VITICULTURE PERFORMANCE AND COLD HARDINESS ATTRIBUTES OF SELECT WINEGRAPE CULTIVARS IN THE WESTERN SNAKE RIVER PLAIN OF IDAHO

by

Jacob Joseph Cragin

A thesis

submitted in partial fulfillment

of the requirements for the degree of

Master of Science in Biology

Boise State University

December 2015

BOISE STATE UNIVERSITY GRADUATE COLLEGE

DEFENSE COMMITTEE AND FINAL READING APPROVALS

of the thesis submitted by

Jacob Joseph Cragin

Thesis Title: Viticulture Performance and Cold Hardiness Attributes of Select Winegrape Cultivars in the Western Snake River Plain of Idaho

Date of Final Oral Examination: 22 April 2015

The following individuals read and discussed the thesis submitted by student Jacob Joseph Cragin, and they evaluated his presentation and response to questions during the final oral examination. They found that the student passed the final oral examination.

Marcelo D. Serpe, Ph.D.	Chair, Supervisory Committee
James F. Smith, Ph.D.	Member, Supervisory Committee
Krista C. Shellie, Ph.D.	Member, Supervisory Committee
Markus Keller, Ph.D.	Member, Supervisory Committee

The final reading approval of the thesis was granted by Marcelo Serpe, Ph.D., Chair of the Supervisory Committee. The thesis was approved for the Graduate College by John R. Pelton, Ph.D., Dean of the Graduate College.

ACKNOWLEDGEMENTS

I would like to thank the Idaho State Department of Agriculture for funding this research. I would like to thank the U.S. Department of Agriculture-Agriculture Research Service for facilitating this study as well as Boise State University for their support. I would like to thank Alan Muir, Monte Shields, and Cheryl Franklin-Miller for their technical expertise and Winemakers LLC for the use of their field resources. I would like to thank Dr. Markus Keller and Dr. James Smith for their insightful comments and suggestions during the course of my research and my thesis. A very special thanks to Dr. Marcelo Serpe and Dr. Krista Shellie for mentoring me through my education and my research.

ABSTRACT

This two part study was carried out in the Snake River Valley American viticulture area (SRV AVA) in Idaho. This area is a northern latitude, high elevation plateau where growing season is delimited by cold temperature. For the first part of the study, the performance of red and white-skinned winegrape cultivars (*Vitis vinifera*, L.) were compared to that of the widely grown cultivars Merlot and Cabernet Sauvignon. Phenology, juice composition, yield, cold injury, and cold hardiness were observed during the 2011 and 2012 growing seasons. Phenological events occurred later in the cooler 2011 season than the warmer 2012 season. At harvest, the sugar to acid ratios in both seasons were higher for Grüner Veltliner, Trousseau, Merlot, and Sauvignon Gris and lower for Aglianico and Aleatico, indicating overripe and unripe fruit, respectively. Touriga Brasileira had high yields, low pruning weights, and a high Ravaz index while Carmenère had lower yields, higher pruning weights, and a low Ravaz index. These results indicated that these vines were out of balance with too much growth directed to either vegetative or reproductive organs. Montepulciano and Tinto Cão had the highest percentage of cold injury, which excluded them from performance evaluations. Maximum cold hardiness occurred during December and January for all tested cultivars, with some month to month differences amongst cultivars. The second part of the study characterized cold hardiness in two widely grown cultivars, Chardonnay and Cabernet Sauvignon, throughout their dormancy cycle. The aims were to identify differences in cold hardiness between the two cultivars, to characterize the relationship between cold

hardiness and stages of dormancy, and to analyze the buds ability to deacclimate and reacclimate during ecodormancy. Data were collected over two seasons (2011-12 and 2012-13) on vines grown in an experimental vineyard in Parma, ID. The stage and depth of bud dormancy was assessed using a forcing bioassay to evaluate percent budbreak and the cold hardiness of buds was evaluated by determining the temperature that caused 50% bud death (LTE_{50}) using a differential thermal analysis (DTA) system. The cold hardiness data was also used to evaluate the accuracy of the Ferguson dynamic thermal time model on predicting bud LTE_{50} values of Chardonnay and Cabernet Sauvignon. Chardonnay acclimated earlier and more rapidly than Cabernet Sauvignon during autumn. The buds of Chardonnay transitioned to ecodormancy earlier than those of Cabernet Sauvignon and in both cultivars maximum bud cold hardiness was acquired during ecodormancy. Acquisition of maximum bud cold hardiness after release from endormancy suggests that some metabolic factors associated with cold acclimation are independent of endodormancy. The dynamic thermal model accurately predicted cold hardiness in both cultivars, though it was more accurate for Cabernet Sauvignon than Chardonnay. Results indicate that Chardonnay is better adapted to areas with colder falls and winters than Cabernet Sauvignon. Furthermore, Chardonnay is better suited than Cabernet Sauvignon for sites that experience early autumn cold events. Cabernet Sauvignon was more resistant to deacclimation and more capable of reacclimation than Chardonnay. These results suggest that Cabernet Sauvignon is better suited than Chardonnay for sites that experience fluctuating mid-winter temperature events and late spring frosts.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER ONE: PERFORMANCE OF LESSER KNOWN CULTIVARS UNDER THE EDAPHOCLIMATIC CONDITIONS OF THE WESTER SNAKE RIVER PLAIN

Abstract

Lesser known red and white-skinned winegrape cultivars (*Vitis vinifera*, L.) were grown in Nampa, Idaho and their performance compared with that of two leading cultivars Merlot and Cabernet Sauvignon. The experimental vineyard is located within the Western Snake River Plain (WSRP); a northern latitude, high elevation plateau where growing season is delimited by cold temperature. Phenology, juice composition, yield, cold injury, and cold hardiness were analyzed during a cooler 2011 growing season (1440 growing degree days ºC) and a warmer 2012 growing season (1523 growing degree days ºC). All evaluated phenological events occurred later in the 2011 season than the 2012 season. Budbreak occurred the earliest for Grüner Veltliner, Verdelho, and Fernão Pires while most other cultivars broke bud on or in between the budbreak of Merlot and Cabernet Sauvignon. Trousseau and Sauvignon Blanc Musqué were cultivars that flowered later and reached veraison early while Aglianico and Aleatico were slow to reach maturity. At harvest, Grüner Veltliner, Trousseau, Merlot, and Sauvignon Gris had the highest sugar to acid ratios in both seasons indicating overripe fruit and Aglianico and Aleatico had the lowest sugar to acid ratios indicating unripe fruit. Touriga Brasileira had high yields and low pruning weights with a high Ravaz index while Carmenère had the lower yields and higher pruning weights with a low Ravaz index indicating that these vines were out of balance with too much growth directed to canopy and not enough

towards fruit. Montepulciano and Tinto Cão had the highest percentage of cold injury, which resulted in them being excluded from phenology, juice, and yield evaluations. The evaluation of cold hardiness determined month to month differences amongst select lesser known cultivars and the standards Cabernet Sauvignon and Merlot with these cultivars reaching maximum cold hardiness during December or January. The selected lesser known cultivars and two standards were cold hardy enough to avoid 50% bud kill during both winter seasons. Cultivars that are cold hardy bud and flower late to avoid frost damage, and ripen early would be the most ideal for growing conditions in the Western Snake River Plain of Idaho.

Introduction

Grapes are the largest fruit crop in the United States and the second largest fruit crop in Idaho (U.S.D.A. 2007). From 1999 to 2010, the United States experienced an increase from 2,688 to 6,668 wineries (U.S. Dept. Commerce 2011). The estimated U.S. wine industry retail value is $30 billion with 44% of all U.S. wineries originating in California and accounting for 89.5% of domestic wine production (U.S. Dept. Commerce 2011). Many new production areas are developing in North America in regions once considered unsuitable or marginal for winegrape production. These areas could be considered marginal for various edaphoclimatic reasons, such as short growing seasons, and saline or sodic soils. However, the high economic value of the wine industry as an agribusiness and increasing tourism has led to a desire to develop these marginal areas. In 2008, it was projected that the total economic impact of the Idaho wine and grape products industry was $73 million to the state as well as 625 full time positions and $19 million in employee wages (Beirle et al. 2008). From 2002 to 2008, winery revenue

increased from $15 to $52 million with the majority of wine and revenue being generated in the Canyon County portion of the Snake River Valley American Viticultural Area (Beirle et al. 2008, Foltz et al. 2007).

The Snake River Valley American Viticulture Area is located in Southwestern Idaho and Eastern Oregon and was established in 2007. The SRV AVA is the third largest AVA in the Western United States in terms of area and spans 21,652 km^2. The SRV AVA is a high plateau, semi-arid sagebrush steppe with most vineyards located at elevations between 695 to 890 m (Gillerman et al. 2006, Jones et al. 2010). In the SRV AVA, the climate is considered intermediate to cool based on the growing season average temperature (GST) index with a GST of 16.1 °C and a historical median of 1329 growing degree days (GDD °C) (Jones et al. 2010). The Snake River AVA has fewer growing degree days, less precipitation and colder winters than better known AVAs such as Napa Valley in California or Walla Walla in Washington (Gillerman et al. 2006). Climate is an important factor in the determination of cultivar suitability for producing quality wine grapes and a classification system was developed to describe and compare wine production regions (Winkler et al. 1974). Based on the Winkler scale, the Snake River Valley AVA is classified as California Climatic Region II (Jones et al. 2010). The semi-arid steppe climate can be compared with growing regions in Eastern Washington such as the Columbia Valley AVA.

The major factors limiting wine grape production in the SRV AVA are tolerance to cold in the fall and spring, tolerance to mid-winter cold during dormancy, and the ability to ripen fruit to maturity. Major advantages for growing wine grapes in this region are the semi-arid climate with a readily available supply of water for irrigation and a high

incidence of cloudless days with high solar radiation. Low humidity and high elevation provide a large diurnal difference in ambient temperature that facilitates fruit maturity by conserving respiratory substrates in the vine and berry. Cultivars of wine grape (*Vitis vinifera* L.) suitable for production in the Western Snake River Plain require the ability to produce and ripen fruit at a commercially competitive quantity and quality during a growing season of fluctuating duration and to survive exposure to winter cold.

Despite the large heterogeneity available among cultivars of wine grape, global wine grape production remains dominated by a few leading cultivars of European origin, such as Cabernet Sauvignon and Merlot (Fegan 2003). Many lesser-known wine grape cultivars have been made available commercially for planting in the U.S. However, research is needed to determine their performance in various U.S. viticultural areas. This is particularly important for the SRV AVA; the high, cold-desert climate of this area contrasts with the climate of the European regions where the lesser known cultivars are grown. Furthermore, little information is available about the performance of lesser-known wine grape cultivars in nontraditional wine grape-growing regions of the U.S., especially in continental regions located at northern latitudes. Additionally, research is needed on wine grape performance in the SRV AVA, as it is a new and developing wine region that needs further characterization of grape cultivar suitability (Shellie 2007, Fallahi et al. 2004).

The aim of this study was to gain information on the performance of lesser known wine grape cultivars for traits that confer adaptations to the condition of the SRV AVA. For this purpose, we analyzed phenology, juice quality, yield, and cold tolerance of a collection of lesser known wine grape cultivars. These cultivars are thought to have the

potential to be commercially viable, but currently are underutilized outside of their limited local regions. Cabernet Sauvignon and Merlot currently comprise the majority of commercial acreage of red-skinned cultivars grown in southwestern Idaho (Gillerman et al. 2006). Red-skinned grapes are primarily used in red and rosé wine production while grapes referred to as white-skinned are typically green in color and produce white wine. Both red and white-skinned grapes are used in sparkling wine production. The fruit produced in Idaho must compete for winery contracts against fruit grown in more established, well-known production regions. Ideally this research will aid the long-term competitiveness of the wine grape industry in Idaho and other continental, northern latitude wine grape regions with similar features and challenges as the SRV AVA.

Materials and Methods

Site Description and Experimental Design

The trial was located at the southwest corner of the Sawtooth Winery in Nampa, Idaho (43^0 28'N -116^0 40'W, 841m). The Koeppen climate classification of this area is BSk (cold semi-arid, steppe) with annual average precipitation of 19.95 cm (U.S. Dept. Interior, 2013). The soil at the field site was well-drained, Scism calcareous silt loam aridisol with 60 cm of the upper layer of soil having a pH of 8.1 and 1.8% organic matter (U.S.D.A. 1972, Shellie 2006). Growing degree days (GDD) are heat accumulation units and were calculated from maximum and minimum temperatures compared to a base temperature of 10°C with no upper limit. The GDD was calculated yearly using weather data recorded from an Agrimet weather station located in Nampa, ID (U.S. Dept. Interior 2013).

The vineyard plot was initially established with thirteen certified virus-free cultivars in 2008 and the remaining five cultivars were planted in 2009. All vines were certified virus-free, dormant rooted cuttings purchased from commercial nurseries (Table 1.1). The vineyard had a 2.44 m row width and 1.83 m vine spacing with guard vines around the perimeter of the vineyard. Vines were trained as a double trunk unilateral cordon arms 0.91 m in length and approximately 1 m above the soil surface. Vines were spur pruned to seven, 2-bud spurs per cordon arm and vertical shoot positions were trained with two movable wind wires. The irrigation system used an above ground drip line attached to a cordon wire with 1.29 liter per hour in-line emitters that were spaced at 0.91 m from each other. The planted in-row cover crop was cereal rye (*Secale cereale*) that was mowed in early spring during vine canopy development and then left to dry during berry development as soil moisture was depleted. All irrigation scheduling, vine management, weed removal, pesticide application, and nutrient management were managed according to standard commercial practices for the SRV AVA.

The *V. vinifera* cultivars were planted following a randomized block design with replications within block oriented in an east to west direction and different blocks oriented north to south. For each cultivar, six panels (replications) were planted with four vines in each panel (Figure 1.1). In addition to the lesser known cultivars, Cabernet Sauvignon and Merlot were included in the trial as standard cultivars for comparison. For each of these standard cultivars, six panels were planted on their own roots and six on grafted rootstock 101-14 (*V. riparia* x *V. rupestris*). The Cabernet Sauvignon and Merlot cultivars planted on grafted rootstock were not used as standard cultivars for the performance analysis. Current industry practice in southwestern Idaho is to grow vines on

their own roots rather than graft to rootstock because phylloxera (*Daktulosphaira vitifoliae*), a sap feeding insect, is not widespread in the region and growing the vines on their own roots facilitates vine retraining in the event of cold injury. Lesser known cultivars were either planted on their own roots or grafted to 101-14 rootstock (*V. riparia* x *V. rupestris*). Grafted rootstock for the lesser known cultivars were used based on availability of plant material. The description of the lesser known cultivars is presented in Table 1.1, and includes red and white grape cultivars from five European sources. During initial establishment in 2008, dead vines were replaced with vines of the same cultivar the following season. Gaps where vines had died were filled in with Pinot Noir (red grape) or Muscadelle du Bordelais (white grape) during the 2012 season. These two cultivars were planted in gaps where vines of opposing colored grapes had died so as to distinguish the replaced vines from the cultivar entries. Vines that died in the border rows were also replaced with Pinot Noir and Muscadelle du Bordelais.

Phenological Measurements, Yield, and Juice Quality

Budbreak, bloom, and veraison were determined by visual inspection for stages 4 (bud break), 23 (bloom), and 35 (veraison) of the modified E-L system (Coombe 1995). During the growing season, data was collected bi-weekly over the course of each major phenological event. Day of year was recorded when 50% of the buds or clusters of each vine was at specified phenological event. The percentage of buds or clusters within a vine that were at a particular phenological stage was rated using an adjusted 0-5 variable line scale (Little and Hills 1978).

Each cultivar was harvested when juice soluble solids concentration (SSC) was approximately 23%, titratable acidity was approximately 6 g/L, and pH was

approximately 3.5. SSC was used as the primary harvest indicator if TA and/or pH were not at target levels. Just prior to harvest, clusters were removed from the interior two vines of each four-vine panel and the number of clusters and yield per vine were recorded. Four clusters sampled at harvest from each side of each harvested vine for a total of eight clusters that were individually weighed. Berries in the eight cluster sample were passed through a hand-operated crusher, filtered, and a 40 mL must sample was used to measure solid soluble concentrations with a model RE40 temperature-compensating refractometer (Mettler-Toledo, Columbus, OH). Juice pH and titratable acidity were analyzed in sequence with an autotitrator as described by Shellie (2006). Dormant canes on the central two vines in each cultivar panel were pruned prior to bud-break and their weight was used to estimate canopy vigor. The ratio of yield to pruning weight (Ravaz index) was calculated to determine vine balance (Vasconcelos and Castagnoli 2000, Howell 2001).

Assessments of Cold Injury and Cold Hardiness

Cold injury to the above-ground perennial tissue was assessed after budbreak during the 2011, 2012, and 2013 growing seasons to determine the percent incidence of cold damage caused from late fall through early spring. Once shoots had developed and the likelihood of a spring frost was low, unbroken buds were assessed for bud death through destructive methods of bud cutting and cordon arms were inspected for cold damage (Figure 1.2) through observing split cordons and trunks and cutting back layers of periderm to observe oxidative browning due to dead and damaged phloem and xylem as described by Goffinet (2004). Similar to major phenological events, the cold injury

ratings were analyzed using an adjusted rating scale that was originally designed to evaluate plant decay used in plant pathology studies (Little and Hills 1978).

Cold hardiness was evaluated on the standard cultivars, Cabernet Sauvignon and Merlot own-rooted, and on eight of the lesser known cultivars that were thought to have the best cold tolerance based on cold injury assessments during the initial vineyard establishment. For each selected cultivar, the cold hardiness of buds, phloem, and xylem tissues were determined from October 2011 until March 2012 and from September 2012 to March 2013. Cold hardiness was estimated based on low temperature exotherms (LTE) generated using a differential thermal analysis (DTA) system as described by Mills et al. (2006). For buds, the LTE values at which damage occurred in 50% of the buds was determined (LTE50). For cane tissue, the LTE values that caused 10% damage to the xylem and phloem tissues were estimated (LTE10). Tissue used in the DTA was obtained from basal nodes three through six of vines in each field replicate. Cane sections were pruned monthly from the vineyard plot to include one cane per replication per cultivar used in the evaluation (Fig 1.2A). Bud and cane tissues were excised following the methods of Wolf and Poole (1987) and Mills et al. (2006) and were placed in the wells of thermoelectric module plates. Five buds or three cane pieces were placed in each well and a total of twenty buds and nine cane sections were measured per sampling date and cultivar (Fig 1.2B). Samples were sealed in module plates (Fig 1.2C) and placed in a Tenney programmable environmental chamber (SPX, Rochester, NY) ramped to cool to -40 ^{0}C at a rate of 4 ^{0}C per hour, and then held at -40 ^{0}C for one hour (Mills et al. 2006). Each DTA plate was connected to a Keithley Multimeter Data Acquisition System

(Keithley Instruments, Cleveland, OH), which recorded voltage output to the Microsoft program ExcelLINX (Keithley Instruments, Cleveland, OH).

Data Analysis

Phenology, yield, juice quality, and cold injury data was analyzed using a linear mixed model Analysis of Variance (program R, version 2.13.1, http://www.r-project.org/) using the linear and nonlinear mixed effects models **(**nlme) data analysis package with cultivar as the fixed effect and blocks as the random effect. The model was built to account for heteroscedastic data sets, and post-hoc multiple comparisons of the cultivars were performed using Tukey's honestly significant difference test with data analysis package simultaneous inference in general parametric models **(**multcomp). Budbreak was standardized around the standard Merlot due to this cultivar having the smallest error in days to budbreak amongst the standards. Merlot and Cabernet Sauvignon rootstock standards were removed from the statistical analysis because they had bigger error values than their own-root counterparts and rootstock is not common for vineyards in Idaho. The DTA system had limited space when measuring cold hardiness; therefore, blocks as random effects could not be accounted for. Cold hardiness data was evaluated using a repeated measure analysis with post-hoc multiple comparisons using Tukey's honestly significant difference test based on cultivar for each month with the data analysis package agricolae in R (http://tarwi.lamolina.edu.pe/~fmendiburu/). Bud, phloem, and xylem LTE values as well as cold injury data were graphed using SigmaPlot (SPSS, Chicago, IL).

Results

Climatic Conditions

Winter minimum temperature and mean temperature of the coldest month were colder than the 10-yr site average in 2009 and 2012, similar to the site average in 2008 and 2011 and warmer than the site average in 2010 (Table 1.2). The number of frost free days during the growing season was less than the 10-yr site average in 2008, 2009, and 2011, similar to the site average in 2010 and greater than the site average in 2012. Growing season heat unit accumulation was lower than the site average in 2010 and 2011, similar to the site average in 2008 and 2009 and higher than the site average in 2012. The last spring frosts occurred later than the 10-yr site average in 2008, 2009, 2010, and 2011 and earlier than the site average in 2012. Seasonal precipitation was lower than the 10-yr site average in 2008 and 2012 and similar to the site average in other study years. Annual precipitation was lower than the site average in 2009 and 2012, similar to the site average in 2008 and higher than the site average in 2010 and 2011. The heat unit accumulation and average growing season temperature at the field trial site in this study corresponds with the upper and lower ranges of Region II and III in the Winkler climate classification system for grape production (Winkler et al. 1974).

Phenological Observations

There were fewer GDD in 2011 resulting in a colder growing season and all phenological events occurred later than the same events in 2012. The average day of year for 50% of budbreak for Merlot was 126 in 2011 while in 2012 it was 112. Grüner Veltliner, Verdelho, and Fernão Pires broke bud earlier than Merlot each year. Furthermore, Grüner Veltliner was the earliest cultivar to break bud in 2011 followed by

Verdelho and Fernão Pires. No differences in days to bud break were detected amongst these three cultivars in 2012, but again all three cultivars were the first in breaking bud (Table 1.3). Another cultivar that broke bud before Merlot in both years was Trousseau, which was earlier by about two days. In contrast, other cultivars showed more variability. For example, Sauvignon Gris and own-rooted Cabernet Sauvignon broke bud earlier than Merlot in 2011, but no differences were observed in 2012. Graciano was the only cultivar to break bud significantly later than Merlot in 2012, even though the opposite trend was observed in 2011 (Table 1.3).

Own-root Merlot standard and Carmenère had the shortest duration of time to flower in 2011 with approximately one day difference between them, while Fernão Pires took the longest period with 64 days to flower from budbreak (Table 1.4). Cabernet Sauvignon own-root had the shortest duration to flower with 48 days in 2012. In contrast, Aleatico had the longest duration flower with 69 days, which was longer than any cultivar in both growing seasons (Table1.4).

Trousseau was the first cultivar to undergo veraison while Aglianico was the last one with approximately 18 days difference between the two in 2011 and a 15-day difference in 2012 (Table 1.4). Sauvignon Blanc Musqué followed Trousseau in both years while own-rooted Merlot and Cabernet Sauvignon underwent veraison around the middle of the range among cultivars. Trousseau also had the shortest time from budbreak to harvest for both years of any cultivar while Graciano and Aglianico had the longest in 2011 and Carmenère, Cabernet Sauvignon, and Aleatico had the longest in 2012 (Table 1.4). Although Trousseau showed the shortest period from budbreak to harvest in 2012,

this period was not significantly different from that of nine other cultivars, which had a budbreak to harvest period within five days of Trousseau.

For budbreak, the relation between budbreak in 2011 and 2012, expressed in relation to the Merlot standard, was positive and significant (budbreak 2012= -2.9 + 1.62 budbreak 2011, $r^2 = 0.69$, $p = 7.3 \times 10^{-5}$). Similar trends were observed for time between budbreak and flowering (flowering 2011 = 42.4 + 0.33 flowering 2011, $r^2 = 0.31$, $p = 0.024$) and budbreak and veraison (veraison 2012 = 30 + 0.87 veraison 2011, $r^2 = 0.83$, $p = 8.5 \times 10^{-7}$). However, when observing all cultivars over both seasons, no significant relation occurred between the duration of budbreak to flowering time and the budbreak to veraison time ($p = 0.11$ and 0.64 for the 2011 and 2012 seasons, respectively).

Fruit Yield and Juice Characteristics

Touriga Brasileira had the highest yield in 2011 (10.3 kg/vine) followed by Grüner Veltliner (8.8 kg/vine). However, the yield in most other cultivars was no different from that of Grüner Veltliner. The exception to this pattern was Carmenère with the lowest yield (3.4 kg/vine) (Table 1.5). Somewhat similar patterns were observed in 2012 with Grüner Veltliner having the highest yield and Carmenère the lowest yield. Furthermore, these two cultivars were the only ones that significantly differed from each other. Grüner Veltliner also had the largest average cluster weights for both years while Carmenère had the lowest cluster weight in 2012 (Table 1.6). The average yield varied among cultivars from 3.4 to 10.3 kg per vine in 2011 and from 2.8 to 10.7 kg per vine in 2012 (Table 1.5). The average cluster weights varied among cultivars from 292.5 to 148.7 grams in 2011 and from 210.3 to 102.1 grams. Carmenère had the lowest Ravaz index value while Touriga Brasileira had the highest Ravaz index value for both years.

Most cultivars had Ravaz indices that ranged between the ideal values of five to ten according to Smart and Robinson (1991). The berry and cluster weight averages were higher in 2011 than in 2012, with most cultivars having fewer clusters per vine in 2011 than in 2012 (Table 1.6). The Merlot and Cabernet Sauvignon standard cultivars were similar in berry and cluster weight, number of clusters per vine, and number of berries per cluster for both years. There was no significant differences in cluster weights of the lesser known cultivars with one or both standard cultivars with the exception of Grüner Veltliner, which in 2011 weighed more than both Merlot and Cabernet Sauvignon. Carmenère had fewer clusters per vine than Merlot and Cabernet Sauvignon as well as most other cultivars in both years. Incidentally, this also led to Carmenère having larger berries and fewer berries per cluster than Merlot and Cabernet Sauvignon as well as most other cultivars in both years. Grüner Veltliner, Graciano, Aglianico, and Fernão Pires had a more berries per cluster than Merlot or Cabernet Sauvignon or both.

Trousseau had the highest percentage of SSC and the highest pH for both 2011 and 2012 while having lower levels of titratable acids (Table 1.7). Sauvignon Gris, Merlot own-root, as well as Sauvignon Blanc Musqué all had SSC values in the range of 24 to almost 26 percent, while also maintaining higher levels of acidity but varying levels of titratable acids for both years (Table1.7). Carmenère, Touriga Brasileira, Graciano, and Cabernet Sauvignon on root stock had the lowest levels SCC while maintaining low pH, but Aglianico had the lowest pH in 2011 and 2012. In 2011, Aglianico, Graciano, Aleatico, own-rooted Cabernet Sauvignon, and Fernão Pires were below the target sugar to acids ratio of approximately 3.8 to 4 (based on our initial harvesting parameters of SSC

of 23% and TA of 6 g/L), while in 2012 Aglianico was below the target ratio. Merlot own-root had the highest sugar to acid ratio for both seasons.

Assessment of Cold Injury and Cold Hardiness

The temperatures from the winter into the spring led to damage on the vines in the 2011, 2012, and 2013 growing season (Table 1.8). The lesser-known cultivars differed in severity of visible injury based on bud, spur, cordon, and trunk damage as well as regrowth, which was greatest after the winter of 2010 (Table 1.8). Tinto Cão suffered almost 100% cold injury to all vines in 2011 through 2013 growing season, which resulted in complete bud death, as well as death to the aboveground portions of the vine. Montepulciano suffered approximately 90% cold injury in 2010-2011 winter and led to dieback to the soil layer. However, Montepulciano was able to recover from this injury, but suffered approximately 45% cold injury in 2011-2012 winter and 62% in the 2012-2013 winter. The high incidence of cold injury and loss of vines of Montepulciano and Tinto Cão resulted in these cultivars being excluded from the phenology, yield components, and juice quality measurements. The Cabernet Sauvignon own-root suffered higher percentages of damage than the Merlot own-root in during all winters although this was not statistically significant during 2010-2011 winter. Grüner Veltliner had the lowest visible three year average cold injury rating followed by Carmenère and Sauvignon Gris.

All cultivars reached maximum bud cold hardiness in December and January (Fig. 1.3, Fig. 1.4, Fig. 1.5). Winter temperatures reached minimum nightly degrees of approximately -12°C during December of 2011 and -21°C in January of 2013 (Table 1.2). During the winter of 2011-2012, phloem cold hardiness reached a maximum in

December, while in most cultivars this maximum was reached in January during the subsequent winter. The minimum temperatures during January of the 2012-2013 winter was cold enough to cause at least 10% phloem damage in most of the cultivars (Fig. 1.3, Fig. 1.5). Maximum xylem hardiness was variable for each cultivar for both years while being more cold hardy than the coldest minimum temperatures during both winter seasons. Phloem and xylem cold hardiness was at maximum before bud hardiness for most cultivars in the 2011 season, but in 2012 bud hardiness was at its maximum before phloem and xylem. The statistical analysis of bud cold hardiness revealed a significant interaction between cultivar and month during both the winter of 2011-2012 ($F=4.65$, $p<0.05$) and the winter of 2012-2013 ($F= 7.07$ $p<0.05$). Therefore, differences in cold hardiness among cultivars were analyzed for each month. During the winter season of 2011-12, Trousseau, Grüner Veltliner, Sauvignon Gris, Sauvignon Blanc Musqué, and Merlot were the most bud cold hardy in December, while in January Trousseau, Grüner Veltliner, Verdelho, Sauvignon Gris, Merlot, and Cabernet Sauvignon were the most bud cold hardy (Fig. 1.3). Verdelho was the least cold hardy, while Sauvignon Gris was the most cold hardy in December of 2012 with all other cultivar hardiness ranging between the two. Grüner Veltliner had the most cold hardy buds in January 2013 while Fernão Pires had the least bud cold hardy values, but was no different from the other cultivars, except for Grüner Veltliner, when the winter weather was the coldest (Fig. 1.6).

Discussion

The winegrape cultivars tested in this study showed differences in their phenology and cold tolerance. Several cultivars including Carmenère, Graciano, and Touriga Brasileira showed phenological characteristics similar to Merlot and Cabernet Sauvignon,

which are widely grown in southwestern Idaho. Similarly, Grüner Veltliner, Trousseau, Sauvignon Gris, and Verdelho appear to have comparable or better cold tolerance than Merlot and Cabernet Sauvignon. In contrast, other cultivars such as Montepulciano, Tinto Cão, Aglianico, and Aleatico were slow to reach fruit maturity or were severely damaged by cold.

A clear difference between some of the cultivars was the time to bud break. In both the short cold season of 2011 and the long warm season of 2012, Grüner Veltliner, Verdelho, and Fernão Pires, all white wine grapes, broke bud earlier than other cultivars. Early budbreak increases the risk of cold damage to emerging shoots. However, early budbreak can also lead to increased flower number per inflorescence due to the exposure of colder air temperatures as well as soil temperature (Dunn and Martin 2000). This early bud break and increased flower number per florescence can potentially modify yields if they are not damaged by early frost. However, in this study, the potential for increased flower number does not appear to be reflected in cluster weights. In the 2011 season, all cultivars broke bud before the last frost of May 7th (DOY 127) except for Merlot, which broke bud approximately on the day of last frost. However, in 2012, all cultivars broke bud after April 6 (DOY 96), which was the day of last frost. Grüner Veltliner, Verdelho, and Fernão Pires, the cultivars that broke early in both seasons, experienced increased yields in the 2012 season. Considering the level of bud injury in 2011 and 2012, it is quite possible that the lower yields in the 2011 season could have been due to frost injury. It could also mean that cultivars that break earlier have the potential to increase in fruitfulness and yields due to the longer growing season.

Differences were also observed among some cultivars on the time between budbreak and flowering, and between budbreak and veraison. For example, Cabernet Sauvignon had in both seasons a shorter time to flowering than several other cultivars including Grüner Veltliner, Verdelho, Sauvignon Gris, Trousseau, and Aleatico. Cold stress is particularly damaging during fruit set and can result in ovule abortion, characteristic shot berries, as well as loose grape clusters (Ebadi et al. 1995, Ewart and Kliewer 1977). Late flowering may seem advantageous because it decreases the risk of late spring frost damage; however, bloom in winegrapes already occurs late in the growing season. A potential disadvantage of late flowering is a reduction in the time for fruit set and fruit development. However, this was not observed. Moreover, some cultivars such as Trousseau and Sauvignon Blanc Musqué, which flowered later, were among the first to reach veraison. Thus, overall late flowering in combination with early ripening is likely to be an advantage under the climatic conditions of Idaho.

The short and cold season in 2011 and the long warm season in 2012 provided contrasting differences with respect to the weather that the vines experienced during the trial. Notwithstanding these differences, overall the cultivars showed similar phenological characteristics in both years; those cultivars that reached a phenological stage early in 2011 tended to be early in 2012 and those that reached phenological stages later in 2011 also reached those same stages later in 2012. However, certain cultivars behaved differently in different years. Clear changes were observed in Graciano, which was earlier than Merlot in 2011, while the opposite was observed in 2012. Similarly, Sauvignon Blanc Musqué and Fernão Pires flowered later than Cabernet Sauvignon in 2011, while no significant differences were noted in 2012. This suggests that the response to changes

in climatic conditions can differ among some cultivars. Buttrose (1970) concluded that most grape vines cultivars will produce better under high temperature and clear day conditions. However, the growth response to challenging environmental conditions will be more variable, when fewer cultivars are able to perform to satisfaction. Jones and Davis (2000) observed that the phenological responses of Merlot were more sensitive to climate than Cabernet Sauvignon, and these types of responses could be regionally unique. Jones and Davis (2000) observed in Bordeaux a long-term lengthening in the growing season that decreased the growth intervals for phenological events, such as flowering and verasion, while improving wine quality. Presently, winegrape growing in the SRV AVA is characterized by short, but intense growing seasons. Climate change could potentially lengthen the growing seasons and improve conditions for winegrape production in Idaho.

Any cultivar that has less than or equal to the duration of time from budbreak to veraison of the established standards Merlot and Cabernet Sauvignon would be favorable for the growing conditions in Idaho. Cultivars that are beyond the standards would need to be planted in sites with warmer and/or longer growing season. This would allow for these cultivars to have the right conditions and time to ripen before the onset of winter temperatures. Aleatico and Aglianico were cultivars that underwent veraison later than the standards and did not reach adequate ripeness during the cooler 2011 season as apparent by the low sugar to acid ratio. Graciano could be considered a marginal cultivar; even though veraison occurred at a similar time as the standards, it did not reach ideal ripening during the colder growing season. Trousseau and Sauvignon Blanc Musqué were two cultivars that underwent early verasion, and completed ripening early in both

seasons. These two cultivars with the addition of the cultivars with the equivalent timing, depending on the season, ripened faster than expected and we were not able to harvest them earlier enough. This resulted in cultivars with higher levels of sugar (SSC%) and lower acidity (TA) than what was anticipated as well as a high pH. However, high sugars and low levels of TA are common in hot dry climates (as is evident for the 2012 harvest). Values of pH exceeding 4.0 can be found in overripe fruit and values exceeding 3.6 can be considered undesirable due to the potential for increased spoilage and oxidation (Keller 2010). Harvesting grapes earlier or focusing on harvest timing in combination with better canopy management may alleviate some of the issues in the earlier ripening cultivars, but can also be crucial for optimizing fruit in all cultivars. For standard wine production, these overripe grapes may need to be watered down and their juices combined with additives to increase acidity or they may be used to fortify other wines.

Touriga Brasileira had a high yield and a moderate to large cluster weight with a lower pruning weight, which might explain why the cultivar had a low SSC% in 2011 with a Ravaz value above 10. The vine was out of balance and was possibly overcropped with too much reproductive growth while balanced vines should have a Ravaz value between 5 and 7 according to Ravaz (1903) or 5 and 10 according to Smart and Robinson (1991). The yield and cluster weight in 2012 was reduced and the grape had a high sugar to acid ratio. Grüner Veltliner also had large yield in both seasons and the biggest cluster size in both years, but was able to ripen and had a higher sugar to acid ratio than the targeted ratio. It is possible that this cultivar was also overcropped, but managed to meet targeted SSC% due to early ripening. The overripe grapes increase sugar concentration due to water loss or dehydration of the berry and not an increase in sugar content

(Jackson 2008). On the opposite end, Carmenère had a very low yield for both seasons as well as lower weight clusters and a low Ravaz index, indicating that it was undercropped and possibly very vigorous and/or out of balance with excessive vegetative growth compared to reproductive growth. Further study on cultivars such Carmenère and Touriga Brasileira would be needed to determine if these levels of yields are typical of these cultivars or if other factors (vine balance, vigor, and water or nutrition status) are causing these issues. Smart and Robinson's (1991) ideal crop balance ratios (Ravaz Index) fall between 5 and 10, however these standards were developed for Australia, Europe, and California and may or may not be optimum for Idaho's edaphoclimatic conditions. Further research will be needed to establish the ideal crop balance for these lesser cultivars as well as commonly grown cultivars in Idaho.

An important part of the study was the evaluation of cold injury and cold hardiness because cold temperatures are the most limiting factor in Idaho viticulture. As was apparent in both the cooler and warmer seasons, Montepulciano and Tinto Cão did not tolerate the cold winters in Idaho. Montepulciano did better both seasons than Tinto Cão; however, it is not feasible to re-grow whole vines year after year. Tinto Cão managed to produce some fruit in 2012 from one vine, while Montepulciano produced inferior fruit from some of the surviving vines (data not shown). Aleatico and Aglianico had low production potential because of cold sensitivity and low fruit maturity. The mean temperature of the coldest month in the principal production regions (Tinto Cão from the Douro region of Portugal, Montepulciano from the Abruzzo region of Italy, Aleatico from Puglia region of Italy, and Aglianico from the Basilicata region of Italy; Fegan 2003) of these four cultivars is warmer than the winter temperatures encountered in this

study. If a grower were determined to plant cold sensitive cultivars, persistent action would be needed to prevent cold damage during the winter, an example of this being the labor-intensive method of full vine burial in the soil (Davenport et al. 2008).

Most cultivars suffered equivalent cold injury to the standards in both season with the exception of cultivars such as Sauvignon Gris, Carmenère, and Grüner Veltliner suffering significantly less damage than Cabernet Sauvignon in 2011. This indicates that these cultivars are less sensitive to winter cold or frost than Cabernet Sauvignon. The major drawback to the visual injury assessment was that it was taken after the last frost and did not distinguish between damage related to cold winter temperatures and damaged caused by early or late frost in fall and spring, respectively. To distinguish damage caused by frost, assessment of visual injuries could have been taken a short period after each cold event. Despite the lack of information on the time at which bud injury occurred, the early frost in the fall 2011 suggests that the higher incidence of damage in 2012 was due to this event.

The DTA system had limited space and availability for determining cold hardiness, so only 10 cultivars (8 lesser known cultivars and the 2 standards) were chosen for these measurements based on preliminary observations that indicated good winter survival after establishment. The results of the cold hardiness evaluation suggest that cold hardiness from month to month can vary greatly as each cultivar has differing rates of acclimation going into winter and deacclimation heading into spring weather. Wample and Bary (1992) and Hamman Jr. et al. (1996) determined that harvest date and levels of carbohydrates in the vine have no detectable effect on cold hardiness, which is contrary to the opinion that harvesting time affects cold hardiness. The differences in the cold

hardiness of the cultivars are a likely combination of genetic factors and environmental cues of day length and temperature (Wample et al. 2000). Our results demonstrate that the temperature of the current major production region is not exclusively predictive of cold tolerance. For example, Trousseau, Verdelho, and Sauvignon Gris exhibited good cold tolerance, even though they are produced in regions with mild winters. There is a wealth of information showing differences in cold tolerance among leading cultivars of European wine grape; however, we could not find published data on which to compare the cold hardiness of the lesser-known cultivars evaluated in this study. The seasonal pattern of cold hardiness we observed in this study was similar to the pattern reported for leading wine grape cultivars (Hamman et al. 1996, Fennell 2004, Mills et al. 2006, Ferguson et al. 2011).

In conclusion results from this study suggest that Montepulciano and Tinto Cão were poorly suited to the edaphoclimatic conditions of the trial site due to cold sensitivity. Aglianico, Aleatico, and Graciano appear best suited to macroclimates with higher GDD accumulation and growing sites with later fall frost than what was found in the trial. Touriga Brasileira and Carmenère could be potential cultivars for the edaphoclimatic conditions of Idaho, but would need more proactive management practices than those provided in this study to prevent overcropping (Touriga Brasileira, 2011 Ravaz index (RA) = 14.24, 2012 RA = 11.97) or under cropping (Carmenère, 2011 RA = 2.48, 2012 RA = 2.40). Grüner Veltliner, Verdelho, Fernão Pires, Sauvignon Gris, Sauvignon Blanc Musqué, and Trousseau ripened early enough at the trial site, and they had the ability to survive the cold winter climate with minimal damage. The average growing season temperatures for the SRV AVA are approximately 16°C and a GDD °C

of 1329 puts this region into the intermediate range (average growing season of 15-17ºC) for a grapevine climate maturity grouping based on range of ripening and average growing season temperatures (Jones 2006). This range is ideal for cultivars such as Chardonnay, Sauvignon Blanc, Semillon, and Cabernet Franc, but also well suited for Merlot and still capable of ripening Cabernet Sauvignon (Jones 2006, Jones et al. 2010). This puts the SRV AVA in the same range as well established and widely known French and Spanish regions of Burgundy, Bordeaux, and Rioja; however, it also puts the SRV AVA below the warmer Italian and Portuguese regions (Jones 2006, Jones et al. 2010). These factors along with the differences in regional GDD ºC may explain some variability in cultivar performance from a country of origin perspective.

To build and improve upon this study, it would be beneficial to introduce a white grape standard such as Chardonnay or Riesling. The addition of a white wine grape standard would allow for separation grapes by a similar wine type. It is common in viticulture for red grapes to be harvested at higher SSC% and lower acids than white wine grapes. Grapevines commonly undergo different canopy management practices depending on vigor, disease incidence, or desired aroma. The white wine grape Sauvignon Blanc Musqué could have benefited from a denser canopy to create a cooler microclimate. This would enhance the levels of methoxypyrazines and acids that are common in Sauvignon Blanc and associated wine styles from New Zealand (Lacey et al. 1991). Furthermore, to fully evaluate a cultivar introduction to SRV AVA, this study needs to be expanded beyond a viticulture component with the addition of wine trials. The survivability of a grape cultivar to a climate such as Idaho is of little significance if the wine grape cannot be made into high quality wine with commercial potential.

References

Bierle K., Holley D., Black G., 2008. The economic impact of the wine industry on Idaho's Economy. Unpublished manuscript. Boise State University Center for Business and Economic Research.

Buttrose, M.S., 1970. Fruitfulness in grape-vines: The response of different cultivars to light, temperature and daylenght. Vitis 9:121-125.

Coombe, B.G., 1995. Adoption of a system for identifying grapevine growth stages. Aust. J. Grape Wine Res. 1:100-110.

Davenport, J.R., Keller, M., Mills, L.J., 2008. How cold can you go? Frost and winter protection for grape. HortScience 43:1966-1969.

Dunn, G.M., Martin, S.R., 2000. Do temperature conditions at budburst affect flower number in Vitis vinifera L. cv. Cabernet Sauvignon? Aus. J. Grape Wine Res. 6:116-124.

Gillerman, V.S., Wilkins, S., Shellie, K., Bitner, R,. 2006. Geology and wine 11: Terroir of the Western Snake River Plain, Idaho. GeoScience Can. 33:37–48.

Ebadi, A., May, P., Sedgley, M. and Coombe, B.G., (1995), Effect of low temperature near flowering time on ovule development and pollen tube growth in the grapevine (*Vitis vinifera* L.), cvs Chardonnay and Shiraz. Aus. J. of Grape Wine Res. 1:11–18.

Ewart, A., Kliewer, W.M., 1977. Effects of controlled day and night temperatures and nitrogen on fruit-set, ovule fertility, and fruit composition of several wine grape cultivars. Am. J. Enol. Vitic. 28:88-95.

Fallahi, E., Shafii, B., Fallahi, B., Stark, J.C., Ebgel, A.L., 2004. Yield, quality attributes, and degree day requirements of various wine grapes under the climatic conditions of Intermountain West region. J. Am. Pomol. Soc. 58:156-652.

Fegan, P.W., 2003. The Vineyard Handbook: Appellations, Maps and Statistics. Chicago Wine School. Chicago, IL 60608.

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

Ferguson J.C., Tarara J.M., Mills L.J., Grove G.G., Keller M., 2011. Dynamic thermal time model of cold hardiness for dormant grapevine buds. Ann. Bot. 107:389-396.

Foltz, J.C., Woodall, S., Wandschneider, P.R., Taylor, R.G., 2007. The contribution of the grape and wine industry to Idaho's economy: agribusiness and tourism impacts. J. Agribusiness 25:77-91.

Goffinet, M., 2004. The anatomy of winter injury and recovery. Cornell University, 5 March 2015. http://www.hort.cornell.edu/goffinet/Anatomy_of_Winter_Injury_hi_res.pdf

Hamman Jr., R.A., Dami, I.E., Walsh, T.M., Stushnoff, C., 1996. Seasonal carbohydrate changes and cold hardiness of Chardonnay and Riesling grapevines. Am. J. Enol. Vitic. 7:31-36.

Howell, G.S., 2001. Sustainable grape productivity and the growth-yield relationship: A review. Am. J. Enol. Vitic. 52:165-174.

Jackson, R.S., 2008. Wine science: principles and applications. 3rd ed. Elsevier Inc. San Diego. pg. 97.

Jones, G.V., Davis, R.E., 2000. Climate influences on grapevine phenology, grape composition, and wine production and quality for Bordeaux, France. Am. J. Enol. Vitic. 51:249-261.

Jones, G.V., 2006. Climate and Terroir: impacts of climate variability and change on wine. In Fine Wine and Terroir - The Geoscience Perspective. Macqueen, R.W., and Meinert, L.D., (eds.), Geoscience Canada Reprint Series Number 9, Geological Association of Canada, St. John's, Newfoundland.

Jones, G.V., Duff, A.A., Hall, A., Myers, J.W. 2010. Spatial analysis of climate in wine grape growing regions in the western United States. Am. J. Enol. Vitic. 61:313-326.

Keller, M., 2010. The science of grapevines. 1st ed. Elsevier Inc. San Diego. pg 188.

Lacey, M.J., Allen, M.S., Harris, R.L.N., Brown, W.V., 1991. Methoxypyrazines in Sauvignon blanc grapes and wines. Am. J. Enol. Vitic. 42: 103-108.

Little, T.M., Hills, F.J., 1978. Agricultural experimentation design and analysis. John Wiley & Sons. New York. pg. 162-164.

Mills, L.J., Ferguson, J.C., Keller, M., 2006. Cold-Hardiness evaluation of grapevine buds and cane tissues. Am. J. Enol. Vitic. 57:194-200.

Ravaz, L., 1903. Sur la brunissure de la vigne. C.R. Acad. Sci 136: 1276-1278.

Shellie, K.C., 2006. Vine and berry response of Merlot (*Vitis vinifera* L.) to differential water stress. Am. J. Enol. Vitic. 57:514-518.

Shellie, K.C., 2007. Viticultural performance of red and white wine grape cultivars in Southwestern Idaho. HortTechnology 17:595-603.

Smart, R., Robinson, M., 1991. Sunlight into wine. Winetitles. Adelaide. pg 25.

United States Department of Commerce. International Trade Administration. U.S. Wine Industry - 2011. 22 Jan. 2013. http://www.ita.doc.gov/td/ocg/wine2011.pdf

United States Department of Agriculture [U.S.D.A.]. 2007 Census of Agriculture. 28 Dec. 2012. http://www.agcensus.usda.gov/Publications/2007/Full_Report/Volume_1,_Chapter_2_US_State_Level/st99_2_032_032.pdf

United States Department of Agriculture [U.S.D.A]. Soil Conservation Service. 1972. Soil survey of Canyon Area, Idaho. U.S. Government Printing Office, Washington, DC.

United States Department of Interior. Agrimet—The Pacific Northwest cooperative agricultural network. 3 Jan. 2013. http://www.usbr.gov/pn/agrimet/wxdata.html

Vasconcelos, M.C., Castagnoli, S., 2000. Leaf canopy structure and vine performance. Am. J. Enol. Vitic. 51:390-396.

Wample, R.L., Bary, A., 1992. Harvest date as a factor in carbohydrate storage and cold hardiness of Cabernet Sauvignon grapevines. J. Amer. Soc. Hort. Sci. 117:32-36.

Wample, R.L., Hartley, S., Mills, L., 2000. Dynamics of grapevine cold hardiness. Am. J. Enol. Vitic. 51:81-93.

Winkler, A.J., Cook, J.A., Kliewer, W.M., Lider, L.A. 1974. General viticulture. 2nd ed. University of California Press, Berkley. pg 61-71.

Wolf, T.K., Pool, R.M., 1987. Factors affecting exotherm detection in differential thermal analysis of grapevine dormant buds. J. Amer. Soc. Hort. Sci. 112:520-525.

Table 1.1 Clonal and Country Origins Including Rootstock and Sourcing of Lesser Known Cultivars and Standard Cultivars Grown at the Trial Site in Nampa, Idaho.

Plot Code	Cultivar (FPS Clone[z])	Acronym	Clone Origin[y]	Country of Origin[y]	Rootstock	Year Planted	Source[x]	Berry Color
A	Graciano (1)	GC	California	Spain	own-root	2009	Inland Desert	Red
B	Aleatico (1)	AL	California - UC Davis	Italy	own-root	2008	Novavine	Red
C	Carménère (VCR 702)	CM	Italy	France	own-root	2008	Novavine & Inland Desert	Red
D	Cabernet Sauvignon (8)	CS-OR	California	France	own-root	2008	Inland Desert	Red
E	Merlot (3)	ME	California	France	own-root	2008	Novavine	Red
F	Merlot (3)	ME1	California	France	101-14	2008	Novavine	Red
G	Grüner Veltliner (1)	GV	Germany	Austria	own-root	2008	Novavine	White
H	Trousseau (10)	TR	Portugal	France	own-root	2008	Novavine	Red
I	Aglianico (1)	AG	California - UC Davis	Italy	101-14	2008	Novavine	Red
J	Fernão Pires (1)	FP	California - USDA	Portugal	101-14	2008	Novavine	White
K	Verdelho (2)	VL	California - UC Davis	Portugal	101-14	2008	Novavine	White
L	Touriga Brasileira (1)	TB	Portugal	Portugal	101-14	2008	Novavine	Red
M	Sauvignon Blanc Musque (27)	SB	France	France	101-14	2008	Novavine	White
N	Sauvignon Gris (1)	SG	Chile	France	101-14	2008	Novavine	Grey
O	Cabernet Sauvignon (8)	CS-OR	California	France	own-root	2009	Inland Desert	Red
P	Tinto Cão (3)	TC	California	Portugal	own-root	2009	Novavine	Red
Q	Montepulciano (1)	MP	Italy	Italy	own-root	2009	Inland Desert	Red
R	Cabernet Sauvignon (8)	CS1	California	France	101-14	2009	Novavine	Red

[z]Foundation Plant Services, University of California, Davis, CA. 95616

[y]National Grape Registry, University of California, Davis, http://www.ngr.ucdavis.edu/

[x] NovaVine Santa Rosa, CA 95409, Inland Desert Nursery, Benton City, WA 99320

Table 1.2 Weather Data for the Trial Vineyard in Nampa, Idaho during Winter Dormancy (November 1 to March 31) and the Growing Season (April 1 to October 31). Accumulated growing degree days (GDD) were calculated from daily average temperature using a base of 10°C with no upper temperature limit.

	Winter ambient temperature (Nov. 1 – March 31) (°C)		Last/first frost (day of year)		GDD (°C)	Precipitation (mm)	
Year	Minimum	Coldest month (mean)	Spring	Fall	Seasonal	Annual	Seasonal
2008	-16	-1.2	122	285	1630	185.42	83.82
2009	-20	-4.0	117	285	1654	175.26	114.30
2010	-13	3.1	127	313	1511	264.16	116.84
2011	-12	-1.7	127	300	1539	205.74	109.22
2012	-21	-8.6	96	310	1755	157.48	60.96
10-yr avg	-15	-1.9	109	298	1642	193.04	101.60

Table 1.3 Budbreak of Wine Grape Cultivars for 2011 and 2012 in Nampa, Idaho. Budbreak was standardized to the mean day to budbreak of own-rooted Merlot, which had a mean day budbreak of 127 and 112 days in 2011 and 2012, respectively. Positive values in days indicate budbreak after, and negative values in days indicate budbreak before the mean day of Merlot. Means within columns followed by the same letter do not differ significantly at $p = 0.05$ by Tukey's honestly significant difference test. ** indicates $P \leq 0.01$.

Cultivar	Budbreak	
	2011	2012
	Standardized	Standardized
Merlot Budbreak DOY	127 f	112 c
Grüner Veltliner	-16 a	-5 a
Verdelho	-12 b	-7 a
Fernão Pires	-11 b	-5 a
Cabernet Sauvignon	-8 c	1 cd
Sauvignon Gris	-6 c	-1 bc
Sauvignon Blanc Musqué	-4 d	-1 bc
Aleatico	-3 de	0 c
Trousseau	-3 de	-2 b
Graciano	-2 e	2 d
Touriga Brasileira	-2 e	-1 bc
Aglianico	-1 ef	0 c
Carmenère	0 f	0 c
Year	**	
Cultivar	**	
Year x Cultivar	**	

Table 1.4 Average Elapsed Days from Budbreak to Flowering, Veraison, and Harvest of Wine grape Cultivars for 2011 and 2012 in Nampa, Idaho. Means within columns followed by the same letter do not differ significantly at $p = 0.05$ by Tukey's honestly significant difference test. ** indicates $P \leq 0.01$.

Cultivar	Budbreak to Flowering (d)		Budbreak to Veraison (d)		Budbreak to Harvest (d)	
	2011	2012	2011	2012	2011	2012
Merlot	57 a	52 ab	125 defg	125 e	149cd	150 ab
Cabernet Sauvignon	61 abc	48 a	124 cde	115 ab	150 d	160 c
Carmenère	56 a	51 ab	125 cdef	120 d	155ef	164 c
Aglianico	59 ab	52 ab	135 g	130 f	171 g	159 bc
Touriga Brasileira	60 abc	51 ab	125 def	113 a	153 def	149 a
Aleatico	61 abc	69 c	125 def	118 bcd	154ef	164 c
Graciano	62 bc	54 ab	130 fg	119 bcd	172 g	147 a
Grüner Veltliner	62 bc	57 b	123 cde	117 abcd	152 de	149 a
Sauvignon Gris	62 bc	56 b	121 bc	116 abcd	145 bc	147 a
Trousseau	62 bc	55 ab	118 a	115 ab	139 a	145 a
Sauvignon Blanc Musqué	62 bc	54 ab	119 ab	115 abc	144 b	146 a

Verdelho	63 bc	56 b	123 cde	118 abcd	145 bc	147 a
Fernão Pires	64 c	54 ab	121 bcd	120 cd	157 f	149 a
Annual mean	61	55	124	119	153	152
Year	**		**		Ns	
Cultivar	**		**		**	
Year x Cultivar	**		**		**	

Table 1.5 Mean Cluster Weight, Yield, Pruning Weight, and Ravaz Index Measurements of the Cultivar Collection from Nampa, Idaho. Means within columns followed by the same letter do not differ significantly at $p = 0.05$ by Tukey's honestly significant difference test. ** indicates $P \leq 0.01$.

Cultivar	2011			2012		
	Yield (kg/vine)	Pruning Weight (kg)	Ravaz Index	Yield (kg/vine)	Pruning Weight (kg)	Ravaz Index
Merlot	6.3 bc	1.1 ab	5.6	8.0 ab	1.1 abc	7.6
Cabernet Sauvignon	5.5 c	*NE*	*NE*	5.8 bc	1.3 a	4.5
Grüner Veltliner	8.8 ab	1.0 ab	9.2	10.7 a	1.0 abc	10.4
Graciano	6.8 abc	0.6 b	11.8	5.1 bc	0.7 bc	7.4
Trousseau	6.9 abc	1.0 ab	7.2	5.7 bc	1.1 ab	5.0
Aglianico	7.8 abc	0.7 ab	10.7	7.6 abc	0.7 bc	10.9
Touriga Brasileira	10.3 a	0.7 ab	14.2	7.4 abc	0.6 c	12.0
Aleatico	7.2 abc	0.9 ab	7.7	6.3 abc	1.2 a	5.1
Fernão Pires	6.9 abc	0.7 ab	9.3	7.1 abc	0.9 abc	8.1
Sauvignon Blanc Musqué	7.9 abc	1.3 ab	6.2	6.9 abc	1.1 abc	6.6
Carmenère	3.4 c	1.4 a	2.5	2.8 c	1.2 a	2.4
Verdelho	7.0 abc	1.1 ab	6.3	8.2 ab	0.9 abc	9.5

Sauvignon Gris	6.6 abc	1.3 ab	4.9	5.4 bc	1.1 abc	5.1
Annual mean	7.0	1.0	8.0	6.7	1.0	7.3
Year	Ns	Ns				
Cultivar	**	**				
Year x Cultivar	**	**				

NE=Not Evaluated

Table 1.6 Mean Cluster and Berry Weight Attributes of the Cultivar Collection from Nampa, Idaho. Means within columns followed by the same letter do not differ significantly at $p = 0.05$ by Tukey's honestly significant difference test. ** indicates $P \leq 0.01$.

Cultivar	2011				2012			
	Cluster Weight (g)	Clusters per vine	Berry Weight (g)	Berries per cluster	Cluster Weight (g)	Clusters per vine	Berry Weight (g)	Berries per cluster
Merlot	180.6 b	37 abc	1.3 bcd	141 cd	154.6 abcd	52 a	0.87 de	178 bcd
Cabernet Sauvignon	155.5 b	38 abc	1.1 d	144 cd	128.8 bcd	46 ab	0.79 e	161 cde
Grüner Veltliner	292.5 a	31 bcd	1.3 bcd	231 a	210.3 a	52 a	1.07 cd	201 abc
Graciano	236.9 ab	29 cd	1.1 cd	221 a	204.2 ab	26 e	0.98 cde	208 ab
Trousseau	235.0 ab	30 cd	1.4 abc	167 bc	187.1 abc	31 cd	1.37 a	137 def
Aglianico	230.4 ab	34 bc	1.2 cd	209 ab	204.0 ab	37 bcd	1.07 cd	195 abc
Touriga Brasileira	221.5 ab	50 a	1.6 ab	150 cd	164.2 abcd	47 ab	1.09 c	147 def
Aleatico	203.5 ab	37 abc	1.3 bcd	160 bcd	124.9 bcd	50 ab	1.04 cd	126 efg
Fernão Pires	198.7 ab	35 bc	1.2 cd	186 abc	172.6 abcd	40 abcd	0.78 e	227 a
Sauvignon Blanc Musqué	181.6 b	43 abc	1.2 cd	155 bcd	159.4 abcd	42 abc	1.06 cd	150 def

Carmenère	173.6 b	18 d	1.7 a	103 e	102.1 d	26 d	1.21 ab	88 g
Verdelho	151.4 b	46 ab	1.1 cd	135 cd	157.0 abcd	52 a	0.78 e	201 abc
Sauvignon Gris	148.7 b	45 abc	1.4 abcd	108 d	115.1 cd	47 ab	1.09 c	109 fg
Annual mean	200.7	36	1.3	162	160.3	42	1.02	164
Year	**	**	**	Ns				
Cultivar	**	**	**	**				
Year x Cultivar	**	Ns	Ns	Ns				

Table 1.7 Berry Maturity Indices at Harvest [soluble solids (SSC), titratable acidity (TA), pH, and sugar to acid ratio (SSC:TA)] for Wine Grape Cultivars Grown in Nampa, Idaho. Means values within columns followed by the same letter are similar at $P \leq 0.05$ by Tukey's honestly significant difference test. ** indicates $P \leq 0.01$.

	2011				2012			
	SSC (%)	TA ($g \cdot L^{-1}$)	pH	SSC:TA	SSC (%)	TA ($g \cdot L^{-1}$)	pH	SSC:TA
Merlot	24.8 ab	3.27 g	4.1 b	7.58	25.6 ab	3.01 g	4.3 bc	8.5
Cabernet Sauvignon	22.2 d	6.51 c	3.6 e	3.41	24.6 bc	4.34 cd	4.1 d	5.67
Grüner Veltliner	23.7 bc	3.61 fg	3.9 c	6.57	23.2 d	3.41 g	4.3 bc	6.8
Touriga Brasileira	19.8 e	4.75 e	3.8 d	4.17	23.4 d	2.98 g	4.4 ab	7.85
Aglianico	22.2 d	12.26 a	3.1 g	1.81	23.4 d	7.23 a	3.6 f	3.24
Verdelho	24.0 b	5.63 d	3.7 d	4.26	24.3 c	4.81 c	4.1 d	5.05
Sauvignon Blanc Musqué	24.2 b	4.85 e	4.0 bc	4.99	25.6 ab	3.98 de	4.4 a	6.43
Fernão Pires	24.2 b	6.7 c	3.6 e	3.61	23.7 cd	4.82 c	4.2 cd	4.92
Aleatico	22.4 cd	7.09 c	3.5 e	3.16	22.9 d	5.69 b	3.9 e	4.02
Trousseau	26.0 a	3.95 fg	4.3 a	6.58	25.8 a	3.88 def	4.5 a	6.65
Graciano	19.8 e	8.11 b	3.3 f	2.44	23.3 d	4.60 c	3.8 e	5.07
Sauvignon Gris	25.7 a	4.17 ef	4.1 b	6.16	25.6 ab	3.42 fg	4.5 a	7.49
Carmenère	21.0 de	5.14 de	3.8 d	4.09	22.8 d	4.02 de	4.1 d	5.67
Annual mean	23.5	5.85	3.8	4.02	24.1	4.32	4.2	5.58
Year	**	**	**					
Cultivar	**	**	**					
Year x Cultivar	**	**	**					

Table 1.8 Percent Cold Injury Observed on Vines of Wine Grape Cultivars Grown in Nampa, Idaho the Growing Season After the Winters (November 1 – March 31) of 2010, 2011, and 2012. Injury was rated on a five point scale where 0 indicated no injury and 4 indicated no growth. Cultivars and years with the same lowercase letter within a column or row, respectively, are similar at $P \leq 0.05$ by Tukey's honestly significant difference test. ** indicate $P \leq 0.01$.

	Winter vine injury rating (%)			
	2010	2011	2012	3-yr avg
Merlot	18 cdef	2 def	3 de	7.7
Cabernet Sauvignon	38 bc	17 c	15 c	23.3
Tinto Cão	100 a	100 a	100 a	100
Montepulciano	95 a	45 b	62 b	67.3
Aglianico	43 b	14 c	22 c	26.3
Aleatico	25 bcd	2 cd	9 cd	12
Graciano	22 bcde	12 c	1 f	11.7
Fernão Pires	10 def	2 def	2 def	4.7
Verdelho	9 def	2 ef	3 def	4.7
Touriga Brasileira	6 ef	2 ef	1 f	3
Trousseau	6 f	1 f	1 def	2.7
Sauvignon Gris	3 f	2 ef	1 ef	2
Sauvignon Blanc Musqué	6 ef	1 f	0 f	2.3
Carmenère	5 f	1 f	0 f	2
Grüner Veltliner	3 f	0 f	0 f	1
Annual mean	25.9 a	13.5 b	14.7 b	18
Year	**			
Cultivar	**			
Year x Cultivar	**			

Rep	VINE #	Border Row 1	4 VINE PANELS 2	3	4	5	6	7	8	9	10	Border Row 11
1	1	X	O1	I1	M1	B1	K1	A1	H1	F1	R1	X
	2	X										X
	3	X										X
	4	X										X
1	5	X	Q1	N1	J1	L1	P1	C1	G1	E1	D1	X
	6	X										X
	7	X										X
	8	X										X
2	9	X	H2	D2	F2	Q2	J2	L2	N2	O2	M2	X
	10	X										X
	11	X										X
	12	X										X
2	13	X	P2	B2	R2	G2	E2	A2	I2	C2	K2	X
	14	X										X
	15	X										X
	16	X										X
3	17	X	B3	J3	C3	K3	O3	I3	G3	P3	H3	X
	18	X										X
	19	X										X
	20	X										X
3	21	X	A3	M3	D3	R3	L3	E3	Q3	F3	N3	X
	22	X										X
	23	X										X
	24	X										X
4	25	X	L4	G4	B4	R4	H4	P4	D4	A4	M4	X
	26	X										X
	27	X										X
	28	X										X
4	29	X	F4	C4	N4	K4	Q4	J4	E4	I4	O4	X
	30	X										X
	31	X										X
	32	X										X
5	33	X	K5	F5	J5	C5	R5	G5	O5	B5	D5	X
	34	X										X
	35	X										X
	36	X										X
5	37	X	I5	P5	M5	A5	Q5	N5	H5	L5	E5	X
	38	X										X
	39	X										X
	40	X										X
6	41	X	D6	L6	E6	M6	N6	I6	Q6	J6	A6	X
	42	X										X
	43	X										X
	44	X										X
6	45	X	C6	O6	F6	B6	K6	G6	H6	P6	R6	X
	46	X										X
	47	X										X
	48	X										X

Figure 1.1 Generalized Randomized Block Design of the Vineyard Plot at Sawtooth Winery in Nampa, Idaho. Each replication represents a four vine panel with replications running north/south and blocked down a south facing aspect. Border rows were filled with an assortment of cultivars not used in the study.

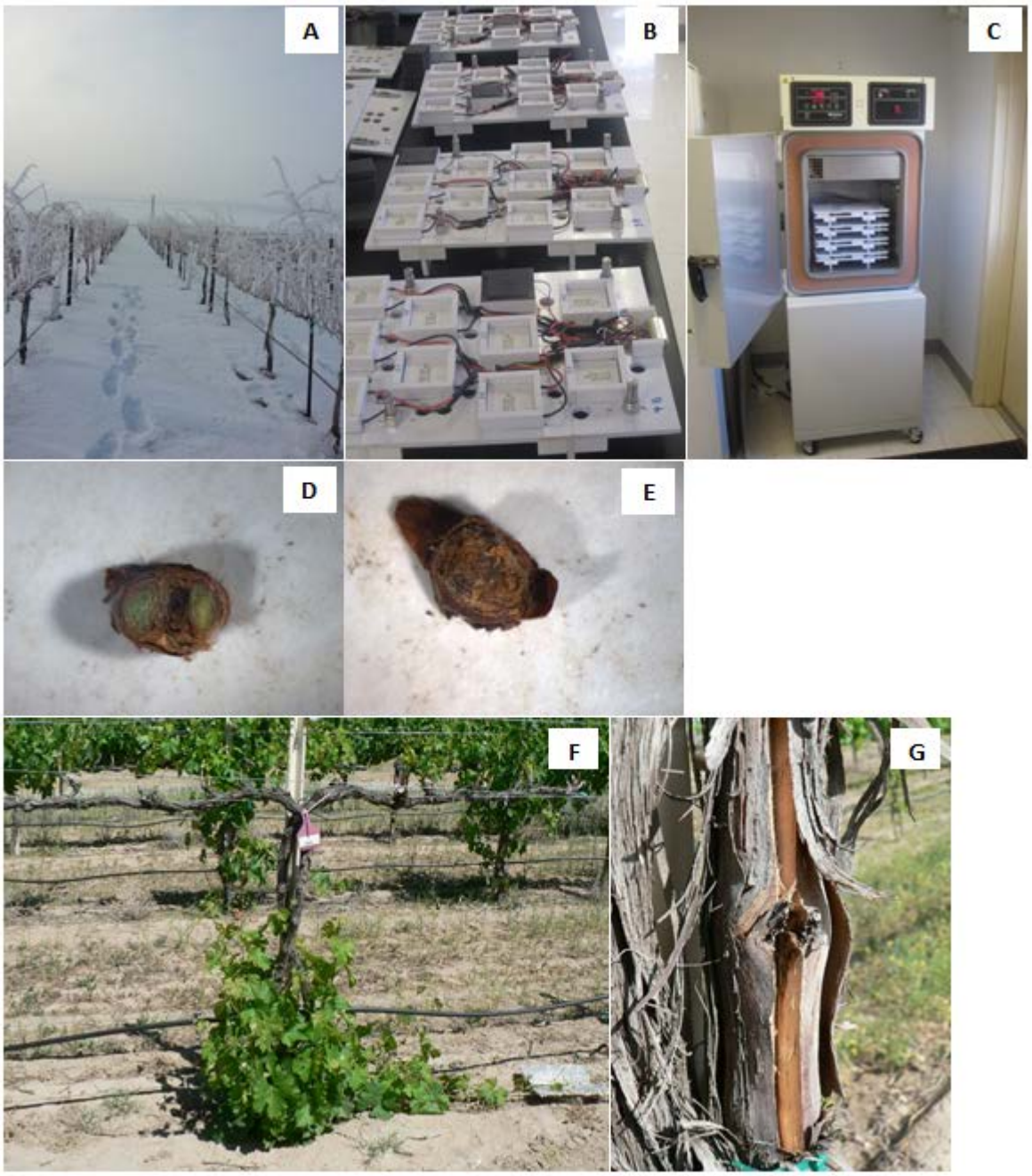

Figure 1.2 Evaluation of Cold Hardiness and Visual Cold Injury of Grapevines. (A) Field samples were collected from the trial site in Nampa, Idaho. (B) Four trays containing ten thermoelectric modules were loaded with cane and bud tissue. (C) Trays were sealed with lids and loaded into an environmental chamber where all four trays could be monitored with a data acquisition system. (D) Compound bud dissection displaying a black and brown cold injured primary bud and live green secondary and tertiary bud. (E) Compound bud dissection displaying black and brown cold injured buds with no viable survivors. (F) Dead vine due to cold damage with sucker regrowth. (G) Visible splitting of the trunk due to cold injury.

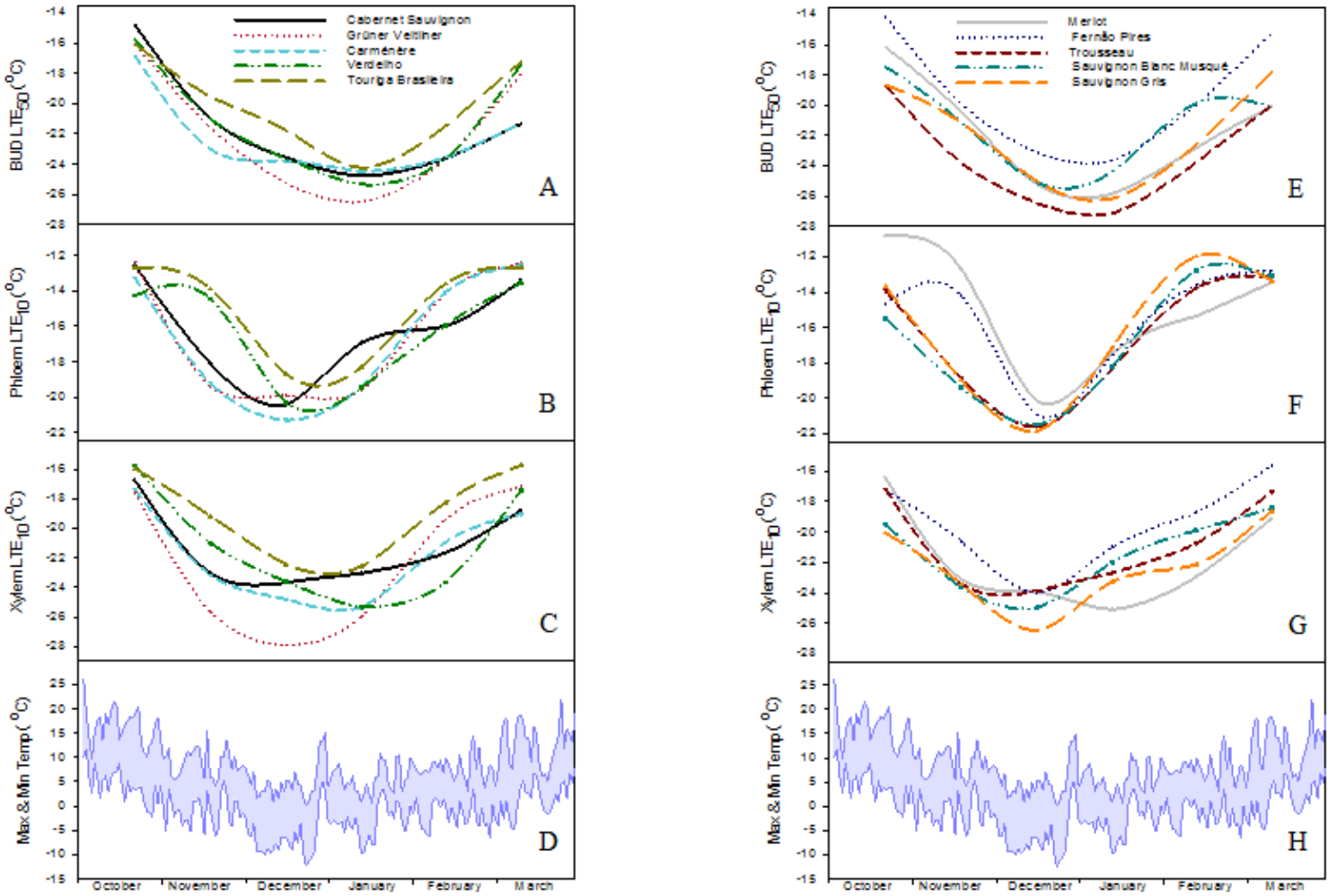

Figure 1.3 Cold Hardiness Values for Buds and Canes Collected from October of 2011 to March of 2012 in Nampa, Idaho. Bud cold hardiness based on LTE50 is represented in (A) and (E) and BUD LTE50 were significant at $p \leq 0.05$ ($n = 10$) for all dates sampled. Cold hardiness of phloem cane tissue based on LTE10 is represented in (B) and (F) with xylem cane tissue represented in (C) and (G). Minimum and maximum temperatures in (D) and (H) are equivalent.

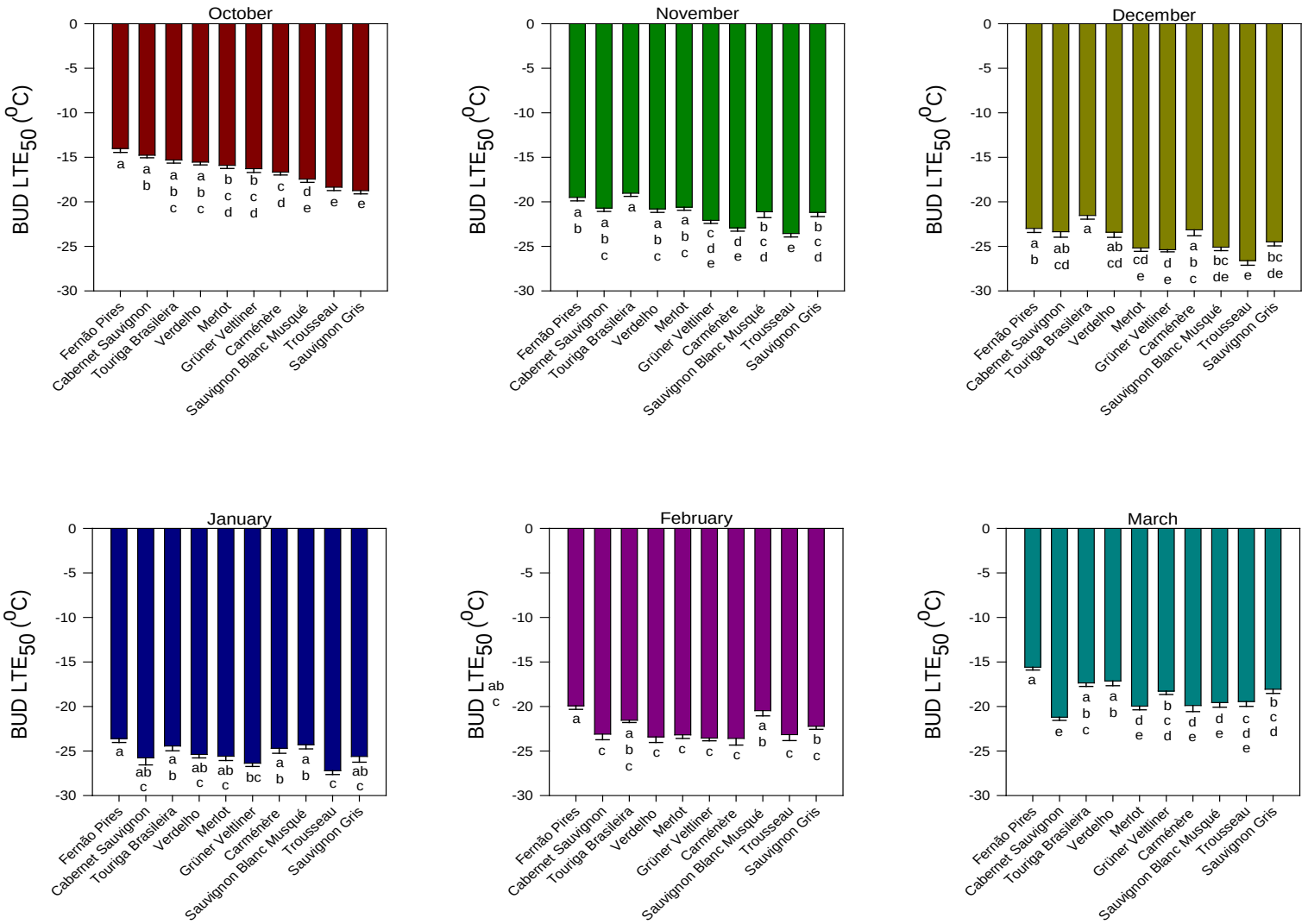

Figure 1.4 Month by Month Cold Hardiness Values for the Dormant Period 2011-2012 of Select Cultivars from Nampa, Idaho. Cultivars with the same lowercase letter are not significantly different at p = 0.05.

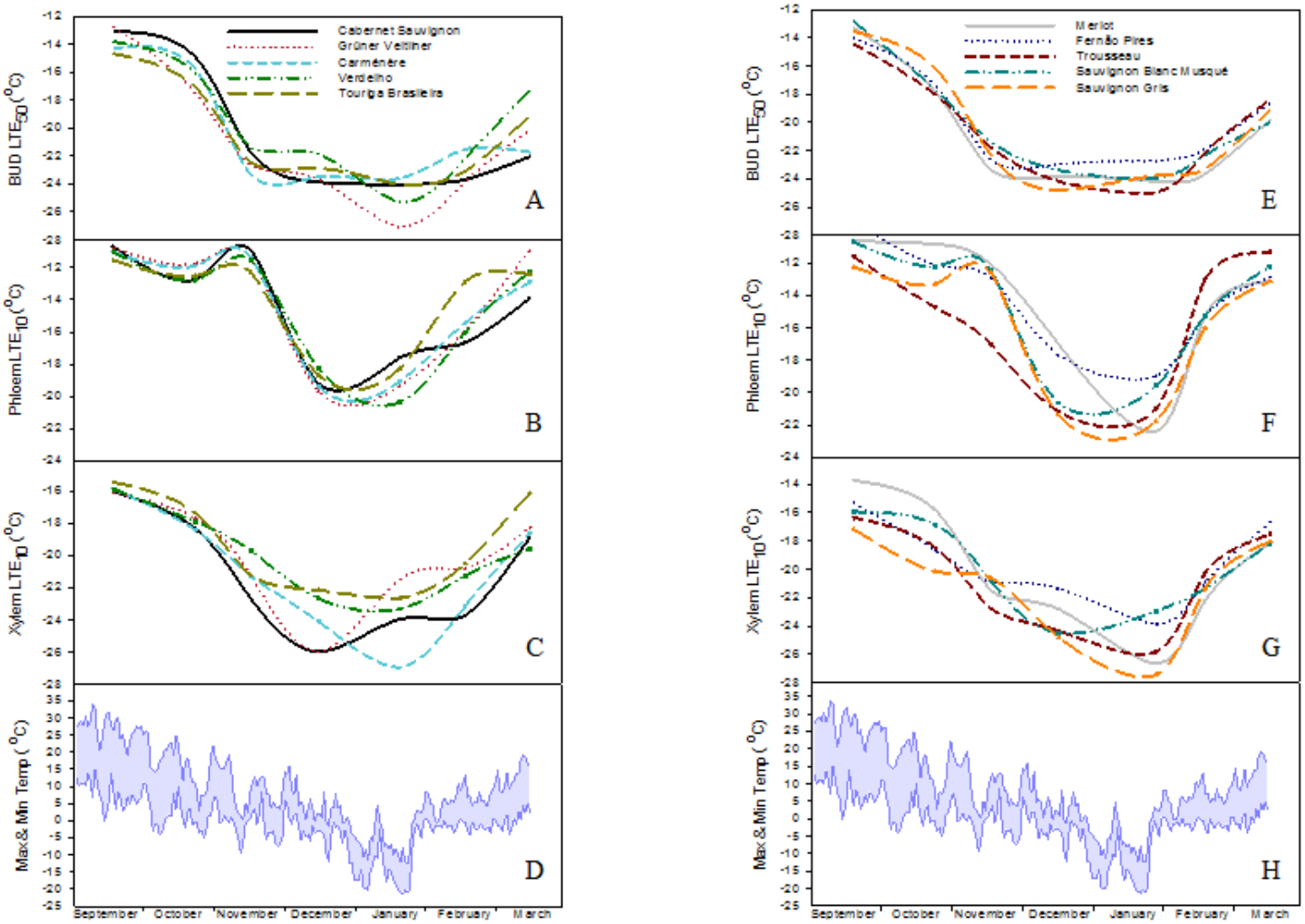

Figure 1.5 Cold Hardiness Values from September of 2012 to March of 2013 in Nampa, Idaho. Bud cold hardiness based on LTE50 is represented in (A) and (E) and BUD LTE50 were significant at $p \leq 0.05$ ($n = 10$) for all dates sampled. Cold hardiness of phloem cane tissue based on LTE10 is represented in (B) and (F) with xylem cane tissue represented in (C) and (G). Minimum and maximum temperatures in (D) and (H) are equivalent.

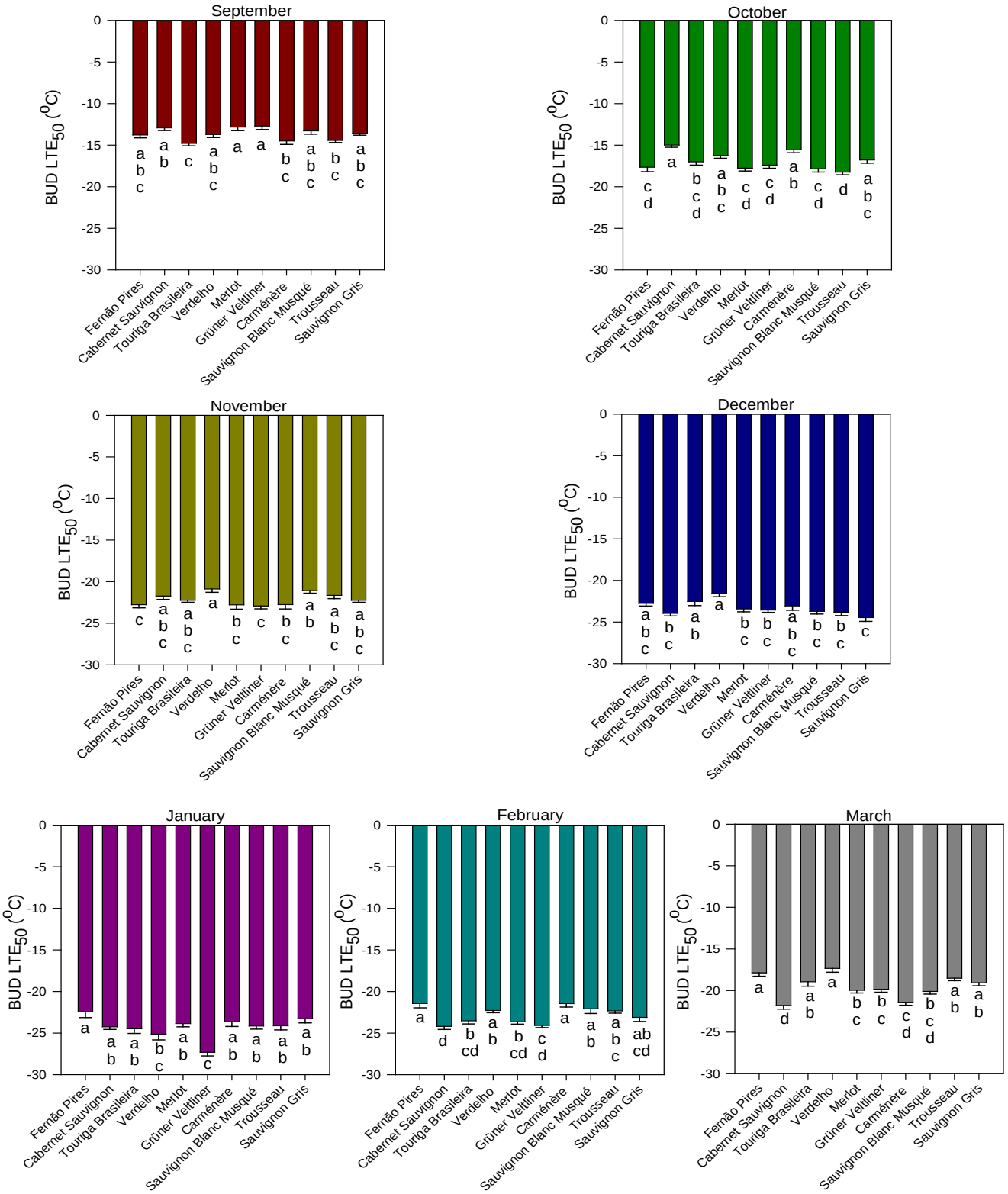

Figure 1.6 Month by Month Cold Hardiness Values for the dormant period 2012-2013 of Select Cultivars from Nampa, Idaho. Cultivars with the same lowercase letter are not significantly different at p = 0.05.

CHAPTER TWO: WINEGRAPE COLD HARDINESS AS AFFECTED BY TEMPERATURE, DORMANCY, AND DEACCLIMATION

Abstract

In the Snake River Valley American Viticultural Area (SRV AVA), major factors causing vine damage are extreme cold temperatures in early and mid-winter, and warm spells followed by freezes in late winter and early spring. This study characterized the cold hardiness of two cultivars widely grown throughout the SRV AVA, Chardonnay and Cabernet Sauvignon, over their dormancy cycle from para- to ecodormancy. The objectives of this research were: to monitor the timing of dormancy transition and its relationship with bud cold hardiness in each cultivar and identify cultivar differences in dormancy transition and cold hardiness. In addition, during the ecodormant period, buds were tested for their ability to deacclimate and reacclimate. Data was collected over two seasons (2011-12 and 2012-13) on vines grown in an experimental vineyard at the University of Idaho Research and Extension Center in Parma, ID. The stage and depth of bud dormancy was assessed using a forcing bioassay to evaluate percent budbreak. The cold hardiness of buds were evaluated by determining the temperature that caused 50% bud death (LTE_{50}) using a differential thermal analysis (DTA) system. A similar approach was used to assess the cold hardiness of the xylem and phloem, except that10% death (LTE_{10}) of these tissues was used for the comparisons of cold hardiness. The cold hardiness data was also used to evaluate the accuracy of the Ferguson dynamic thermal time model on predicting bud LTE_{50} values of Chardonnay and Cabernet Sauvignon

under the climatic conditions of southern Idaho. Chardonnay acclimated earlier and more rapidly than Cabernet Sauvignon during autumn. The buds of Chardonnay transitioned to ecodormany earlier than those of Cabernet Sauvignon and in both cultivars maximum bud cold hardiness was acquired during ecodormancy. Acquisition of maximum bud cold hardiness after release from endormancy suggests that at least some metabolic factors associated with cold acclimation are independent of endodormancy. In the first year of the study, maximum bud cold hardiness was approximately -26 °C for both cultivars. In the second year of the study, maximum bud cold hardiness was -28 and -26°C for Chardonnay and Cabernet Sauvignon, respectively. The dynamic thermal model accurately predicted cold hardiness in both cultivars, though it was more accurate for Cabernet Sauvignon than Chardonnay. The Willmot index of agreement between observed and predicted bud LTE_{50} was 0.95 and 0.85 for Cabernet Sauvignon and Chardonnay, respectively. Actual bud cold injury in February 2013 was greater than would be expected from the bud LTE_{50} value predicted by the dynamic thermal model and by DTA and this discrepancy warrants further research. During ecodormancy, the buds of Cabernet Sauvignon reacclimated to a lower temperature after deacclimation than that of Chardonnay. Results indicate that Chardonnay is better adapted to areas with colder fall and winters than Cabernet Sauvignon. Furthermore, Chardonnay is better suited than Cabernet Sauvignon for sites that experience early autumn cold events. Cabernet Sauvignon was more resistant to deacclimation and more capable of reacclimation than Chardonnay. These results suggest that Cabernet Sauvignon is better suited than Chardonnay for sites that experience fluctuating mid-winter temperature events and late spring frosts.

Introduction

Cold injury occurs in winegrapes when they are exposed to temperatures that are colder than their current level of cold hardiness. Cold hardiness is an important factor for cultivar selection and for the success of a cultivar within a particular wine appellation (Ferguson et al. 2014). Cold injury is common in areas with variable macro and mesoclimates such as those often found at mid and high latitudes (Kovacs et al. 2003; Shellie et al. 2014). In these variable areas, unpredictable seasonality tends to occur during the cold periods of the year typically late fall, winter, and early spring. Any combination of fall and spring frost, or deep midwinter freezing may occur causing damage to plants without sufficient cold hardiness. Many plants including winegrapes of European origin (*Vitis vinifera* L.) have the ability to supercool tissues to avoid freeze injury (Jones et al. 1999, Andrews et al. 1984). Nevertheless, parts of the plant and in particular buds can be susceptible to freezing injury. The damage caused by cold on buds leads to a reduction in yield, thus resulting in economic losses for the grower (Clore et al. 1974).

To increase tolerance to cold, grapes and many other plants go through cold acclimation. Cold acclimation is an increase in freeze tolerance triggered by environmental changes in photoperiod and/or temperature (Fennell and Hoover 1991, Kozlowski and Pallardy 2002). These changes lead to molecular and cellular responses, which are ultimately responsible for freeze tolerance (Wisniewski et al. 2014a, Arora 2011). In *Vitis*, it is thought that photoperiod in combination with temperature have a greater effect on cold hardiness than the individual environmental factors alone (Schnabel and Wample 1987). Deacclimation is the loss of cold hardiness at the cellular, tissue, or

whole plant level while reacclimation is the plant's ability to regain some or all lost cold hardiness (Kalberer et al. 2006). A grapevine must be able to acclimate to tolerate midwinter freezing temperatures. In addition, the grapevines must be able to prevent early deacclimation during midwinter warming and/or have a strong ability to reacclimate to avoid early frost in late winter and early spring (Kalberer et al. 2006). Once the buds have broken, their ability to reacclimate is lost. Temperature cycles from winter to spring cause deacclimation and reacclimation until the plant slowly loses cold hardiness as warmer spring weather sets. Interestingly, Wolf and Cook (1992) observed in three tested cultivars that the most cold hardy were the least resistant to deacclimation, while the least cold hardy cultivars were the most deacclimation resistant.

In grapes, a decrease in photoperiod and temperature induces cold acclimation and changes in bud dormancy. Lang et al. (1987) divided bud dormancy into three phases, para-, endo-, and ecodormancy. Paradormancy is dormancy primarily induced from the distal organs and occurs during active growth. Endodormancy is regulated by internal physiological conditions that are triggered by environmental cues such as changes in temperature and photoperiod (Fennell and Hoover 1991, Olsen 2010, Wake and Fennell 2000). Release from endodormancy requires exposure to cold, also known as chilling, which allows the buds to enter into ecodormancy. Ecodormancy is defined as dormancy regulated by the environment primarily due to winter temperatures and reduced water content. With increases in temperature, ecodormant buds break and the active cycle for the growing season begins again.

Most studies on cultivar cold hardiness has been conducted in viticulture appellations found at higher latitudes, where cold temperatures are more likely to occur

and cause damage to the vines (Hamman et al. 1996, Kovacs et al. 2003, Mills et al. 2006). This has been done as an attempt to understand how specific cultivars can withstand freezing events as a means to determine their suitability for particular regions and sites (Ferguson et al. 2011 & 2014, Proebsting et al. 1980). On the other hand, studies on chilling and dormancy of grapevines have been primarily conducted in warm production areas where cold requirements may not be fully met to break dormancy (Botelho et al. 2007, Dokoozlian 1999, Dokoozlian et al. 1995, Trejo-Martínez et al. 2009). Dormancy transitions may correspond with changes in bud cold hardiness (Arora et al. 2003, Zhang and Dami 2012). However, the relationship between dormancy phases and bud cold hardiness has not been well characterized. Knowledge in this area may provide information on the degree to which factors and mechanisms that control cold hardiness and dormancy overlap.

The development of cold hardiness is affected by various factors including rootstock, cultural practices, photoperiod, temperatures fluctuations, and bud water status (Dami et al. 2013, Ding and Gu 2001, Fennell 2004, Gu and Read 2003, Hubackova 1996, Wample et al. 1994). Thus, the cold hardiness of a particular cultivar is not only determined by its genotype, but also by the environment and vineyard management practices where the cultivar grows. Given these sources of variation, an important goal of this study was to investigate the relationship between the stage of dormancy and seasonal changes in cold hardiness in two widely grown winegrape cultivars, Chardonnay and Cabernet Sauvignon, under the climatic conditions of the Snake River Valley American Viticultural Area (SRV AVA) in southwestern Idaho.

In the SRV AVA, major losses of yield can occur as result of warms spells followed by early freezes in late winter and early spring. Consequently, a characteristic that contributes to the success of a cultivar is its ability to delay deacclimation and/or rapidly reacclimate. To assess the susceptibility of Chardonnay and Cabernet Sauvignon to cold damage during early spring, I also analyzed changes in bud cold hardiness associated with deacclimation and reacclimation.

Overall, determinations of midwinter cold hardiness and of changes in cold hardiness during deacclimation and reacclimation in Chardonnay and Cabernet Sauvignon would allow assessing their potential susceptibility to cold damage in the SRV AVA. Moreover, if cold hardiness of these cultivars could be predicted based on environmental factors, this could be used to estimate the risk of injuries at a particular site and time, and implement practices aimed at reducing the negative impact of cold events. A few models have been developed to predict cold hardiness based on ambient air temperatures (Ferguson et al. 2011, Hoegh and Leman 2015). In particular, the dynamic thermal time model developed by Ferguson et al. (2011 & 2014) accurately predicts bud cold hardiness in Eastern Washington, where the model was developed. Since the climate in this area is similar to that of southwestern Idaho, I used the ambient air temperature and cold hardiness data from my research to test the predictive power of the Ferguson model (Ferguson et al. 2011) for the SRV AVA.

As discussed above, decreases in photoperiod and temperature during the fall increase cold hardiness and bring about a change in bud dormancy phases from para- to endodormancy. Subsequently, exposure to chilling temperatures cause a transition from endo- to ecodormancy. Presently, it is not clear whether bud and cane tissue reach

maximum cold hardiness during endodormancy or whether cold acclimation continues during ecodormancy. Furthermore, the transition from endo- to ecodormany is likely to affect the capacity of the buds to deacclimate and reacclimate (Arora and Rowland 2011). Given the potential effect of dormancy transitions on processes that affect cold hardiness, an additional motivation for the present study was to investigate the relationship between seasonal changes in cold hardiness and stage of dormancy.

Materials & Methods

Field Site

All grape vine plant material was grown at the USDA ARS research vineyard (43° 49' N, 116° 56' W, elevation 760 m) located at the University of Idaho Parma Research and Extension Center in Parma, ID. Chardonnay and Cabernet Sauvignon were planted on their own roots in 1997 and 1998 (Fallahi et al. 2004 & 2005), and five block replications of each cultivar were selected at random throughout the vineyard with 8 vine panels per replication. The vine rows were orientated north to south with 2.74 by 2.13 m row by vine spacing (Shellie 2007). The vines were double trunked with each trunk trained to form a unilateral cordon. Canes were spur pruned, and shoots were vertically positioned. Vines were irrigated at 70% of maximum evapotranspiration from fruit set to veraison and were fully irrigated pre-fruit set and post veraison. Vines were managed according to the commercial standards for viticulture in eastern Washington (Shellie 2007, Watson 1999). Weather data for the vineyard site was obtained from the Agrimet weather station located in Parma, Idaho (http://www.usbr.gov/pn/agrimet/; 43.80 °N, 116.933° W, 703 m a.s.l.).

Cold Hardiness Evaluation

The cold hardiness evaluation for each cultivar was determined using a differential thermal analysis (DTA) system to observe low temperature exotherms (LTE) of bud and cane tissues (Burke et al. 1976). Analysis of cane tissue provided values of LTEs for both the xylem and the phloem. The DTA system used for the evaluation was designed and used by Washington State University researchers to determine cold hardiness of bud and cane material (Mills et al. 2006). Cane sections were sampled from the vineyard on a monthly, bi-weekly, or weekly schedule based on seasonality, availability of plant material, and stage of the experiment. Sampling started during late summer to early fall and ended in March. Canes were pruned above the second node on the spur and further cut into cane samples containing internodes 3-8. Buds were excised from the cane samples with the addition of 2 mm of surrounding cane and nodal tissues to prevent damage during bud sampling and LTE determination (Wolf and Poole 1987). Excised buds were placed in thermoelectric model (TEM) wells at 3 to 4 buds per well for a total of 40 buds per cultivar for each evaluation date. Cane samples were further cut into 35 mm sections between internodes 3-8 and placed in the TEM wells with 3 cane section in each well for a total of 15 sections per cultivar for each evaluation date. Once all buds and canes were situated in the TEM, the wells were covered with high density foam and the DTA plates were sealed and placed in a Tenney Environmental Chamber (SPX, Rochester, NY). Voltage output was read by a Keithley Multimeter Data Acquisition System (DAS) (Keithley Instruments, Cleveland, OH) that was linked to each DTA plate. The DAS read the output to the Microsoft Excel-based program ExcelLINX (Keithley Instruments) where the raw data could be analyzed and

manipulated into graphical form. The Tenney Chamber was programmed to run for a 19 hour duration per run cycle. Each run cycle included a 1 hour hold at 4 ^{0}C followed by a decrease in temperature to -40 ^{0}C at a rate of 4 ^{0}C per hour, and a -40 ^{0}C hold for 1 hour. The run cycle was concluded with a 5 hour increase in temperature to 4 ^{0}C and a final 1 hour hold (Mills et al. 2006).

Dormancy Evaluation

The stage of dormancy in the vines (para-, endo-, ecodormancy; Lang et al. 1987) were observed during the fall and winter via a budbreak bioassay. The vine material was collected monthly (2011) to bi-weekly (2012) based on projected availability of materials per season. Vine material used in the determination of dormancy phases was collected at the same time as the material used for evaluation of cold hardiness. Canes were cut at nodes 3 through 8 into approximately 8.25 cm segments containing a single node. These one node segments were then placed into standard floral wet foam blocks that had been halved width-wise to conserve materials. Each block contained exactly 20 single node segments for a total of 5 foam blocks to represent each replication block in the vineyard. All 5 blocks per sampling date were placed in a planting tray. Planting trays were marked with the sampling date and filled with water by hand every other day during observation. Planting trays were then placed in the Boise State research greenhouse under a 15 hour photoperiod and day/night conditions of 25/20 (±2) °C. Buds were observed for 60 days and measured for percentage of budbreak and time to budbreak. Budbreak was identified using stage 4 of the modified E-L system. This stage is known as budburst and it occurs when green leaf tips are first visible (Coombe 1995). At the end of the 60 day cycle, buds that had not broken were dissected to determine if they were dead or alive and still

dormant with dead buds being removed from budbreak calculations. Budbreak bioassays were conducted on samples collected between July 2011 and January 2012 and between August 2012 and January 2013. For samples collected during the summer and early fall, buds were considered ecodormant when most of them failed to sprout under the conditions of the budbreak bioassay. Similarly for samples collected during the fall and winter, buds were considered ecodormant when most of them burst under the conditions of the bioassay.

Deacclimation and Reacclimation

Once ecodormancy was established, the dormancy evaluation was suspended and the vine material collected after this point used for measurements of deacclimation and reacclimation. At the time of sampling, cane material (nodes 3-8) were separated so that 40 buds and 15 cane sections per cultivar went through the cold hardiness evaluation to establish cold hardiness at sampling. The remaining material was wrapped in bundles representing the block replications. Moist towels were placed at each bundle end and the whole bundle was covered with polyvinyl wrap and housed in an incubator. The incubator was set to forcing conditions of 15 hour photoperiod and 25/20 (+/- 0.5) °C day to night temperature cycles. After 2 d, 40 buds and 15 cane sections per cultivar were removed from the incubator and underwent the cold hardiness evaluation. This procedure was then repeated at 4 d of deacclimating conditions. After the 4 d of deacclimation, the remaining material in the incubator was subjected to reacclimation forcing conditions. This material received no light and the temperatures were reduced to 0°C (+/- 0.5) °C. After 3 or 5 d under reacclimation conditions, 40 buds and 15 cane sections per cultivar and reacclimation period were sampled and underwent cold hardiness evaluation. The

entire protocol described above to characterize cold hardiness following deacclimation and reacclimation was repeated bi-weekly during the ecodormant period until the vineyard was pruned for the next growing season or the vine material was no longer available.

Ferguson Dynamic Thermal Time Model of Cold Hardiness

All cold hardiness data from field samples that had not been manipulated for experimental procedures (i.e., forcing and chilling conditions) was collected and analyzed. The observed cold hardiness values and the Agrimet weather data of the recorded daily temperature minimum, maximum and mean values were then inputted into the Ferguson dynamic thermal time model of cold hardiness with each cultivar using a unique set of cultivar specific model parameters as described by Ferguson et al. (2011). Using a Visual Basic macro in Microsoft Excel the output of predicted values was evaluated and graphed against observed cold hardiness of grapevines in the research vineyard.

In addition to evaluating the model with data from Idaho, I also evaluated it with data from eastern Washington. Bud LTE_{50} values of Chardonnay and Cabernet Sauvignon growing in Roza location of Eastern Washington (46.29 ^{0}N, 119.73 ^{0}W; 360 m) during the fall-winter of 2011-2012 and 2012-2013 were generously provided by researchers at Washington State University. Weather information for these periods was downloaded from the Washington State University's AgWeatherNet (http://weather.wsu.edu/awn.php) at the Roza location. The weather data was entered into the model and evaluated for its capacity to predict bud cold hardiness. The purpose of this

evaluation was to determine whether the capacity of the model to predict cold hardiness in Idaho was similar to that in eastern Washington, where the model was developed.

Data Analysis

Statistical analyses were carried out using the program R (program R, version 2.13.1, http://www.r-project.org/), including various packages written for this program. Cultivar comparison was evaluated using a repeated measure analysis and post-hoc multiple comparisons were analyzed using Tukey's honestly significant difference test with the data analysis package Agricolae. Evaluation of the predictive capacities of the model was performed using the Willmott Index of Agreement (Willmott 1981) using the data analysis package hydroGOF. Correlation analysis was used to evaluate the models predictive capacities. Bud, phloem, and xylem LTE values as well as dormancy data were graphed using SigmaPlot (SPSS, Chicago, IL). The correlation analysis was graphed using R.

Results

Cold Hardiness

During the 2011-12 experimental period, temperatures were recorded from the beginning of September of 2011 to the end of March 2012. The 2011-2012 evaluation was ended at this point because the vineyard was pruned in preparation for the following growing season. During the experimental period, the temperatures ranged from a maximum of 32.6 °C on September 6, 2011 to a minimum of -11.2 °C on December 23, 2011 (Fig. 2.1). For Cabernet Sauvignon, cold hardiness increased until the end of December, when bud cold hardiness (Bud LTE_{50}) reached -24 °C. Similar levels of cold hardiness were observed during the next two months (Fig. 2.1). In Chardonnay the cold

hardiness increased more rapidly than in Cabernet Sauvignon. As a result, in October, November, and most of December, Chardonnay bud LTE was lower than those of Cabernet Sauvignon. However, in both cultivars, the values of maximum bud cold hardiness were similar, approximately -24 ^{0}C to -26 ^{0}C. Cabernet Sauvignon was most cold hardy on January 30, 2012 at -25.9 ^{0}C, while Chardonnay was most cold hardy on December 21, 2011 at -25.6 ^{0}C (Fig. 2.1). At the time of the last measurement at the end of March 2012, bud cold hardiness of both cultivars had not returned to the pre-winter cold hardiness values that were initially measured in mid-September.

LTE_{10} values for the xylem and phloem followed initially similar patterns as those of the buds LTE_{50s}; LTE_{10} values decreased between September and December of 2011 (Fig. 2.2). Subsequently, the patterns of changes in phloem and xylem LTE_{10} were somewhat different than those of the buds. Particularly for Chardonnay, LTE_{10} of phloem and xylem tissue began to increase in January. Furthermore, for both cultivars, the phloem and xylem LTE values at the end of the experimental period in March were similar to those measured in September. No clear differences in LTE_{10} values were detected between the cultivars, except for the measurements made at the end of January. At this time, Chardonnay showed higher phloem and xylem LTE_{10} values than Cabernet Sauvignon. In both cultivars, the phloem had the highest LTE_{10} values, indicating that this tissue is more susceptible to cold than the xylem.

During the 2012-2013 experimental period, temperatures ranged from 33.72 ºC to -22.87 ^{0}C. The winter of 2013 experienced average temperatures 5 to 10 °C below the average values for the area (http://www.noaa.gov/). January in particular was very cold; there was a cold span of eight days where daily minimum temperatures were between -20

to -23^{0}C and daily maximums were not above -8 ^{0}C (Fig. 2.3). This cold event was preceded by an earlier event that albeit not as extreme also occurred in January. Through most of the experimental period, bud LTE_{50} values for Cabernet Sauvignon were higher than those for Chardonnay (Fig. 2.3). However, the patterns of changes in cold hardiness were similar. Both cultivars reached maximum bud cold hardiness in mid-December. Subsequently, LTE_{50} values for Cabernet Sauvignon fluctuated between -24 ^{0}C to -25 ^{0}C, while those of Chardonnay fluctuated between -26 ^{0}C to -28 ^{0}C. Cabernet Sauvignon's lowest recorded bud cold hardiness was -25.75 ^{0}C on December 17, 2012 and Chardonnay was -28.03 ^{0}C on January 14, 2013. The January cold events caused major damage to Cabernet Sauvignon, which was not predicted by the model or the DTA system for buds. After these events, the number of canes collected was doubled to obtain a sufficient number of undamaged buds for the measurements of cold hardiness. Similar to the 2011-2012 experiment, when cold hardiness was last measured on March 2013, LTE_{50} values for both cultivars were significantly lower than those measured in early fall.

From September 2012 to March 2013, the changes in LTE_{10} of phloem and xylem tissue followed a similar pattern as those observed during the September 2011 to March 2012 period. The phloem and xylem cold hardiness for Cabernet Sauvignon and Chardonnay increased until January and maximum hardiness was reached when the midwinter temperatures were the coldest (Fig. 2.4). Subsequently, LTE_{10} values increased sooner in Chardonnay than Cabernet Sauvignon and at the time of the last measurements in March LTE_{10} values were similar to those observed in September.

Dormancy

Dormancy during the 2011-2012 experimental period was first evaluated from samples collected in July. Chardonnay buds collected at this time showed 80% budbreak while those of Cabernet Sauvignon had lower budbreak, at 50% (Fig. 2.5). In addition, the average time to budbreak was shorter in Chardonnay than in Cabernet Sauvignon (Fig. 2.5). Based on the percent budbreak, in July Chardonnay buds were predominantly paradormant, while Cabernet Sauvignon buds were in transition from para- to endodormancy. By September of 2011, both Cabernet Sauvignon (2% budbreak) and Chardonnay (10% budbreak) were endodormant and no budbreak occurred for samples collected in October. For Chardonnay, buds collected in November appeared to have begun the transition out of endodormancy, as judged by a significant increase ($p < 0.05$) in budbreak between October and November of 31%. In contrast, no budbreak occurred in Cabernet Sauvignon for samples collected in November. By December of 2011, both Chardonnay (99% budbreak) and Cabernet Sauvignon (98% budbreak) were fully ecodormant (Fig. 2.1 and 2.5). However, the time to budbreak was shorter in Chardonnay than Cabernet Sauvignon (Fig 2.5).

The analysis of dormancy conducted from the summer of 2012 to the winter of 2013 showed that both cultivars transition from para- to endodormancy at about the same time, between the end of August and the beginning of September. However, the period of endodormancy was shorter for Chardonnay than for Cabernet Sauvignon. Chardonnay was ecodormant by mid-October, while Cabernet Sauvignon did not reach ecodormancy until November (Fig. 2.6). Even when samples were at the same phase of dormancy, significant differences were observed between cultivars in average days to budbreak.

Except for the first sampling date in October, the time to budbreak was shorter in Chardonnay than Cabernet Sauvignon (Fig 2.6).

Deacclimation and Reacclimation

Five sets of deacclimation/reacclimation trials were performed during 2012 and another five during 2013. In 2012, deacclimation/reacclimation experiments were conducted between late January and late March and in 2013 between mid-January and mid-March. At these times, buds were ecodormant (Fig. 2.1, 2.3, 2.5, and 2.6). In both years, system errors or power failure occurred during the experiments; consequently, some data was lost in two of the five trials in 2012 and in one of the five trials in 2013. For Chardonnay buds collected in January 30 and February 15, 2012, deacclimation for 4 days resulted in higher LTE_{50} values (Fig. 2.7). Subsequent reacclimation for 3 or 5 days led to LTE_{50} values similar to those prior to deacclimation, but also similar to those observed after deacclimation thus suggesting that reacclimation was minimal. For samples collected on February 27, deacclimation for 4 days had a similar effect, increasing LTE_{50} values, while reacclimation did not decrease LTE_{50} values. Deacclimation followed by reacclimation did not have an effect on samples collected in March. At this time, the LTE_{50} values of buds prior to deacclimation were significantly higher than that of buds collected in January or February. Cabernet Sauvignon showed somewhat different results. During the trial period from January to March, Cabernet Sauvignon did not lose the ability to reacclimate (Fig. 2.8). However, for the trial started on February 15th, neither deacclimation nor acclimation had an effect on LTE_{50} values and for the February 27 trial reacclimation did not fully compensate for the changes in LTE_{50} that occurred during deacclimation.

The measurements conducted in 2013 showed that for both cultivars and the five trials deacclimation for 4 days significantly increased LTE_{50} values (Fig. 2.9 and 2.10). Similar results were observed for 2 days deacclimation except for the last trial with Cabernet Sauvignon. Reacclimation after 4 days deacclimation had negligible effect on LTE_{50} values. Chardonnay and Cabernet Sauvignon were not able to reacclimate to the cold hardiness level observed prior to deacclimation. Furthermore, most trials showed LTE_{50} values after reacclimation that were not significantly different from those after deacclimation.

Ferguson Dynamic Thermal Time Model of Cold Hardiness

Ambient temperature and cold hardiness data collected during the 2011-2012 and 2012-2013 experimental periods were used to test the Ferguson model for predicting cold hardiness. During the fall of both experimental periods, the model predicted higher LTE_{50} values than those observed (Fig. 2.11 and 2.12). These differences were more marked for Chardonnay than for Cabernet Sauvignon. During the midwinter of both experimental periods, the model predicted LTE_{50} values that were very similar to those observed (Fig. 2.11 and 2.12). Similar results were observed for both cultivars, although in the winter of 2013 the model was somewhat more accurate in predicting LTE_{50} for Cabernet Sauvignon than for Chardonnay. During the deacclimation phase in late winter of 2012, the model predicted for both cultivars higher LTE_{50} values than those observed (Fig. 2.11). Unfortunately in late winter 2013, there was no available bud material to determine the differences between predicted and observed values during the deacclimation phase.

Notwithstanding some of the differences between predicted and observed LTE_{50} values, the correlation between these values was high. After combining data from both

experimental periods, the r^2 values were 0.90 and 0.95 for Chardonnay and Cabernet Sauvignon, respectively (Fig. 2.13 and 2.14). Furthermore, the root mean square error between predicted and observed values was 3.71 °C for Chardonnay and 2.36 °C for Cabernet Sauvignon. The accuracy of the model was also tested using the Willmott Index of Agreement. The strength of the agreement as determined by this index was 0.95 for Cabernet Sauvignon and 0.85 for Chardonnay.

When the model was evaluated with data from eastern Washington, the predicted and observed values of cold hardiness for Chardonnay had an r^2 of 0.96 with a root mean square error of 1.06 °C and a Willmot index of agreement of 0.99 (Fig. 2.15). Similarly, the predicted and observed cold hardiness values for Cabernet Sauvignon had a r^2 of 0.91 with a root mean square error of 2.38 °C and a Willmot index of Agreement of 0.92 (Fig. 2.16).

Discussion

Differences in Cold Hardiness Between Cultivars and Years

During most of the acclimation period in 2011 and 2012, Chardonnay was more cold hardy than Cabernet Sauvignon. Similar results have been reported in other studies (Mills et al. 2006, Ferguson et al. 2011 & 2014, Wample et al. 2000). However, midwinter LTE_{50} values were only lower in one of the years of the study. After acclimation during the fall of 2011, the two cultivars showed similar LTE_{50} values, suggesting that they had reached analogous levels of cold hardiness. A similar trend was initially observed during the fall of 2012; but during January 2013, an additional decrease in bud LTE_{50} was observed for Chardonnay. This decrease was, however, transient in nature, and no difference in bud LTE_{50} values were observed between the two cultivars at

the end of January. Nevertheless, the results suggest that Chardonnay was able to further adjust its cold hardiness in response to the very cold temperatures experienced during January of 2013.

In late winter, both cultivars started to lose cold hardiness in buds and vascular tissues, but this occurred sooner and to a larger degree in Chardonnay than Cabernet Sauvignon. This is in agreement with results observed in eastern Washington (Ferguson et al. 2011, Wample et al. 2000). Also, in both cultivars, vascular tissues began to lose cold hardiness before the buds. LTE_{10} values in the phloem were higher than in the xylem and the cold temperatures in January of 2013 caused phloem damage in both cultivars, as judged by the brown coloration observed in the canes harvested after January's cold events. However, this may not have been of major consequence to yield. Keller and Mills (2007) showed that phloem damage has little to no effect on budbreak because this event is initially sustained by sugars moving through the xylem until the phloem reactivates and repairs.

As mentioned above, loss of cold hardiness during late winter was more pronounced for Chardonnay than Cabernet Sauvignon. Despite these differences, the response to the deacclimation protocol followed similar trends in the two cultivars. Particularly, in 2013, both cultivars showed similar degrees of deacclimation, and deacclimation occurred at all the dates tested (Fig. 2.9 and 2.10). Similar results were observed in 2012, except that Chardonnay did not show any deacclimation after February, when substantial deacclimation appeared to have already occurred in the field. In contrast, Cabernet Sauvignon showed a small degree of deacclimation in March.

Clear differences in the extent of deacclimation were observed between the two years of the study. Based on the results from the deacclimation protocol, buds were more resistant to deacclimation in the winter of 2012 than in the winter of 2013. For both cultivars, the maximum deacclimation observed in 2012 was about 3°C, while that in 2013 was about 8°C (Fig. 2.7 to 2.10). This difference in deacclimation resistance was not correlated with maximum mid-winter cold hardiness. The lowest LTE_{50} value for Cabernet Sauvignon in 2011-2012 was similar to that measured in 2012-2013. Furthermore, the lowest LTE_{50} for Chardonnay was about 2 °C higher in 2011-2012 than in the 2012-2013. Thus, resistance to deacclimation was higher in 2012 than 2013 despite similar or less cold hardiness in the first year of measurements.

Lack of a relationship between maximum cold hardiness and deacclimation resistance has been observed in other woody species. For example, azalea and blueberry genotypes with high mid-winter cold hardiness varied in their resistance to deacclimation (Arora and Rowland 2011, Rowland et al. 2008). Among grape cultivars and *Hydrangea* species, an inverse relationship between maximum cold hardiness and deacclimation resistance has been reported (Pagter et al. 2011, Wolf and Cook 1992). Taken together, my results with Chardonnay and Cabernet Sauvignon and findings from the studies mentioned above suggest that the processes determining maximal cold hardiness and resistance to deacclimation are not linked (Arora and Rowland 2011). Under this scenario, the evaluation of cultivars for cold hardiness appears to require independent assessment of both maximum cold hardiness and deacclimation resistance.

A factor that may affect resistance to deacclimination is the intensity of dormancy (Kalberer et al. 2006). In 2011, buds reached ecodormancy one month later than in 2012,

the beginning of December and November for 2011 and 2012 buds, respectively. During the measurements made in December of 2011, ecodormant buds under forcing conditions had average days to budbreak that ranged from 48 to 55 days. During the same month in 2012, average days to budbreak ranged from 26 to 32 days. These results indicate that in 2012, buds had a higher capacity to resume growth. The reasons for such difference are unclear. Within the ecodormant period, a progression of developmental stages may exist, resulting in increased capacities to resume growth when conditions are favorable (Lavee and May 1997). However, if this were true, buds sampled later should have been progressively less resistant to deacclimation, a trend which was not observed.

A difference in the number of days to reach 50% budbreak was also observed between cultivars. In both years, the average number of days to reach 50% budbreak in ecodormant buds was lower in Chardonnay than Cabernet Sauvignon, suggesting that Chardonnay was either more advanced in its developmental cycle or its dormancy was not as deep as Cabernet Sauvignon. This paralleled the tendency of Chardonnay to lose cold hardiness sooner than Cabernet Sauvignon.

In addition to resistance to deacclimation, an important trait to tolerate late freezes is the capacity to reacclimate. Chardonnay showed minimal, if any, ability to reacclimate; LTE_{50} values after reacclimation were similar to those following deacclimation, despite increases in LTE_{50} values of up to 8°C during deacclimation in 2013. Cabernet Sauvignon showed some capacity for reacclimation with gains in cold hardiness during the return to cold conditions ranging from 1.8 to 3.5 °C. In 2012, reacclimation resulted in some instances in bud LTE_{50} values after reacclimation similar to those observed prior to deacclimation. In contrast, in 2013, reacclimation when it occurred, only partially

compensated for the loss of cold hardiness during deacclimation. Little is known about reacclimation of grape vines, but based on my results the extent of reacclimation seems to be lower than those that have been reported for other woody species such as azaleas, raspberries, and hydrangeas (Kalberer et al. 2007, Pagter and Williams 2011, Palonen and Linden 1999).

The reasons for the lack of reacclimation in Chardonnay and the relative low capacity of Cabernet Sauvignon to reacclimate, particularly in 2013, are not clear. It is possible that the temperature used to trigger reacclimation, 0°C, was not effective for inducing reacclimation. This notion requires further testing, but based on studies with other species, 0 °C is an adequate temperature to induce reacclimation (Kalberer et al. 2007). Another possibility for the lack or low extent of reacclimation is that buds were at development stages when the energy reserves needed for reacclimation were declining (Kalberer et al. 2006). If that is the case, the expected response would be a gradual decrease in the ability to reacclimate as the winter progresses, as it has been reported for other species (Kalberer et al. 2007; Pagter and Williams 2011; Palonen and Linden 1999). However, the results with Cabernet Sauvignon did not clearly show such a pattern. Consequently, further work is needed to ascertain whether the observed reacclimation response reflects an experimental artifact or genetic constrains to undergo re-hardening in the studied cultivars.

Overall, the analysis of cold hardiness in the two cultivars revealed some differences. Based on these differences, Chardonnay is better adapted to areas with colder falls and winters than Cabernet Sauvignon. In contrast, Cabernet Sauvignon appears to deacclimate later than Chardonnay and showed some capacity to reacclimate. Both of

these characteristics suggest that Cabernet Sauvignon would perform better than Chardonnay in sites where warm days are common in late winter and early spring, when subsequent freezing events are still likely to occur.

Differences in the Dormancy Cycle Between Cultivars and Relationship Between Cold Hardiness and Dormancy

The budbreak bioassays showed difference in the duration of endodormancy between the two cultivars. Chardonnay shifted from endodormancy to ecodormancy earlier than Cabernet Sauvignon in both seasons. This suggests that the chilling requirements to fulfill endodormancy were less for Chardonnay than Cabernet Sauvignon. Additionally, temperatures outside the chilling range may have reduced the accumulated chilling hours and this reduction could have been somewhat more pronounced in Cabernet Sauvignon than Chardonnay. Analysis of the chilling requirements of the two cultivars under controlled temperatures may provide an answer to these questions. In addition, there were some differences between cultivars in the time at which they entered endodormancy, particularly during 2011. In 2011, Cabernet Sauvignon entered endodormancy earlier than Chardonnay, and the former also entered endodormancy sooner in 2011 than 2012. The summer of 2012 was on average about 1 °C warmer than that of 2011. Warmer temperatures may delay the entrance of Cabernet Sauvignon into endodormancy, but further experimentation is needed to test this notion.

During the fall of 2011, most cold acclimation occurred during endodormancy. In contrast, during the fall of 2012 significant cold acclimation occurred during ecodormancy. Similar results were observed in the two cultivars. The differences between years may be attributed to the duration of endodormancy, which was longer in

2011 than 2012. The fall of 2011was milder than that of 2012 and consequently a longer period may have been required to fulfill chilling requirements to break endodormancy. For example, from 9/1/2011 to 10/31/11, the number of accumulated hours with temperatures between 0 and 7 °C, which could have contributed to satisfy chilling requirements, was 180 h. In contrast, during the same period in 2012, the numbers of hours with temperatures between 0 and 7 °C was 307 h, and at this time the buds in both cultivars were ecodormant.

A pioneer study in *Vitis labruscana* and *V. riparia* (Fennell and Hoover 1991) showed that short days and mild temperatures of about 25 °C induced bud endodormancy with minimal cold acclimation. The separate induction of endodormancy and cold hardiness suggested that these processes are regulated by different metabolic processes (Fennell and Hoover 1991). Results obtained by Salzman et al. (1996) in *V. labruscana* supported this notion. They observed that a set of 47 kD glycoproteins accumulated in buds in response to short photoperiods, while an additional set of 27 kD proteins accumulated in response to the combined effects of short photoperiod and low temperatures. Presumably, the 47 and 27 kD proteins affected processes specific to endodormancy and cold hardiness, respectively (Salzman et al. 1996).

In my study, I did not evaluate the separate effects of photoperiod and temperature on inducing endodormancy and cold hardiness. However, some of my results suggest that both decreases in photoperiod and temperatures contributed to induce endodormancy and cold hardiness. In particular for Chardonnay, buds entered endodormancy sooner in 2011 than 2012; this would not be expected if photoperiod were the only factor controlling the transition from para- to endodormancy. By the middle of

September, Chardonnay and Cabernet Sauvignon buds were endodormant, but also had LTE_{50} values between -12 and -15 °C, indicating that substantial cold acclimation had already occurred. At this time, the buds had been exposed to decreasing photoperiods during the summer and to a few nights were minimum temperatures decreased to 10 to 5 °C (Fig. 2.1 and 2.3). Presumably, shorter days in combination with cooler nights triggered cold acclimation.

Even though endodormancy and cold acclimation may be induced by similar environmental factors, the metabolic processes responsible for cold hardiness may differ from those causing endodormancy. The results obtained in the fall of 2012 tend to support this notion. During this period, cold acclimation continued after the release from endodormancy. This indicates that at least after a certain stage in the dormancy cycle factors causing endodormancy are not the same as those that determine cold hardiness. After the induction of cold hardiness and endodormancy, the subsequent effect of environmental conditions on these processes was different. Exposure to cold temperatures and continually decreasing photoperiods were associated with an increase in cold hardiness. In contrast, exposure to chilling temperatures between 0 and 7 °C presumably fulfilled the requirements to break endodormancy. Within the context of Salzman et al. (1996), it would be interesting to determine whether gene products analogous to the 47 kDa proteins may decline in expression during the endo- to ecodormancy transition, while other products such as the 27 kD proteins may continue increasing.

Assessment of the Dynamic Thermal Time Model of Cold Hardiness for the SRV AVA

The Ferguson dynamic thermal time model of cold hardiness has been shown to accurately predict grape cold hardiness in eastern Washington (Ferguson et al. 2011 & 2014) . To evaluate the capacity of this model to predict cold hardiness in Idaho, I estimated the Willmot index of agreement between predicted and observed values. An index value of 1 indicates a perfect match, while 0 indicates no match at all. Based on the Willmot index, the model was particularly accurate at predicting cold hardiness of Cabernet Sauvignon. For this cultivar, the index of agreement for Idaho was higher than that for Washington, with values of 0.95 and 0.92, respectively; however, these small differences would likely not be statistically significant. The Ferguson model was less accurate in predicting cold hardiness of Chardonnay in Idaho. The model underestimated autumn cold acclimation because the measured bud hardiness was greater than that predicted by the model. Also, there was a rather large difference between the Willmot index estimated based on the data from Idaho and that from Washington, 0.85 and 0.99, respectively. Thus, suggesting that for Chardonnay, the model is less precise at predicting cold hardiness at the study site than at the place where the model was developed. However, it is not clear whether the differences in the Willmot index between Idaho and Washington reflect a general trend for the model to be more accurate at one site than another or an effect attributed to the particular years when the comparisons were made. Comparisons made using several years of data would be needed to assess how annual variations in weather affect the correlation between observed and predicted values, and thereby the Willmot index.

The Columbia Valley in eastern Washington and the Snake River Valley in Idaho have both a continental semiarid climate with sunny summers and cold winters. These similarities may explain the success of the model at predicting winter hardiness for Cabernet Sauvignon and to a lesser extent for Chardonnay vines grown in Parma, Idaho. It is also plausible that the inputs to the model, mainly temperatures, may be the principal factors in determining cold acclimation. In this case, the model would be valuable over a wide geographical area.

An important goal in evaluating the Ferguson model was to determine if the model could be used to predict whether the vines in Idaho vineyards have sufficient hardiness to avoid damage during cold events. A model that can accurately predict cold damage based on ambient temperatures could be used for site selection as well as in established vineyards. For site selection, the aim would be to avoid sites where, based on climate, the vines will be periodically exposed to temperatures below the predicted cold hardiness. In established vineyards, if the temperature forecast is below the predicted cold hardiness, the information could be used to implement practices to protect the vines. As measured by LTE_{50} values, the Ferguson model predicted cold hardiness with a root mean square error of 3.71 °C for Chardonnay and 2.36 °C for Cabernet Sauvignon. A remaining question is whether this accuracy is sufficient to predict the potential damage to the vines. Bud LTE_{50} values were obtained during a decrease in temperature at a constant rate that overall took place in about 10 h. Furthermore, the same protocol was used by Ferguson et al. (2011) to determine bud LTE_{50s} that were used to calculate the model's parameters. The effect of cold on plant tissues is determined by the value of the temperature, but also by the duration of exposure to a specific temperature (Gusta &

Wisniewski 2013). Based on these considerations, the protocol used to determine LTE_{50s} is likely to provide a good estimate of the vine response to freezing and extreme cold weather events that are completed within a relatively short period, such as those that may last throughout the night and early morning. However, if vines were exposed to several days of unusual cold temperatures, these conditions would be different from those I used to estimate LTE_{50s} and from those used to estimate the parameters of the Ferguson model. If lengthy periods of extreme cold cause more damage to buds than overnight cold exposure, the predictions of the Ferguson model would tend to underestimate this damage.

In January of 2013, a long-term cold event occurred in which maximum temperatures for 8 days were below -8 °C and minimum temperatures were between -20 and -23 °C. Following this event, a discrepancy was observed between the values of cold hardiness predicted by the Ferguson model and the damage to the vines. During this period, the predicted cold hardiness values for Chardonnay and Cabernet Sauvignon were very similar. However, most of the bud damage was in Cabernet Sauvignon, which prematurely halted additional sampling due to a lack of viable material. At least two reasons could explain the differences between predicted cold hardiness and the observed damage. For Chardonnay, the Ferguson model predicted higher bud LTE_{50s} than those observed. A more accurate prediction of LTE_{50s} would have led to lower estimates of LTE_{50s} for Chardonnay than Cabernet Sauvignon, which could explain at least part of the observed differences in bud damage. Calibration of the model parameters with data from Idaho may improve the model's ability to estimate LTE_{50s} in Chardonnay.

An alternative possibility to explain the discrepancies between the predicted cold hardiness and the observed damage is that the duration of exposure to cold resulted in damage at temperatures higher than those that caused damage in the DTA system. Presently, little is known about mechanism that confer tolerance to long term cold exposure or whether these mechanisms differ from those conferring tolerance to transient cold temperature events (Gusta & Wisniewski 2013, Wisniewski et al. 2014b). Prolonged exposure to cold is likely to increase ice formation in the apoplast with the ensuing loss of intracellular water (Gusta et al. 1983). Consequently, under extended exposure to cold, the cells are increasingly subjected to dehydration, increasing the risk of membrane damage and protein denaturation (Yamaguchi-Shinozaki and Shinozaki 2006). Cultivar differences in susceptible to prolonged cold exposure could reflect differences in the ability to slow or impair extracellular ice formation. This could be related to differences in cell wall composition and/or differences in their ability to accumulate hydrophilic proteins in the cytoplasm to reduce protein denaturation (Moffatt et al. 2006, Wisniewski et al. 2014a). The differences between Chardonnay and Cabernet Sauvignon in incidence of injury after exposure to the January 2013 cold event merits further investigation. A first step could be to test if differential damage in response to prolonged cold exposure is also observed under controlled temperature conditions. In that case, the phenomenon could be further explored to determine its molecular basis.

Recently, Ferguson et al. (2014) developed an updated model with cultivar specific parameters and a prediction of a date of budbreak. This model was developed under the assumption that the required chilling hours to fulfill release from endodormancy will be met. For the SRV AVA, this assumption is valid since

endodormancy release occurred late in fall or early winter before any budbreak can occur. Thus, it would be valuable to test the ability of the Ferguson model to predict budbreak in Idaho. If the model is accurate, it could provide an additional approach to assist in site selection for specific cultivars or to forecast the potential damage associated with late cold events.

Conclusions

The results of this study revealed differences in cold hardiness and the dormancy cycle between two cultivars widely grown in the SRV AVA. Chardonnay was more cold hardy than Cabernet Sauvignon during the fall, while Cabernet Sauvignon showed more capacity to reacclimate during late winter. The transition from endodormancy to ecodormancy occurred earlier in Chardonnay than Cabernet Sauvignon, suggesting that the former has a lower chilling requirements than the latter. Maximum cold hardiness of bud tissue was attained while buds were in an ecodormant state. This suggests that metabolic processes associated with the transition from endo to ecodormancy are independent of cold acclimation. For both cultivars, the ability of the buds to deacclimate was lower in 2012 than in 2013. Further work is needed to determine the factors responsible for these differences.

Overall the Ferguson model accurately predicted bud LTE_{50} values for the vines grown in the SRV AVA. However, additional data for Chardonnay may allow changing the model's parameters to better predict LTE_{50s} in this cultivar. Some questions also remain regarding the ability of the model to predict cold damage when vines are exposed to unusual cold temperatures for several days.

References

Andrews P.L., Sandidge III C.R., Toyama T.K., 1984. Deep supercooling of dormant and deacclimating *Vitis* buds. Am. J. Enol. Vitic. 35:175-177.

Arora R., Rowland L.J., Tanino K., 2003. Induction and release of bud dormancy in woody perennials: A science comes of age. Hortscience 38: 911-921.

Arora R., Rowland L.J., 2011. Physiological research on winter-hardiness: deacclimation resistance, reacclimation ability, photoprotection strategies, and a cold acclimation protocol design. HortScience 46: 1070-1078

Botelho R.V., Pavanello A.P., Paioli Pires E.J., Terra M.M., Lopes Müller M.M., 2007. Effects of chilling and garlic extract on bud dormancy release in Cabernet Sauvignon grapevine cuttings. Am. J. Enol. Vitic. 58: 402-404.

Burke M.J., Gusta L.V., Quamme H.A., Weiser C.J., Li P.H., 1976. Freezing and injury in plants. Ann. Rev. Plant Physiol. 27:507-528.

Coombe B.G., 1995. Adoption of a system for identifying grapevine growth stages. Aust. J. Grape Wine Res. 1: 100-110.

Clore W.J., Wallace M.A., Fay R.D., 1974. Bud survival of grape varieties at sub-zero temperatures in Washington. Am. J. Enol. Vitic. 25: 24-29.

Dami I., Ennahli S., Scurlock D., 2013. A Five-year study on the effect of cluster thinning and harvest date on yield, fruit composition, and cold-hardiness of 'Vidal Blanc' (Vitis spp.) for ice wine production. Hortscience 48: 1358-1362.

Ding P., Gu S., 2001. Exotherm characteristics in relation to bud water status during acclimation and deacclimation of grape primary bud cold hardiness. Hortscience 36: 603-603.

Dokoozlian N.K., Williams L.E., Neja R.A., 1995. Chilling exposure and hydrogen cyanamide interact in breaking dormancy of grape buds. HortScience. 30:1244-1247.

Dokoozlian N.K., 1999. Chilling temperature and duration interact on the budbreak of ‘Perlette’ grapevine cuttings. HortScience. 34:1054-1056.

Fallahi E., Shafii B., Fallahi B., Stark J.C., Engel A.L., 2004. Yield, quality attributes, and degree day requirements of various wine grapes under climatic conditions of intermountain west region. J. Amer. Pomolo. Soc. 58:158-162.

Fallahi E., Fallahi B., Shafii B., Stark J.C., 2005. Performance of six wine grapes under southwest Idaho environmental conditions. Small Fruits Rev. 4:77-85.

Fennell, A., 2004. Freezing tolerance and injury in grapevines. J. Crop Improv. 10:201-235.

Fennel A., Hoover E., 1991. Photoperiod influences growth, bud dormancy, and cold acclimation in *Vitis labruscana* and *V. riparia.* J. Amer. Soc. Hort. Sci. 116:270-273.

Ferguson J.C., Tarara J.M., Mills L.J., Grove G.G., Keller M., 2011. Dynamic thermal time model of cold hardiness for dormant grapevine buds. Ann. Bot. 107:389-396.

Ferguson J.C., Moyer M.M., Mills L.J., Hoogenboom G., Keller M., 2014. Modeling dormant bud cold hardiness and budbreak in twenty-three *Vitis* genotypes reveals variation by region of origin. Am. J. Enol. Vitic. 65:59-71.

Gu S., Read P., 2003. Rootstocks and mounding affect growth and cold hardiness of young 'Gewurztraminer' (*Vitis vinifera*) vines. Hortscience 38: 796-796.

Gusta L.V., Fowler D.B., Tyler N.J., 1983. An evaluation of several chemical tests as possible selection measures for winter hardiness in wheat. Can. J. Plant Sci. 63: 115-119.

Gusta L.V., Wisniewski M., 2013. Understanding plant cold hardiness: an opinion. Physiologia Plantarum 147:4-14.

Hamman R.A., Dami I.E., Walsh T.M., Stushnoff C., 1996. Seasonal carbohydrate changes and cold hardiness of Chardonnay and Riesling grapevines. Am. J. Enol. Vitic. 47: 31-36.

Hoegh A., Leman S., 2015. A spatio-temporal model for assessing winter damage risk to east coast vineyards. J. Appl. Stat. 42: 834-845.

Hubackova M., 1996. Dependence of grapevine bud cold hardiness on fluctuations in winter temperatures. Am. J. Enol. Vitic. 47: 100-102.

Jones K.S., Paroschy J., McKersie B.D., Bowley S.R., 1999. Carbohydrate composition and freezing tolerance of canes and buds in *Vitis vinifera*. J. Plant Physiol. 155: 101-106.

Kalberer S.R., Arora R., Leyva-Estrada N., Krebs S.L., 2007. Cold hardiness of floral buds of deciduous azaleas: Dehardening, rehardening, and endodormancy in late winter. J. Am. Soc. Hort. Sci. 132: 73-79.

Kalberer S.R., Wisniewski M., Arora R., 2006. Deacclimation and reacclimation of cold-hardy plants: current understanding and emerging concepts. Plant Science 171: 3-16.

Keller M., Mills L.J., 2007. Effect of pruning on recovery and productivity of cold-injured Merlot grapevines. Am. J. Enol. Vitic. 58: 351-357.

Kovacs L.G., Byers P.L., Kaps M.L., Saenz J., 2003. Dormancy, cold hardiness, and spring frost hazard in *Vitis amurensis* hybrids under continental climatic conditions. Am. J. Enol. Vitic. 54: 8-14.

Kozlowski T.T., Pallardy S.G., 2002. Acclimation and adaptive responses of woody plants to environmental stresses. Bot. Rev. 68: 270-334.

Lang G.A., Early J.D., Martin G.C., Darnell R.L., 1987. Endo-, para-, and ecodormancy: physiological terminology and classification for dormancy research. HortScience 22:371-377.

Lavee S., May P., 1997. Dormancy of grapevine buds – facts and speculation. Aust. J. Grape Wine Res. 3:31-46.

Mills L.J., Ferguson J.C., Keller M, 2006. Cold-Hardiness evaluation of grapevine buds and cane tissues. Am. J. Enol. Vitic. 57:194-200.

Moffatt B., Ewart V., Eastman A., 2006. Cold comfort: plant antifreeze proteins. Physiol. Plant. 126: 5-16.

National Oceanic and Atmospheric Administration. National Weather Service Online Weather Data. 12 January 2015. http://www.noaa.gov/

Olsen J.E., 2010. Light and temperature sensing and signaling in induction of bud dormancy in woody plants. Plant Mol. Biol. 73: 37-47.

Pagter M., Lefevre I., Arora R., Hausman J.F., 2011. Quantitative and qualitative changes in carbohydrates associated with spring deacclimation in contrasting Hydrangea species. Environ. Exp. Bot. 72: 358-367.

Pagter M., Williams M., 2011. Frost dehardening and rehardening of Hydrangea macrophylla stems and buds. Hortscience 46: 1121-1126.

Palonen P., Linden L., 1999. Dormancy, cold hardiness, dehardening, and rehardening in selected red raspberry cultivars. J. Am. Soc. Hort. Sci. 124: 341-346.

Proebsting E.L., Ahmedullah M., Brummund V.P., 1980. Seasonal changes in low temperature resistance of grape buds. Am. J. Enol. Vitic. 31:329-336.

Rowland L.J., Ogden E.L., Ehlenfeldt M.K., Arora R., 2008. Cold tolerance of blueberry genotypes throughout the dormant period from acclimation to deacclimation. Hortscience 43: 1970-1974.

Salzman R.A., Bressan R.A., Hasegawa P.M., Ashworth E.N., Bordelon B.P., 1996. Programmed accumulation of LEA-like proteins during desiccation and cold acclimation of overwintering grape buds. Plant Cell and Environ. 19: 713-720.

Schnabel B.J., Wample R.L., 1987. Dormancy and cold hardiness of *Vitis vinifera* L. cv. White Riesling as influenced by photoperiod and temperature. Am. J. Enol. Vitic. 38: 265-272.

Shellie K.C., 2007. Viticultural performance of red and white wine grape cultivars in Southwestern Idaho. Hort Technology 17:595-603.

Shellie K., Cragin J., Serpe M., 2014. Performance of alternative European wine grape cultivars in Southwestern Idaho: Cold hardiness, berry maturity, and yield. Hort Technology 24: 138-147.

Trejo-Martínez M.A., Orozco J.A., Almaguer-Vargas G., Carvajal-Millán E., Gardea A.A., 2009. Metabolic activity of low chilling grapevine buds forced to break. Thermochimica Acta 481: 28-31.

U.S. Department of Interior. Agrimet—The Pacific Northwest cooperative agricultural network. 27 June 2013. http://www.usbr.gov/pn/agrimet/wxdata.html

Wake C.M.F., Fennell A., 2000. Morphological, physiological and dormancy responses of three *Vitis* genotypes to short photoperiod. Physiol. Plant. 109: 203-210.

Wample R.L., Mills L., Wichers A., 1994. Effect of crop load and mechanical pruning on cold hardiness of concord buds in Washington State. Am. J. Enol. Vitic. 45: 364-365.

Wample R.L., Hartley S., Mills L., 2000. Dynamics of grapevine cold hardiness. Proceedings of the ASEV 50th Anniversary Meeting. Am. J. Enol. Vitic. 51: 81-93.

Watson, J. (ed.) 1999. Growing grapes in eastern Washington: Proceedings from the 1998 Washington State University shortcourse for establishing a vineyard and producing grapes. Good Fruit Grower, Yakima, WA.

Willmott, C. J. 1981. *On the validation of models. Physical Geography. 2: 184–194.*

Wisniewski M., Gusta L., Neuner G., 2014a. Adaptive mechanisms of freeze avoidance in plants: A brief update. Eviron. Exp. Bot. 99: 133-140.

Wisniewski M., Nassuth A., Teulieres C., Marque C., Rowland J., Cao P.B., Brown A., 2014b. Genomics of Cold Hardiness in Woody Plants. Cr. Rev. Plant Sci. 33: 92-124.

Wolf T.K., Cook M.K., 1992. Seasonal deacclimation patterns of three grape cultivars at constant, warm temperature. Am. J. Enol. Vitic. 43: 171-179.

Wolf T.K., Pool R.M., 1987. Factors affecting exotherm detection in differential thermal analysis of grapevine dormant buds. J. Amer. Soc. Hort. Sci. 112:520-525.

Yamaguchi-Shinozaki K., Shinozaki K., 2006. Transcriptional regulatory networks in cellular responses and tolerance to dehydration and cold stresses. Annu. Rev. Plant Biol. 57: 781-803.

Zhang Y., Dami I.E., 2012. Foliar application of abscisic acid increases freezing tolerance of field-grown *Vitis vinifera* Cabernet Franc grapevines. Am. J. Enol. Vitic. 63: 377-384.

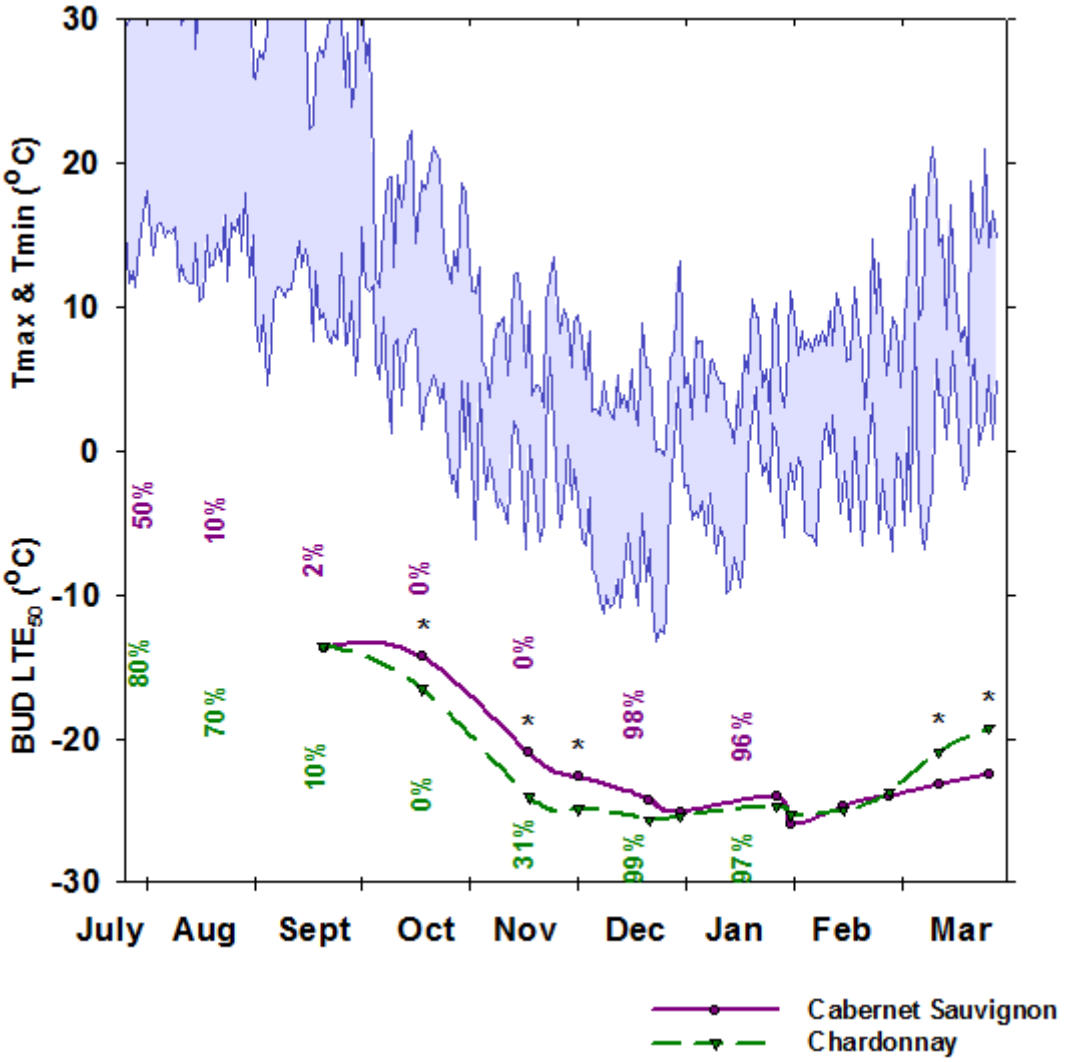

Figure 2.1 Bud Cold Hardiness of Cabernet Sauvignon and Chardonnay from September 2011 through March 2012 in Parma, Idaho. The graph includes daily maximum and minimum ambient temperatures during this period. The asterisks (*) indicate sample dates when differences in the bud LTE50 were significant ($p < 0.05$). Percentage budbreak is overlaid with recorded cold hardiness from July to January to identify para-, endo-, and ecodormancy.

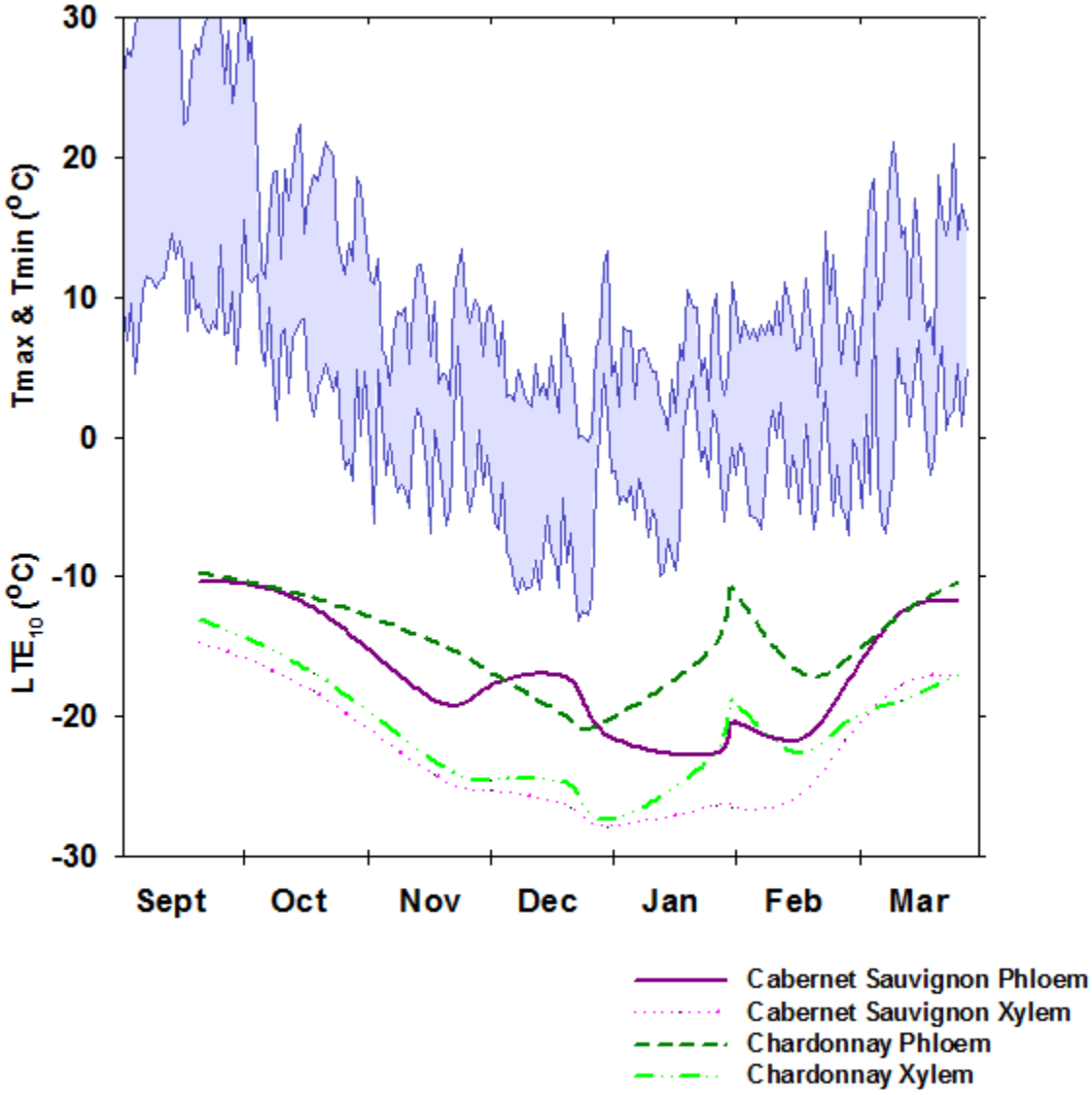

Figure 2.2 Xylem and Phloem Cold Hardiness of Cabernet Sauvignon and Chardonnay during the 2011-2012 Fall-Winter Seasons in Parma, Idaho.

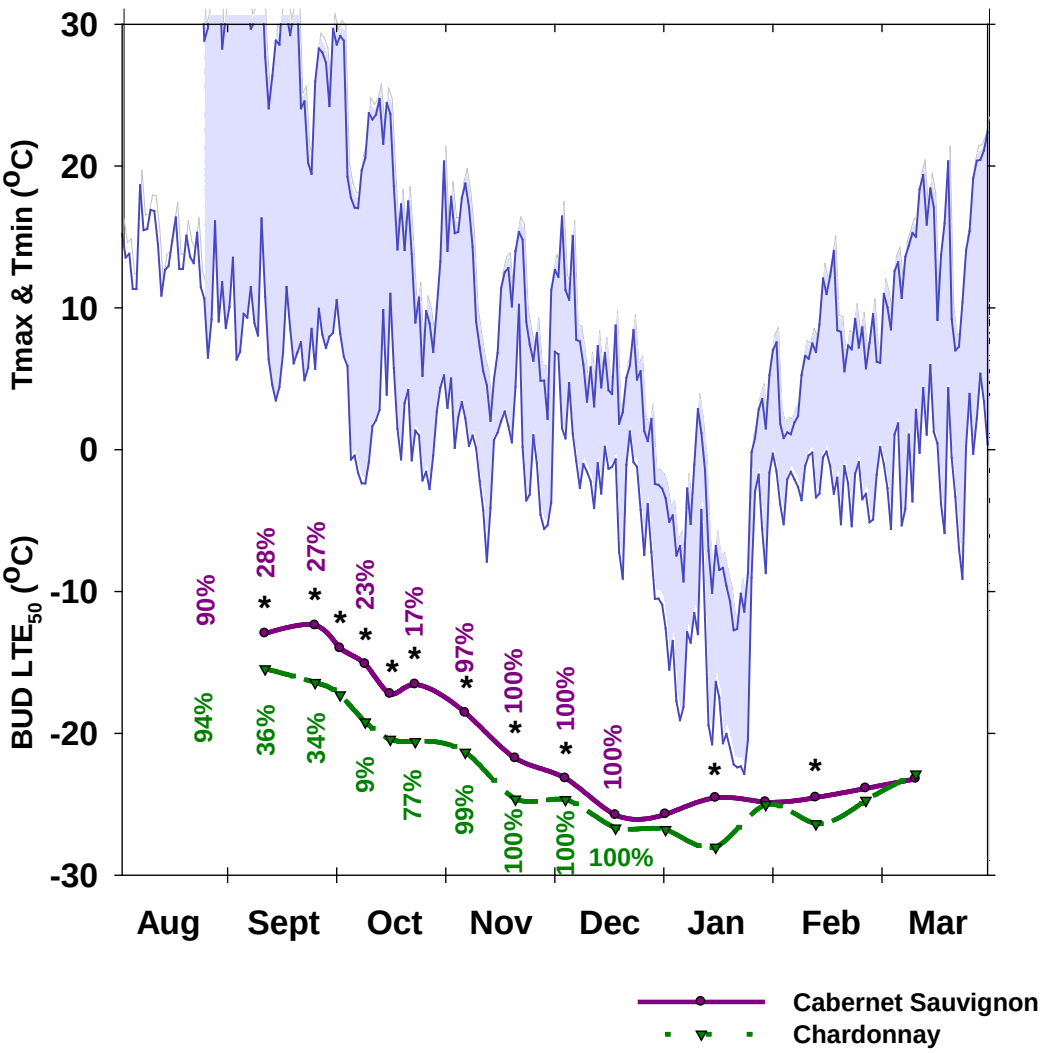

Figure 2.3 Bud Cold Hardiness of Cabernet Sauvignon and Chardonnay from August 2012 through March 2013 in Parma, Idaho. The figure includes daily maximum and minimum ambient temperatures during this period. The asterisks (*) indicate sample dates when differences in the bud LTE50 were significant ($p < 0.05$). Percentage budbreak is overlaid with recorded cold hardiness from August to December to identify para-, endo, and ecodormancy.

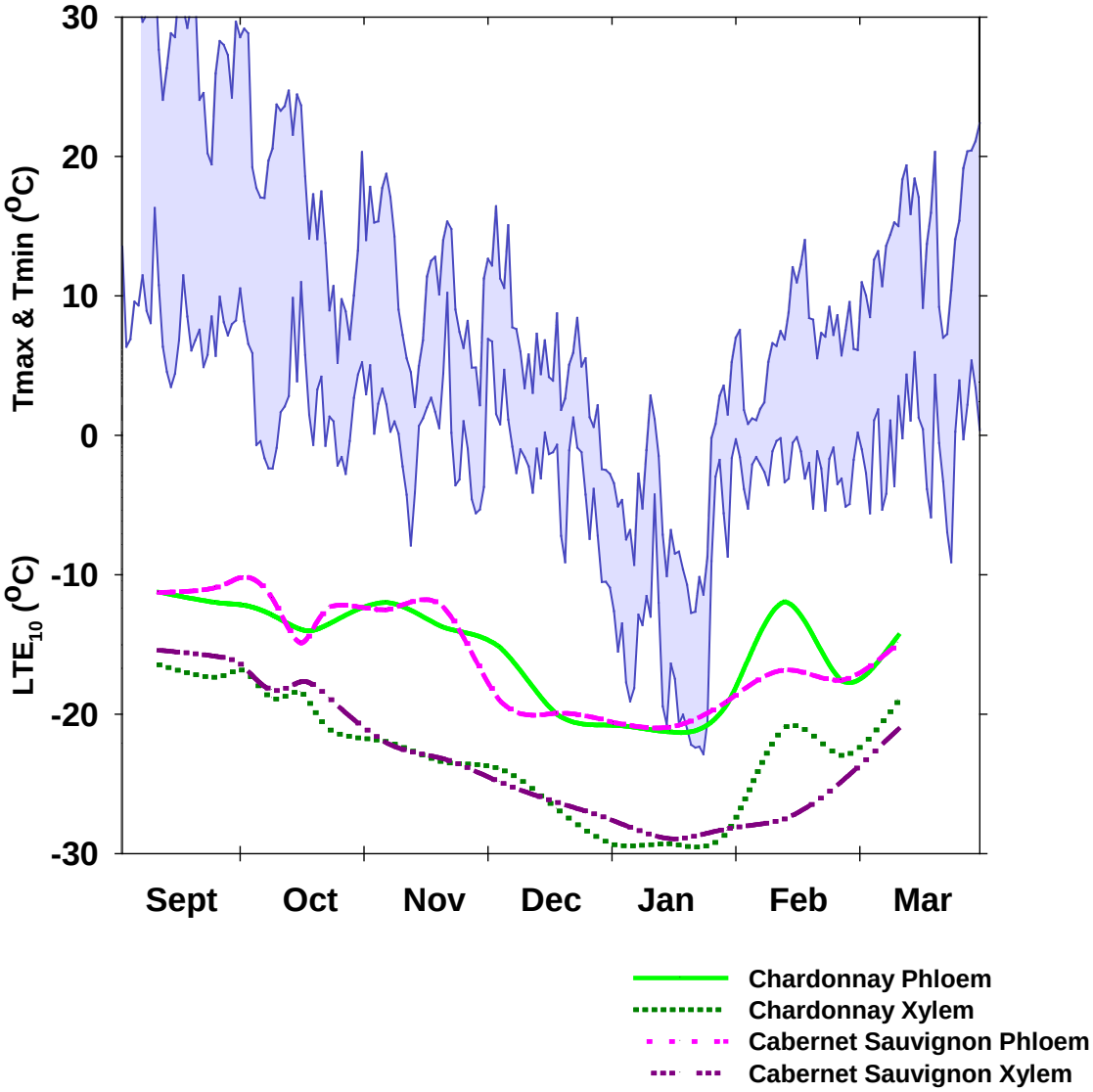

Figure 2.4 Xylem and Phloem Cold Hardiness of Cabernet Sauvignon and Chardonnay during the 2012-2013 Fall-Winter Seasons in Parma, Idaho.

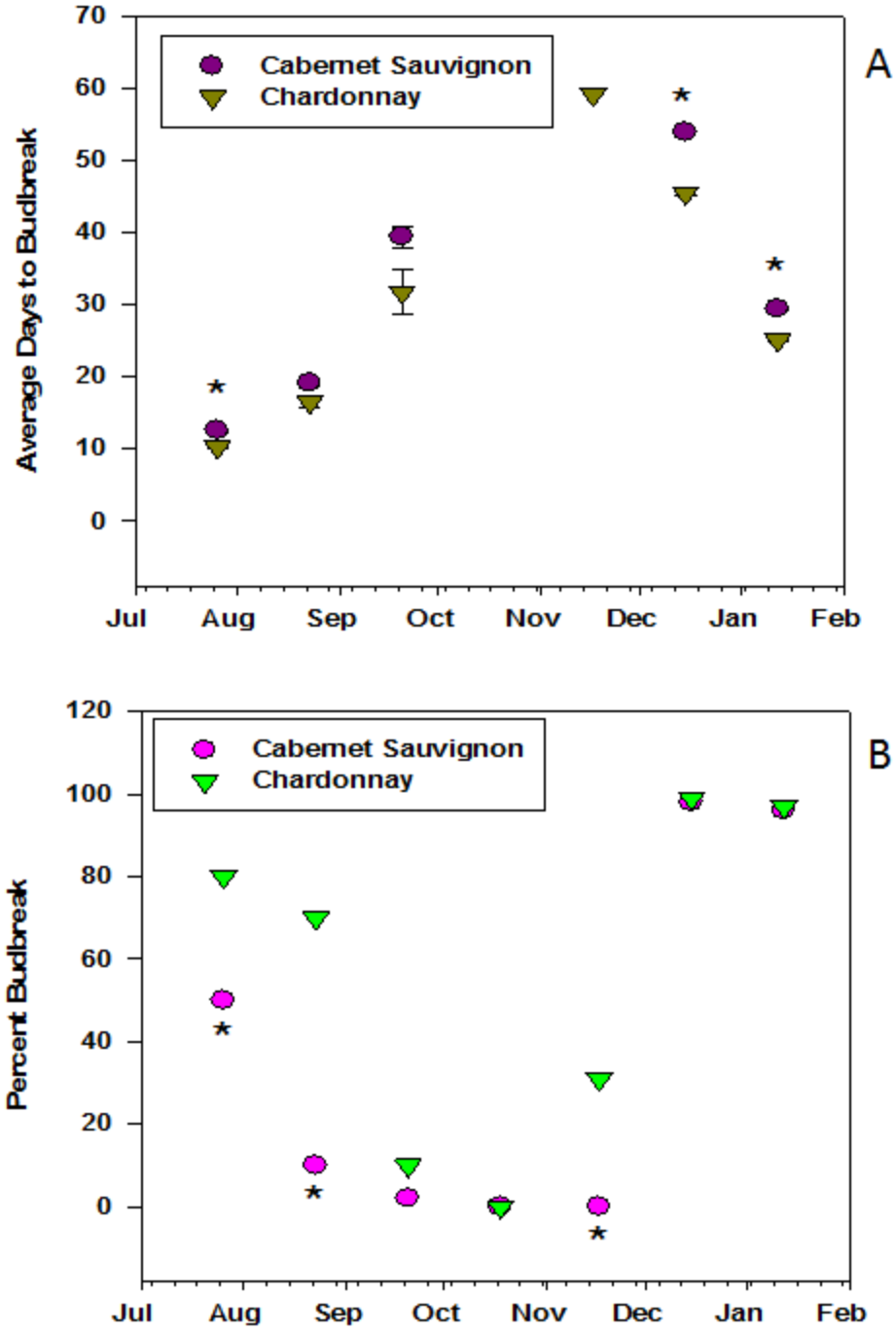

Figure 2.5. Days to Budbreak (mean ± SE) for Cabernet Sauvignon and Chardonnay (A) and Percent Budbreak (B) During the 2011-2012 Fall-Winter Seasons in Parma, Idaho. The asterisks (*) indicate sample dates when differences between cultivars were significant ($p < 0.05$).

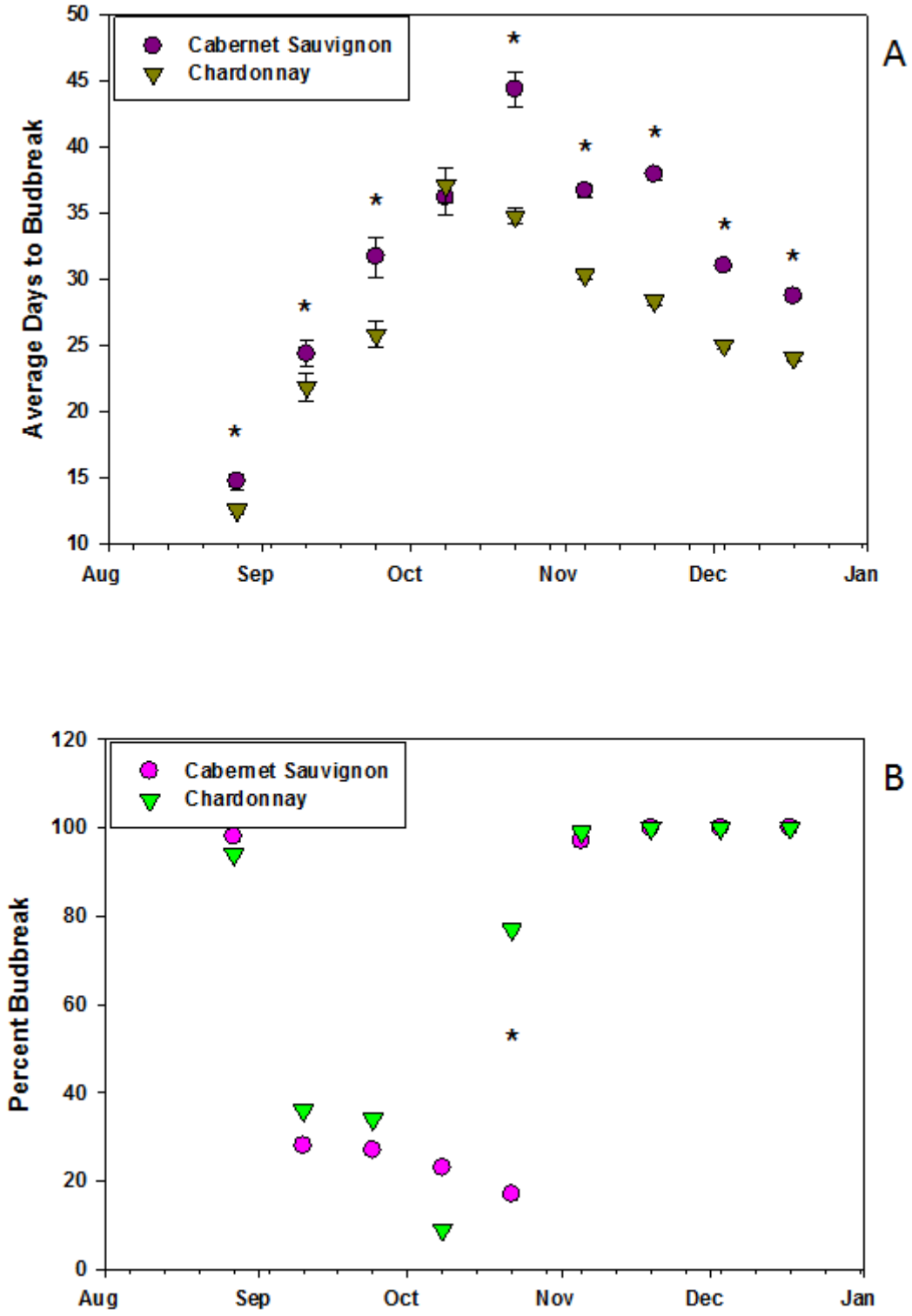

Figure 2.6 Days to Budbreak (means ± SE) for Cabernet Sauvignon and Chardonnay (A) and Percent Budbreak (B) During the 2012-2013 Fall-Winter Seasons in Parma, Idaho. The asterisks (*) indicate sample dates when differences between cultivars were significant ($p < 0.05$).

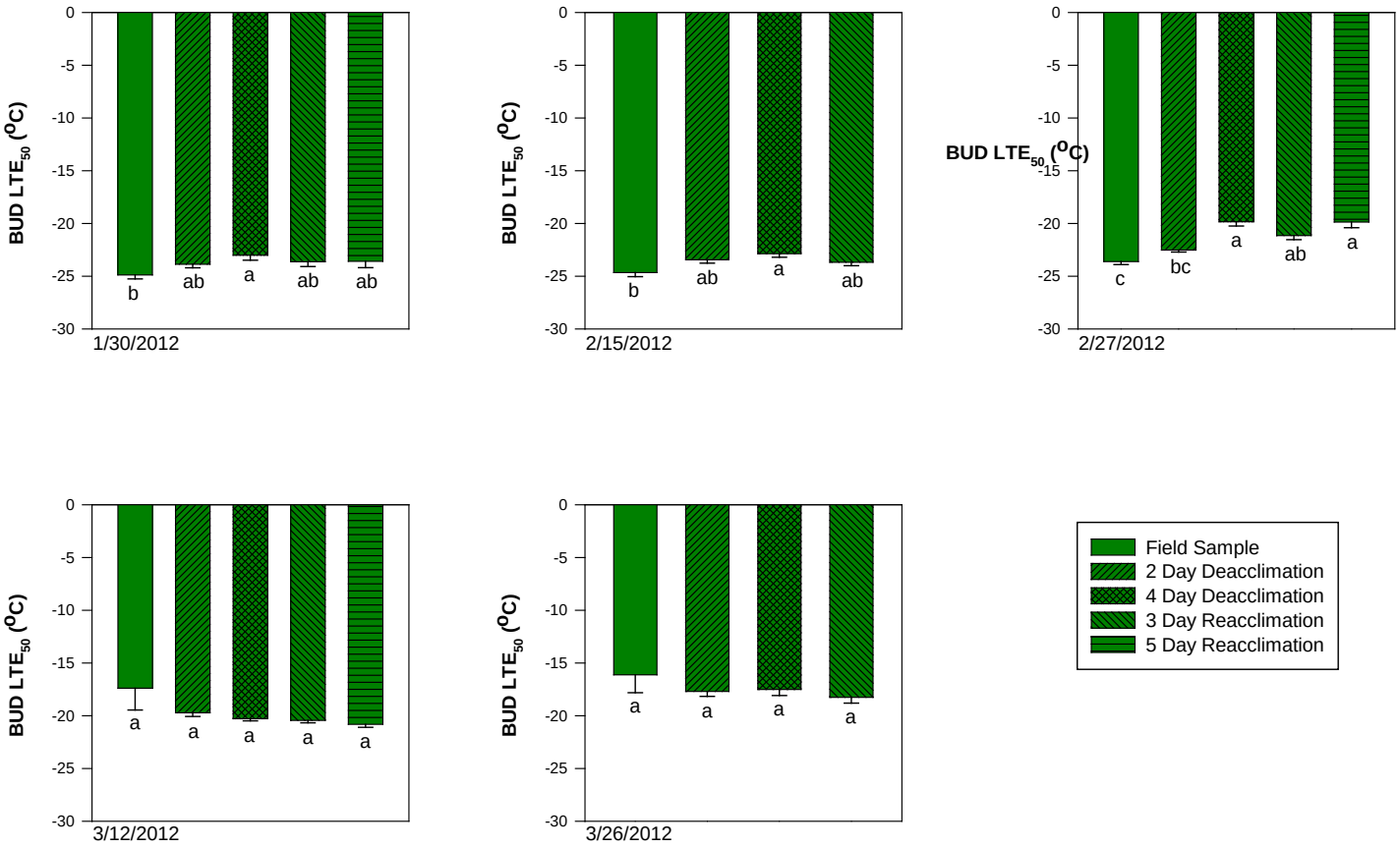

Figure 2.7 Bud Cold Hardiness During Deacclimation and Reacclimation of Chardonnay Buds Harvested in Winter and Early Spring of 2012. Each graph in the figure represents a trial where field samples were collected at the indicated date in the lower left of each graph. Cold hardiness was measured at the initial time of sampling and following periods of deacclimation and reacclimation. Bud LTE_{50} values with the same letter are not significantly different based on Tukey's honestly significant difference test ($p > 0.05$).

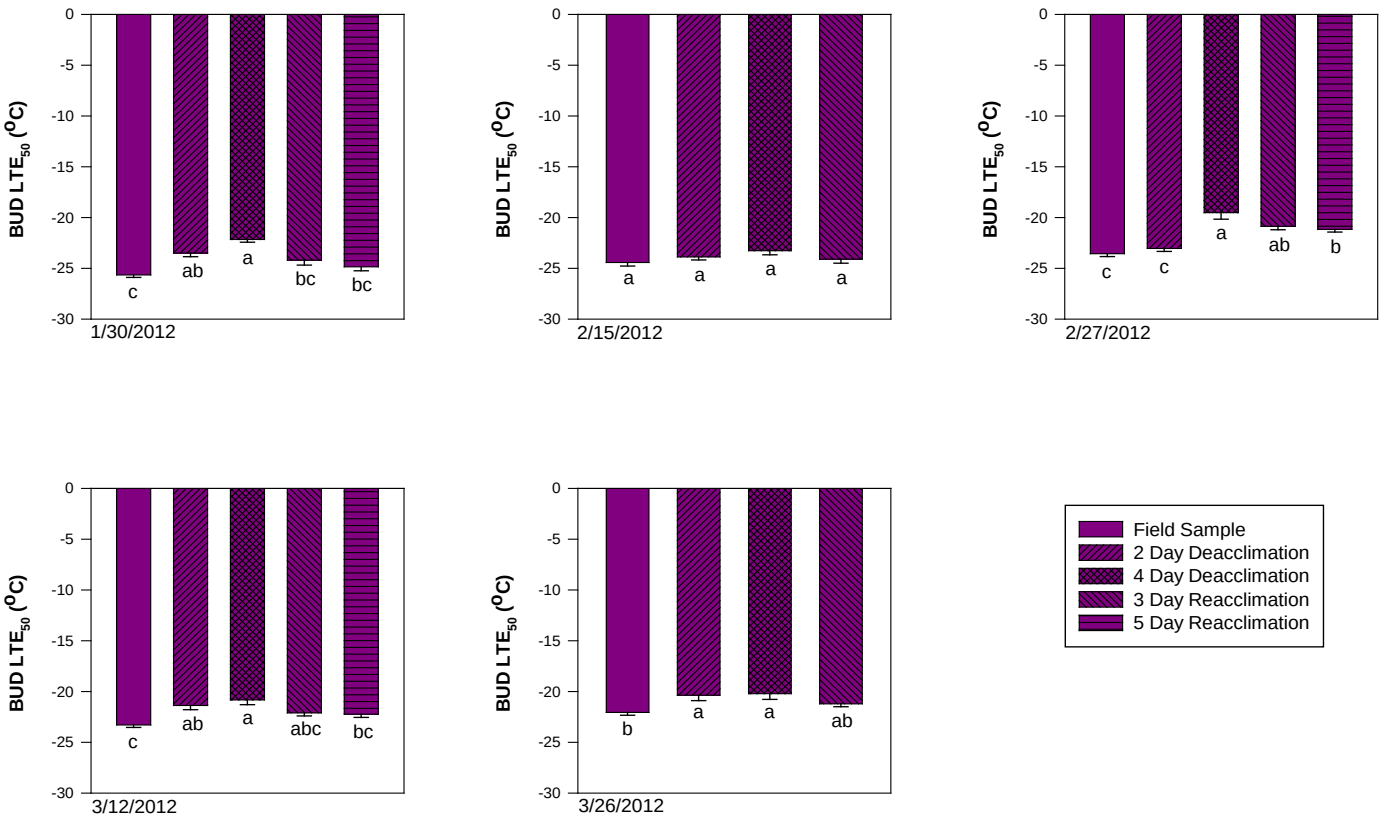

Figure 2.8 Bud Cold Hardiness During Deacclimation and Reacclimation of Cabernet Sauvignon Buds Harvested in Winter and Early Spring of 2012. Each graph in the figure represents a trial where field samples were collected at the indicated date in the lower left of each graph. Cold hardiness was measured at the initial time of sampling and following periods of deacclimation and reacclimation. Bud LTE_{50} values with the same letter are not significantly different based on Tukey's honestly significant difference test ($p > 0.05$).

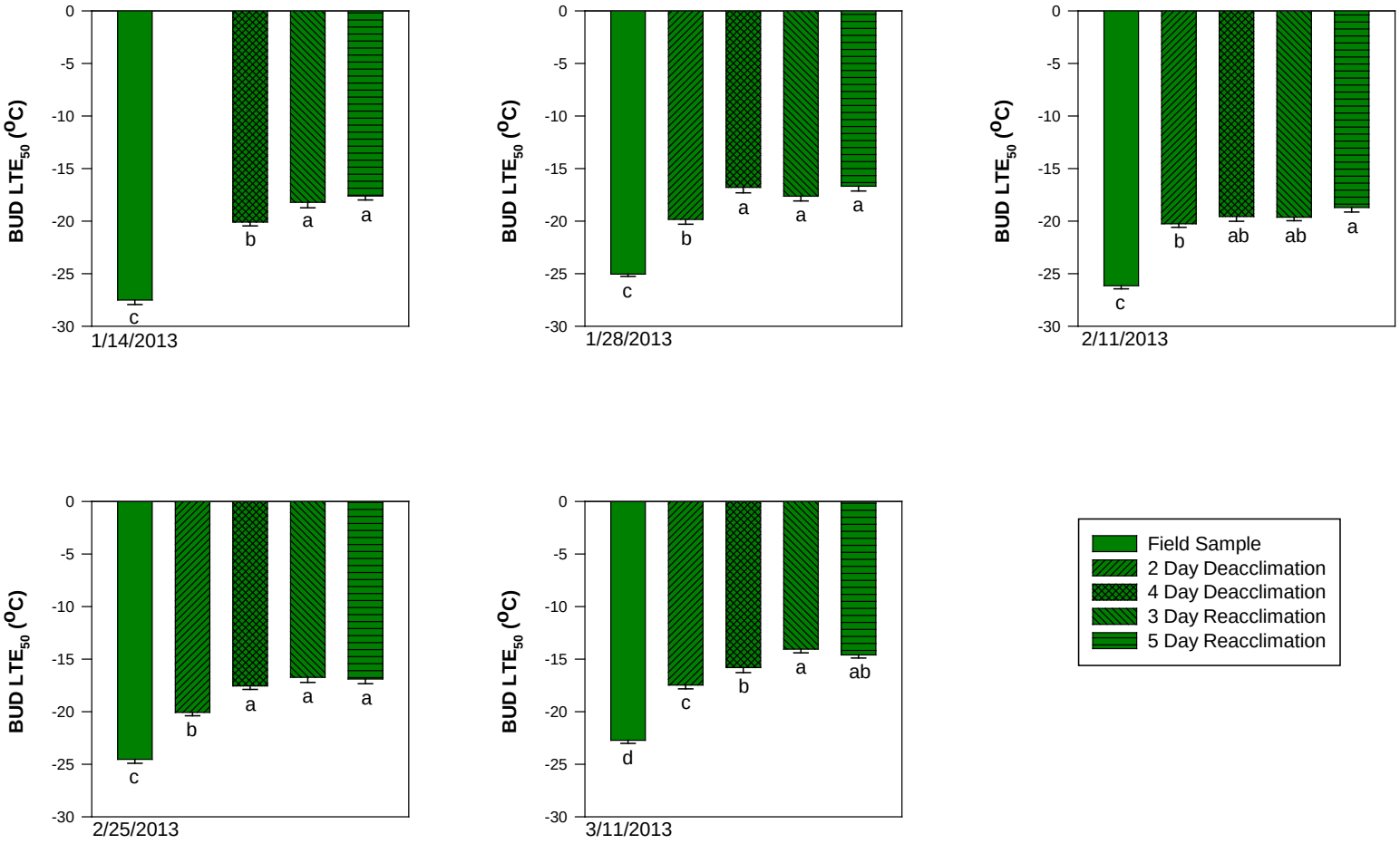

Figure 2.9 Bud Cold Hardiness During Deacclimation and Reacclimation of Chardonnay Buds Harvested in the Winter of 2013. Each graph in the figure represents a trial where field samples were collected at the indicated date in the lower left of each graph. Cold hardiness was measured at the initial time of sampling and following periods of deacclimation and reacclimation. Bud LTE_{50} values with the same letter are not significantly different based on Tukey's honestly significant difference test ($p > 0.05$).

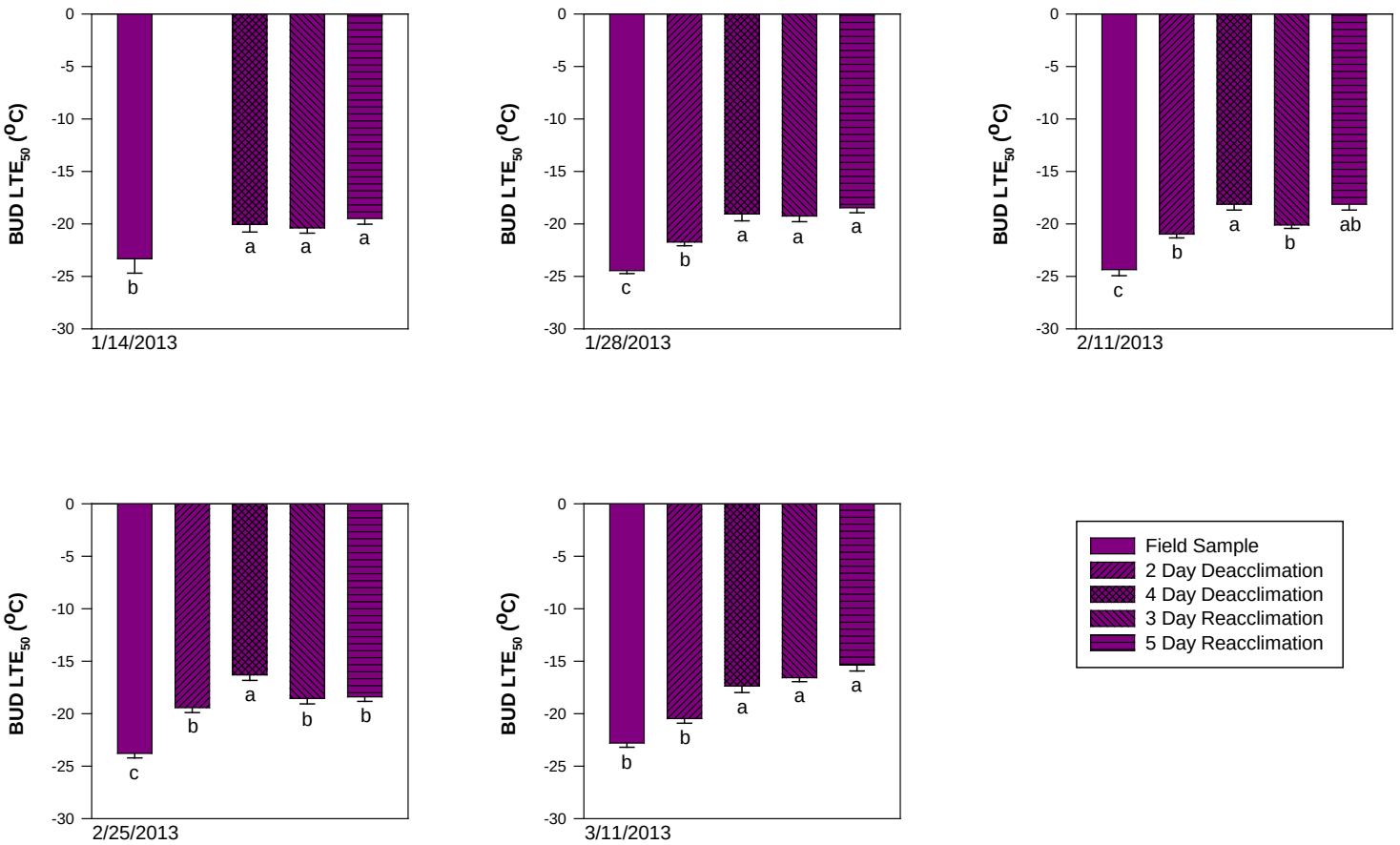

Figure 2.10 Bud Cold Hardiness During Deacclimation and Reacclimation of Cabernet Sauvignon Buds Harvested in the Winter of 2013. Each graph in the figure represents a trial where field samples were collected at the indicated date in the lower left of each graph. Cold hardiness was measured at the initial time of sampling and following periods of deacclimation and reacclimation. Bud LTE50 values with the same letter are not significantly different based on Tukey's honestly significant difference test ($p > 0.05$).

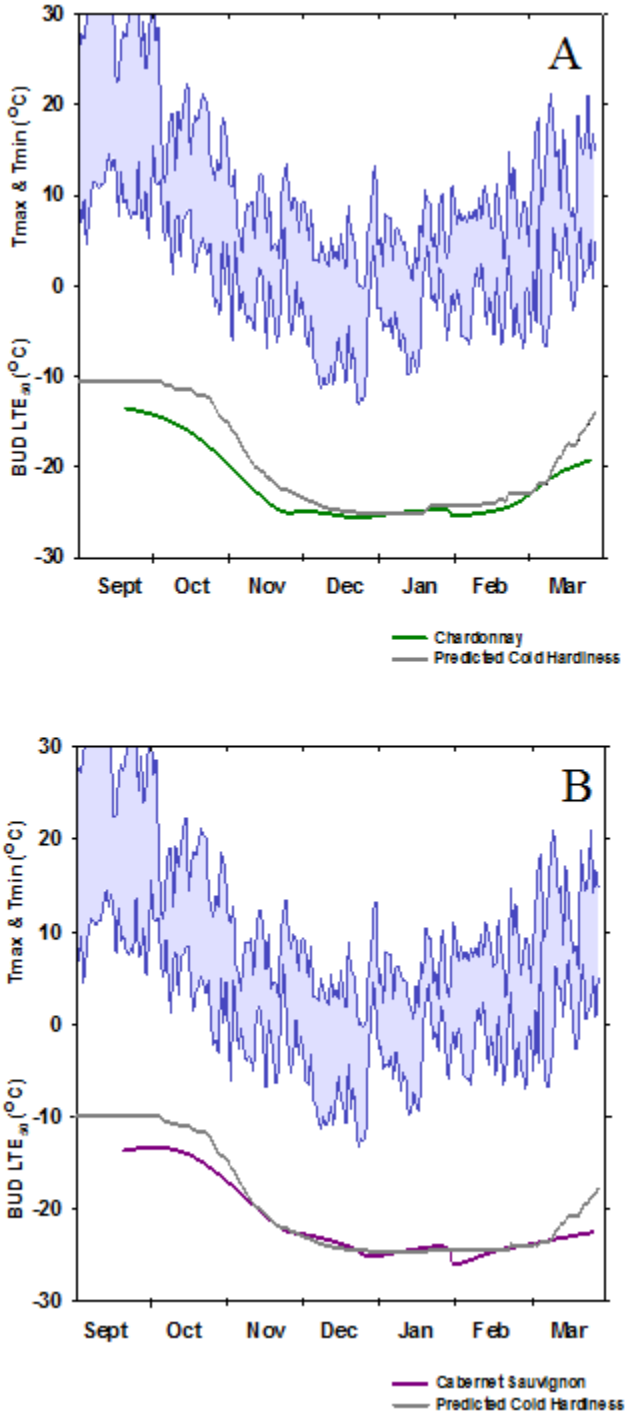

Figure 2.11 Measured Bud Cold Hardiness (LTE_{50}) of Chardonnay (A) and Cabernet Sauvignon (B) and Predicted Cold Hardiness According to the Ferguson Model. The graph includes daily minimum and maximum temperatures during the 2011- 2012 fall-winter seasons.

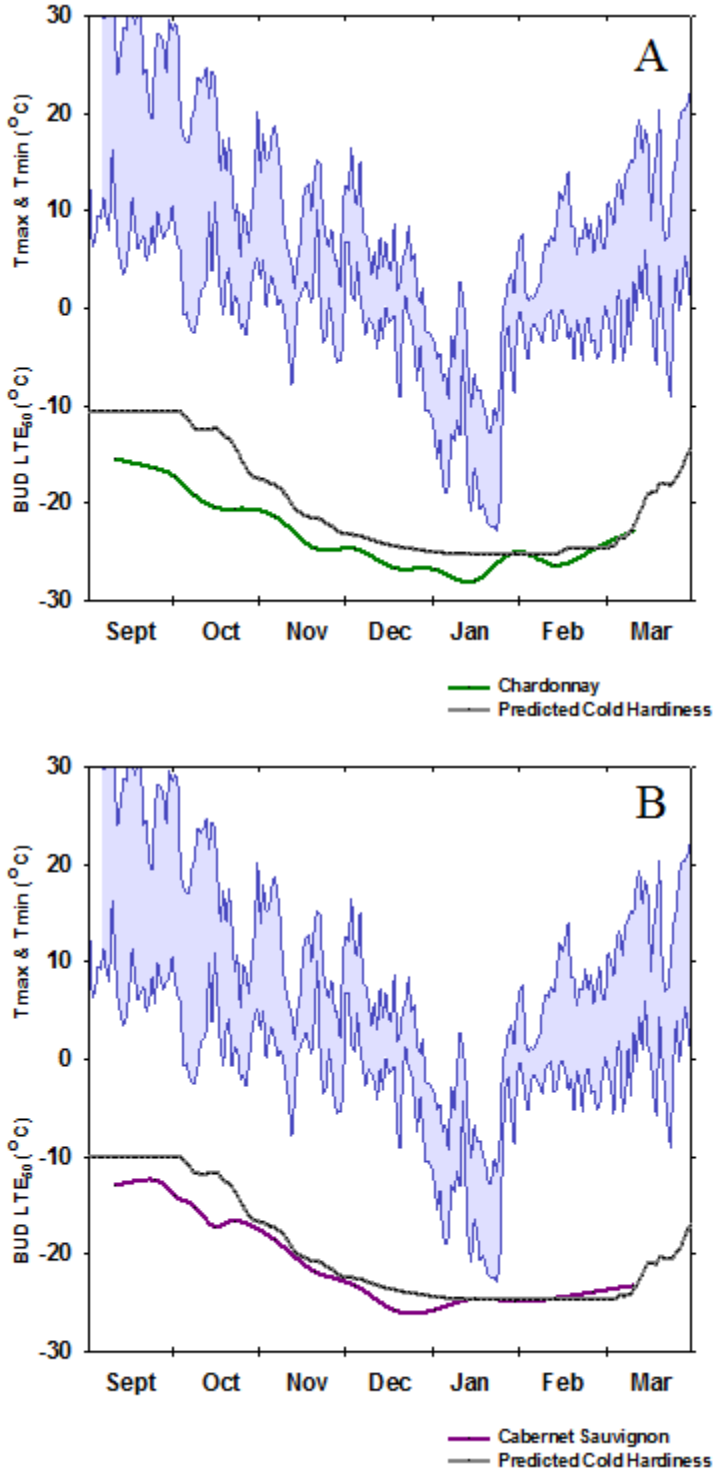

Figure 2.12 Measured Bud Cold Hardiness (LTE_{50}) of Chardonnay (A) and Cabernet Sauvignon (B), and Predicted Cold Hardiness According to the Ferguson Model. The graph includes daily minimum and maximum temperatures during the 2012- 2013 fall-winter seasons.

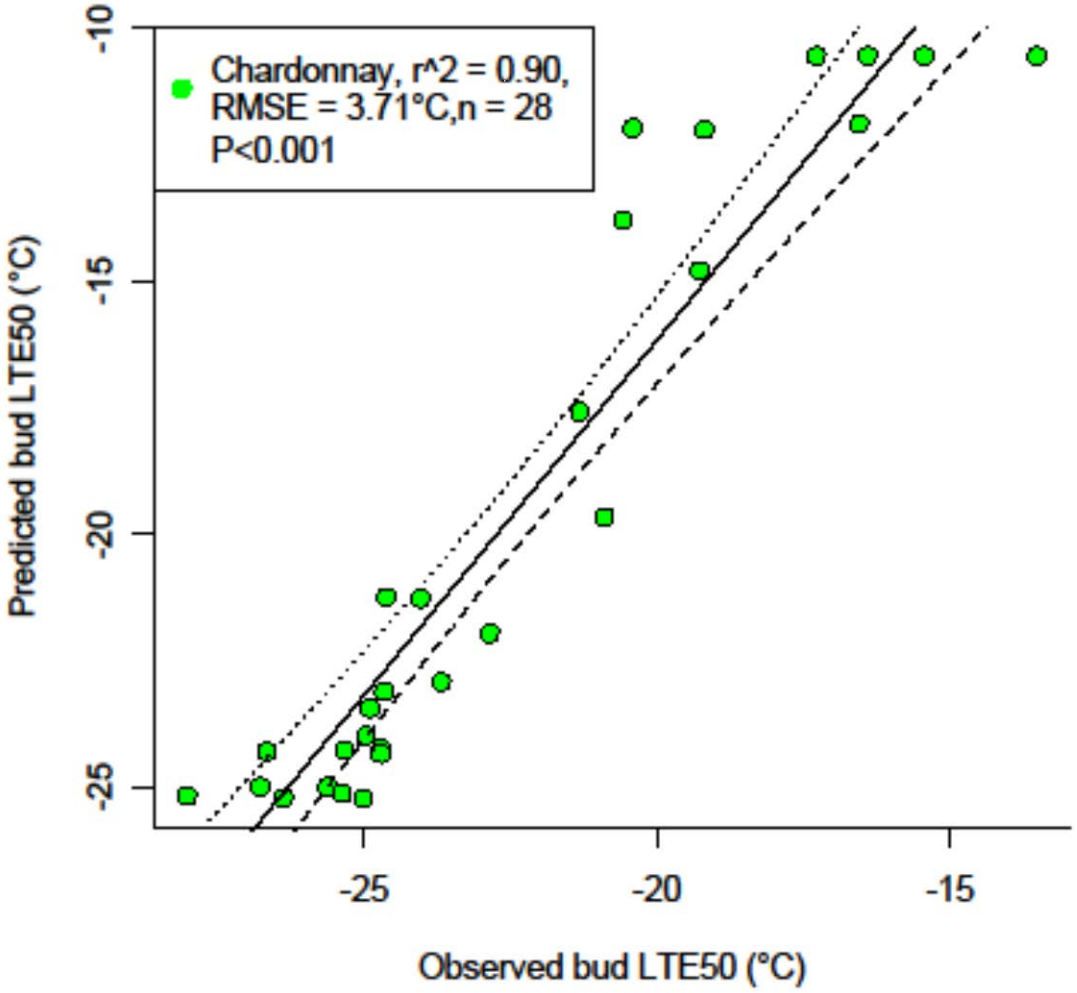

Figure 2.13 Comparison of the Predicted Values of the Ferguson Dynamic Thermal Time Model of Cold Hardiness and the Observed Bud Cold Hardiness Values of Chardonnay from the Fall-Winter Seasons of 2011-2012 and 2012-2013 in Parma, Idaho. Bud cold hardiness was estimated based on the low temperature exotherms at which 50% of the buds were damaged.

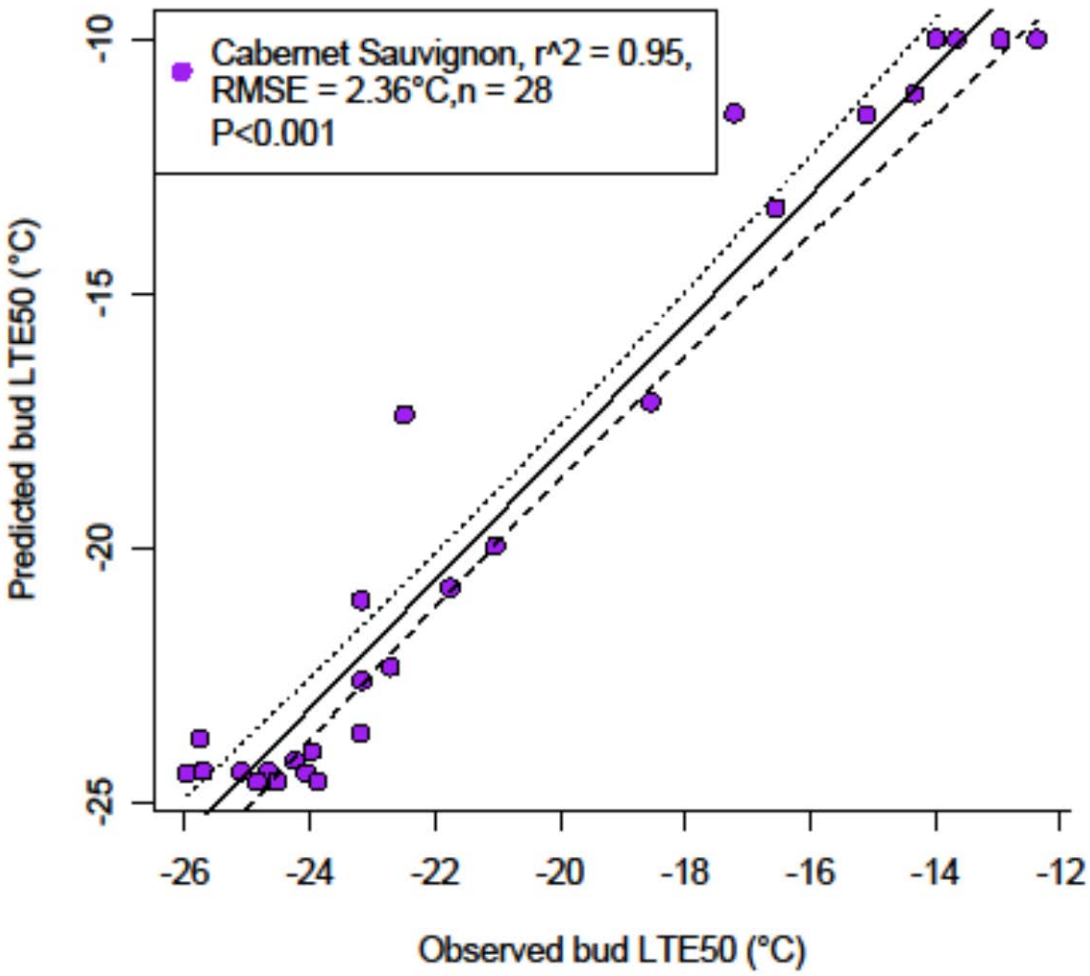

Figure 2.14 Comparison of the Predicted Values of the Ferguson Dynamic Thermal Time Model of Cold Hardiness and the Observed Bud Cold Hardiness Values of Cabernet Sauvignon from the Fall-Winter Seasons of 2011-2012 and 2012-2013 in Parma, Idaho. Bud cold hardiness was estimated based on the low temperature exotherms at which 50% of buds were damaged.

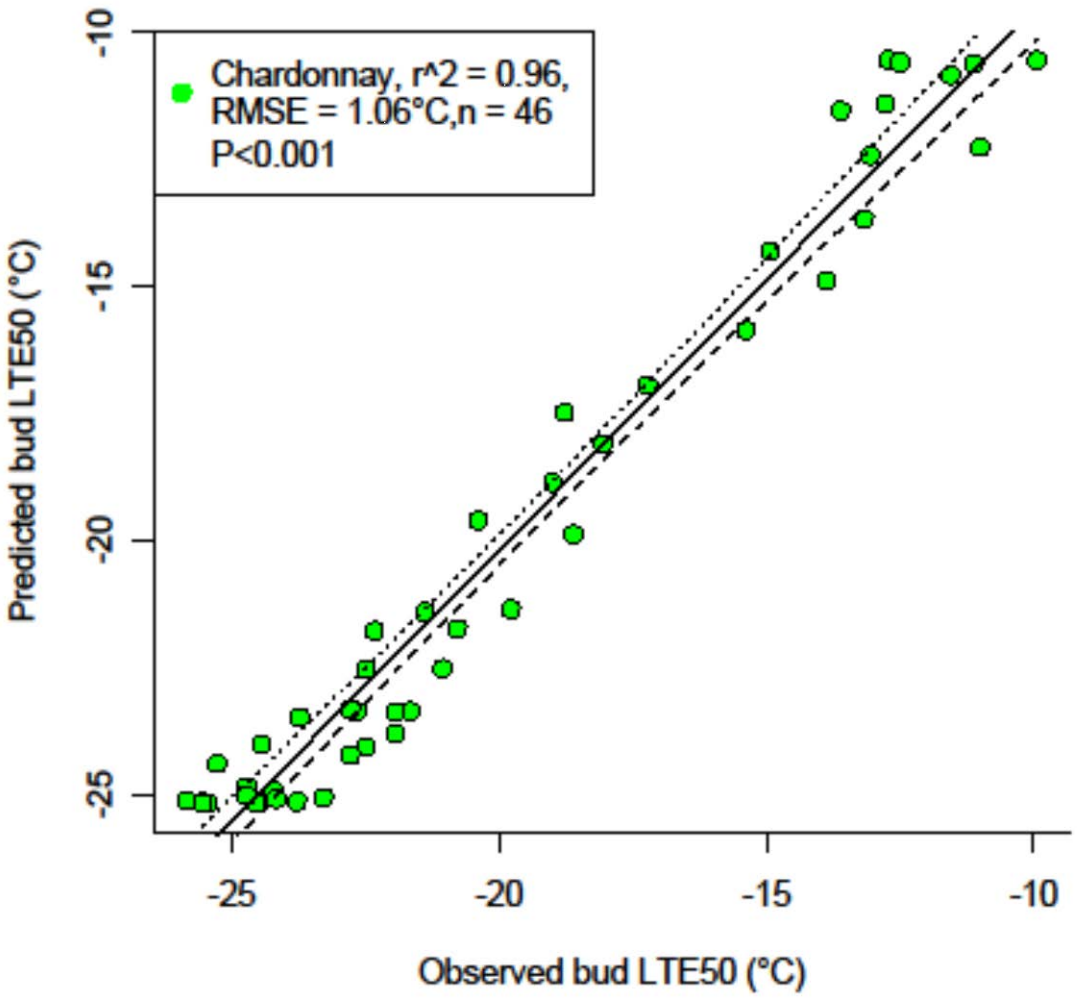

Figure 2.15 Comparison of the Predicted Values of the Ferguson Dynamic Thermal Time Model of Cold Hardiness and the Observed Bud Cold Hardiness Values of Chardonnay from the Fall-Winter Seasons of 2011-2012 and 2012-2013 in the Washington State University Roza Location. Bud cold hardiness was estimated based on the low temperature exotherms at which 50% of buds were damaged.

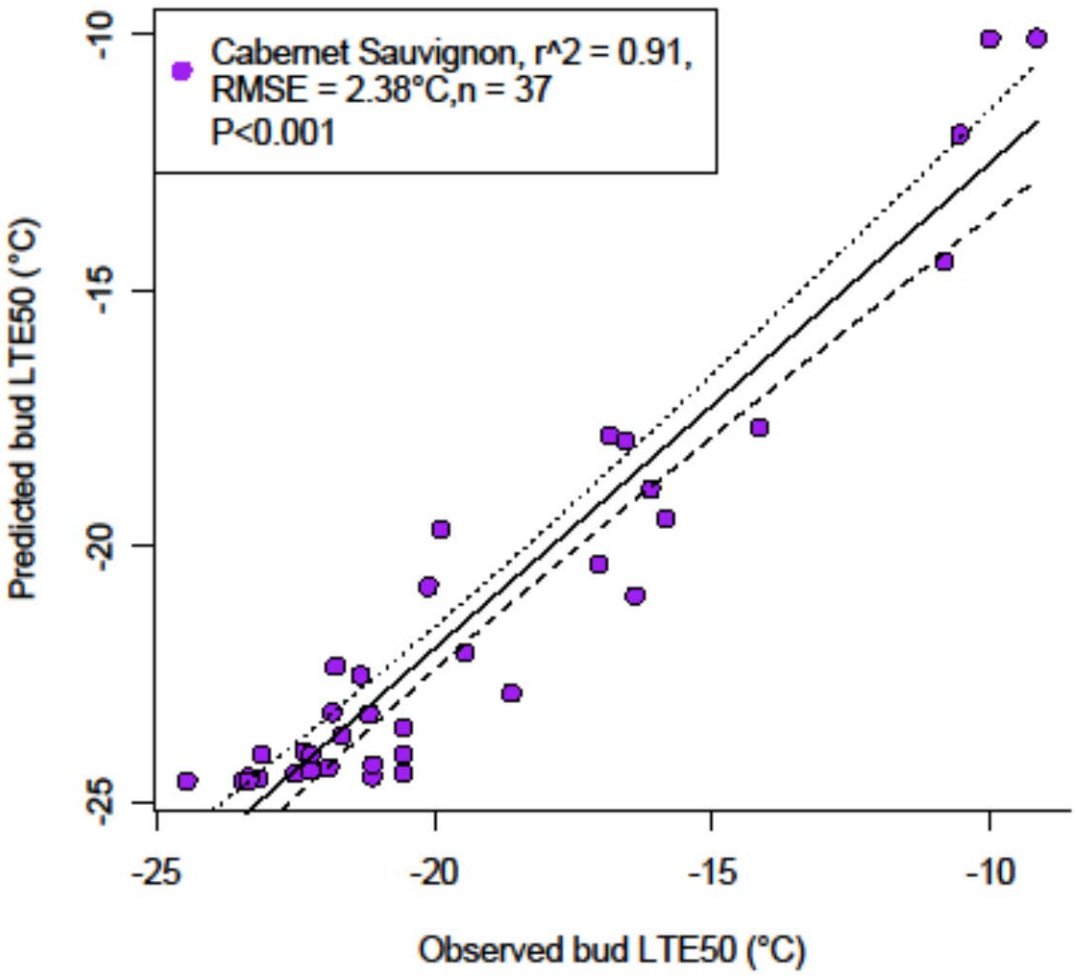

Figure 2.16 Comparison of the Predicted Values of the Ferguson Dynamic Thermal Time Model of Cold Hardiness and the Observed Bud Cold Hardiness Values of Cabernet Sauvignon in the Fall-Winter Seasons of 2011-2012 and 2012-2013 in the Washington State University Roza Location. Bud cold hardiness was estimated based on the low temperature exotherms at which 50% of buds were damaged.