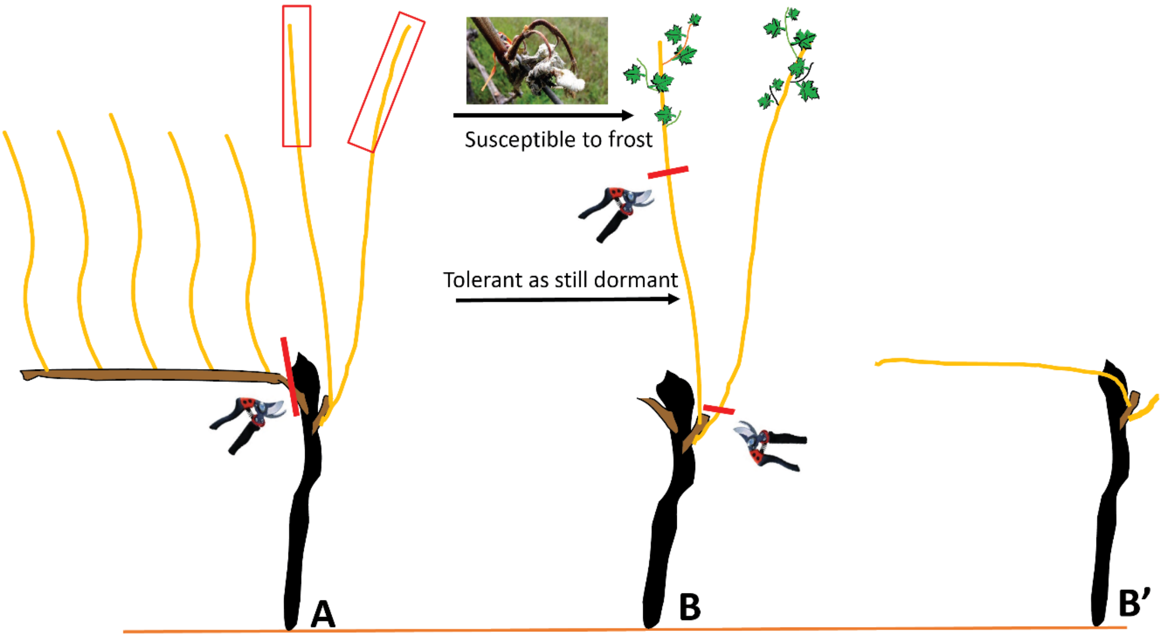

Figure 4 Diagram of the pruning steps recommended for delayed winter pruning in a cane pruned training system (i.e. Guyot type). In (A) first run of hand pruning is performed anytime during the dormant season to remove the previous year production cane and to select at least two long canes maintaining them in nearly vertical positions. In (B), at the optimal stage of 2-3 unfolded leaves developed in the apical part of the retained canes, manual shortening to the desired cane length is performed as well as positioning and tying on the horizontal support wire (B'). Red boxes in panel B indicate selected canes extra length which should be maintained to: i) increase acrotony control of the subtending nodes and ii) assure suitable cane length to fill space on trellis.

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Figure 5 In (A) a spurred cordon in Central Italy (cv. Sangiovese) showing almost 100% main shoots killed by late spring frost in 2021. In (B) and (C) two different details of the stage of growth of canes two weeks after the frost occurred. Notably, the already developed apical shoots are dead, whereas underneath located nodes either show healthy green tissue or are still dormant.

Figure 6 In (A) a spur-pruned vineyard of Sangiovese in the Chianti Classico area photographed 22 April 2021 at it appears after mechanical pre-pruning performed December 2020 and before spur shortening. Earlier severe frost had occurred on 6-8 April. In (B) the same vineyard where a variant of stage two was adopted and only one long cane per each of the previous year spur was maintained and then shortened to the desired spur length.