Journal of the American Pomological Society 72(2): 80-93 2018

Evaluation of Cold-climate interspecific Hybrid Wine Grape Cultivars for the Upper Midwest

Amaya Atucha[1*], Janet Hedtcke[2], and Beth Ann Workmaster[1]

Additional index words: cold-hardy, Wisconsin, Marquette, Frontenac, Brianna, La Crescent, La Crosse

Abstract

Cold-climate interspecific hybrid wine grape cultivars with largely *Vitis riparia* Michx. parentage, including several released since the early-1980s, have created opportunities for new and rapidly expanding grape and wine industries in the Northeast and upper Midwest of the United States. The objective of this study was to evaluate the viticulture performance of a selection of cold-climate wine grape cultivars grown in the upper Midwest, and to provide information on growth, yield, and fruit composition traits. Fruit yield (kg m^{-1} cordon) variation among years was not significant for red cultivars; however, white cultivars had significant differences in fruit yield produced during the extent of the study. 'Marquette', 'Maréchal Foch', and 'La Crescent' produced the most consistent yields among years, while 'Frontenac', 'Brianna', and 'La Crosse' were the top yielding cultivars. Fruit composition traits (soluble solids concentration (SSC) and titratable acidity (TA)) measured at harvest, varied among cultivars and years. 'Marquette' had the highest average SSC, while 'Léon Millot' had the lowest average levels of TA for all years of the red cultivars. Among white cultivars, 'Brianna' had the lowest average levels of TA in all years, and 'La Crosse' had the lowest average SSC. Differences in seasonal weather patterns among years influenced yield, vine vigor, and fruit composition data. 'Aromella' and 'Vignoles' were removed from the study due to poor winter survival, and these cultivars are not recommended for commercial production in growing regions with climate conditions similar to Wisconsin.

Introductions over the twentieth century, as well as into the early 2000s, of several interspecific hybrid wine grape (*Vitis* spp.) cultivars adapted to cooler climates has helped propel the expansion of the wine industry to upper Midwestern states, such as Michigan, Minnesota, Illinois, Indiana, Iowa, Ohio, and Wisconsin (Dami et al., 2005; Luby et al., 2006). The ideal cultivar for this northern temperate climate must be able to withstand low winter temperature extremes, in addition to grow with moderate vigor, produce substantial yields, and possess good fruit quality. Cultivars must also produce consistent and reliable crops. Consistency is key to the success of the wine grape industry in northern temperate zones by securing supplies of local and regional fruit. However, limiting factors, such as severe winter freezing temperatures, late spring frosts, adequate number of frost-free days, and high inter-seasonal variation in precipitation and temperature patterns, significantly challenge the goal of producing consistent high yields of quality fruit. Stress factors such as over- and under-cropping, excessive vegetative growth, disease infections, and drought can impact cold hardiness, overwintering capacities, and general growth of vines (Fennell, 2004; Howell, 2001), and pose an economic threat to growers and winemakers in cold-climate regions (Zabadal et al., 2007).

Cold-climate cultivars have been developed by breeders in France and the United States (Wisconsin, New York, and Minnesota) (Table 1) using primarily riverbank grape (*Vitis riparia* Michx.), as well as sand grape (*V. rupestris* Scheele), fox grape (*V. labrusca*

[1] Department of Horticulture, University of Wisconsin-Madison, 1575 Linden Drive, Madison, WI 53706
[2] West Madison Agricultural Research Station, University of Wisconsin-Madison, 8502 Mineral Point Road, Verona, WI 53593
[*] To whom reprint request should be addressed: Email address: atucha@wisc.edu

Table 1. Description of the nine cold-climate wine grape cultivars included in this study, grown at the West Madison Agricultural Research Station (WMARS) in Verona, Wisconsin (compiled from Smiley et al., 2016 and the National Grape Registry (http://ngr.ucdavis.edu/index.cfm).

Cultivar	Wine Color	Pedigree	Institution/Breeder	Release/ introduction
Aromella	White	'Traminette' and Ravat 34	Cornell University	2013
Brianna	White	'Kay Gray' x E.S. 2-12-13 (includes *V. labrusca* and *V. riparia*)	Elmer Swenson of Osceola, Wisconsin	2001
Frontenac	Red	Landot 4511 x MN 89 (includes *V. riparia*, *labrusca*, *vinifera*, *aestivalis*, *lincecumii*, *rupestris*, *cinerea,* and *berlandieri*)	University of Minnesota	1996
La Crescent	White	'St. Pepin' x E.S. 6-8-25 (*V. riparia* x 'Muscat Hamburg') (includes *V. vinifera*, *riparia*, *labrusca*, *aestivalis*, and *rupestris*)	University of Minnesota	2002
La Crosse (ES 294)	White	(MN 78 x Seibel 1000) x 'Seyval' (includes *V. labrusca*, *lincecumii*, *riparia*, *rupestris*, *vinifera*)	Elmer Swenson of Osceola, Wisconsin	1983
Léon Millot	Red	Millardet et Grasset 101-14 O.P. x 'Goldriesling' [sibling of 'Maréchal Foch']	Eugene Kuhlmann of Alsace, France	1920
Maréchal Foch	Red	Millardet et Grasset 101-14 O.P. x 'Goldriesling' (*V. riparia* x *V. rupestris*) x *V. vinifera*) [sibling of 'Léon Millot']	Eugene Kuhlmann of Alsace, France	1920 (France); 1951 (USA)
Marquette	Red	MN 1094 (a complex hybrid of *V. riparia*, *V. vinifera*, and other *Vitis* species) x Ravat 262 (offspring of 'Pinot noir')	University of Minnesota	2006
Vignoles	White	Unclear, either 8-Seibel 6905 x 'Pinot de Corton' or Seibel 5455 ('Plantet') x Seibel 880 (includes *V. vinifera*, *lincecumii,* and *rupestris*)	J.F. Ravat, Montpellier, France	1949

L.), and other *Vitis* species. Many of the European wine grape (*V. vinifera* L.) -based cultivars, which comprise much of wine grape production worldwide, require more than 180 frost-free days to fully ripe fruit and cannot reliably survive the harsh winter climates of places like the upper Midwest. While the hybrids possess improved cold-temperature adaptation, as well as higher degrees of resistance to the pest phylloxera (*Daktulosphaira vitifoliae* Fitch), vineyard practices for optimal fruit production are still being determined. Appropriate cultivar selection and suitable management practices for economically sustainable production of these hybrids are proving to be different from those for *V. vinifera* cultivars and often require modification according to climate patterns, geography, and local site and soil conditions. These issues are being addressed

in multi-institutional collaborative research efforts like the Northern Grapes Project (Particka and Martinson, 2016). In 2007, a survey from USDA-Risk Management Agency reported that 87% of Minnesota and 85% of Wisconsin growers had only been growing grapes for less than 10 years and more than 50% of current vineyard operators are looking for information on cultivar selection (Anonymous, 2007). Pest control, canopy management and pruning were among the top five issues cited by Wisconsin growers at commercial vineyards (USDA, 2013b). In Wisconsin, the most popular cultivars growers indicated they would like to plant in the future are 'Marquette' (17.5%), 'La Crescent' (8.5%), and 'Frontenac' (8.1%) (USDA, 2013c). Across the Midwest region, 'Marquette' (39%), 'Frontenac' (26%), and 'Maréchal Foch' (11%) are the most popular choices (Tuck and Gartner, 2013). The objective of this study was to evaluate the viticulture performance of a range of cold-climate wine grape cultivars under the growing conditions of southern Wisconsin, and to provide information on growth, yield, and vine winter survival.

Materials and Methods

Site description. The trial was established in 2008 at the West Madison Agricultural Research Station (WMARS) in Verona, Wisconsin (lat. 43°03'37"N, long. 89°31'54"W) in USDA Plant Hardiness Zone 5 (USDA, 2012). The soil is a deep, well-drained Griswold loam (fine loamy, mixed mesic, Typic Argiudoll) (USDA, 2013a), with 2 to 6% slope with moderate fertility. At the onset of the study, soil pH was 7.2 and organic matter level was 31 g kg^{-1}. Soils had high phosphorus (143 mg kg^{-1} Bray I), and high potassium (225 mg kg^{-1} exchangeable K). The mean annual number of frost-free days, and precipitation at WMARS are 157 days and 903 mm, respectively (1981–2010, NOAA National Center for Environmental Information). The average first and last frost dates (2000-2017) are 18 Oct. and 23 April , respectively (National Oceanic and Atmospheric Administration weather station at Charmany Farm, about 5 km east of the station).

Plant material and vineyard establishment. Vines of nine cold-climate interspecific hybrid cultivars were obtained from commercial nurseries and the University of Minnesota and Cornell University grape breeding programs as research material (details in Table 1): 'Aromella', 'Brianna', 'Frontenac', 'La Crescent', 'La Crosse', 'Léon Millot', 'Maréchal Foch', 'Marquette', and 'Vignoles'. Self-rooted vines were planted in 2008. Vines were cordon-trained with double trunks in year two and spur-pruned in year three. Each trunk was trained into a unilateral cordon (one meter/three feet high) utilizing the vertical shoot positioning (VSP) system on a three-wire trellis. The vines were planted in a randomized complete block design with four blocks with each cultivar replicate planted in 8.5 m (28 ft) long four-vine panels. Rows were oriented north-to-south with 3.4 m (11 ft) between rows and 2.1 m (7 ft) between vines and a total density of 1398 vines ha^{-1} (566 vines $acre^{-1}$).

The vineyard was subject to standard cultural practices for commercial vineyards (Dami et al., 2005; Wolf, 2008) with permanent sod alleyways and intra-row strips were maintained with post-emergence herbicide. Wood chip mulch was placed beneath the vines in order to minimize herbicide usage. The vineyard was not fertilized from the point of establishment through the timeframe presented here. Drip irrigation was installed at the time of planting and irrigation frequency was determined by tensiometer measurements. All vines were spur-pruned to two to three nodes. The double pruning method was utilized to minimize the effects of any spring frost injury (Dami et al., 2005). Winter survival of vines was noted, along with general assessments of bud cold damage, but specific bud damage ratings or quantification was not performed.

During 2010 and 2011 while vines were

establishing, crop level was reduced by thinning to one cluster per shoot. From 2012 onward, vines were thinned to two clusters per shoot. Bird netting was installed at veraison. Data sample collection times ranged from Aug. 2010 (yield) to March 2015 (pruning weights).

Pruning weights and crop load. Fresh dormant pruning biomass was measured by weighing one-year-old wood trimmings for individual vines from the initial pruning the winters following the 2011, 2013, and 2014 seasons, and expressed as kg of biomass per meter of cordon (kg m^{-1}). Individual vine pruning weights were not collected in 2012. The ratio of the weight of a season's yield to the cane biomass produced that season (taken as the pruning weights the following dormant season) is expressed as the Ravaz index (Ravaz, 1911). The Ravaz index was used as an expression of crop load and was calculated as the ratio of fruit-to-cane production of a given year, for the years 2011, 2013, and 2014. Balanced pruning for maintaining or adjusting vine balance was used according to the general growth-yield relationship formula '30+X': 30 buds kept for the first 0.45 kg (1.0 pound) of pruning biomass with an additional 5, 10, or 15 buds kept for every additional 0.45 kg (up to 1.8 kg) (based on general description by Dami et al., 2005) as follows: +0 buds for 'Maréchal Foch'; +5 buds for 'Aromella'; +10 buds for 'Frontenac', 'La Crescent', and 'La Crosse'; +15 buds for 'Brianna', 'Léon Millot', 'Marquette', and 'Vignoles'.

Fruit Yield. Data were collected from 2010 to 2014, as total kg of fruit per meter of cordon. Fruit from each cultivar was harvested as a single harvest event. Harvest occurred each year over a two to three-week period by criteria described below.

Fruit composition. Fruit composition data were collected in 2011, 2012, and 2014 as parameters of fruit maturity. Fruit harvest was determined by monitoring weekly soluble solids concentration (SSC), titratable acids (TA), and pH, as well as fruit condition, such as berry drop or degradation. SSC was the primary harvest indicator with a target of 22.0 %SSC. Additional targets of pH of 3.5 and TA of 6.0 g L^{-1} were considered, as well, based on local grower and winemaker advice. Berries were randomly selected from the four-vine panel and pooled to collect approximately 100 ml of juice weekly from veraison to harvest. Berries were transported to the laboratory on ice and subsequently kept in the refrigerator until analysis. Berries were crushed and juiced manually in plastic bags, and juice decanted. SSC was quantified with a HI96801 digital refractometer (Hanna Instruments, Woonsocket, Rhode Island) within 24 hours of sampling. Titratable acidity and pH values were determined with a HI902c titration system (Hanna Instruments, Woonsocket, Rhode Island) using a fixed end-point method of pH 8.2, 5 or 10 ml of sample, and 0.1 N sodium hydroxide titrant.

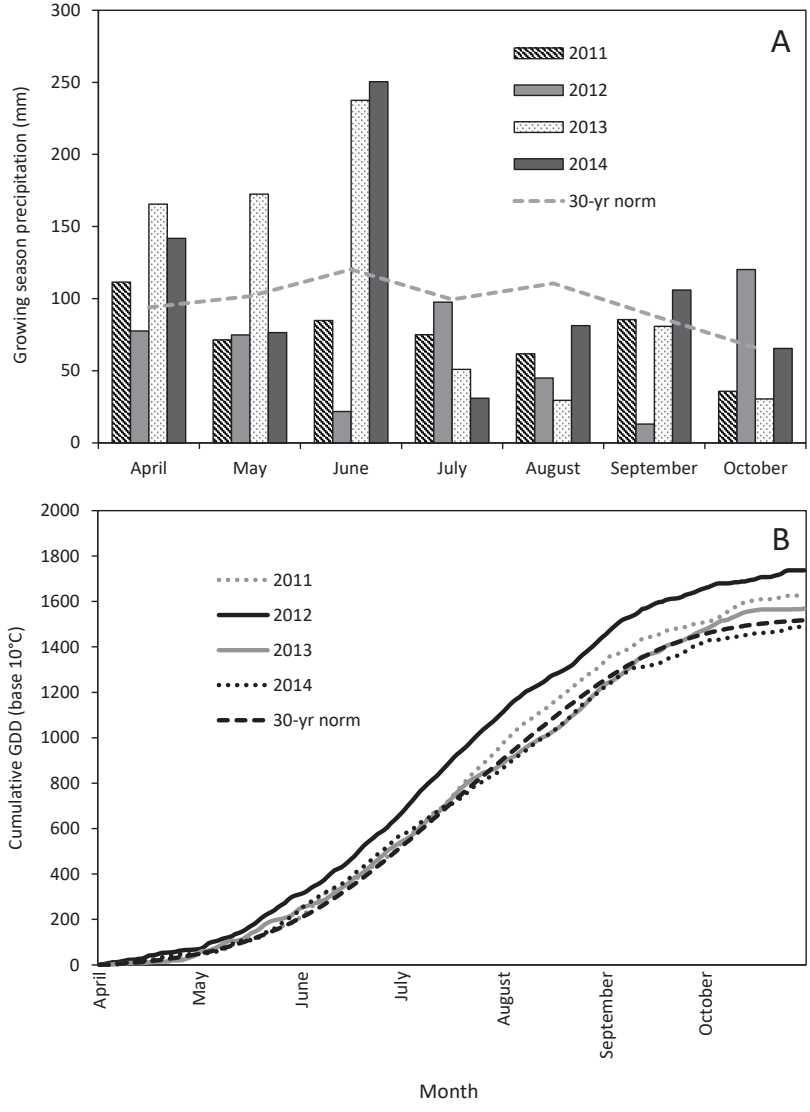
Weather conditions. Weather data were collected with an on-site weather station (WatchDog Micro Station, Spectrum Technologies, Inc., Aurora, Illinois) that recorded rainfall and hourly ambient temperature at cordon height (1 m). Additional temperature data (30-year norm (1981-2010) and daily minimum) were collected from the National Oceanic and Atmospheric Administration weather center at Charmany Farms (NOAA, 2014). Precipitation was summarized as monthly totals. Daily average temperatures were used to calculate growing degree-days (GDD) (base temperature 10 °C) for the growing season 1 April to 31 Oct. Dormant season daily minimum temperatures were summarized from 1 Nov. through 1 April.

Statistical analysis. Statistical analysis was conducted using the mixed model analysis of variance with covariance structures (SAS, Version 9.3. SAS Institute, Cary, NC). Model assumptions were confirmed with the UNIVARIATE procedure. Year was considered random for fruit yield analysis. For all other analyses, year and cultivar were fixed and block was random. If there was a significant year x cultivar interaction, the analysis

was performed by year. The repeated measures statement was used to account for correlation of plots being repeatedly sampled every year and degrees of freedom were adjusted using Kenward-Roger (Gbur et al., 2012; Littell et al., 2006; Loughin, 2006; Schabenberger and Pierce, 2001). Significance was determined using $\alpha = 0.05$ and Tukey's HSD test was used for mean separation. For statistical analysis and discussion purposes, cultivars were separated into red or white categories, the color referring to the product (i.e., wine), not the berry.

Results

Weather conditions. Since the establishment of the vineyard in 2008, there was a wide range in weather conditions across seasons (Fig. 1). The numbers of frost-free days were 186, 178, 167, and 171 for



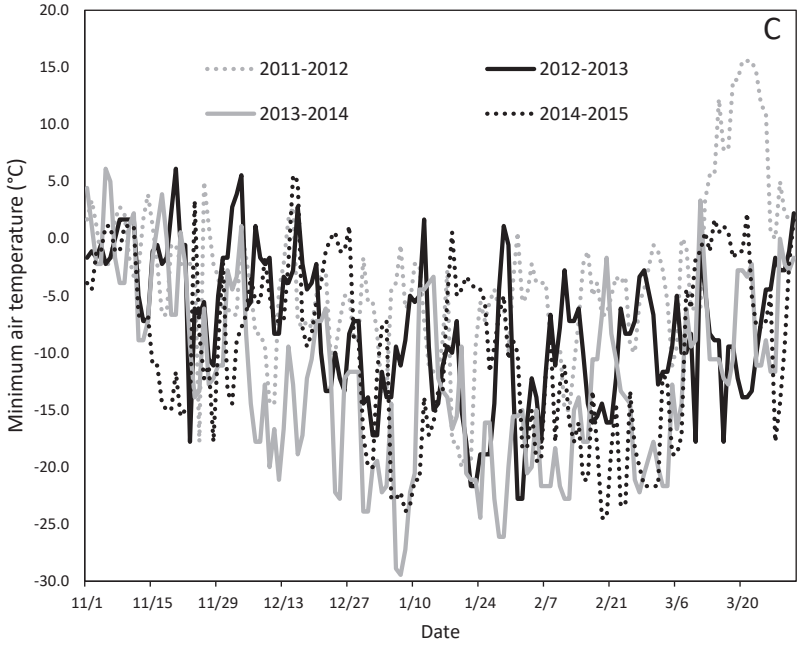


Figure 1. Summary of weather conditions at or near the West Madison Agricultural Research Station (WMARS), Verona, Wisconsin from 2011-2014 and the corresponding 30-year norm data (1981-2010, from the National Weather Service): A) Monthly precipitation totals (mm) from April through Oct.; B) Cumulative growing degree-days (GDD, base 10°C), 1 April through 31 Oct.; C) Daily minimum temperatures recorded at Charmany Farm (about 5 km east of WMARS) for NOAA Online Weather Data.

2011, 2012, 2013, and 2014, respectively (WMARS weather station). A chart of growing degree-days (Fig. 1B) shows that the entire 2012 season was the warmest, while Aug. through Oct. 2011 experienced warmer temperatures than in 2013 or 2014. In 2012, there was lack of rainfall, particularly in June and Sept. (Fig. 1A), as well as record high temperatures. The springs of 2013 and 2014 had higher precipitation than the 30-year normal, with June receiving more than twice the 30-year normal in both years (Fig. 1A). Of the four years considered here, the highest late summer (Aug. + Sept.) rainfall occurred in 2014 with a total of 187 mm. The winter of 2013-2014 was the most severe since the vines were planted (Fig. 1C). There were eight days with minimum temperature below -24 °C, with the lowest temperature experienced at -29 °C. Although there were periods of severe cold in each winter, the season of 2013-2014 had three-fold more days with temperatures below freezing than any other winter during this study.

Vine establishment. By 2010, cordons filled the trellis at the 2.1 m (7 ft.) vine spacing. Differences in vine vigor were noted across years and cultivar (Fig. 2). For all cultivars, pruning biomass was equal or higher in 2013 and 2014 vs. 2011 ($p < 0.0001$ for reds and for whites), which reflects that the vines continued to mature and gain vigor. Among the red cultivars, 'Maréchal Foch' had the lowest pruning weight each year and maintained a low level of vigor with age (Fig. 2A). There were no pruning biomass differences among red cultivars in 2011, while in both 2013 and 2014 'Maréchal Foch' was significantly lower than 'Léon Millot' and 'Marquette' ($p < 0.0136$ and 0.0156, respectively). Among the

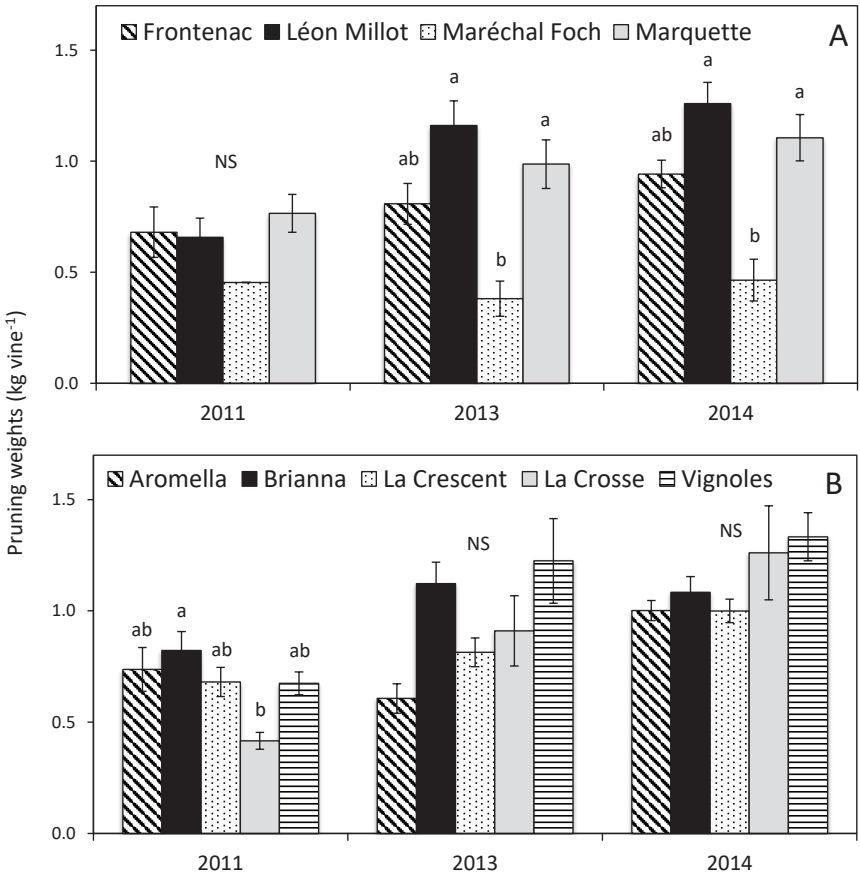


Figure 2. Mean pruning weights (kg m^{-1} of cordon) of four red (A) and five white (B) wine grape cultivars grown at the WMARS in Verona, Wisconsin from 2011, 2013, and 2014. Pruning weights were not collected in 2012. Means ± SEM (n=4), averaged over four blocks. Lower case letters indicate statistically significant differences among cultivars within years, according to Tukey's HSD test (α=0.05). For red cultivars (A), significant differences occurred among cultivars during 2013 (p=0.0136) and 2014 (p=0.0156), while no differences were observed in 2011 (p≥0.05). For white cultivars (B), significant differences occurred among cultivars during 2011 (p=0.0361), while no differences were observed in 2013 and 2014 (p>0.05).

white cultivars, 'La Crosse' showed slower establishment than the others in 2011 ($p < 0.0361$), especially compared to 'Brianna' (Fig. 2B). By 2013 and 2014 there were no pruning biomass differences among the white cultivars. 'Marquette' grew vigorously at our site, particularly as lateral shoots.

Fruit yields. Across all years among the red cultivars, 'Frontenac' was significantly higher yielding (average of 3.9 kg m^{-1}) than 'Maréchal Foch', 'Léon Millot', and 'Marquette' ($p<0.0001$) by nearly two-fold but there was no difference among those latter cultivars (Fig. 3A). 'Marquette' was the most consistent, yielding an average 2.1 kg m^{-1} yr^{-1} (range 1.6 to 2.7 kg m^{-1}; Fig. 3A). Across all years among the white cultivars, 'Brianna' and 'La Crosse' were the most productive, each yielding an average of 3.3 kg m^{-1} (Fig. 3B). 'Aromella' and 'Vignoles' produced

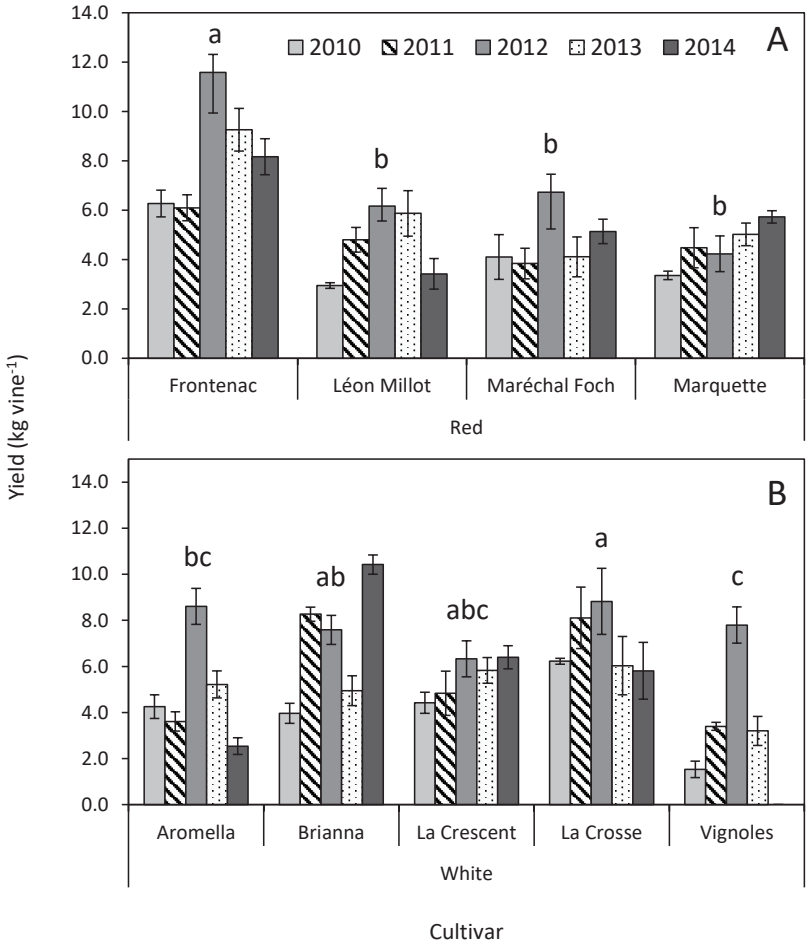


Figure 3. Mean fruit yield (kg m^{-1} of cordon) of four red (A) and five white (B) wine grape cultivars grown at the WMARS in Verona, Wisconsin over five years (2010-2014). Means ± SEM (n=4), averaged over four blocks. Lower case letters indicate statistically significant differences among cultivars for a repeated measures model that includes the five years of observation, according to Tukey's HSD means separation test (α=0.05).

lower yields with averages of 2.3 and 1.5 kg m^{-1}, respectively (Fig. 3B). These were also the most inconsistent yielding cultivars; both only had moderate yields in 2012 and otherwise were the lowest yielding. 'Vignoles' was not cropped in 2014, as a management decision due to severe winter injury. 'La Crescent' ranked midway (average 2.6 kg m^{-1}) among the whites with very consistent yields from year to year (2.1 to 3.0 kg $vine^{-1}$; Fig. 3B).

Crop load. Ravaz index values are shown in Table 2 for 2011, 2013, and 2014. Among the red cultivars, there was a significant year x cultivar effect ($p < 0.0002$). 'Maréchal Foch' had a higher index (16.5) than 'Léon Millot' (3.0) and 'Marquette' (5.8) in 2014 ($p < 0.0022$), but no differences among red cultivars were found in 2011 or 2013. There was a significant year x cultivar effect for the

Table 2. Crop load ratios using the Ravaz index (ratio of fruit to cane production of a given year) for 2011, 2013 and 2014 (n=36).

	Ravaz Index			
Cultivar	2011	2013	2014	
Reds				
Frontenac	9.7	12.4	9.1	ab[z]
Léon Millot	7.4	6.2	3.0	b
Maréchal Foch	7.8	17.0	16.5	a
Marquette	5.8	6.3	5.8	b
p-value	0.2143	0.0601	0.0022	
Whites				
Aromella	5.2 b	9.5	2.6	b
Brianna	10.3 b	4.6	10.2	a
La Crescent	5.8 b	8.3	6.6	ab
La Crosse	23.2 a	8.5	7.8	a
Vignoles	5.1 b	7.9	- -	
p-value	0.0001	0.7802	0.0060	

[z] Values within columns and color followed by common letters do not differ, by Tukey's HSD test (α=0.05).

white cultivars ($p < 0.0001$). All the white cultivars had an index less than 10 except for 'La Crosse' in 2011 (23.2) and 'Brianna' in 2011 (10.3) and 2014 (10.2). 'La Crosse' had exceptionally low vine vigor (Fig. 2B) but high fruit yield (Fig. 3B) in 2011, while 'Brianna''s crop load was the highest of all in 2014 (Fig. 3B).

Fruit composition. Among the red cultivars and across all years, 'Marquette' had the highest SSC ($p<0.0001$, =0.0003, and =0.0054 for 2011, 2012, 2014, respectively), with no significant difference between the others. 'Léon Millot' had the lowest TA and highest pH values during 2011 ($p<0.0001$ and =0.0001) and 2014 ($p<0.0001$ and =0.0026) among the red cultivars (Fig. 4). 'Maréchal Foch' had the next lowest TA levels in 2011 and 2014, while TA levels in 'Frontenac' and 'Marquette' were among the highest. There were no significant differences among the red cultivars for TA or pH during 2012 (p=0.3634 and =0.0576). For the years in which 'Vignoles' was cropped (2011 and 2012), those fruit had the highest SSC levels (p=0.0059 and =0.0008). Each year 'La Crescent' had some of the highest SSC levels (2014 p=0.0253). 'La Crosse' had the lowest values of SSC of the white cultivars, however not significantly different from 'Aromella' or 'Brianna'. 'Brianna' had the lowest TA levels for 2011, 2012, and 2014 (p=0.0004, =0.0003, and <0.0001, respectively), followed by 'La Crosse'. In 2011 and 2014, 'Vignoles', 'Aromella', and 'La Crescent' had TA levels greater than 11.0 g L^{-1}, more than twice that of 'Brianna'. 'Brianna' reached the highest pH values each year, as well (p=0.0021, =0.0008, and <0.0001, 2011, 2012, and 2014, respectively).

Discussion

Successful performance of cold-climate interspecific hybrid wine grape cultivars in the U.S. upper Midwest includes, along with strong winter survival, a moderate vigor for ease of canopy management, high and consistent yields, and fruit quality traits of good sugar accumulation, yet low to moderate titratable acidity, as berries mature. The climate experience over the four years reported here, 2011-2014, varied notably in

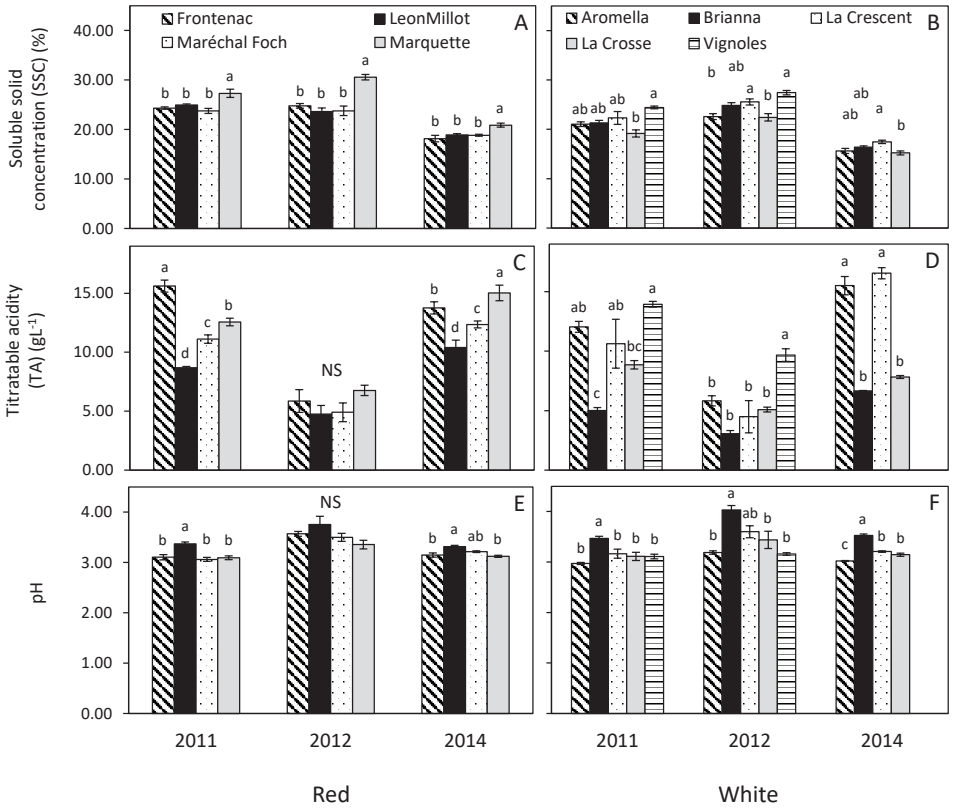


Figure 4. Fruit quality indexes at harvest (soluble solid concentration (SSC), titratable acidity (TA), and pH) of four red (A, C, and E) and five white (B, D, and F) wine grape cultivars grown at the WMARS in Verona, Wisconsin, for 2011, 2012, and 2014. Means ± SEM (n=48), averaged over four blocks. Lower case letters indicate statistically significant differences among cultivars, according to Tukey's HSD test (α=0.05).

both temperature and precipitation over the growing seasons, as well as in winter low temperature (Fig. 1), and as such, has proven to be a good test of cultivar performance.

Variability existed among the cultivars in their ability to thrive, despite their selection for being cold hardy. Although we did not fully evaluate cold damage of buds during the span of the study, 'Vignoles' and 'Aromella' exhibited cold damage most years, which contributed to the highly significant cultivar x year interaction for yield. Likewise, at a more northern sister UW Agricultural Research Station (Zone 3b), 'Vignoles' and 'Aromella' suffered >75% primary bud loss in 2014 (Volenberg, 2014), that was in addition to significant injury in previous winters (M. Stasiak, personal communication). 'Maréchal Foch' and 'Léon Millot' were also reported to have suffered notable primary bud injury in 2014, but secondary and tertiary buds were largely still viable (Volenberg, 2014). Zabadal et al. (2007) categorizes 'Vignoles' as moderately hardy (-23 to -26 °C) and 'Frontenac', 'Maréchal Foch', and 'La Crescent' at very hardy (-29 to -34 °C). Our observations confirm that the Wisconsin winter climate is too severe to

reliably produce 'Vignoles' and 'Aromella', while 'Frontenac' and 'La Crescent' can be successfully grown in Southern Wisconsin. It is interesting to note that 'Frontenac and 'La Crescent' were also identified as being two of the most popular and sought after cultivars by Wisconsin grape growers (Rochester, 2011; Tuck and Gartner, 2013; USDA, 2013c).

Despite these overwintering challenges, most of the cultivars continued to gain vigor over time, except for 'Maréchal Foch', which had the lowest pruning weight each year while maintaining a consistent level of vigor with age (Fig. 2). Increased vigor that is the result of on-going establishment of the vine is qualitatively different from the vigor that is stimulated in response to non-lethal stress, such as severe midwinter temperatures. We hypothesize the high vigor of 'Léon Millot', 'Vignoles', and 'Aromella' in the years after establishment may be due to the stimulation of increased vegetative growth after notable winter injury. The low Ravaz indexes (3.0 or less; Table 2) for these cultivars in 2014 reflect the combination of low (or no, in case of 'Vignoles') yields and high vegetative biomass production. Moderate vigor, such as demonstrated by 'La Crescent' and 'Frontenac', is desirable to produce a balanced growth to support fruit production, but also to keep canopy management tasks (e.g., thinning, shoot positioning, and leaf pulling) reasonable. 'Marquette' demonstrated vigorous growth at our site, largely marked by abundant lateral growth.

Two important aspects of yield when considering successful cultivars for a growing region are: total yield and year-to-year consistency. In this trial, 'Frontenac', 'La Crosse', and 'Brianna' were the highest producing cultivars (Fig. 3). Among the white cultivars, 'La Crescent' had the least variation from year to year, but had overall yields that were not statistically different from those of 'Vignoles', and 'Aromella'. Yields of 'La Crescent' were reduced likely due to its nature of shelling (premature berry drop) (Thull and Luby, 2016). The steady and large yield decline of 'Aromella' and 'Vignoles' since 2012 is indicative of the poor winter survival of these cultivars in the severe winter of the U.S. upper Midwest. 'Marquette' was the most consistently producing red cultivar, while 'Frontenac' was the highest yielding, as well as most variable, over the years of this trial.

Recommended ranges of the fruit maturity parameters for wine production from *V. vinifera* grapes are widely used (Amerine et al., 1967; Winkler et al., 1974; Boulton et al., 1996; Dami et al., 2005). However, there is a critical need to develop similar criteria for cold-climate cultivars that will provide guidance to growers in establishing optimal harvest times. In both 2011 and 2012, all red cultivars produced higher SSC than the *V. vinifera* recommended range of 20.5-23.5 %SSC (as summarized in Rolfes et al., 2015), while in 2014 all but 'Marquette' were below this range (Fig. 4). The recommended TA concentration for juice of red wine cultivars (6.0-8.0 g L^{-1}) (Rolfes et al., 2015) was exceeded in both 2011 and 2014. Only in the warmer year of 2012 were these concentrations close to the recommended *V. vinifera* range, and those for 'Léon Millot' and 'Maréchal Foch' were both below this (4.57 and 5.42 g L^{-1}, respectively). The shorter ripening period of the cold-climate cultivars relative to *V. vinifera* and the often lack of abundant heat units in the upper Midwest climate contribute to fruit maturity profiles characterized by higher titratable acidity with often moderate sugar accumulation (Haggerty, 2013; Teh et al., 2014). Researchers in central Iowa found similar fruit ripening profiles for 'Marquette', 'Frontenac', and 'La Crescent' to those in our study (Rolfes et al., 2015). Bavougian et al. (2013) studying 'Frontenac' in Nebraska under various trellis training systems, including those utilizing VSP, reported lower sugars and higher TA levels than in this trial. The Northern Grapes Project reported higher sugars but also much higher TA in 2012 and 2013 in New York state than at WMARS for

'Marquette' and 'Frontenac' (Martinson and Particka, 2015).

The harvest fruit maturity targets for this trial (SSC 22 %SSC, TA 6.0 g L^{-1}, and pH 3.5) were met inconsistently over the seasons reported. Variability in weather conditions experienced in southern Wisconsin during the study strongly affected fruit quality traits of these cold-climate cultivars. Higher accumulation of GDD during 2012 affected primarily the reduction of TA while only slightly affecting the accumulation of SSC. In comparison, the more moderate warm temperature experience in 2011 resulted in comparable sugar accumulation to those of 2012, but conditions were not sufficient to modulate high organic acid levels (Lakso and Kliewer, 1975). The coolest (and wettest) year, 2014, led to the lowest concentrations of SSC coupled with high TA values. In a study in Minnesota, Teh et al. (2014) reported that TA levels in cold-climate cultivars decline only gradually toward harvest time, and that during 2012, ratios of tartaric to malic acid were fairly constant in 'Frontenac' and 'La Crescent', while this ratio increased in 'Marquette' due to a significant decrease in malic acid concentration. Also in that study, the attainment of fruit maturity corresponded with the accumulation of 1400 to 1500 GDD (base 10°C). At our location, 1400 GDD accumulations were not reached until late Sept. in 2013 and 2014. In contrast, relatively rapid heat unit accumulation occurred in the latter part of the 2012 season, such that 1400 GDDs was reached by the beginning of Sept. In 2011, this GDD threshold was attained in early Sept., but did not reach 1500 GDD until the end of the month. Based on our observations, greater heat accumulation during the growing season has a significantly higher impact on acid degradation than on the production and accumulation of sugars.

Another aspect of vineyard management for the production of substantial and consistent yields of higher quality is decisions on the amount of fruit to carry per unit of canopy, or vine balance. Crop load (i.e., fruit:cane biomass, Ravaz index) ratios are often between 4 to 12 for most *V. vinifera* cultivars and above 12 for hybrids (Zabadal et al., 2007). Reynolds and Wolf (2008) state that for many cultivars crop load ratios between 10 to 12 are optimum, while in areas where heat accumulation is more of a challenge, crop load ratios as low as 5 may be reasonable. Most Ravaz indexes for the cultivars in this study were around 10 or below, with only a few below 5 (Table 2). Crop load ratio values for 'Maréchal Foch' and 'Frontenac' were 2-2.5 times higher than either 'Marquette' or 'Léon Millot' in 2013 and 2014, which is interesting given the fact that 'Léon Millot' is a sibling of 'Maréchal Foch'. Vos (2014) found that a range of crop load treatments from 2 to 14 did not have associated negative effects on future vine productivity in 'Frontenac' grown in Iowa. In our study 'La Crosse' had an exceptionally high crop load in 2011, but more moderate values in 2013 and 2014. In 2011 and 2014, 'Brianna' had relatively high crop load ratios among the white cultivars. The generally low (<10) Ravaz values may indicate that many of these cultivars can handle greater fruit load, especially 'Marquette' and 'La Crosse'. This would require a revision of the growth-yield relationship formula for calculating bud counts.

Conclusion

Our evaluation of cold-climate interspecific hybrid wine grape cultivars considered a balance of yield and fruit maturity parameters, along with a concern for vine balance. 'Aromella' and 'Vignoles' have been removed from the WMARS vineyard due to their poor winter survival and resulting lack of production. These cultivars are not recommended for commercial production in Wisconsin, unless local winter minimum temperatures warmer than at WMARS are feasible. Of the other cultivars being grown at WMARS, no one cultivar was both the highest and most consistent producer; however, several are promising. While not the highest yielding of the red cultivars, 'Marquette' had

consistent yields, as well as the ability to reliably produce higher sugars than the other reds, although it is also typically high in TA. 'Marquette' may be able to carry heavier crop loads, which may help to control its shoot vigor. 'Frontenac' possessed moderate vigor and was the best yielding red cultivar. However, it promises to be consistently high in TA, save in exceptionally warm growing seasons. No one white cultivar stood out as exceptional in sugar production. 'Brianna' was a high yielding white cultivar whose fruit composition was comparable to the other whites in SSC production, while consistently low in TA, even in the cool growing season of 2014. 'La Crosse' was only moderate in SSC production, but had relatively lower levels of TA, high yields, and consistent vine balance. 'La Crescent' was consistent and moderate in yields, and its popularity among growers indicates possesses other desirable qualities than its fruit composition traits (as reported here) would indicate. Further evaluation is required, but the fruit quality and control of vegetative vigor of several of these cold-climate interspecific hybrids may be influenced by carrying larger crop loads. 'Frontenac', 'Marquette', and 'La Crescent' showed the most stable vine balance, based on the Ravaz index.

Acknowledgments

We thank Judith Reith, Brian Emerson, and Rebecca Harbut for their work in the design and establishment of the WMARS vineyards and oversight of data collection. Also, we thank all the UW-Madison undergraduate interns and graduate students who assisted in the daily and seasonal tasks of vineyard management and data collection. Funding for this project was provided by the UW-Madison College of Agriculture and Life Sciences, UW-Madison ARS, and USDA Specialty Crop Block Grant #10-012.

Literature Cited

Amerine, M.A., Berg, H.W., and Cruess, W.V. 1967. The Technology of Wine Making. Avi Publishing Company, Westport, Conn.

Anonymous. 2007. Risk management tools for the grape industry in Minnesota and Wisconsin. 24 June 2016. http://www.agmrc.org/media/cms/MNandWISurveyResults_894C57D3D946F.pdf

Bavougian, C.M., Read, P.E., Schlegel, V.L., and Hanford, K.J. 2013. Canopy light effects in multiple training systems on yield, soluble solids, acidity, phenol and flavonoid concentration of "Frontenac" grapes. HortTechol. 23:86-92.

Boulton, R.B., Singleton, V., Bission, L.F., and Kunkee, R.E. 1996. Principles and Practices of Winemaking. Springer Publishing Co., New York.

Dami, I., Bordelon, B., Ferree, D.C., Brown, M., Ellis, M.E., Williams, R.N., and Doohan, D. 2005. Midwest grape production guide, Bulletin 919. Ohio State University, Columbus, Ohio.

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

Gbur, E.E., Stroup, W.W., McCarter, K.S., Durham, S., Young, L.J., Christman, M., West, M., and Kramer, M. 2012. Analysis of Generalized Linear Mixed Models in the Agricultural and Natural Resources Sciences. ASA, CSSA, and SSSA, Madison, WI.

Haggerty, L. 2013. Ripening Profile of Grape Berry Acids and Sugars in University of Minnesota Wine Grape Cultivars, Select Vitis vinifera, and Other Hybrid Cultivars. University of Minnesota, St. Paul, MS thesis.

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

Lakso, A.N. and Kliewer, W.M. 1975. The influence of temperature on malic acid metabolism in grape berries I. Enzyme responses. Plant Physiol. 56:370-372.

Littell, R.C., Stroup, W.W., Milliken, G.A., Wolfinger, R.D., and Schabenberger, O. 2006. SAS for mixed models. SAS institute, Cary, NC.

Loughin, T.M. 2006. Improved experimental design and analysis for long-term experiments. Crop Sci. 46:2492-2502.

Luby, J., Mansfield, P., Hemstad, P., and Beam, B. 2006. Development and evaluation of cold-hardy wine grape breeding selections and cultivars in the upper Midwest, Progress Report for Viticulture Consortium-East. Cornell University, Geneva, NY.

Martinson, T. and Particka, C. 2015. A Tale of Two Crops: Impact of late-spring frost on Frontenac Fruit Composition. 29 June 2016. http://northerngrapesproject.org/wp-content/uploads/2015/12/Martinson-presentation-PDF.pdf

NOAA. 2014. National Climate Data Center. 16 March 2015. http://www.ncdc.noaa.gov/oa/ncdc.html

Particka, C. and Martinson, T. 2016. Year 4 Progress Report-Northern Grapes: Integrating Viticulture, Winemaking, and Marketing of New Cold-Hardy Cultivars Supporting New and Growing Rural Wineries. 20 January 2017. http://northerngrapesproject.org/wp-content/uploads/2016/02/Year-4-Northern-Grapes-Project-Progress-Report.pdf

Ravaz, M.L. 1911. L'effeuillage de la vigne. Annales de l'Ecole Nationale d'Agriculture de Montpellier 11:216-244.

Reynolds, A.G. and Wolf, T.K. 2008. Pruning and Training, p. 98-123. In: Wolf, T. K. (ed.), Wine Grape Production Guide for Eastern North America. Plant and Life Sciences Publishing, Ithaca, NY.

Rochester. 2011. Report of Wisconsin Grape Growers Survey. 30 June 2016. https://fruit.wisc.edu/wp-content/uploads/sites/36/2016/06/Report-of-the-Wisconsin-Grape-Growers-Survey.pdf

Rolfes, D., Nonnecke, G., and Domoto, P.A. 2015. Effects of canopy management practices on cold-hardy grape cultivars. 24 June 2016. http://northerngrapesproject.org/wp-content/uploads/2015/03/2015MarchNGPnewsletter.pdf

Schabenberger, O. and Pierce, F.J. 2001. Contemporary statistical models for the plant and soil sciences. CRC Press, Boca Raton, FL.

Smiley, L., Domoto, P.A., and Cochran, D. 2016. A Review of Cold Climate Grape Cultivars. 20 Jan 2015. http://www.extension.iastate.edu/viticulture/cold-climate-cultivars

Teh, S., Haggerty, L., Hegeman, A., and Luby, J. 2014. Fruit Ripening Profiles of Cold Climate Wine Grape Cultivars. 24 June 2016. http://northerngrapesproject.org/wp-content/uploads/2014/02/FruitRipeningProfiles.pdf

Thull, J. and Luby, J. 2016. Brianna and La Crescent: Ten Viticulture Tips. June 13. http://northerngrapesproject.org/wp-content/uploads/2016/03/Brianna-and-La-Crescent-Viticulture-enology-and-tasting.pdf

Tuck, B. and Gartner, W. 2013. Vineyards and Grapes of the North: A status report. 30 December 2014. http://www.extension.umn.edu/community/economic-impact-analysis/reports/docs/2013-Vineyards-Grapes-North.pdf

USDA. 2013a. Web Soil Survey. 15 January 2015. http://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm

USDA, A. 2012. USDA Plant Hardiness Zone Map, 2012. May 15 2015. http://planthardiness.ars.usda.gov/.

USDA, N.A.S.S. 2013b. 2011 Grape and wine industry survey. 5 February 2015. http://www.nass.usda.gov/Statistics_by_State/Wisconsin/Publications/Crops/WIGrapeWine

USDA, N.A.S.S. 2013c. 2011 Grape and wine industry survey addendum. 2 January 2015. http://www.nass.usda.gov/Statistics_by_State/Wisconsin/Publications/Crops/WIGrapeWineAddendum.pdf

Volenberg, D. 2014. Vineyard IPM scouting report for week of 19 May 2014 UW-Extension Door County and Peninsular Agricultural Research Station. 24 June 2016. https://fruit.triforce.cals.wisc.edu/wp-content/uploads/sites/36/2014/06/IPM-Report-week-1-5.19.2014.pdf

Vos, R. 2014. Stage of maturation, crop load, and shoot density affect the fruit quality of cold-hardy grape cultivars. PhD Diss.Dept. of Horticulture, Iowa State Univ., Ames.

Winkler, A.J., Cook, J.A., Kliewer, W.M., and Lider, L.A. 1974. General Viticulture. Univ. of California Press, LTD, London.

Wolf, T.K. 2008. Wine grape production guide for eastern North America. Plant and Life Sciences Publishing, Ithaca, NY.

Zabadal, T., Dami, I., Goffinet, M., Martison, T., and Chien, M. 2007. Winter injury to grapevines and methods of production, p. 16, Michigan State Extension E2930. Michigan State Univ., East Lansing, MI.