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ARTICLE

Cold hardiness of select apple cider cultivars in Canada

John A. Cline, Amanda Beneff, and A. Michelle Edwards

Abstract: There is increasing interest in growing European origin apple cultivars for the production of hard cider in Canada; however, little is known about their winter hardiness. Eleven promising cider cultivars were evaluated for cold hardiness over two consecutive winters and compared with the winter tender cultivar 'Golden Delicious'. Sections of the current season's dormant shoots were frozen in a series of test temperatures ranging from −20 °C to −40 °C in a programmable freezer. Xylem tissue browning ratings were used to assess injury after thawing. The temperature of incipient damage (TID), the warmest temperature at which 1-yr-old shoot segments begin to show injury, was obtained from tissue browning curves using non-linear regression. TID varied significantly among cultivars and between sampling years. Overall, the cultivars could be classified according to relative winter hardiness as follows: Ashmead's Kernel, Bramley's Seedling (very tender) < Calville Blanc d'Hiver, Porter's Perfection, Bulmer's Norman (intermediate) < Crimson Crisp, GoldRush, Golden Delicious, Enterprise, Yarlington Mill, Enterprise (hardy) < Golden Russet (hardy). These data indicate nearly a 10 °C range in winter hardiness amongst the 11 cultivars studied, depending on the sampling date. Ashmead's Kernel and Bramley's Seedling appear to be particularly winter tender, whereas Bulmer's Norman, Porter's Perfection, and Calville Blanc d'Hiver demonstrated less hardiness during three of the four sampling dates. Based upon these findings, it would be prudent to consult long-term climate normals and consider the frequency of extreme weather events for potential susceptibility to winter injury, particularly prior to establishing more injury-prone cultivars.

Key words: hard cider, European cider cultivars, winter injury, acclimation, de-acclimation.

Résumé : La culture de pommiers européens pour la production de cidre suscite de plus en plus d'intérêt au Canada. Malheureusement, on en sait peu sur la rusticité de ces variétés. Les auteurs ont évalué la résistance à l'hiver d'onze cultivars à cidre prometteurs pendant deux années consécutives puis l'ont comparée à celle du cultivar Golden Delicious, peu rustique. Les pousses d'un an en dormance ont été partiellement gelées dans un congélateur programmable, à une température de –20 °C à –40 °C. Les auteurs se sont servis du brunissement du xylème pour évaluer les dommages au dégel, ce qui leur a permis d'établir la température des dommages initiaux (TDI), c'est-à-dire la température à laquelle les rameaux d'un an commencent à présenter des dommages dus au gel, à partir de la courbe de brunissement des tissus obtenue par régression non linéaire. La TDI varie sensiblement d'un cultivar et d'une année à l'autre. Dans l'ensemble, on peut classer les cultivars comme suit, selon leur rusticité : Ashmead's Kernel, Bramley's Seedlings (très sensibles) < Calville Blanc d'Hiver, Porter's Perfection, Bulmer's Norman (intermédiaires) < Crimson Crisp, GoldRush, Golden Delicious, Enterprise, Yarlington Mill, Enterprise (rustiques) < Golden Russet (rustique). D'après ces données, la rusticité des onze cultivars examinés varie sur une plage de près de 10 °C, selon la date de l'échantillonnage. Ashmead's Kernel et Bramley's Seedling semblent particulièrement sensibles aux conditions hivernales, tandis que Bulmer's Norman, Porter's Perfection et Calville Blanc d'Hiver ont révélé une rusticité moins prononcée à trois des quatre dates d'échantillonnage. En raison de ces observations, la prudence commande qu'on consulte les normales climatiques à long terme et tienne compte de la fréquence des épisodes de froid extrême pour déterminer la sensibilité éventuelle des variétés plus fragiles aux dommages hivernaux avant d'en entreprendre la culture. [Traduit par la Rédaction]

Mots-clés : cidre, cultivars à cidre européens, destruction par l'hiver, acclimatation, perte de la tolérance au froid.

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Table 1. Apple cultvars, cider type, breeding parents, status, and hardiness used in this cold hardiness study.

Cultivar	Cider type[a]	Parents	Status	Hardiness[b]
Ashmead's Kernel	Sharp	Chance seedling	Discovred in 1782 in Gloucester, UK (Smith 1971). New to Ontario.	Unknown
Bramley's Seedling	Sharp	Chance seedling	Discover in Southwell, England circa 1867 (Taylor 1948). New to Ontario.	Hardy (Beach et al. 1905)
Bulmer's Norman	Bittersweet	Chance seedling	Originated in the early 20th century from Normandy, France. Old cultivar, new to Ontario.	Unknown
Calville Blanc d'Hiver	Sweet	Chance seedling	Likely orginated in France or Germany from the 16th century (Bultitude, 1983). New to Ontario.	Unknown
Crimson Crisp	Sweet	PCFW2-134 × PRI 669-205 (G. Delicious in heritage)	Bred from the PRI breeding program (Janick et al. 2006)	Unknown
Enterprise	Sharp	PRI 1661-1 × PRI 1661-2 (McIntosh, Delicious, G. Delicious and Rome Beauty in heritage)	Released in 1993 from the PRI breeding progam. Scan immune (Crosby et al. 1994)	Unknown
Golden Delicious	Sweet	Unknown; circumstantial evidence suggests Grimes Golden × Golden Reinette.	Originated from n Clay County, West Virgina. Reference cultivar. Widly grown and Canada and world-wide	Tender (Khanizadeh 2007; Quamme and Hampson 2004)
Golden Russet	Sweet	Unknown parentage	An old English variety with unknown history. Dating back to as early as 1876 (Taylor 1948). Grown currently and in the past in Ontario.	Unknown
GoldRush	Bittersweet	A cross between Golden Delicious and Coop 17	Widely grown for retail sales and cider production in North America. Named in 1994 from the PRI breeding program (Janick 2001)	At least −27 °C. Grown for over 25 yr at the Simcoe Research Station without any winter injury
Porter's Perfection	Bittersharp	Chance seedling	Originated in the 19th century in Somerset, UK.Old cultivar (new in Ontario)	Hardy to at least −29 °C (Trees of Antiquity 2021)
Yarlington Mill	Bittersweet	Chance seedling	Originated as a change seedling in 1898 in Yarlington, UK. (new to Ontario)	Unknown

[a]Based on the Long Ashton Research Station classification system (Lea 2008).
[b]Hardiness is based on previous reports in the literature as cited.

Introduction

There has been a resurgence in growing apples (*Malus domestica* Borkh.) for cider production in North America because of increased consumer demand for hard cider. Traditionally, cider, often referred to as 'hard cider', was produced primarily in Europe and made from bittersweet and bittersharp apple cultivars. These were typically higher in tannins and organic acids (Wilson et al. 2003) than the more recent North American cider that is often made from or blended with culinary apples (Cline et al. 2021). Ciders fermented with juice from cider-specific apple cultivars typically have higher tannin and acidity levels than their culinary counterparts and produce a more flavorful and aromatic product (Cline et al. 2021). In a recent study evaluating the horticultural and juice characteristics of cider-specific apple cultivars in Ontario (Plotkowski 2020; Plotkowski and Cline 2021*a*, 2021*b*), among 29 cultivars tested, 16 showed promise for their horticultural suitability and juice characteristics. These included: Ashmead's Kernel, Bramley's seedling (sharp), Bulmer's Norman, Yarlington Mill (bittersweet), Porters Perfection (bittersharp), Calville Blanc d'Hiver (sweet), Enterprise, Crimson Crisp Golden Russet, GoldRush (North American cultivars) (Table 1).

Some of these are not widely produced in Canada at this time.

There is a paucity of information on how well many of these and other cider cultivars perform in the colder regions of the United States and Canada, which represent a wide range of environments and hardiness zones from 8a to 4a and 4b (Natural Resources Canada 2021). Winter injury to trees continues to be a major constraint restricting Canadian fruit production (Lapins 1962; Quamme and Hampson 2004). To mitigate cold damage to trees, orchards are typically established near the moderating influence of large water bodies such as the Great Lakes in Ontario; Lake Okanagan in British Columbia; and the Atlantic Ocean in Nova Scotia, Prince Edward Island, and New Brunswick. Despite this, microclimates within these areas (particularly the Maritime provinces) lead to geographical pockets where winter damage is more prevalent. It has been reported that winter injury sufficient to cause damage to apple trees occurs once every 5–7 yr (Quamme 1976) in western Canada, and perhaps more frequently in eastern Canada (Coleman and Easterbrooks 1985). With changing climate patterns and microclimates within regions, increased variable temperatures and soil moisture conditions may lead to further risk of damage (Wolfe et al. 2018). Based on the literature and empirical evidence, temperate tree fruit crops in general — and fresh market apples specifically — differ in their susceptibility to winter injury (Cline et al. 2012).

Depending upon the region, cold temperatures can damage apple trees in the late autumn or midwinter. For example, in the Okanagan Valley of British Columbia, the most vulnerable period is late fall, when outbreaks of Arctic air flow southward and cause damage before the trees have fully acclimated (Caprio and Quamme 1999). In Ontario and Eastern Canada, the most vulnerable period is mid-to late winter, after unseasonably warm temperatures have caused early de-hardening followed by very lethal cold temperatures (Warner and Nickerson 1996; Westwood 2009). Late winter freezes can also cause injury to apple trees in climates where freeze–thaw cycles are frequent or in regions where apples are grown in extreme cold conditions (Coleman et al. 1985).

The lack of data on cold hardiness of cider cultivars makes it difficult for cidermakers and producers to identify which cultivars will have the greatest chance of being successful in Canada and other regions with similar climatic conditions. The objective of this study was to determine the winter hardiness of several promising apple cultivars used for cider and to determine minimum temperatures at which winter injury can be anticipated.

Materials and Methods

Wood tissue from 10 apple cultivars suitable for hard cider was sampled from research orchards at the Horticultural Experiment Station, Simcoe (lat. 42°51′40″ N, long. 80°16′8″ W) on 30 Jan. 2019, 27 Feb. 2019, 15 Dec. 2020, and 12 Feb. 2021 from mature fruiting trees on M.9 rootstock trained to a vertical axis orchard system. Pests and diseases were managed with convention pesticide (OMAFRA 2019) and were trickle irrigated. Trees were not fertilized with nitrogen. Daily minimum and maximum temperatures at 1.5 m above ground were recorded at the Simcoe Research Station weather station. The cultivars examined were Ashmead's Kernel, Bramley's Seedling, Bulmer's Norman, Calville Blanc d'Hiver, Crimson Crisp, Enterprise, Golden Russet, GoldRush, Porter's Perfection, and Yarlington Mill (Table 1). Golden Delicious was selected as a control cultivar because it is known to be sensitive to winter injury (Quamme and Hampson 2004). All trees from which samples were selected appeared healthy, free of disease and displayed typical growth and size representative of that cultivar. The early December sampling date was chosen for greater propensity to damage following an early cold period when trees would not be fully acclimated. The January and February dates were selected to represent the period in which trees would be at their maximum hardiness. Wood hardness and derivation of the temperature of incipient damage (TID) — the temperature at which the first detectable injury can be observed — was determined using a protocol described previously (Cline et al. 2012).

Ten 1-yr-old extension shoots that were at least 30 cm in length were sampled from each of seven individual tree replicates of each cultivar. Shoots were approximately 6–10 mm in diameter and were sampled from all parts of the canopy 1.2 m to 2 m above ground. All samples were collected from trees within 150 m radius of each other and were thus exposed to similar environmental conditions. Shoots of each cultivar were cut into lengths of about 4 cm. Shoot segments smaller than 6 mm diameter were discarded. Each segment included at least one vegetative bud (node). The wood segments were mixed in a plastic container and five to six pieces were sealed into each of ten 5 cm × 7.5 cm polyethylene zip-lock bags pre-labelled with a coded reference number and target temperature. The cultivar name was not included on the label to prevent biasing injury ratings.

The bags were transferred to a 0 °C chamber and stored overnight. Samples were then placed in a commercial chest freezer (Model 40–12, Scientemp, Adrian, MI) equipped with a circulating fan. Tissues were exposed to a series of test temperatures between −20 °C and −40 °C (2019/20) and −20 and −37.5 °C (2020/21), with a temperature ramp of −1 °C/h. Samples were removed at 2.5 °C intervals, beginning at −20 °C. When the target temperature was reached, the samples were removed from the freezing chamber, transferred to a cooler, and held in the dark at 1 °C for 24 h. Samples were then transferred to the lab and kept at ambient temperature

(22 °C) and 100% relative humidity for 24 h to allow tissue browning to occur, then stored at 4 °C in the dark to prevent decay over the 1–4 wk required to complete sample scoring.

Tissue browning was rated on a scale of 0 to 10 (photos can be found in Cline et al. 2012), modified from the original 0–5 scale described by Quamme (1987). Each shoot piece (5 pieces per replication per temperature per cultivar) was re-cut and viewed in cross-section with a stereomicroscope (Zeiss STEMI SV8, Carl Zeiss Canada, Don Mills, ON). Xylem tissue browning was rated by estimating the percent area affected, where 0 equals no visible damage, 1 equals 10% damage, 2 equals 20% damage, and so forth.

The shape of a typical freeze-tissue injury curve followed a sigmoidal pattern with the high rating scores (most severe injury) corresponding with the lowest temperatures.

Mean scores for each cultivar were regressed against temperature using eq. 1 and nonlinear regression using PROC NLMIXED in SAS (version 9.4, SAS Institute, Cary, NC).

$$r = \frac{a}{1 + e^{-[(x - x_0)/b]}} \quad (1)$$

Equation 1 is a sigmoidal function used to determine the relationship between temperature and xylem damage rating, where r is the damage rating, a and x_0 are coefficients, and x is temperature in °C.

The temperature corresponding to a rating of '1' (trace amount of injury) was interpolated from each curve and was designated as TID, also sometimes called the minimum survival temperature (Chilton et al. 1994, Fujikawa et al. 2009, Quamme et al. 2009). This rating, while somewhat arbitrary, would likely result in xylem damage in the orchard and manifest itself through typical cold injury symptoms such as shoot top dieback (H. Quamme, personal communication). Mean rating scores for each cultivar and exposure temperature were analyzed using PROC GLMMIX (SAS version 9.4; SAS Institute, Cary, NC) and cultivar lsmeans were separated using Tukey's HSD at $P = 0.05$.

Results and Discussion

Xylem injury

Significant cultivar differences in winter cold hardiness, as indicated by xylem browning, were observed during all four sampling dates (Table 2). The overall temperatures at which injury was observed were consistent with those published previously using data from Ontario and British Columbia (Cline et al. 2012). Significant cultivar differences in xylem injury were not observed when exposed to temperatures at or warmer than −22.5 °C on any sampling date, except 30 Jan. 2019 when slight injury was observed in Bramley's Seedling at −20 °C. Cultivar differences in tissue browning were observed at temperatures colder than −25 °C on all sampling dates. Xylem injury with a TID rating greater than 1.0 became evident at temperatures of −27.5 °C on 30 Jan. 2019, −30.0 °C on 27 Feb. 2019, −27.5 °C on 15 Dec. 2020, and −35 °C on 12 Feb. 2021 and increased in a sigmoidal fashion with decreasing temperatures (Table 2). It is at these temperatures that damage to xylem ray parenchyma cells occurs (Hampson et al. 2005; Wilner 1964), and consequently could negatively affect tree health and performance in the orchard (Palonen and Buszard 1997).

TID, calculated using eq. 1, varied markedly between cultivars and sampling dates for each cultivar (Table 3). For the winter of 2019/20, TID values were relatively consistent between 30 Jan. 2019 and 27 Feb. 2019 and ranged from −27.0 °C to −34.7 °C and −27.0 °C to −33.3 °C, respectively. Ashmead's Kernel, Bramley's Seedling, Porter's Perfection, and Bulmer's Norman had TID values above −28 °C during these dates, indicating that these cultivars had the greatest likelihood of winter injury. In contrast, Golden Russet, Yarlington Mill, Enterprise, Golden Delicious, GoldRush, and Crimson Crisp were the most winter hardy cultivars, with TID values below −31 °C.

For the winter of 2020/21, TID values were markedly higher on 15 Dec. 2020 compared with 12 Feb. 2021, where they ranged from −24.9 °C to −36.0 °C and −33.8 °C to −49.5 °C, respectively. On 15 Dec. 2020, Calville Blanc d'Hiver, Ashmead's Kernel, and Bramley's Seedling had TID values close to or above −28 °C, indicating they were the cultivars with the greatest likelihood of cold injury in the early winter when trees were acclimating. In contrast, Golden Russet, Golden Delicious, Porter's Pefection, GoldRush, and Yarlington Mill were the most winter hardy cultivars, with TID below −31 °C. On 12 Feb. 2021, no cultivars had TID values above −33.8 °C, indicating that all cultivars had acclimated well and were showing excellent winter hardiness. However, on this sampling date, the relationship between the tissue rating and exposure temperature provided a less pronounced sigmoidal patter (data not shown), likely leading to an over-estimation of the lower TID temperatures. For example, Golden Russet, Bulmer's Norman, and Calville Blanc d'Hiver had TID values of 49.5 °C, −43.4 °C, and −49.5 °C, respectively. Apple stem xylem ray parenchyma and pith cells avoid freezing by deep supercooling (Quamme 1991; Malone and Ashworth 1990), but the limits of supercooling are −40 °C (Palonen and Buszard 1997). Based on the known limits of apple production in Canada, as well as biophysical aspects of cold hardiness and supercooling, TID values below −40 °C are unlikely and unreliable predictors of apple cultivar sensitivity to winter injury. Consequently, the TID values generated on 12 Feb 2021 should be interpreted with caution.

Overall, in Table 4 and Fig. 1, the winter hardiness of cider cultivars summarized in order of increasing winter

Table 2. Lsmean shoot xylem injury rating of several cider apple cultivars sampled on four dates from the Simcoe Reseach Station and exposed to temperatures ranging from −22.5 °C to −40 °C.

Cultivar	−20.0 °C	−22.5 °C	−25.0 °C	−27.5 °C	−30.0 °C	−32.5 °C	−35.0 °C	−37.5 °C	−40.0 °C	Overall average
	30 Jan. 2019									
Ashmead's Kernel	0.0	0.1	0.2	1.2	2.5	2.0	3.5	5.1	6.4	2.4
Bramley's Seedling	0.1	0.1	0.1	1.2	2.0	3.2	5.1	7.6	8.2	3.1
Bulmer's Norman	0.0	0.0	0.1	0.2	1.9	3.7	4.5	6.4	6.2	2.6
Calville Blanc d'Hiver	0.0	0.0	0.0	0.4	1.7	2.6	5.3	5.5	5.8	2.4
Crimson Crisp	0.0	0.0	0.0	0.0	0.3	1.0	3.2	5.6	6.6	1.8
Enterprise	0.0	0.0	0.0	0.0	0.0	0.2	3.6	3.4	5.2	1.4
Golden Delicious	0.0	0.0	0.0	0.8	1.3	0.4	1.5	3.0	4.6	1.3
Golden Russet	0.0	0.0	0.0	0.2	0.4	0.2	2.4	4.3	3.1	1.2
GoldRush	0.0	0.0	0.0	0.0	0.0	0.8	1.6	4.8	5.9	1.5
Porter's Perfection	0.0	0.0	0.0	0.4	1.2	2.6	5.9	6.2	6.8	2.6
Yarlington Mill	0.0	0.0	0.0	0.2	0.0	0.1	1.0	2.7	3.6	0.8
P value	0.0134	0.0786	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
	27 Feb. 2019									
Ashmead's Kernel	0.0	0.1	0.0	0.0	3.4	3.9	6.4	7.4	9.7	3.4
Bramley's Seedling	0.0	0.1	0.0	0.7	0.8	3.8	4.9	8.2	8.8	3.0
Bulmer's Norman	0.1	0.0	0.0	0.2	3.1	5.8	7.3	8.0	8.8	4.2
Calville Blanc d'Hiver	0.0	0.0	0.0	0.0	1.3	3.4	5.0	8.1	9.0	3.0
Crimson Crisp	0.0	0.0	0.0	0.0	0.5	1.0	5.0	7.4	8.3	2.5
Enterprise	0.0	0.0	0.0	0.0	0.1	0.9	3.9	6.4	8.9	2.2
Golden Delicious	0.1	0.0	0.2	0.1	0.2	0.8	3.9	5.1	7.3	2.0
Golden Russet	0.0	0.0	0.0	0.0	0.3	0.0	2.6	5.5	9.0	1.9
GoldRush	0.0	0.0	0.0	0.0	0.9	0.6	4.4	5.5	9.8	2.7
Porter's Perfection	0.0	0.0	0.0	0.6	4.2	5.9	6.6	7.3	8.0	3.6
Yarlington Mill	0.1	0.1	0.0	0.1	0.4	2.0	3.6	5.7	9.1	2.3
P value	0.0632	0.495	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.0338

Table 2. (*concluded*).

Cultivar	−20.0 °C	−22.5 °C	−25.0 °C	−27.5 °C	−30.0 °C	−32.5 °C	−35.0 °C	−37.5 °C	−40.0 °C	Overall average
	15 Dec. 2020									
Ashmead’s Kernel	0.3	0.0	0.1	0.6	2.9	2.5	3.2	6.4	—	2.0
Bramley’s Seedling	0.0	0.0	0.5	1.0	1.9	2.2	3.1	5.6	—	1.8
Bulmer’s Norman	0.0	0.0	0.1	0.4	1.3	2.2	2.2	3.3	—	1.2
Calville Blanc d’Hiver	0.0	0.1	0.4	1.5	4.5	3.9	5.0	7.4	—	2.8
Crimson Crisp	0.0	0.0	0.1	0.1	0.9	2.3	2.4	4.0	—	1.1
Enterprise	0.0	0.1	0.0	0.1	0.7	1.4	1.3	1.8	—	0.7
Golden Delicious	0.0	0.0	0.1	0.4	0.7	0.4	2.2	5.2	—	1.1
Golden Russet	0.0	0.1	0.0	0.1	0.1	0.1	0.7	1.7	—	0.3
GoldRush	0.0	0.0	0.1	0.0	0.0	1.3	2.8	6.8	—	1.4
Porter’s Perfection	0.0	0.1	0.0	0.2	0.6	0.7	2.2	4.3	—	1.0
Yarlington Mill	0.0	0.2	0.0	0.3	0.7	1.2	2.9	5.5	—	1.3
P value	<0.001	0.0855	0.002	<0.001	<0.001	<0.001	0.0002	0.0004		<0.001
	12 Feb. 2021									
Ashmead’s Kernel	0.0	0.0	0.1	0.0	0.0	0.6	0.8	3.2	—	0.6
Bramley’s Seedling	0.0	0.0	0.0	0.0	0.2	0.8	1.9	3.7	—	0.8
Bulmer’s Norman	0.1	0.0	0.0	0.1	0.3	0.8	2.2	1.8	—	0.6
Calville Blanc d’Hiver	0.0	0.1	0.0	0.0	0.0	0.2	0.8	4.1	—	0.6
Crimson Crisp	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.8	—	0.1
Enterprise	0.0	0.0	0.0	0.0	0.1	0.2	1.0	1.2	—	0.3
Golden Delicious	0.0	0.1	0.0	0.1	0.1	0.4	0.8	0.3	—	0.2
Golden Russet	0.0	0.0	0.0	0.1	0.0	0.1	0.3	0.5	—	0.1
GoldRush	0.0	0.0	0.0	0.2	0.0	0.1	0.1	0.4	—	0.1
Porter’s Perfection	0.0	0.1	0.0	0.0	0.0	0.4	1.8	0.8	—	0.4
Yarlington Mill	0.0	0.1	0.0	0.1	0.0	0.1	0.1	1.3	—	0.2
P value	0.465	0.717	0.465	0.649	0.012	0.001	<0.001	<0.001		0.0008

Table 3. Regression parameters, regression coefficient (R^2), and predicted temperatures when assessment of tissue browning reached a value of 1 (temperature of incipient damage) for several cider apple cultivars sampled on four dates. University of Guelph Research Station, Simcoe.

Cultivar	Parameter a[a]	Parameter x0[a]	Parameter b[a]	R^2	Estimated temperatue (°C) at which TID was associated with a rating of 1
	30 Jan. 2019				
Ashmead's Kernel	10.3	−37.8	−4.61	0.96	−27.0
Bramley's Seedling	9.8	−34.4	−3.00	0.97	−27.6
Bulmer's Norman	6.4	−32.2	−2.09	0.98	−28.3
Calville Blanc d'Hiver	5.9	−32.4	−1.86	0.96	−29.1
Crimson Crisp	7.0	−35.3	−1.60	0.99	−32.2
Enterprise	4.3	−34.1	−0.55	0.96	−33.3
Golden Delicious	274.5	−60.0	−4.93	0.94	−32.4
Golden Russet	3.7	−34.8	−0.41	0.99	−34.2
GoldRush	6.3	−36.2	−1.29	0.96	−33.8
Porter's Perfection	6.8	−32.9	−1.51	0.93	−30.0
Yarlington Mill	3.7	−36.3	−1.26	0.98	−34.7
	27 Feb. 2019				
Ashmead's Kernel	10.4	−33.8	−2.92	0.96	−27.0
Bramley's Seedling	9.8	−34.4	−2.36	0.97	−29.0
Bulmer's Norman	8.3	−31.2	−1.63	0.98	−27.7
Calville Blanc d'Hiver	10.0	−34.5	−2.32	0.96	−29.2
Crimson Crisp	8.2	−34.5	−1.15	0.99	−32.1
Enterprise	9.7	−36.0	−1.78	0.96	−32.0
Golden Delicious	7.8	−35.6	−1.89	0.94	−31.8
Golden Russet	10.9	−37.4	−1.72	0.99	−33.3
GoldRush	16.5	−39.0	−2.85	0.96	−31.0
Porter's Perfection	7.3	−29.9	−1.42	0.93	−27.1
Yarlington Mill	15.0	−38.7	−2.99	0.98	−30.7
	15 Dec. 2020				
Ashmead's Kernel	125.2	−52.9	−5.2	0.78	−27.8
Bramley's Seedling	88.7	−51.7	−5.2	0.86	−28.3
Bulmer's Norman	3.3	−31.6	−2.5	0.82	−28.7
Calville Blanc d'Hiver	8.1	−32.0	−3.4	0.81	−24.9
Crimson Crisp	4.7	−33.8	−2.7	0.80	−29.7
Enterprise	1.6	−30.3	−1.2	0.64	−29.7
Golden Delicious	46.8	−42.8	−2.6	0.96	−33.0
Golden Russet	17.1	−42.6	−2.3	0.73	−36.0
GoldRush	81.6	−43.7	−2.6	0.91	−32.3
Porter's Perfection	19.7	−41.1	−2.8	0.54	−32.6
Yarlington Mill	35.0	−42.8	−3.2	0.89	−31.6
	12 Feb. 2021				
Ashmead's Kernel	5.2	−37.4	−2.2	0.77	−33.8
Bramley's Seedling	7.9	−39.6	−2.5	0.94	−34.4
Bulmer's Norman	5.6	−38.0	3.1	0.73	−43.4
Calville Blanc d'Hiver	10.5	−43.0	−1.3	0.83	−40.0
Crimson Crisp	6.7	−41.1	−2.0	0.58	−37.3
Enterprise	8.4	−43.2	−2.3	0.51	−38.2
Golden Delicious	5.4	−40.3	−3.1	0.14	−35.1
Golden Russet	14.7	−49.7	0.0	0.44	−49.5
GoldRush	3.9	−38.7	−2.8	0.22	−34.9
Porter's Perfection	6.2	−40.2	−3.1	0.30	−34.5
Yarlington Mill	6.8	−41.8	−2.3	0.35	−37.4

[a]Ratings approximated a decay model, where rating, $r = a \times e^{-bx}$, x = temperature (°C).

Table 4. Predicted temperatures when assessment of tissue browning reached a value of 1 (TID °C) for eleven apple cider cultivars over several dates. University of Guelph Research Station, Simcoe[a]

Cultivar[a]	30 Jan. 2019	Rank[c]	27 Feb. 2019	Rank	15 Dec. 2020	Rank	12 Feb. 2021	Rank	Overall maximum TID (°C)	Overall mean	
Golden Russet	−34.2	10	−33.3	11	−36.0	11	−49.5	11	−33	−38 ± 7.6	Very hardy
Yarlington Mill	−34.7	11	−30.7	6	−31.6	7	−37.4	7	−31	−34 ± 3.1	Hardy
Enterprise	−33.3	8	−32.0	9	−29.7	6	−38.2	8	−30	−33 ± 3.6	
Golden Delicious	−32.4	7	−31.8	8	−33.0	10	−35.1	5	−32	−33 ± 1.5	
GoldRush	−33.8	9	−31.0	7	−32.3	8	−34.9	4	−31	−33 ± 1.7	
Crimson Crisp	−32.2	6	−32.1	10	−29.7	5	−37.3	6	−30	−33 ± 3.2	
Bulmer's Norman	−28.3	3	−27.7	3	−28.7	4	−43.4	10	−28	−32 ± 7.6	Intermediate
Porter's Perfection	−30.0	5	−27.1	2	−32.6	9	−34.5	3	−27	−31 ± 3.2	
Calville Blanc d'Hiver	−29.1	4	−29.2	5	−24.9	1	−40.0	9	−25	−31 ± 6.5	
Bramley's Seedling	−27.6	2	−29.0	4	−28.3	3	−34.4	2	−28	−30 ± 3.1	Tender
Ashmead's Kernel	−27.0	1	−27.0	1	−27.8	2	−33.8	1	−27	−29 ± 3.3	

[a]Cultivars ranked in order of most to least winter hardy.
[b]Ratings approximated a sigmoidal model, where rating, $r = \frac{a}{1 + e^{-[(x-x_0)/b]}}$ and x = temperature (°C).
[c]Ranking from least (1) to most winter hardy (11).

hardiness are: Ashmead's Kernel < Bramley's Seedling< Calville Blanc d'Hiver < Porter's Perfection < Bulmer's Norman < Crimson Crisp < GoldRush < Golden Delicious < Enterprise < Yarlington Mill < Golden Russet. In other studies, Golden Delicious has been described as a winter sensitive (Cline et al. 2012) cultivar. Similarly, in this study, only three cultivars (Enterprise, Yarlington Mill, and Golden Russet) had TID values lower than Golden Delicious. However, variation existed in TID values for individual cultivars between the four sampling dates, with the greatest variation observed for Golden Russet, Bulmer's Norman, and Calville Blanc D'hiver and the least variation observed for Golden Delicious and GoldRush. Golden Russet, Yarlington Mill, Enterprise, Golden Delicious, and GoldRush were ranked as the most cold-hardy cider cultivars, while Ashmead's Kernel and Bramley's Seedling were ranked as the least cold-hardy cultivars.

Weather and environmental conditions

To understand short- and long-term climatic effects on acclimation and de-acclimation processes and how these may have influenced the hardiness values, daily minimum and maximum temperatures are presented for the winters in which this study was conducted (Fig. 2). Air temperatures prior to 30 Jan. 2019 ranged from a low of −14.8 °C on 20 Jan. and a high of 13 °C on 11 Jan. Temperatures 7 d preceding sampling ranged from 4.8 °C to −6.4 °C. During the month of February, air temperatures ranged from a minimum of −16.6 °C to a maximum of 9.7 °C and overall were colder than in January. The winter of December of 2020 was relatively mild, with temperatures fluctuating between 10 °C and −6 °C. However, temperatures decreased in January and February prior to the 12 Feb. sampling date. Temperatures 7 d preceding sampling ranged from 2.0 °C to −16.5 °C.

Ten days prior to the 30 Jan. 2020 sampling date, relatively low minimum temperatures were experienced, but then were followed by warmer temperatures, with 6 d reaching temperatures above 0 °C. Ashmead's Kernel and Brameley's seedling showed markedly higher TID values and therefore may have de-acclimated more rapidly than the other cultivars under study. Thirteen days prior to the 27 Feb. 2020 sampling date, low minimum temperatures of −16.6 °C were experienced but were then followed by temperatures above 9 °C within 4 d of the testing date. Ashmead Kernel, Porter's Perfection, Bulmer's Norman, Bramley's Seedling, and Calville Blanc D'Hiver had the most visible xylem injury (highest TID) at this time. It seems that Porter's Perfection, Bulmer's Norman, and Calville Blanc D'Hiver may de-acclimate more rapidly in the late winter, based on their higher TID values compared with the 30 Jan 2020 sampling date. Air temperatures prior to the 15 Dec. 2020 sampling date were variable, but typical of those experienced in Simcoe during early

Fig. 1. Estimate of temperatures at which xylem injury equalled a value of 1 (temperature of incipient damage, TID) for 11 cider cultivars across four sampling dates (30 Jan. 2019, 27 Feb. 2019, 14 Dec. 2020, 12 Feb. 2021). Error bars represent the standard deviation of the fours sampling dates, divided by two.

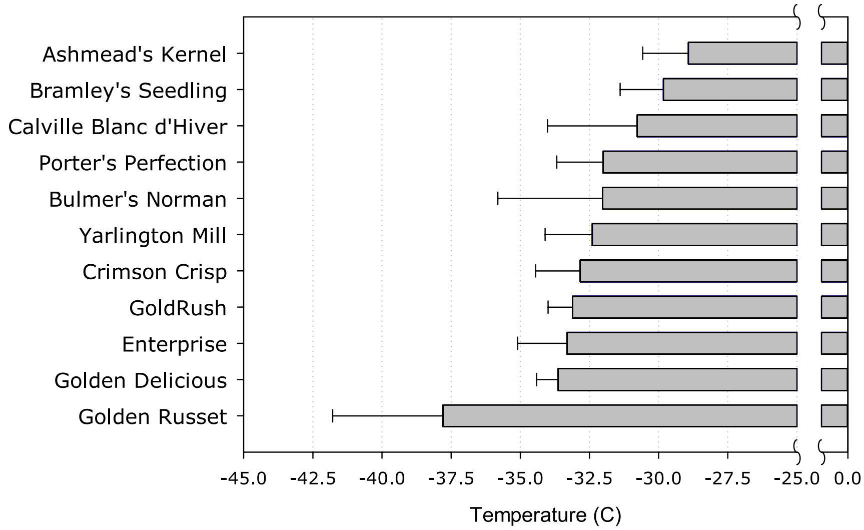
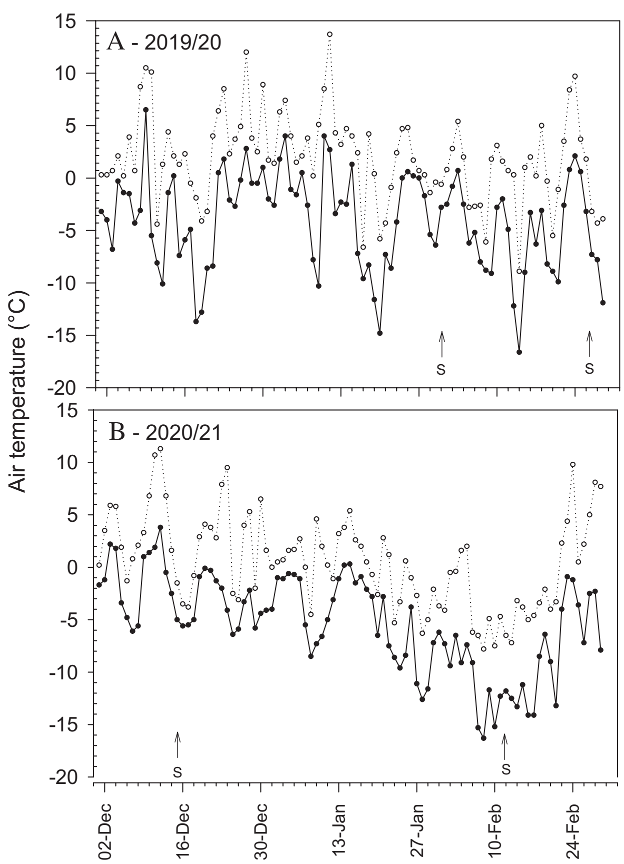


Fig. 2. Minimum (•, solid line) and maximum (○, dashed line) air temperatures at the University of Guelph Simcoe Research Station, Simcoe, ON between 1 Dec. 2019–29 Feb. 2020 (A) and 1 Dec. 2020–28 Feb. 2021 (B). The sample dates are indicated by "S".



December. Minimum air temperatures did not exceed −6.1 °C prior to 15 Dec. and the daily maximum temperatures were above 0 °C for 14 of the 15 d, with maximum temperatures reaching 11.3 °C. Calville Blanc D'Hiver, Ashmead's Kernel, and Bramley's Seedling had the highest TID values, which were relatively consistent with the previous sampling dates. Calville Blanc D'Hiver's particularly high TID value of −24.9 °C in mid-December suggests that it may not have acclimated as well as the other cultivars under study at the time. Temperatures in early February 2021 represented the coldest period during the winter of 2020/21, with a minimum of −16.3 °C and most daily maximums below 0 °C. Based on the significantly lower TID values, all cultivars had lower xylem injury TID values. Consistent with other sampling dates, Ashmead's Kernel, Bramley's Seedling, and Porter's Perfection had the highest TID values (all below −33.8 °C) on 12 Feb. 2021.

Based on several studies reviewed by Kalberer et al. (2006), de-acclimation occurs more rapidly (days to weeks) than acclimation (weeks to months). In one study on apple in Michigan, a de-acclimation loss of 15 °C in hardiness occurring over 1 d required three cold days to be reversed (Howell and Weiser 1970). The acclimation and de-acclimation processes in the present study were clearly influenced by both air temperature and the apple cultivars assessed (Khanizadeh 2007), but further comment on these effects is beyond the scope of this study.

There are few studies in the scientific literature that have quantified the winter hardiness of cider cultivars, and specifically those investigated in this study. While some anecdotal information exists, no information in the scientific literature was readily found regarding the winter hardiness of the following cider cultivars: Ashmead's Kernel, Bulmer's Norman, Calville Blanc D'hiver, Crimson Crisp, GoldRush, and Enterprise; consequently, this study offers new insight into the potential hardiness of these cultivars. Many empirical observations have been made on the other cultivars that were investigated, but often with imprecise classification. Jolicoeur (2013) found Bramley's seedling not sufficiently hardy in hardiness zone 4 (min temperatures of −34.4 °C), whereas Beach et al. (1905) considered it "hardy". Jolicoeur (2013) reported "good" hardiness of Golden Russet, Porter's Perfection, and Yarlington Mill in Quebec (hardiness zone 4). Other work (Trees of Antiquity 2021) has reported that Porter's Perfect is hardy to −29 °C; however, in Nova Scotia, producers found Golden Russet to be only "moderately hardy" (Nova Scotia Apples 2021). Quamme and Hampson (2004) observed that GoldRush had an average TID value of −26.8 °C, similar to Golden Delicious, when grown in the Okanagan Valley of British Columbia. Crimson Crisp, GoldRush, and Enterprise are all well-established fresh-market cultivars in the apple growing regions of Ontario, the Great Lakes and New England. Based on several decades of empirical observations at the Simcoe Research Station (hardiness zone 6a, minimum winter temperatures of −23.3 °C), these cultivars have not suffered from winter injury.

Collectively, these data indicate nearly a 10 °C range in winter hardiness amongst the 11 cultivars studied, depending upon the sampling date. Ashmead's Kernel, and Bramley's Seedling appear to have the least winter resistance, but acclimation and de-acclimation events may also predispose Porter's Pefection, Bulmer's Norman, and Calville Blanc D'hiver to winter injury when grown in Ontario. Further data are required to substantiate these results, and apple growers are cautioned to avoid planting these cultivars in the colder apple producing regions of Canada and other regions with a similar climate. To gauge the level of risk for the cider apple cultivars identified as being susceptible to winter injury prior to establishment, it would be prudent to consult long-term climate normals (Environment Canada 2021) and to consider the frequency of extreme weather events.

Competing Interest

The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Contributors' Statement

J. Cline conceptualized and planned the experiment and developed the methodology. A. Beneff conducted the laboratory analyses and assisted with data processing. M. Edwards advised on the statistical procedures, and J. Cline conducted the data analyses. J. Cline reviewed the literature. J. Cline wrote the original manuscript and compiled revisions and M. Edwards and A. Beneff assisted with editing.

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