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Mitigating grapevine winter damage in cold climate areas

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Abstract: Growing grapes in cool climate areas is incredibly challenging due to the high risk of winter injury. Passive and active methods can be used to reduce or prevent cold damage and protect the vineyards. Passive protection methods are generally cultural practices and performed before cold damage events, such as cultivar and rootstock selection. The proper scion-rootstock combination would ideally help the vines acclimate earlier in the fall, allowing them to withstand colder weather in the fall and winter and de-acclimate later in the spring to minimise the late spring frost damage. The introduction of new North American hybrid cultivars accompanied with other cultural practices has increased the hope for developing viticulture in areas with lower cold hardiness zones. Furthermore, active protection methods are usually performed at the time of cold damage events to protect the vineyard by preventing or reducing the loss of thermal energy from vine tissues. The objective of this manuscript is to review the viticulture challenges in cold climates and mitigate the risks with Ontario, Canada as an example of a cold climate area.

Keywords: grapes; cold hardiness; cold climate; winter damage; acclimation; dormancy; de-acclimation

Grapes have the largest production area among horticultural crops in the world. About 75 million metric tonnes of grapes are harvested annually from over seven million hectares in more than 100 countries (OIV 2016). Unfortunately, most common grape cultivars are adapted to warm climates and are sensitive to cold temperatures in winter (Blue 2018). Insufficient cold hardiness is a major factor limiting viticulture in the eastern United States and Canada (Striegler, Howell 2005). Frost injury may occur in the fall before the vines have fully acclimated or in late spring in the de-acclimation period after sap flow is re-initiated. This may kill or damage the developing flower buds, potentially causing significant yield losses. Also, severe cold temperatures in mid-winter can sometimes cause complete vine mortality. Winter damage can also affect the fruit quality by creating a growth imbalance (fruit to vegetative growth ratios) and, thus, potentially impact the wine quality. Vineyards in cold climates are limited to local macroclimates that are slightly warmer during winter periods and have more favourable conditions for vine growing, such as areas close to large bodies of water (rivers or lakes) or areas with lower altitudes. A survey of 16 cool-climate wine regions worldwide showed that due to climate change, the average temperature increased at the rate of 0.17 °C per decade during the period from the late 1800s through 2015. As a result, many new potential areas are emerging, and existing cool climate areas are becoming more suitable for viticulture (Jones, Schultz 2016). However, grape growing in these areas is still incredibly challenging. Climate change may lead to a small decrease in the spring frost risk in the warmer areas, but in the cooler areas, may hasten the bud break, increasing the risk of spring frost damage (Meier et al. 2018). Therefore, the application of specific, appropriate cultural practices is also needed for grape production success. Practices can be classified into those which are performed prior to the establishment and those

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which are performed after the vineyard establishment (Dethier, Shaulis 1964). The major decision pre-establishment is the site and cultivar selection (Striegler, Howell 2005). The objective of this manuscript is to review the viticulture challenges in cold climates mitigating the risks with Ontario, Canada as an example of a cold climate area.

Grape climate classification and cold climates. There are different methods that have been developed to classify a viticultural climate.

1. Growing degree days (GDDs), which are calculated from April to September/October (with a base temperature of 10 °C).

2. Growing season temperature (GST), which is calculated based on the average monthly temperature over the seven months of the growing season.

There are two methods to classify the climate of wine growing regions based on the GDDs or heat accumulation. The Winkler index uses GDDs from April 1st to October 31st based on the following formula by taking the average daily maximum and minimum temperatures at a base temperature of 10 °C:

$$GDD = \sum_{Apr\ 1}^{Oct\ 31} (Ta - Tb) \tag{1}$$

where: *Ta* – average daily temperature; and *Tb* – base temperature (10 °C).

In this method, the geographical areas are divided into five climate regions based on the growing degree-days, and are commonly known as Regions I–V. The regions are R I (850–1 389 GDDs), R II (1 390–1 667 GDDs), R III (1 668–1 944 GDDs), R IV (1 945–2 222 GDDs), and R V (2 223–2 700 GDDs) (Winkler 1974). The Winkler index is widely used in many growing regions in the United States and Canada. However, it is less widely used in Europe where they use a second method, the Huglin index. The Huglin index uses a similar formula for the period from April 1st to September 30th, but gives more weight to the maximum temperatures and uses an adjustment for longer lengths of the day found at higher latitudes:

$$GDD = K \sum_{Apr\ 1}^{Sep\ 30} (Ta - Tb) \tag{2}$$

where: *K* – parameter dependent on the latitude of the location; *Ta* – average daily temperature; and *Tb* – is the base temperature (10 °C).

The categories are: I (< 1 500 GDDs),II (1 500–1 599 GDDs), III (1 600–1 699 GDDs), IV (1 700–1 799 GDDs), V (1 800–1 899 GDDs), VI (1 900–1 999 GDDs), VII (2 000–2 099 GDDs), VIII (2 100–2 199 GDDs), IX (2 200–2 299 GDDs), and X (2 300–2 399 GDDs; Huglin 1978).

The growing season temperature (GST) is another method used to measure climate suitability for grape growing, which is based on the average growing season temperatures (April–October). The GST is identical to the GDDs, but is easier to calculate and shows that quality wine production is limited to areas with a GST of 13–21 °C. Regional GDDs of 850–1 389 on the Winkler index or 1 200–1 800 on the Huglin index, and a GST of 13–15 °C are known as classic cool climate regions for grapevines (Jones, Schultz 2016).

A cultivar may be able to survive during winter in a cold climate area, but it needs a long enough season for crop ripening with no cold injury symptoms (Smiley 2016). The length of the growing season is determined by calculating the average number of frost-free days (FFDs) for each area (which is equal to the number of days with a temperature of ≥ –2 °C).

Grape cultivars are usually classified based on their ripening duration according to the frost-free days and their growing degree day (GDD) requirements. These classifications are ultra-early varieties (600–800 GDDs, and 110–135 FFDs), early (800–1 000 GDDs, and 135–150 FFDs), mid-season varieties (1 000–1 250 GDDs, and 150–180 FFDs), late-season varieties (1 250–2 250 GDDs, and 180–190 FFDs; MGA 2018). Therefore, in cooler regions with shorter growing seasons, it is necessary to use early ripening varieties to obtain ripe fruit and allow for good acclimation (Rahemi 2016).

Cold hardiness zones in North America. In the United States, thirteen cold hardiness zones based on the average annual minimum temperature, are defined by the United States Department of Agriculture (USDA 2021), with zone 1 being the coldest and zone 13 the warmest. These are: zone 1 (–51.1 to –45.6 °C), zone 2 (–45.6 to –40.0 °C), zone 3 (–40.0 to –34.4 °C), zone 4 (–34.4 to –28.9 °C), zone 5 (–28.9 to –23.3 °C), zone 6 (–23.3 to –17.8 °C), zone 7 (–17.8 to –12.2 °C), zone 8 (–12.2 to –6.7 °C), zone 9 (–6.7 to –1.1 °C), zone 10 (–1.1 to 4.4 °C), zone 11 (4.4 to 10 °C), zone 12 (10 to 15.6 °C), and zone 13 (15.6 to 21.1 °C). Each zone consists of two sub-zones (a and b, a being the coldest and b the warmest). Grapes can grow on USDA plant hardiness zones 3 through 10b. The available grape cultivars can grow in USDA plant hardiness zones 5 through 10b. However, new

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cold-hardy grapevines were recently introduced for zones 3 and 4.

The USDA climate zones were also adapted by Canada, which divides Canada into 10 zones (0 to 9). Zone 0 being the coldest zone and zone 9 is the warmest. Zones 1–9 in Canada have the same temperature range as the US zones. Zone 0, is a special zone for Canada that covers a temperature range of –56.7 to –51.1 °C. The USDA climate zone uses one climate variable: the average of the annual extreme minimum temperature for the period of 1981 to 2010. However, Canadians further developed an individual hardiness map which was introduced by Natural Resources Canada (NRC 2021). The map is based on a formula using seven important variables that influence plant survival including the monthly mean of the daily minimum temperatures of the coldest month, mean frost-free period (above 0 °C) in days, amount of rainfall from June to November, monthly mean of the daily maximum temperatures of the warmest month, a winter harshness index related to the rainfall in January, mean maximum snow depth, and maximum wind gust over a 30-year period. This hardiness map also divides Canada into 10 zones (0 to 9). These *zones* provide insights about as what can be grown where.

Winter severity index. A winter severity index (WSI) determines the different categories for each area based on the mean temperature of the coldest month (usually January or February) in any given 30-year period. Cold areas are categorised as extremely cold (< –15 °C), very cold (–15 °C to –10 °C), cold (–10 °C to –5 °C), and mildly cold (–5 °C to 0 °C; Kurtural et al. 2008). In cold climate wine growing regions, severe low temperatures during winter are often the limiting factor with regards to the yield (Jones 2015).

Phenological progression and physiological events. The buds start to go dormant in the fall (under the influence of reduced day length and temperature), which induces physiological changes in the bud cell contents and intercellular water levels in the vines, as well as chemical changes. This kind of dormancy is called endodormancy. During winter, grapevine buds require certain chilling requirements (Dokoozlian 1999) before vine growth can resume. The chilling hours are calculated based upon the hourly field temperature data. They are calculated as the number of hours between 0–7 °C using the following formula (Črepinšek et al. 2012):

$$CHt = \sum_{i=1}^{t} h;\ \text{if } 0°C < T < 7\ °C\text{, then add 1, else 0} \qquad (3)$$

where: *CH* – chilling hours; *h* – hour; and *T* – temperature.

If a certain amount of chilling is not received (insufficient chilling), it will lead to the delayed full foliation, as well as forming a small tuft of leaves near the tips of the canes, more suckers from the lower parts of the vine, late-blooming or extended bloom, poor fruit set and yield, increased flower dropping, the formation of small-sized berries, and reduced berry quality (Corrales-Maldanado et al. 2010).

The chilling requirement is different for different grapevine cultivars. For example, the chilling requirement for 'Chardonnay' and 'Riesling' are about 650 and 750 chill unit factors (CUFs), respectively (Rahemi 2016). Londo and Johnson (2014) have reported different chilling requirements (hours) for the grape species: *Vitis amurensis* (500), *V. riparia* (750), *V. vinifera* (750–1 000), *V. labrusca* (1 000), *Hybrids* (1 000), *V. rupestris* (1 250), *V. cinerea* (1 500), *V. aestivalis* (1 750), and *V. vulpina* (2 000–2 250).

Different methods and models are used to calculate the chilling requirements, such as 'cumulative chilling hours' (Weinberger 1950), Utah weighted 'chill units' (Richardson et al. 1974; Anderson et al. 1986), and the Dynamic Model 'chilling portions' (Fishman et al. 1987; Erez et al. 1990).

Buds cannot sprout after the fulfilment of endodormancy until they receive a certain amount of heat units. This is a second dormancy period called ecodormancy. It is a later stage of dormancy when vines are no longer resistant to late winter changes, during which buds will burst if placed in warm conditions (Londo, Martinson 2016). The heat accumulation requirement is calculated based on GDDs) from April 1st till bud break, and it varies for different grapevine cultivars. For example, the heat requirement for bud break of 'Chardonnay' and 'Riesling' are about 200 and 300 GDDs, respectively (Rahemi 2016). Cultivars with a high amount of chilling (endodormancy) and heat requirements (ecodormancy) are usually late-budding cultivars (Rahemi 2016). In the spring, temperatures above 10 °C initiate vegetative growth. The time of bud break for grape varieties has been divided into five categories: 1 – very early; 3 – early; 5 – medium; 7 – late, and 9 – very late (IPGRI/UPOV/OIV 1997).

Acclimation in the fall. Grapevines need to 'harden off' or acclimate for the winter (Blue 2018).

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The absolute cold hardiness of the vine is genetically defined, but the phenotypic response may be modified by the cold-acclimation process. The capacity to acclimate early in the fall, to become cold-hardy during the winter, to have a slow response to temperature changes in the winter, and to have delayed de-acclimation during the spring is necessary for survival in cold climates (Howell 2000). Gu et al. (2002) also reported that the greater cold hardiness of *non-vinifera* cultivars is due to their ability to acclimate faster and deeper at low temperatures.

Early acclimation means better preparation for absolute cold hardiness, reducing the risk of early fall frost and/or mid-winter damage. If extreme cold temperatures occur when the vine is not quite acclimated, cold damage can occur (Rahemi 2016).

Wolpert and Howell (1985) suggested that grapevine cold hardiness is associated with the vine maturity and low water content of the tissues. During acclimation, the water content of the cells will decrease, and the cold hardiness will increase in the primary buds and canes (Striegler, Howell 2005). Striegler, Howell (2005) suggested that cold acclimation occurs in grapevines in two stages: first, cold hardiness associated with tissue maturation and changes in the water content (before the first killing frost) and then cold hardiness that is not associated with tissue maturation and water content (after the first killing frost). In Ontario, acclimation typically starts from early September, and full chilling requirements are fulfilled by late December. In some years, during the acclimation process, warming and cooling cycles may occur (Rahemi 2016). This can delay reaching full cold hardiness (Stafne 2007).

Cold climate risks

Fall frost. In years with an early fall freeze where vines have not been able to fully acclimate, there can be an increase in the incidence of cane tip dieback (Rahemi 2016). Early frost in the fall can prevent the vine from acclimating properly, resulting in reduced nutrient storage, and impacting the overwintering and vine development in the subsequent year.

Winter damage. There are many limiting factors for grape production, but one of the most challenging is winter damage (Chien, Moyer 2014). Damage to the cluster primordia of the primary and secondary buds can drastically reduce the crop yield (Fennell 2004). Winter damage is not limited to crop failure, but may result in damage to the canes, cordons, trunk, graft union, roots, and even the death of the whole vine (Goffinet 2001, 2004). Winter damage can occur particularly at high latitude areas.

Studies to determine the degree of damage after severe cold events describe the percent injury or mortality of the primary, secondary, and tertiary buds, degree of damage on the canes and trunks, and whole vine survival (Miller et al. 1988b; Martinson 2011; Ker 2013; Fiola 2018). The primary buds are usually the main cropping ones. However, secondary buds are productive in some cultivars. Researchers at the University of Minnesota have classified the cultivars secondary buds into three groups: productive, moderate productivity, and no productivity (Anonymous 2016).

Bud mortality should be assessed 24–48 hours after the purported injury has occurred. Buds need to thaw at normal room temperatures (20 °C or warmer) for 24 to 48 hours to allow oxidation to occur. With a sharp blade, the buds are cut horizontally in five consecutive steps, and all the primary, secondary, and tertiary buds checked for green (alive) or yellow to brown (dead) tissue. Ten buds on ten canes (100 buds in total) per cultivar per site must be evaluated (Ker 2013). If the primary bud mortality is 0–15%, the vines should be pruned as usual. If the mortality is 16–30%, an additional 50% more nodes would be retained. If the mortality is 31–50%, the number of buds left would be doubled. If the primary bud mortality is more than 60%, the vineyard should not be pruned at all (Willwerth et al. 2014).

Winter damage is a significant problem in Canada's vineyards due to the cold temperatures in high latitude areas. In Ontario, the severe cold usually happens during January or February, when the vine has begun de-acclimation and may no longer be at its maximum cold hardiness. If the temperature is lower than the cultivar's mortality threshold at that point, the vine will suffer from cold damage (Rahemi 2016). Based on Grape Growers of Ontario (GGO 2017) reports, crop production was reduced by one third due to mid-winter damage and was a huge loss to Ontario growers in 2005 and 2015 (GGO 2016).

The duration of the threshold cold temperatures, the time during the season which the cold temperature occurred, the number of cold temperature events, the rate of the temperature descent (from high to low), and the duration of the total winter season could individually and collectively affect the amount of winter injury to the vines and buds (Rahemi 2016).

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Vine physiology is complicated among mid-winter acclimation, late winter/spring de-acclimation and re-acclimation phases. De-acclimation (or loss of winter hardiness) may be a response to abnormally warm winter temperatures. Exposure to warm temperatures, even for just a few days, can initiate some de-acclimation, which progresses faster than the acclimation process. The vine will lose hardiness and become more sensitive to the cold. This can result in serious winter damage (Rahemi 2016).

In addition to a single extreme cold weather event, injury can occur from a series of less severe cold events. In the Niagara Peninsula, Ontario, in years without extreme low temperatures, several repeated episodes where low-temperature exotherm (LTE) values were reached allowing repeated injury to occur, resulting in significant bud loss (Willwerth et al. 2014).

Cold hardiness measurements. A differential thermal analysis (DTA) is a method of measuring low-temperature tolerance in a single dormant excised bud. This method measures the actual lethal temperature rather than estimating it (Dami 2007). Dormant buds are placed on thermoelectric plates (5 per plate) in a controlled-temperature freezer, and through progressive temperature declines over 24 hours, the temperature that causes bud death (lethal temperatures) is determined. This method detects ice formation in the bud by measuring the heat released by the latent heat of fusion upon crystallisation. The ice crystals rupture the cell membrane and causing electrolyte leakage (EL), and, subsequently, death. Damaged buds leak more electrolytes than healthy buds. When an acclimated bud is cooled, the DTA temperature curve consists of a high-temperature exotherm peak which occurs between –5 °C and –10 °C and is produced by the ice formation in the inter-cellular bud scales. This temperature does not cause bud injury. The second series of peaks or low-temperature exotherms (LTEs) occurs < –10 °C, which is caused by the freezing of super-cooled intra-cellular water (within the cells). This typically results in bud death due to the cell wall injury and membrane rupture (Dami 2007). The LTEs are associated with bud death (Pierquet, Stushnoff 1980). At the end of the freezing sequence, the data is analysed, and the LTE 10, 50, and 90 are recorded as the death of 10%, 50%, and 90% of the primary buds, respectively (Andrew et al. 1984; Zabadal et al. 2007; Mussell et al. 2011).

The information collected from different growing areas and grape varieties in Ontario is provided online by a 'Vine Alert' for growers to be aware of the sensitivity of their vines throughout the dormant season (CCOVI 2018). Growers can then initiate preventive or protective methods to protect their vines against cold damage.

Spring frost. As vines exit dormancy each spring, freezing vulnerability returns quickly (Fennell 2004). By late March, vines begin to accelerate the de-acclimation process, and they undergo budburst by mid-May. Before and during budburst, they are sensitive to late spring frosts (Rahemi 2016). In bud break time in spring, a temperature around 0 °C can adversely affect the vegetative growth and, at < –2.2 °C, may significantly reduce the yield (Jones 2015). Fuller and Telli (1999) believed that the newly emerged green tissues can suffer injury at just –2.5 °C, and Fennell (2004) reported that damage to the floral primordia of the primary and secondary buds can drastically reduce crop yields. Therefore, delaying the de-acclimation and bud break will decrease the risk of late spring frost damage (Fennell 2004).

Cold damage mitigating methodologies. There are two types of cold protection methods for vineyards, passive and active methods. Passive protection methods are generally cultural practices and performed substantially before cold damage events. These are site selection, vine selection (cultivar and rootstock), proper pruning, and vine covering. Active protection methods are usually performed at the time of cold damage events and either prevent or reduce the loss of thermal energy from vine tissues. Active protection methods include heaters, wind machines, and a combination of the methods.

Passive protection methods. Some cultural practices, like proper site selection, proper slope, good soil and drainage, and cold air drainage could help to protect vines from winter damage. Some growers have used straw mulches on planting rows to cover the crown and root areas, while others have used geotextile materials (white blanket) on the planting rows which cover all the vegetative parts. Depending on the soil type, hilling soils on planting rows with about 20–25 cm height (to cover the graft unions and lower the trunk) before the soil freezes (rehilling if the soil was washed away by a heavy rain) or possibly burying the whole vine with soils is an option (Rahemi 2016). Other cultural practices, such as enhancing the acclimation, frost avoidance activi-

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ties, and cultivar/rootstock selections, will also help to mitigate the cold damage in the vineyards.

Practices to enhance acclimation. Grapevine growth is indeterminate, meaning vines in ideal summer growth conditions will continue to grow unless they receive the environmental signals early enough to stop the growth, acclimate properly, and prepare for winter. Some cultivars have little or no response to the shortening day length and reduction of the mean daily temperature that would normally initiate acclimation. These cultivars are prone to produce more shoots and leaves later into the growing season that could be damaged with an early fall frost (Rahemi 2016). When vines do not fully acclimate, winter injury will occur, resulting in cracks in the trunk and may lead to potential infectious diseases or other organisms, such as crown gall (*Agrobacterium* sp.), which may kill the vine in subsequent growing seasons (Rahemi 2016). In this situation, it is necessary that growers utilise cultural practices that induce the vine (e.g., reducing irrigation and fertilisation) and to slow down the vegetative growth in order for it to adapt for winter.

During acclimation, carbohydrates and nutrients accumulate in the root and cane tissues are a source of energy for the vine survival and enhance good winter hardiness (Rahemi 2016). Activities that promote acclimation are a reduction in the nutrient use (for example, elimination of late compost applications; Westover 2006) after the fruit-set to reduce the vegetative growth, elimination of irrigation post-veraison, avoiding top hedging at least three weeks before harvest, removing any grow-tubes around the trunks in mid-August to give enough time for the trunk acclimation, and thinning the excessive crop by cluster thinning at veraison (Rahemi 2016). However, Keller et al. (2014) reported that the early fruit removal of vines with a commercially acceptable yield did not impact the cold acclimation on the grapevines tested in Washington state.

Spring frost avoidance. To delay de-acclimation and bud break and avoid late spring frost damage, growers have used a vegetable oil spray, or NAA (Naphthaleneacetic acid) during the dormant season, but the cultivar response is highly variable (Qrunfleh 2010). Another method is delayed pruning, for example, pruning twice (first a lighter one when the vines are fully dormant and a second final bud-count pruning when all risk of frost has passed).

Cold-hardy cultivars. Some grape cultivars may not be hardy enough for very cold areas (Reisch, Luce 2005). Cold hardiness depends heavily on the genetics of the grape species and/or cultivar (Centinari 2016). Differences in cold hardiness among diverse grape cultivars have been studied extensively (Clore et al. 1974; Wolf, Miller 2001; Khanizadeh et al. 2004; Smiley 2016; Bradshaw et al. 2018). Most grape cultivars in the world belong to the Eurasian grape species *V. vinifera* L. The cultivars found in this species, may not be very cold-hardy, and they have little ability to withstand serious cold mid-winter weather (Stafne 2007).

Most *V. vinifera* cultivars can tolerate −15 °C without serious injury if the acclimation is gradual. Depending on geographical location, the bud injury may begin to occur at −17.8 °C in most of the very cold tender *V. vinifera* cultivars (Bradshaw 2016). Some north European cultivars have better cold hardiness than others. For example, the maximum cold hardiness values (LT50 lethal temperature) for 'Cabernet Franc' and 'Riesling' wine grape cultivars are −24.6 °C and −26.2 °C, respectively (Londo, Martinson 2015).

Genetic variation within each cultivar due to clonal variation may confer differing levels of cold hardiness. For example, clone scion #95 of 'Chardonnay' and clone scion #115 of 'Pinot Noir' have shown slightly greater cold hardiness compared to other clones of each cultivar (Kemp et al. 2017).

Species that are native to North America show relatively better cold hardiness than *V. vinifera*. Many cold hardiness genes are present in American grape species such as *V. labrusca* L., *Vitis aestivalis* Michx., and *V. riparia* Michx. (Fennell 2004). North American grape species can withstand −30 °C and lower (Fennell 2004). Some *V. riparia* hybrids have survived −38 °C with less than 50% bud injury (Hemstead, Luby 2000). The grape cultivar 'Concord', *V. labruscana* Bailey, can tolerate −29 °C (Fennell 2004). This cultivar has a different flavour than Eurasian grapes, and its wine may only be locally marketable. The main reason for its original expansion in Canada was its cold tolerance and utilisation in port, sherry, and non-alcoholic juices (Rahemi 2016). Some researchers propose that Concord is a hybrid because it has complete flowers, which is a characteristic of *V. vinifera* L., but is very much like *V. labruscana* Bailey (Shoemaker 2012). The first hybrid cultivar known as an American hybrid, 'Isabella' (*V. labrusca* × *V. vinifera*), was introduced to the eastern United States in 1816 (Hedrick et al. 1908).

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French American hybrids are a little more tolerant than the *V. vinifera* cultivars (Shoemaker 2012). The critical threshold temperature for hardy French American hybrid cultivars is –26 °C (Bradshaw 2016).

Crosses between *vinifera* cultivars and native North American species have shown the inheritance of good cold hardiness traits (Hemstead, Luby 2000). These are sometimes known as Northern grapes (Shoemaker 2012), or cold climate interspecific hybrid grapevines (CCIHG; North et al. 2021). Breeding of wine grape cultivars hardy to winter conditions in the northern United States, where annual minimum temperatures of –25 °C or lower are common, is relatively new (Bradshaw et al. 2018).

'Valiant' is a cross introduced by South Dakota State University and developed from *V. labrusca* (Fredonia) × *V. riparia* (wild accession SD62-9-39 from NE Montana; Smiley 2016). It has been reported to possibly be the hardiest cultivar withstanding temperatures up to –45.5 °C. It is a red wine grape cultivar suitable for protected cultivation on the Canadian Prairies and mid-western United States, but it has a *V. labrusca* flavour (Nixon 2001; Kaban 2009; Smiley 2016).

There are hybrids of some cold-hardy *V. vinifera* wine grape cultivars with cold-resistant North American grape species (Shoemaker 2012). Minnesota hybrid cultivars have good potential for cold hardiness due to the introduction of the northern native grape species *V. riparia*, in the breeding programme with a high inheritance of cold hardiness. These include 'Frontenac gris' (–39 °C), 'La Crescent' (–38 °C), 'Frontenac blanc' (–38 °C), 'Frontenac' (–37 °C), 'Marquette' (–37 °C), and 'Itasca' (–37 to –34 °C; Clark et al. 2017; UMN 2018). Many of these hybrid cultivars are now growing in cold areas such as the northern and mid-western states of the United States, Canada, and northern Europe (Shoemaker 2012). For example, 'Frontenac gris' can grow in USDA plant hardiness zone 4 and 5 of the eastern United States and Canada (Smiley 2016).

A simple classification for winter hardiness grapevine cultivars in Ontario is achieved based on the relative index of the ten different criteria from most hardy (#1) to least hardy (#10). This classification is based on the temperatures at which the LT50 of the primary buds occurred in mid-winter (GGO 2017).

A classification of cold hardiness for Manitoba divides grape varieties into groups labelled tender (–18 °C to –23 °C), slightly hardy (–21 °C to –26 °C), moderately hardy (–23 °C to –29 °C), hardy (–26 °C to –32 °C), very hardy (–32 °C to –37 °C) and super hardy (below –37 °C; MGA 2018). Vermont and Bradshaw (2016) used a winter hardiness classification of 1 – very cold tender (–17.7 °C, almost any grapes), 2 – cold tender (–20.5 °C, most northern *V. vinifera*), 3 – moderately hardy (–23.3 °C, hardy *V. vinifera*, moderately hardy French hybrids.), 4 – hardy (–26.1 °C, hardy French hybrids, most *V. labrusca*), 5 – very hardy (–28.9 °C, hardy *V. labrusca*, most *V. riparia* hybrids).

Grapes grown in areas with a long growing season and moderate winter temperatures usually have decreased winter damage. Cultivars with a high amount of chilling (endodormancy) and heat requirements (ecodormancy) are usually late budding cultivars (Rahemi 2016).

Cold-hardy rootstocks. The most effective way to grow grapes in a cold climate is to choose both cold-hardy varieties and rootstocks with a proper vine balance. Cold hardiness is one of the main selection criteria for rootstock breeding programmes in cold climates (Rahemi 2016). Cousins (2005) stated that the cold hardiness of a rootstock and its parents is not directly related to the improved cold hardiness of the scion grafted onto it. Grafting a scion onto a cold-hardy rootstock may improve the scion's cold hardiness as it may reduce the vegetative growth and vine size, and enhance the earlier acclimation, but not through the movement of a 'cold hardiness factor' to the scion. Some rootstock selections may tolerate cold temperatures better than others. Rootstocks with parentage from warm regions are not suitable for use in cold winter areas. For example, 039–16, a *V. rotundifolia* hybrid, and Dog Ridge, a *V.* × *champinii* selection, should only be considered in warmer climates where nematodes are an issue, especially in comparison with rootstocks such as 3309C and 5BB with some *V. riparia* heritage (Cousins 2005).

The *V. riparia* species, either directly (i.e., Riparia Gloire de Montpellier-RGM) or in hybrids with other species (i.e., as 3309C) are used as rootstocks for grapes. *V. riparia*, a highly cold-hardy species native to North America, is reported to tolerate temperatures up to –40 °C (Stenger 2016). It is reported that a *V. riparia* ecotype (accession SD62-9-39) from the foothills of Montana showed extreme cold tolerance (–57 °C; Kaban 2009). Miller et al. (1988a) found that canes and buds on rootstock 3309C (*V. riparia* × *V. rupestris*) were the most desirable in relation to winter survival compared with

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5BB and SO4 when used as rootstocks for 'Riesling' in Michigan. The cane and bud on 3309C acclimated faster in fall and de-acclimated slower in spring compared to the 5BB and both SO4 (*V. riparia* × *V. berlandieri*) rootstocks. Moreover, grafted 'Riesling' was significantly hardier than its own-rooted vines (Miller et al. 1988b). In general, RGM, 3309C, and 101–14 rootstocks have shown good cold hardiness at Simcoe, Ontario, Canada (Rahemi 2016).

Identification of cold-hardy rootstocks is performed by surveying several traits that are genetically controlled to identify vines with better acclimation. Some of these traits are the periderm lignification development (best indicator), early defoliation in fall (leaf abscission), male vines (earlier acclimation), late bud burst in spring (late deacclimation), early veraison (early berry colouring), early fruit ripening, broad/flat bud shape, and ability to replace damaged buds with vegetative- latent buds (Rahemi 2016). Howell (2005) suggested that short-cycle rootstocks would be most desirable for a cool climate. A short-cycle rootstock may increase the rate of cold acclimation of the scion (Perry, Sabbatini 2015).

Guo et al. 1987 stated that the grape rootstock is useful to reduce the root cold injury in areas where soil temperatures fall extremely low in winter. There are some reports that confirm the influence of the rootstock on the cold hardiness of the scion (Hubackova, Hubacek 1984; Pool, Howard 1984; Shamtsyan et al. 1984; Gu et al. 2005). In contrast, many other reports show that the scion cold hardiness was not affected by various rootstocks (Shaulis et al. 1968; Wolf, Pool 1988; Striegler, Howell 2005). Striegler and Howell (2005) reported that the rootstock did not have a consistent effect on the primary bud cold hardiness of the scion cultivar. They stated that the rootstock had little effect on cold hardiness or water content during the acclimation time. However, they observed that the rootstock could affect the de-acclimation period.

Since different clones are introduced and available for each rootstock, they must be tested for their winter hardiness, as they have shown differences in variety trials for both the scion and rootstock (Rahemi 2016). A temperature sensor should be used at a depth of one foot (approximately 30 cm) in the ground to collect and monitor real-time temperature data in the vine root zone (Rahemi 2016).

Control of cold hardiness genetically. The grapevine is affected by the dormancy initiation time and freezing tolerance in the fall and winter, chilling fulfilment and bud break in the spring. These traits are controlled by genetic bases and the temperatures in the vineyard are contributing factors (Yilmaz et al. 2021). Knowledge of the genetic background of a cultivar is a key component in choosing genotypes that are adapted to a cold climate (Stafne 2007).

By understanding the genes inducing cold resistance in grapes, it is possible to decrease the risk of winter damage to protect crops (Kovaleski et al. 2019). Using genetic technologies, specific genes can be linked to traits in Norton hybrids. The associated markers can be used to screen for those genes and, consequently, the desired traits when the plants are still very young. This allows breeders to find which hybrids will likely perform in the desired way well before spending any effort in planting and maintaining them (Adams 2017). However, Londo (2017) mentioned that many genes are involved in cold hardiness on grapevines (a polygenic trait which is controlled by multiple genes, gene interactions, and significant crosstalk with other stresses). Therefore, controlling the cold hardiness by genetic modification is not easy.

Cold hardiness genes are more abundant in North American grape species. CBF (C-repeat binding factor), CAMTA (Calmodulin-binding transcription activator), and COR (cold response) genes are the most well-documented cold resistance genes in grapes (Nassuth 2013; Rahman 2015). ICE (inducer of the CBF expression) gene is a protein that has a role in cold hardiness gene make-up. The 'Felicia' cultivar (a hybrid of 'Sirius' × 'Vidal blanc') has the biggest potential for the development of freeze tolerance molecular markers. It has different alleles from CBF1 (A/C and B) and CBF4 (A and B) genes. CBF1B and CBF4B are candidates for freeze tolerance markers for grapes (Nassuth 2013). Research is ongoing to identify cultivars that have more cold hardiness genes in their genetic structure. The BON (bacterial OsmY and nodulation) domain is found in the bacterial osmotic-shock-resistance protein, Osm. BON association protein 1 (BAP1) is a recently discovered phospholipid-binding protein. The VvBAP1 gene was cloned in grape cultivars by Hou et al. (2018). The expression level of VvBAP1 in the cold-resistant varieties was significantly higher than in the cold-sensitive varieties, indicating that VvBAP1 could be associated with the cold response processes in the grapevine.

Active protection methods. Other strategies include low temperature mitigation equipment such as wind machines and air movement devices

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if the wind speed is less than 6 km/hour and a radiation frost condition exists. Wind machines mix warm air 20 m above the ground, which can be 5 to 10 °C warmer than at the vine level. Also, heating the vineyards would be possible with different methods, such as using commercial orchard heaters (Smudge Pots) in small vineyards (Khanizadeh et al. 2004; Fraser et al. 2008; Rahemi 2016). Weather forecasts are a useful tool for growers in applying mitigation strategies to help minimise winter injury, e.g., to activate wind machines. Real-time temperature loggers are used to activate wind machines. Today, growers usually have access to short- and long-term weather forecasts based on standard meteorological models (Rahemi 2016).

CONCLUSION

Grape growing in cold climate areas is incredibly challenging, and the application of specific cultural practices are needed for success. Winter damage occurs in vineyards that are subjected to low winter temperatures around the world, and it is a significant threat for many northern vineyard sites. Grapevines' hardiness to cold temperatures is highly variable and depends on the site, mesoclimate management, and cultivar. Cold hardiness directly depends on the amount of cold acclimation. Cold hardiness determines if growers need to use passive or active methods to prevent or protect vines against cold damage. Cultural practices could be employed to better acclimate grapevines. Some activities could promote acclimation, some could help protect vines from winter damage, and some could delay de-acclimation and bud sprouting (bud break) to avoid late spring frost. The best way to grow a grapevine in a cold area is to choose cold-hardy cultivars that can withstand local conditions (low winter temperatures), and utilise appropriate hardy rootstocks that will lead to balanced growth, productivity and enhance acclimation necessary to achieve optimum cold hardiness to the scion.

REFERENCES

Adams D.B. (2017): Genetic analysis of cold hardiness in a population of Norton (*Vitis aestivalis*) and 'Cabernet Sauvignon' (*Vitis vinifera*) hybrids. Missouri State University, [Ph.D. Thesis.]: 60.

Anderson J.L., Richardson E.A., Kesner C.D. (1986): Validation of chill unit and flower bud phenology models for 'Montmorency' sour cherry. Acta Horticulturae (ISHS), 184: 71–78.

Andrews P.K., Sandidge C.R., Toyama T.K. (1984): Deep supercooling of dormant and de-acclimating *Vitis* buds. American Journal of Enology and Viticulture, 35: 175–177.

Anonymous (2016): Grape growing in Minnesota, Minnesota Grape Growers Association: 183. Available at https://reapmatters.org/wp-content/uploads/2017/06/GGIM_Best_Practices-book.pdf (accessed Oct 20, 2020).

Blue M. (2018): Grapevines that can handle cold temperatures. Home Guides, SF Gate. Available at http://homeguides.sfgate.com/grapevines-can-handle-cold-temperatures-47998.html (accessed Oct 18, 2018).

Bradshaw T. (2016): Growing grapes in Vermont. University of Vermont. Available at http://www.uvm.edu/~fruit/grapes/gr_horticulture/GrowingGrapesinVermont.pdf (accessed Sep 17, 2018).

Bradshaw T.L., Kingsley-Richards S.L., Foster J., Berkett L.P. (2018): Horticultural performance and juice quality of cold-climate grapes in Vermont, USA. European Journal of Horticultural Science, 83: 42–48.

CCOVI, Cool Climate Oenology and Viticulture Institute. (2018): Vine Alert. Brock University. St. Catherines, ON. Available at http://www.ccovi.ca/vine-alert

Chien M., Moyer M. (2014): Cold injury in grapevines. Extension. Available at https://articles.extension.org/pages/63372/cold-injury-in-grapevines (accessed Sep 17, 2018).

Centinari M. (2016): Winter notes: What is going on in your vineyard right now? Pennsylvania State University. Available at https://psuwineandgrapes.wordpress.com/tag/cold-acclimation/ (accessed June 11, 2019).

Clark M., Hemstad P., Luby J. (2017): 'Itasca' Grapevine, a new cold-hardy hybrid for white wine production. Horticultural Science (Prague), 52: 649–651.

Clore W.J., Wallace M.A., Fay R.D. (1974): Bud survival of grape cultivars at subzero temperature in Washington. American Journal of Enology and Viticulture, 25: 24–29.

Corrales-Maldanado C., Orozco-Avitia A., Vargas-Arispuro I. (2010): Organic alternative for breaking dormancy in table grapes grown in hot regions. American Journal of Agricultural and Biological Sciences, 5: 194–198.

Cousins P. (2005): Evolution, genetics, and breeding: Viticultural applications of the origins of our rootstocks. In: Proceedings of the Grapevine Rootstoscks: Current Use, Research and Aplication, 2005 Rootstock Symposium. Feb 5, 2005, Osage Beach, Missouri.

Črepinšek Z., Štampar F., Kajfež-Bogataj L., Solar A. (2012): The response of *Corylus avellana* L. phenology to rising temperature in north-eastern Slovenia. International Journal of Biometeorology, 56: 681–694.

https://doi.org/10.17221/176/2020-HORTSCI

Dami I. (2007): Freezing and survival mechanisms of grapevines. In: Proceeding of the Understanding and Preventing Freeze Damage in Vineyards, Columbia, USA: 13–20.

Dethier B.E., Shaulis N. (1964): Minimizing the hazard of cold in New York vineyards. Cornell Extension Bulletin 1127.

Dokoozlian N.K. (1999): Chilling temperature and duration interact on the bud break of 'Perlette' grapevine cuttings. Horticultural Science (Prague), 34: 1054–1056.

Erez A., Fishman S., Linsley-Noakes G.C., Allan, P. (1990): The dynamic model for rest completion in peach buds. Acta Horticulturae (ISHS), 276: 165–174.

Fennell A. (2004): Freezing tolerance and injury in grapevines. Journal of Crop Improvement, 10: 201–235.

Fiola J.A. (2018): Timely Viticulture, Understanding Grapevine Bud Damage. Available at https://extension.umd.edu/learn/understanding-grapevine-bud-damage (accessed Oct 18, 2018).

Fishman S., Erez A., Couvillon G.A. (1987): The temperature dependence of dormancy breaking in plants: Computer simulation of processes studied under controlled temperatures. Journal of Theoretical Biology, 126: 309–321.

Fraser H., Slingerland K., Ker K., Fisher K., Brewster R. (2008): Wind machines for minimizing cold injury. Infosheet, Ontario Ministry of Agriculture, Food and Rural Affairs: 8.

Fuller M.P., Telli G. (1999): An investigation of the frost hardiness of grapevine (*Vitis vinifera*) during bud break. Annals of Applied Biology, 135: 589–595.

Goffinet M.C. (2000): The anatomy of low-temperature injury of grapevines. In: Proceedings of the ASEV 50th Anniversary Meeting, Seattle, Washington, June 19–23, 2000: 94–100.

Goffinet M.C. (2004): Anatomy of Grapevine Winter Injury and Recovery. New York State Agricultural Experiment Station, Geneva, New York, 21. http://www.hort.cornell.edu/goffinet/Anatomy_of_Winter_Injury_hi_res.pdf

GGO, Grape Growers of Ontario (2016): Available at http://www.grapegrowersofontario.com (accessed Jan 1, 2017).

Gu S., Ding P., Howard S. (2002): Effect of temperature and exposure time on cold hardiness of primary buds during the dormant season in 'Concord', 'Norton', 'Vignoles' and 'St Vincent' grapevines. The Journal of Horticultural Science and Biotechnology, 77: 635–639.

Gu S., Read P.E., Gamet S. (2005): Rootstock influence on scion performance. In: Grapevine Rootstocks; Current Use, Research and Application. Proceedings of the 2005 Rootstock Symposium: 57–60.

Guo X.W., Fu W.H, Wang G.J. (1987): Studies on cold hardiness of grapevine roots. Vitis, 26: 161–171.

Hedrick U.P., Booth N.O., Taylor O.M., Wellington R., Dorsey M.J. (1908): The Grapes of New York. State of New York, Dept. of Agriculture. Fifteenth Annual Report, vol. 3. J.B. Lyon Co., Albany, NY. Part II.: 564.

Hemstead P.R., Luby J.J. (2000): Utilization of *Vitis riparia* for the development of new wine varieties with resistance to disease and extreme cold. Acta Horticulturae (ISHS), 528: 487–490.

Hou L., Zhang G., Zhao F., Zhu D., Fan X., Zhang Z., Liu X. (2018): VvBAP1 is involved in cold tolerance in *Vitis vinifera* L. Frontiers in Plant Science, 9: 726.

Howell G.S. (2005): Rootstock influence on scion performance. In: Grapevine Rootstocks; Current Use, Research and Application. Proceedings of the 2005 Rootstock Symposium: 47–55.

Hubackova M., Hubacek V. (1984): Frost resistance of grape buds on different rootstocks. Vinohrad, Bratislava, 22: 55–56.

Huglin P. (1978): Nouveau mode d'Évaluation des possibilités héliothermiques d'un milieu viticole. Comptes Rendus de l'Académie d'Agriculture de France, 64: 1117–1126.

IPGRI/UPOV/OIV, International Plant Genetic Resources Institute/International Union for the Protection of New Varieties of Plants/Office International de la Vigne et du Vin. (1997): Descriptors for Grapevine (*Vitis* spp.). Available at http://www.cgiar.org/ipgri/ (accessed Jan 1, 2017).

Jones G.V. (2015): Climate, grapes, and wine: Terroir and the importance of climate to wine grape production. Available at https://www.guildsomm.com/public_content/features/articles/b/gregory_jones/posts/climate-grapes-and-wine (accessed Oct 19, 2018).

Jones G.V., Schultz H.R. (2016): Climate change: Climate change and emerging cool climate wine regions. Wine & Viticulture Journal, 31: 51–53.

Kaban T. (2009): Cold Hardiness Screening of Grape Seedlings for the Prairies: 28.

Keller M., Mills L.J., Olmstead. M.A. (2014): Fruit ripening has little influence on grapevine cold acclimation. American Journal of Enology and Viticulture, 65: 417–423.

Kemp B., Willwerth J., Jasinski M., Onguta E., Inglis D. (2017): A comparison of clones from Champagne and Burgundy grown in Ontario for sparkling wine production, Brock University, St. Catharines, CA. Available at https://brocku.ca/ccovi/wp-content/uploads/sites/125/Kemp-2017-clones.pdf (accessed Sep 23, 2020).

Ker K. (2013): Assessing bud injury to grapes. Brock University, St. Catharines, CA., Calibrate your vineyard. Workshop: Growing Grapes in Ontario's South Coast. February 12, 2013, Burning Kiln Winery, St. Williams, ON.

Khanizadeh S., Rekika D., Levasseur A., Groleau Y., Richer C., Fisher H. (2004): Growing grapes in a cold climate with winter temperature below –25 °C. Acta Horticulturae (ISHS), 663: 931–936.

Kovaleski A.P., Londo J.P., Finkelstein K.D. (2019): X-ray phase contrast imaging of *Vitis* spp. buds shows freezing

https://doi.org/10.17221/176/2020-HORTSCI

pattern and correlation between volume and cold hardiness. Scientific Report, 9: 14949.

Kurtural K., Wilson P.E., Dami I.E. (2008): Vineyard Site Selection in Kentucky Based on Climate and Soil Properties. University of Kentucky Cooperative Extension Service, HO-87: 1–4.

Londo J.P., Johnson L.M. (2014): Variation in the chilling requirement and budburst rate of wild *Vitis* species. Environmental and Experimental Botany, 106: 138–147.

Londo J.P., Martinson T. (2015): Geographic trend of bud hardiness response in *Vitis riparia*. Acta Horticulturae (ISHS), 1082: 299–304.

Londo J.P., Martinson T. (2016): Grapevine winter survival and prospects in an age of changing climate. Research News: Cornell Viticulture and Enology Program Research Focus 2016-1: 7.

Londo J. (2017): Genetics and physiology of cold stress in Grapevine. USDA. Available at www.ars.usda.gov/ARSUserFiles/np305/GrapeandWine/2017%20Grape%20Research%20Workshop/6%20-%20Londo.pdf.

MGA, Manitoba Government Agriculture (2018): Available at https://www.gov.mb.ca/agriculture/crops/ production/fruit-crops/grape-growing-in-manitoba-and-on-the-prairies.html (accessed Oct 20, 2018).

Martinson T. (2011): Assessing winter cold injury to grape buds. Available at http://www.fruit.cornell.edu (accessed Oct 2, 2018).

Meier M., Fuhrer J., Holzkämper A. (2018): Changing risk of spring frost damage in grapevines due to climate change? A case study in the Swiss Rhone Valley. International Journal of Biometeorology, 62: 991–1002.

Miller D., Howell G.S., Striegler R.K. (1988a): Cane and bud hardiness of selected grapevine rootstocks. American Journal of Enology and Viticulture, 39: 55–59.

Miller D., Howell G., Striegler R. (1988b): Cane and bud hardiness of own-rooted white 'Riesling' and scion of 'White 'Riesling' and 'Chardonnay' grafted to selected rootstocks. American Journal of Enology and Viticulture, 39: 60–66.

Mussell A., Willwerth J., Fisher H. (2011): Grape varieties in Ontario wine regions, understanding the potential and the risks. Grape Growers of Ontario Publication.

Nassuth A. (2013): Can grapes avoid getting frostbite, Presentation, OSCWGA, Simcoe Research Station, ON, May 24, 2013.

Nixon L. (2001): Grape growers have their own language: foxy, earthy, Valiant. Farm & Home Research, 52: 1–7.

North M., Workmaster B.A., Atucha A. (2021): Cold hardiness of cold climate interspecific hybrid grapevines grown in a cold climate region. American Journal of Enology and Viticulture, 72: 318–327.

OIV, The International Organisation of Vine and Wine (2016): Table and dried grapes, FAO-OIV Publication: 64.

OIV, The International Organisation of Vine and Wine (2017): Distribution of the world's grapevine varieties, OIV Publication: 54. ISBN: 979-10-91799-89-8. Available at http://www.oiv.int/public/medias/5888/en-distribution-of-the-worlds-grapevine-varieties.pdf

Outreville J.F. (2009): Wine production in Québec. Conference Paper, Bacchus Goes Green, Dijon, France, July 2009. Available at https://www.researchgate.net/publication/293796850_Wine_Production_in_Quebec

Perry R.L., Sabbatini P. (2015): Grape rootstocks for Michigan. Michigan State University, MSU Extension bulletin, 3298: 8.

Pierquet P., Stushnoff C. (1980): Relationship of low temperature exotherms to cold injury in *Vitis riparia*. American Journal of Enology and Viticulture, 31: 1–6.

Plocher T.A., Parke B. (2001): Northern winework: Growing grapes and making wine in cold climates. In: Plocher T.A., Parke R.J. (eds): Winework Inc. Minnesota, USA, 178.

Pool R.M., Howard G.E. (1984): Managing vineyards to survive low temperatures with some potential varieties for hardiness. Proceedings of the International Symposium on Cool Climate Viticulture and Enology: 184–197.

Qrunfleh I.M. (2010): Delaying Bud Break in 'Edelweiss' Grapevines to avoid spring frost injury by NAA and vegetable oil applications, [Ph.D. Thesis.], University of Nebraska, Lincoln, 108.

Rahemi A. (2016): Breeding of grapevine rootstocks for adaptability to the environmental stresses. Third National Conference of Grape and Raisin, Research Institute of Grape and Raisin (RIGR), 27–29 September 2016, Malayer University, Malayer, Iran. (in Persian).

Rahman M.A. (2015): Analysis of the Role of; Grape ICE Proteins in the CBF Pathway and Stomatal Development, Ph.D. Thesis, University of Guelph, Canada: 171.

Reisch B.I., Luce S. (2005): Less Risky Varieties, Old and New, NYS Agricultural Experiment Station, Cornell University, Geneva, New York. Finger Lakes Grape Growers' Convention, March 4, 2005.

Richardson E.A., Seeley S.D., Walker D.R. (1974): A method for estimating the completion of rest for 'Redhaven' and 'Elberta' peach trees. HortScience, 9: 331–332.

Shamtsyan S.M., Mikeladze E.G., Abramidze S.P., Radmadze N.G. (1984): The effect of grafting on grapevine frost resistance. Soobshchenija Akademii Nauk, Tbilisi, 113:145–148.

Shaulis N., Einset J., Pack A.B. (1968): Growing cold-tender grape varieties in New York. N.Y. State, Agricultural Extension Stationensiontion Bulletin: 821.

Shoemaker W. (2012): What are Northern Grapes, In: Northern Grapes News, 1: 1–3.

Smiley L. (2016): A Review of Cold Climate Grape Cultivars. Extension of Iowa State University, 147.

https://doi.org/10.17221/176/2020-HORTSCI

Stafne E.T. (2007): Factors affecting cold hardiness in grapevines. Res. Ext. Bull., Department of Horticulture and Landscape Architecture, Oklahoma State University.

Stenger E. (2016): Environmental influence on cold-climate grapevine (*Vitis* spp.) Fall acclimation response and fruit ripening. [Ph.D. Thesis.]. North Dakota State University: 208.

Striegler R.K., Howell G.S. (2005): Influence of rootstock on the cold hardiness of potted Seyval grapevines during acclimation and deacclimation. Grapevine rootstocks; current use, research, and application. Proceedings of the 2005 Rootstock Symposium: 94–105.

UMN, University of Minnesota. (2018): University of Minnesota Grape Hardy Varieties, https://mnhardy.umn.edu/varieties/fruit/grapes (accessed Dec 12, 2018).

USDA, United States Department of Agriculture (2021): USDA Plant Hardiness Zone Map, https://planthardiness.ars.usda.gov/PHZMWeb/

Warmund M.R. (2006): Rest completion and susceptibility of blackberry floral buds to low temperature injury. University of Missouri, University of Massachusetts Amherst Extension, Berry Notes, 18: 2–5.

Weinberger J.H. (1950): Chilling requirements of peach varieties. Proceedings of the American Society for Horticultural Science, 56: 122–128.

Westover F. (2006): Compost use in the vineyard. In: Annual winter conference, Virginia Tech. Feb 10, 2006. Available at https://www.arec.vaes.vt.edu/content/dam/arec_vaes_vt_edu/alson-h-smith/grapes/viticulture/extension/growers/documents/compost-vineyard.pdf (accessed Oct 19, 2020).

Willwerth J., Ker K., Inglis D. (2014): Best management practices for reducing winter injury in grapevines. CCOVI, Brock University. Avaliable at https://brocku.ca/ccovi/wp-content/uploads/sites/125/Research-Best-Practices-Manual-Winter-Injury.pdf

Winkler A.J. (1974): General viticulture. University of California Press.

Wolf T.K., Miller M.K. (2001): Crop yield, quality, and winter injury of 12 red-fruited wine grape cultivars in Northern Virginia. Journal American Pomological Society, 55: 241–250.

Wolf T.K., Pool R.M. (1988): Nitrogen fertilization and rootstock effects on wood maturation and dormant bud cold hardiness of cv. 'Chardonnay' grapevines. American Journal of Enology and Viticulture, 39: 308–312.

Wolpert J.A., Howell G.S. (1985): Cold acclimation of Concord grapevines. II. Natural acclimation pattern and tissue moisture decline in canes and primary buds of bearing vines. American Journal of Enology and Viticulture, 36: 189–194.

Yilmaz T., Alahakoon D., Fennell A. (2021): Freezing tolerance and chilling fulfillment differences in cold climate grape cultivars. Horticulturae, 7: 4.

Zabadal T.J., Dami I.E., Goffinet M.C., Martinson T.E., Chien M.L. (2007): Cold hardiness of grapevines. Winter injury to grapevines and methods of protection, Michigan State University Extension Bulletin E, 2930: 7–18.

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