Annual Report

July 1, 2016 – June 30, 2017

Viticulture and Enology programs for the Colorado Wine Industry

PRINCIPAL INVESTIGATORS

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COLLABORATING INSTITUTIONS

- Colorado Department of Agriculture
- The Colorado Wine Industry Development Board
- Colorado State University

Summary

The reporting period covers the second half of the 2016 growing season, the 2016/17 dormant period, and the first half of the 2017 growing season. Consequently, the work performed during the reporting period covers a full seasonal cycle, albeit from two different growing seasons. Work included seasonal tasks such as vine training, canopy management, crop thinning, harvest, winemaking, preparing vineyards for dormant season, bud cold hardiness evaluations, dormant pruning, a continuation of a study on methods to increase bud cold hardiness, a study on the climate and climatic trends in SW Colorado as it relates to wine grape production, data entry and analysis, and the annual Colorado Grape Grower Survey. In addition, since the discovery of phylloxera (*Daktulosphaira vitifoliae*) in the Grand Valley in November 2016, significant efforts have been directed towards outreach, grower education, phylloxera surveys, and new research projects that were not envisioned in the original plan of work for FY17.

Most of the vineyard work was performed by five student interns (three from the Viticulture & Enology program at CSU; one from the Viticulture & Enology program at WCCC), a high school student, a visiting scholar from Spain, and CSU staff at WCRC. Two other student interns from the Viticulture & Enology program at CSU were responsible for all vineyard work in the new variety trial in Fort Collins. The climate study in SW Colorado was conducted by staff from the Colorado Climate Center.

Weather conditions in the Grand Valley were slightly warmer than average in July, but slightly cooler in August. September was slightly warmer than average followed by the second-warmest October and warmest November since record-keeping began at the Western Colorado Research Center – Orchard Mesa in 1964. The mean temperature for November was almost 7 F higher than average. A season-ending killing frost occurred on October 20 in the main growing areas in Delta County, but not until November 17 in central and eastern parts of the Grand Valley. December temperatures were slightly above average. There was a gradual decline in minimum temperatures in December 2016

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which resulted in good and gradual vine cold acclimation. There was, however, a sharp temperature drop at the end of the first week of January 2017 when once again temperatures dropped below 0 F in many parts of Western Colorado. Weekly bud evaluations from vines growing at the Western Colorado Research Center – Orchard Mesa and commercial vineyards nearby confirmed that this very brief cold spell did not result in any significant bud cold injury. The remainder of the dormant season was very mild; in fact, February 2017 was the second warmest February on record at WCRC-OM while March was the warmest. The deviation from average for both months was close to 8 F. The outcome of this very early warming trend was a rapid loss of bud cold hardiness during March, and an early bud break of early varieties such as Marquette. April temperatures were close to average, resulting in a more gradual bud deacclimation of later-breaking varieties. However, overall bud break was about one to two weeks earlier than the long-term average. Two late spring freezes (April 28 and 30) caused damage to some varieties and sites – predominantly in the western part of the Grand Valley, but also in Delta County and in some Front Range locations.

Similar to 2015, most of the 48 varieties grown in the research vineyards produced a crop in 2016. Data from the 2016 Colorado Grape Grower Survey indicate that the 2016 harvest was the biggest ever, surpassing the record set in 2015. Similar to the 2015 harvest, there was a surplus of grapes. This surplus appears to have been equal to, if not larger than in the previous year. With close to 200 new acres reaching full production potential within the next 2-3 years, the oversupply of grapes during the past two vintages raises serious concerns about the future balance in grape supply and demand.

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Growing conditions, July 2016 – June 2017

Temperatures recorded at the Western Colorado Research Center - Orchard Mesa (WCRC-OM) and Western Colorado Research Center - Rogers Mesa (WCRC-RM) were near average during July, August, and September 2016. Temperatures in October and November were much higher than normal, while mean temperatures in December were near average. Precipitation from July to December were near average. Annual precipitation at WCRC-OM and WCRC-RM was 7.15" and 7.70", respectively, slightly below normal.

The very warm October and November allowed for most grapes to be harvested prior to killing frosts. Most of the vineyards in Delta County had a killing frost before the end of October. In contrast, most vineyards in Mesa County did not have a killing frost until the second half of November. Temperatures throughout December were near average, and unlike December 2015 there were no extreme temperature swings.

There was a sharp temperature drop at the end of the first week of January 2017 when once again temperatures dropped below 0 F in many parts of Western Colorado. This cold spell lasted only two days, and temperatures were warmer than average for most of the remainder of January. Much warmer than average temperatures continued throughout February and March. At WCRC-OM, February 2017 was the second warmest February on record, and March the warmest ever recorded. Even with the brief cold spell in early January, the average temperature at WCRC-OM for the first three months of 2017 was 53.3 F. This was 7 F above long-term average, and the second warmest January to March period on record (after 2015).

April started out with temperatures near normal, much warmer than average temperatures in the middle of the month, and two late freezes on April 28 and 30. At that time most varieties in Mesa County were already past bud break, and some vineyards suffered significant spring frost damage. May temperatures were near average, but two late spring frost events (May 19 and 20) were recorded in other parts of Western Colorado, causing damage to some vineyards.

June temperatures were well above average, with high temperatures in the Grand Valley reaching or exceeding 100 F for several days at the end of the third week. The monthly mean temperature at WCRC-OM was 77.1 F, the sixth-warmest on record.

Precipitation for the first six months of 2017 was well below average. The later part of spring into early summer has been especially dry, with only 0.01" of precipitation at WCRC-OM in June, tying 1968 for the third-driest June (no precipitation was recorded in June 2001 and 2002).

Research Update

I. Cropping Reliability

1. Grape varieties and clones suited to Colorado temperature conditions

Since 2004 we have greatly expanded the number of varieties under testing. The first-ever replicated variety trial in Delta County was planted at the Western Colorado Research Center - Rogers Mesa site in 2004. This trial was expanded with new entries in 2009 as part of the USDA Multistate NE-1020 project (see below). Also in 2009 and as a part of NE-1020, 26 "new" varieties were planted at the WCRC Orchard Mesa site. An additional replicated trial focused on cold-hardy, resistant varieties was established on a grower cooperator site in Fort Collins in 2013 to identify grape varieties that can be grown successfully along the Front Range. And in 2014, a fourth trial focused on cold-hardy, resistant varieties was established with a grower-cooperator in the Grand Valley.

- Rogers Mesa variety trial. (Caspari, Menke, and Sterle)

  A new vineyard was planted at the Rogers Mesa site in the spring of 2004, with additional vines added in the spring of 2005 and 2006. With the exception of a few missing vines, this planting is complete. Genetic backgrounds of the varieties include both cold-hardy, resistant varieties, mainly from the grapevine breeding program from Geneva, NY, and *Vitis vinifera* varieties. Vines of Pinot noir, P. Meunier, and Malbec were removed from this trial in the spring of 2015 due to very poor performance.

  The comparatively mild temperatures during winter 2015/16 resulted in minimal bud damage to the remaining test varieties. Six varieties were harvested between 19 and 21 October, 2016. Results are summarized in Table 1. Only Traminette was used for micro-vinification.

Table 1: Harvest dates and yield information for 6 (out of 8) grape varieties planted in 2004 at the Western Colorado Research Center – Rogers Mesa near Hotchkiss, CO.

Variety	Harvest date 2016	Yield (ton/acre)[1]
Chambourcin	21 October	3.63
Corot noir	19 October	2.70
Noiret	21 October	2.35
Rkatsiteli	19 October	2.85
Traminette	19 October	3.49
Valvin Muscat	21 October	1.32

[1] Yield calculation based on number of vines with crop. Vine survival is >90 % for all varieties.

- Multi-state evaluation of wine grape cultivars and clones. (Caspari, Menke, and Sterle)

  This long-term (2003-2017), USDA multi-state research project (NE-1020) tests the performance of clones of the major global cultivars and new or previously neglected wine grape cultivars in the different wine grape-growing regions within the U.S. and is a collaboration of more than 20 states. All participating states follow the same experimental protocol. In Colorado, 10 varieties were established in 2009 and 2010 at Rogers Mesa, and 25 varieties at Orchard Mesa between 2009 and 2012.

  At Rogers Mesa, eight out of ten varieties were harvested between 21 September and 19 October 2016. Yields ranged from 0.7 to 3.9 ton/acre (Table 2). Micro-vinification was used to produce six varietal wines.

  At Orchard Mesa, all 25 varieties produced a crop. Harvest started with Marquette on 22 August 2016, and ended with six varieties on 31 October 2016. A summary is presented in Table 3. Ten varietal and one blended wine were produced using micro-vinification techniques.

Table 2: Harvest dates and yield information for 8 (out of 10) grape varieties planted in 2008 and 2009 at the Western Colorado Research Center – Rogers Mesa near Hotchkiss, CO.

Variety	Harvest date 2016	Yield (ton/acre)[1]
Aromella	29 September	2.70
Auxerrois		0
Bianchetta trevigiana	7 October	0.70
Blauer Portugieser		0
Chambourcin	19 October	3.86
Grüner Veltliner	7 October	1.62
Marquette	21 September	1.52
MN 1200	21 September	1.27
NY 81.0315.17	19 October	3.67
Vidal	19 October	2.35

[1] Yield calculation based on number of vines with crop. Vine survival (out of 24 vines planted originally) ranges from 46 % for Auxerrois to 100 % for Marquette and MN 1200.

Table 3: Harvest dates and yield information for 25 grape varieties planted in 2008 and 2009 at the Western Colorado Research Center – Orchard Mesa near Grand Junction, CO.

Variety	Harvest date 2016	Yield (ton/acre)[1]
Albarino	19 September	3.84
Barbera	27 October	4.56
Cabernet Dorsa[2]	2 September	2.66
Cabernet Sauvignon	17 October	2.29
Carmenere[3]	31 October	1.29
Chambourcin[2]	17 October	2.08
Cinsault	18 October	2.76
Durif[2]	31 October	0.53
Graciano[3]	18 October	1.64
Grenache	31 October	2.23
Malvasia Bianca	19 September	1.85
Marquette[2]	22 August	1.65
Marsanne	17 October	1.57
Merlot	9 September	0.82
Mourvedre	31 October	1.93
Petit Verdot[3]	31 October	1.70
Refosco[3]	18 October	4.50
Roussanne	18 October	1.33
Souzao	26 October	2.70
Tinta Carvalha[3]	31 October	1.00
Tocai Friulano	31 October	4.45
Touriga Nacional	26 October	2.98
Verdejo	31 October	6.29
Verdelho	19 September	3.64

Table 3 continued: Harvest dates and yield information for 25 grape varieties planted in 2008 and 2009 at the Western Colorado Research Center – Orchard Mesa near Grand Junction, CO.

Zweigeltrebe[2]	9 September	2.38

[1] Yield calculation based on number of vines with crop. Vine survival (out of 24 vines planted originally) ranges from 4 % for Tocai Friulano to 96 % for Zweigeltrebe.
[2] Planted in 2011 and 2012.
[3] Planted in guard rows; not part of the NE-1020 study. However, experimental design and management follow NE-1020 protocol.

- Variety evaluation for Front Range locations, Fort Collins. (Caspari, Menke and grower cooperator)

  A new vineyard was established on a grower cooperator site in Fort Collins in 2013 to identify grape varieties best suited along the Front Range. Repeated cold events have led to a slow vine establishment. Two extreme cold temperature events during dormancy (-9 F on 12 November, and -22 F on 30 December 2014) caused near 100 % bud and trunk damage to Chambourcin, Noiret, and Traminette. In contrast, Aromella, Frontenac, and Marquette had about 90 % live fruitful buds (primary and secondary). However, a severe freeze event on 11 May 2015, when most varieties were near or already past bud break, caused significant cold damage to emerging shoots and near 100 % crop loss. Consequently, many vines needed re-training during 2015. Milder minimum temperatures during the 2015/16 dormant season resulted in no bud damage, and there were no late spring freezes. Fruit was harvested from all varieties (Table 4), and six varietal wines were produced.

Table 4: Harvest dates and yield information for 6 (out of 8) grape varieties planted in 2013 at a commercial vineyard in Fort Collins, CO.

Variety	Harvest date 2016	Yield (ton/acre)[1]
Aromella	4 October	0.94
Chambourcin	4 October	0.92
Frontenac	4 October	0.88
La Crescent	18 September	1.58
Marquette	18 September	1.71
Vignoles	4 October	0.82

[1] Yield calculation based on number of vines with crop. Vine survival is >95 % for all varieties.

- Cold-hardy, resistant varieties for the Grand Valley. (Caspari, Menke, Sterle, and grower cooperator)

  A new replicated variety trial was established in 2014 on a grower cooperator site near Clifton to identify grape varieties that can be grown successfully in cold Grand Valley sites. Not all vines had sufficient vigor during 2015 for shoots to be tied down to the fruiting wire. However, all varieties produced at least a small amount of fruit (Table 5). Nine varietal and one blended wine was produced.

Table 5: Harvest dates and yield information for 12 grape varieties planted in 2013 at a commercial vineyard near Clifton, CO.

Variety	Harvest date 2016	Yield (ton/acre)[1]
Arandell	1 September	1.34
Aromella	9 September	3.47
Brianna	22 August	3.05
Cayuga White	12 September	3.37
Chambourcin	17 October	3.07
Corot noir	21 September	2.45
La Crescent	1 September	1.86
Marquette	22 August	2.00
Noiret	21 September	1.48
St Vincent	17 October	4.01
Traminette	22 September	1.43
Vignoles	22 September	1.65

[1] Yield calculation based on number of vines with crop. Vine survival is >90 % for all varieties.

- Clonal trial with Cabernet Franc. (Caspari, Menke, Sterle, and grower cooperator)

  Cabernet Franc is one of Colorado's most-planted varieties, and varietal wines made from this variety have received national recognition. A recent review of data from Colorado's annual grape growers survey from 2000 to 2014 showed that Cabernet Franc was the only variety that produced above-average yields in all 15 years, and returned the greatest average revenue per acre (Caspari and Lumpkin, 2015). It may indeed be one of the best-suited *Vitis vinifera* varieties for the Grand Valley AVA.

  Most older-aged blocks of Cabernet Franc are planted with clone FPS 01. While this clone is high yielding and appears to have very good cold hardiness, it is also considered as having lower fruit quality. Since no information on Cabernet Franc clonal performance is available in Colorado, a trial with four clones (FPS 01, 04, 09, 11) was established in 2009 on a grower cooperator's vineyard[2].

  On 6 October 2016, approximately 285 lbs of fruit per clone were harvested from 5 to 6 replicates per clone. The number of vines harvested was recorded separately for each clone. Fruit was taken to WCRC-OM, weighed, and then used to produce triplicate small-scale wine lots. Must samples were analysed using an OenoFoss analyser (Foss North America, Gusmer Enterprises Inc., Fresno, CA). Following must analyses, must of each wine lot were adjusted to a target of 24 Brix soluble solids and 7 g/l total titratable acidity. Wines will be used for future analysis, formal wine evaluations, and industry tastings.

  Consistent with observations in previous years, yields were highest for clones FPS 01 and 09, and lowest for clone FPS 11 (Table 6). It should be noted, however, that vines of clone FPS 11 are grafted to rootstock 110 Richter whereas vines of all other clones are own-rooted. Grafted vines of clone FPS 11 are less vigorous than own-rooted vines.

[2] The trial was set up as a randomized complete block design with 10 full-row replications, and a total number of 500 vines per clone. Rows are 2 m apart with vines spaced in-row at 5 feet.

Table 6: Clonal effects on 2016 yield of Cabernet Franc growing in the Grand Valley AVA in Western Colorado.

Clone / rootstock	Yield (lb/vine)	Yield (ton/acre)
FPS 01 / own	6.16	4.09
FPS 04 / own	4.56	3.03
FPS 09 / own	7.50	4.98
FPS 11 / 110R	2.22	1.47

As was the case in 2015, despite having the lowest yield, musts of clone FPS 11 also had the lowest nitrogen concentration (Table 7). Musts of clone FPS 09 had the lowest pH, and highest titratable acidity and malic acid concentration. The result on must composition as well as those on yield are consistent with the results from the 2015 season.

Table 7: Clonal effects on must parameters of Cabernet Franc growing in the Grand Valley AVA in Western Colorado.

Clone / rootstock	pH	Brix	TA (g/l)	Tartaric acid (g/l)	Malic acid (g/l)	α-amino nitrogen (mg/l)	Ammonia (mg/l)
FPS 01 / own	3.64	26.1	4.67	5.89	2.08	72	79
FPS 04 / own	3.59	26.4	4.92	5.44	1.99	86	70
FPS 09 / own	3.47	26.5	5.23	5.49	2.26	71	82
FPS 11 / 110R	3.59	28.0	4.52	5.60	1.70	59	74

Wines made in 2015 were tasted at the annual VinCO conference in mid-January 2017. About 60 industry personnel participated in the tasting. The tasting was set up as a Triangle test. In a Triangle test participants are presented with one different and two alike samples. In this case, participants were presented three glasses (labeled “A”, “B”, “C”) of wine; two glasses contained wine from the same clone, and one glass contained wine made from a different clone. Participants were then asked to identify which of the three glasses was the wine made from the different clone. The probability that a participant correctly identifies the odd wine simply by guessing is $p = 1/3$. There were six flights organized at random.

Participants were not able to distinguish between wine pairings of clones FPS 01 and FPS 04, and FPS 04 and FPS 09 (Table 8). In contrast, results from all other pairings indicate highly significant differences between the wines.

Table 8: Triangle test results for wines made from four clones of Cabernet Franc growing in the Grand Valley AVA in Western Colorado.

Clone pairing	Number of responses	Percent of correct answer	Significance (%)
FPS 01 / 04	51	37.3	ns
FPS 01 / 09	48	64.6	0.1
FPS 01 / 11	48	54.2	1.0
FPS 04 / 09	56	41.1	ns
FPS 04 / 11	48	60.2	0.1
FPS 09 / 11	51	56.9	0.1

At the end of the tasting the participants were given four wines – one made from each clone – without disclosing the clonal identity and asked which one they liked the most. Wines made from clones FPS 09 or 11 were preferred by 34 % of the participants, 24 % choose wine from clone FPS 04, and 7 % preferred wine from clone FPS 01.

2. Cold temperature injury mitigation and avoidance.

Low yields and large year-to-year yield fluctuations are characteristic of Colorado grape production, even in the Grand Valley AVA, due to cold temperature injury. The research projects outlined below try to identify best methods to either avoid cold injuries altogether, or mitigate cold temperature negative effects on vine survival, yield, quality, and vineyard economics. It should be noted that the identification of varieties that are best suited to Colorado's climate (see variety trials above) is a fundamental component for avoiding cold injury.

- Characterizing cold hardiness. (Caspari and Sterle)

  There are substantial varietal differences in cold hardiness. Understanding the patterns of acclimation, mid-winter hardiness, and deacclimation is a prerequisite to developing strategies that reduce cold injury. Since 2004, we have been testing bud cold hardiness during dormancy of Chardonnay, Syrah, Chambourcin, Rkatsiteli that differ in rate and timing of acclimation and deacclimation, as well as mid-winter hardiness. During the 2013/14 and 2014/15 dormant seasons, we have done the first-ever characterization of the seasonal pattern changes for Aromella.

  Since fall of 2004 we have used a freezing protocol with a step-wide temperature drop in a programmable freezer, followed by bud dissection and visual inspection of oxidative browning (Caspari and Sterle, 2017). In the fall of 2016, and in collaboration with Dr Ioannis Minas and the Pomology Program at WCRC-OM and assistance from Dr Todd Einhorn at Oregon State University, we developed a new system to test cold hardiness using Differential Thermal Analysis (DTA) (Gerard and Schucany, 1997; Mills et al., 2006). Similar state-of-the-art systems are used by viticulture programs at Washington State University (Dr Keller lab), Ohio State University (Dr Dami lab), and Cornell University (Dr Martinson lab), amongst others. The main components of the DTA system consist of a new programmable freezer (Tenney, model TUJR-A-WF4, TPS Thermal Products Solutions, New Columbia, PA), Keithley data loggers (Model 2700 Integra Series, Keithley Instruments Inc., Cleveland, OH) with software, three plates of cells containing thermoelectric modules, and a dedicated computer for data capture. For a brief description of our system see Minas et al. (2017).

  With two systems we are now able to run simultaneous tests on the same varieties using different freezing protocols, or run the same protocols with a larger number of varieties.

  Cold hardiness test were initiated in mid-September. Since late October, tests have been conducted on an approximately weekly basis. Results were made available via our Webpage, and growers are able to use this information when deciding if freeze/frost protection is needed. In addition to the ~weekly tests on Chardonnay and Syrah the following varieties were tested at a less frequent interval: Albarino, Aromella, Cabernet Franc, Chambourcin, Marquette, Merlot, Souzao, and Traminette. While Chambourcin from the WCRC-RM site has been included in cold hardiness tests in previous years, these were the first data for Chambourcin, as well as Marquette and Traminette, growing in the Grand Valley.

- Advancing cold hardiness. (Caspari and Sterle)

  Cold injury to buds and trunks frequently occurs in late-fall prior to vine tissues reaching maximal cold hardiness. One approach to reduce this type of cold damage is to advance cold hardiness acclimation. Several recent studies have shown that a new plant growth regulator product containing 20% abscisic acid (ABA)[3] can advance cold acclimation. Initial trials by M.S. candidate Ms. Anne Kearney during the 2014/15 dormant season tended to confirm earlier bud cold acclimation in three-out-of-four tested varieties. However, the best timing for the ABA application differed between varieties. In the 2015/16 dormant season, four different ABA treatments were tested on three varieties. Not all treatments were applied to all varieties. Results once again suggested a potential advancement in fall acclimation but no effect on cold hardiness for the remainder of the dormant season.

  Based on the results from the previous two seasons a follow-up study was conducted in 2016 using mature Chardonnay and Syrah vines growing at WCRC-OM. A foliar application of ABA (500 ppm) was applied 20 days after veraison. Two controlled freezing tests – one in mid-November 2016 and one in early February 2017 – showed no treatment effect on cold hardiness of either Chardonnay or Syrah (data not shown).

3. *Alternatives to bilateral VSP to optimize yield and quality with different trellis/ training systems.*

- Training system and pruning method effects on grape yield and wine quality of Syrah. (Caspari, Menke, and Sterle)

  Vines with bilateral cordon, spur pruned, and trained into a Vertical Shoot Positioning (VSP) system are the standard in Colorado. Our research on bud survival, shoot density, and yield following cold events in 2009, 2013, and 2014 show a limited capacity of this system to overcome high levels of cold damage. From 2010 to 2012, we have demonstrated the advantages of simple adjustments to change the bilateral VSP to a quadrilateral system. As a result, many growers are now training to four cordons or canes. Other training/trellis systems (Pendelbogen, Sylvoz, Lyre, High Cordon, Low Cordon, and Geneva Double Curtain) have been tested since 2006 using own-rooted Syrah vines growing at the Orchard Mesa site.

  Yield and fruit maturity differs from the South to the North end of the Syrah block. Consequently, pre-harvest fruit samples are taken from three areas within the block, and these areas may be picked on separate dates, based on the fruit analysis results. In 2016, the entire block was harvested on 12 October. Yields ranged from 0.9 ton/acre with Pendelbogen to 2.9 ton/acre with Lyre (Table 9). Yields were almost linearly related to cluster number. Higher cluster number in itself is an outcome of a higher bud number left after pruning resulting in higher shoot numbers per vine on systems like the Lyre, GDC, and Sylvoz.

[3] ProTone, manufactured by Valent BioSciences.

Table 9: Effect of training/trellis system on yield and yield components of Syrah growing at the Western Colorado Research Center – Orchard Mesa near Grand Junction, CO.

Treatment	Clusters per vine	Yield (ton/acre)
Low Cordon	21.4	1.72
Vertical Shoot Positioning	17.1	1.27
Sylvoz	30.6	2.35
Pendelbogen	11.9	0.87
Lyre	32.7	2.85
Geneva Double Curtain	28.1	2.17

Since 15-20% of Colorado's vineyard area has recently been planted to cold-hardy resistant varieties – most of which having a "droopy" growth habit and are thus not suited for VSP trellising – this training/trellis system block will serve as an instructional resource for workshops on pruning and training of varieties with downward shoot growth habits.

4. Identifying areas suitable for expanded wine grape production

- Western Slope microclimates suitable for wine grape production. (Doesken, Goble, and Caspari)

The high elevation of Colorado's Western Slope in combination with frequent sunshine, low humidity, and diurnal temperature fluctuations offer unique growing conditions for some varieties of wine grapes. Unfortunately, only small areas are likely available with appropriate soils, available water, and microclimatic conditions that minimize the occurrence of damaging spring freezes and mid-winter extreme cold events. This project offers an initial approach to identify areas with medium- and high-potential for expanded grape production by examining climate trends to assess the likelihood of improved or reduced site potential.

Section 1 - Local expert interviews: As a part of a trip around southwest and south-central Colorado involving multiple projects, Nolan Doesken and Peter Goble traveled to Montezuma County, and interviewed local agricultural experts. The visit took place in the third week of October. These experts were Tom Hooten of the Colorado State University Montezuma County Extension Office, Jude and Addie Schuenmeyer of the Montezuma Orchard Restoration Project, and Bob Schuster, who is a local wine grape grower operating in McElmo Canyon. These interviews allowed us to catalog some of the struggles of local wine grape growers in recent years, and identify parts of the county where fruits that prefer similar climes have been grown in the past. Some highlights from these interviews include the following:

1. There are areas to the north of Cortez near Lebanon Road and Road T where apple orchards have been located in the past. Some orchard activity persists in this area.
2. Grape activity has also occurred in the area north of town as well. While this area is higher in elevation than Cortez, and temperatures on average cool with height, it still has the potential to sustain less hardy flora as the coolest air drains

into the valleys below at night. Bill Russell has grown grapes in this area of the county.

3. Bob Schuster claims that while large summer rainfall events are seen as a detriment to wine grape growth, his property in the McElmo Canyon is dry enough that summer rain events are typically welcome.

Section 2 - Thermometer deployment: Previous work suggests that the greatest limiting factor to potential wine grape growth in southwestern Colorado is cold temperature injury. Dormant season low temperatures on occasion are sufficiently cold for damaging wine grapes. On cold nights the large-scale airflow is often nearly calm, and the coldest, most dense air, drains to the lowest elevations. This can create stark temperature contrasts over horizontal spatial scales on the order of hundreds of meters. Late spring freezes, shortly prior to bud break or after shoots have emerged, are another serious threat to grape production in the area.

In the third week of December, 15 thermometers were installed at a total of six locations across Montezuma County. Locations of installation were primarily current vineyards, but included one property recently acquired by Guy Drew intended for a future vineyard.

Thermometers are battery-powered. They take a reading every five minutes, and have an advertised lifespan of 120 days when recording at five-minute intervals. Important details of installation are as follows:

- All thermometers were installed at cordon height (4ft above ground)
- All thermometers were the same make and model (Make: Measurement Computing. Model: USB-501-PRO)
- At each location where two or more thermometers were installed, at least one was installed at the high end of the property, and one at the low end
- At each location where three thermometers were installed, two were installed at the high end of the property. One thermometer of the two was sheltered by a PVC housing with air holes drilled for ventilation. These thermometers were installed in order to allow for accurate temperature readings in the event that exposed thermometers become snow or ice-covered.

Locations of thermometer installations are as follows (see Fig. 1 for additional details:

- Three thermometers were installed at:
    1. Vineyard Behind the Yucca House Monument (County Road 20.5)
    2. Bill Russel’s vineyard at 16473 Road 26
    3. Montezuma Orchard Restoration Project at 17312 County Rd G
    4. Bob Schuster’s vineyard at 6090 County Road G
- Two thermometers were installed at Guy Drew’s new property at 27244 Rd T
- One thermometer was installed at Jerry Fetterman’s grape plot near Yellow Jacket off of County Road 16.5

Primary analysis goals of thermometer installations were:

- To compare winter daily minimum temperatures to nearby Cooperative Observing Network and Colorado Agricultural Meteorological Network stations. Areas suitable for wine grape growth should remain warmer than surroundings on cold winter nights.

- To compare temperatures recorded at a high point on a growing property to temperatures recorded at a low point on a growing property, which will help to quantify the impact of cold air drainage on calm, cold nights.
- To compare temperatures recorded from sheltered thermometers to those recorded from neighboring unsheltered thermometers. The most obvious difference should be higher daytime temperatures for unsheltered thermometers, but large differences in readings overnight may indicate that unsheltered thermometers were snow or ice-covered.

Thermometers are currently installed at the same, or similar locations again to catalog which areas of Montezuma County are most likely to stay warmest during other harmful event types in FY 2018. These event types include the following:

1. Freezes after bud break
2. Summer heat waves
3. Intense cold waves in late fall

Section 3 – Dormant season thermometer data retrieval and findings. Thermometer data were retrieved from all sites on March 30 and 31, 2017. Data from the highest elevation open air thermometer located at each site were compared with local Cooperative Observing (COOP) Network and Colorado Agricultural Meteorological (CoAgMET) Network stations. Only one of the thermometers from each site was ultimately used in this study. This was done for a few reasons:

1. Unsheltered thermometers were a better reflection of the conditions a grape vine is actually experiencing.
2. Daytime temperatures were predictably much higher for unsheltered thermometers due to direct exposure to sunlight, but because this study looked at overnight lows, unsheltered thermometers were appropriate to analyze.
3. Of the properties tested, temperature differences between the high and low ends of the property were found to be negligible.
4. Sheltered thermometers stayed 1-2 F cooler at night, likely because their PVC housings were radiating away energy.

The target of this particular thermometer campaign was to find locations that stay warmest during the coldest events. Daily minimum temperature was recorded for the stations in Table 10 from December 21, 2016 to March 30, 2017. Station locations are mapped in Fig. 1.

Historic growing records indicate that the McElmo Creek Canyon and the hills to the north of Cortez may cater to grape growth better than the valley of Cortez. Findings from the winter of 2017 corroborate this hypothesis. Furthermore, sites all around the valley where Cortez is located stayed warmer on average on cold winter nights than Cortez itself (Fig. 2), suggesting that the valley is conducive to cold air drainage during wintertime cold snaps. Cortez 8SE, which is the highest station used in this study, stayed warmer than the Cortez Airport by an average of 7.7 F on the coldest winter nights. The elevation difference between these two stations is 2124 ft. Mancos is 730 ft higher than the city of Cortez, but also in a valley, and also prone to cold air drainage. Of all locations in this study, the Mancos CoAgMET station reported the coldest wintertime events followed by the Mancos COOP station.

Table 10: Metadata for all thermometer sites used in this study.

Name	Network	Latitude	Longitude	Elevation (ft)	Sensor Height (ft)
Cortez	COOP	37.344	-108.595	6167	6
Cortez Airport	COOP	37.307	-108.626	5910	6
Cortez 8SE	COOP	37.255	-108.507	8034	6
Mesa Verde	COOP	37.200	-108.489	7142	6
Mancos	COOP	37.335	-108.316	6897	6
Yellow Jacket	CoAgMET	37.530	-108.724	6900	6
Cortez	CoAgMET	37.225	-108.673	6015	6
Yucca House	CoAgMET	37.248	-108.687	5975	6
Mancos	CoAgMET	37.322	-108.338	6730	6
Dove Creek	CoAgMET	37.727	-108.954	6595	6
Towac	CoAgMET	37.189	-108.935	5319	6
MORP	Producer	37.330	-108.729	5695	4
Drew	Producer	37.447	-108.551	6811	4
Schuster	Producer	37.318	-108.928	5242	4
Fetterman	Producer	37.493	-108.748	6855	4
Russel	Producer	37.448	-108.576	6668	4
Yucca House	Producer	37.250	-108.691	5984	4

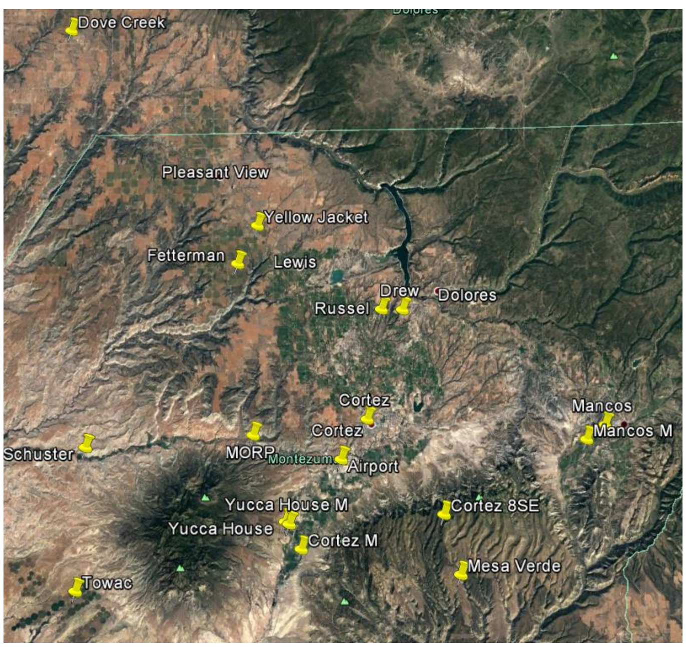


Fig. 1: Google Earth map of the Montezuma County area. The locations of all thermometers used are marked with a yellow pin. Names correspond to Table 10. If a pin has a capital "M" attached to it, that station is a CoAgMET station. This labeling convention was used to avoid duplicate names.

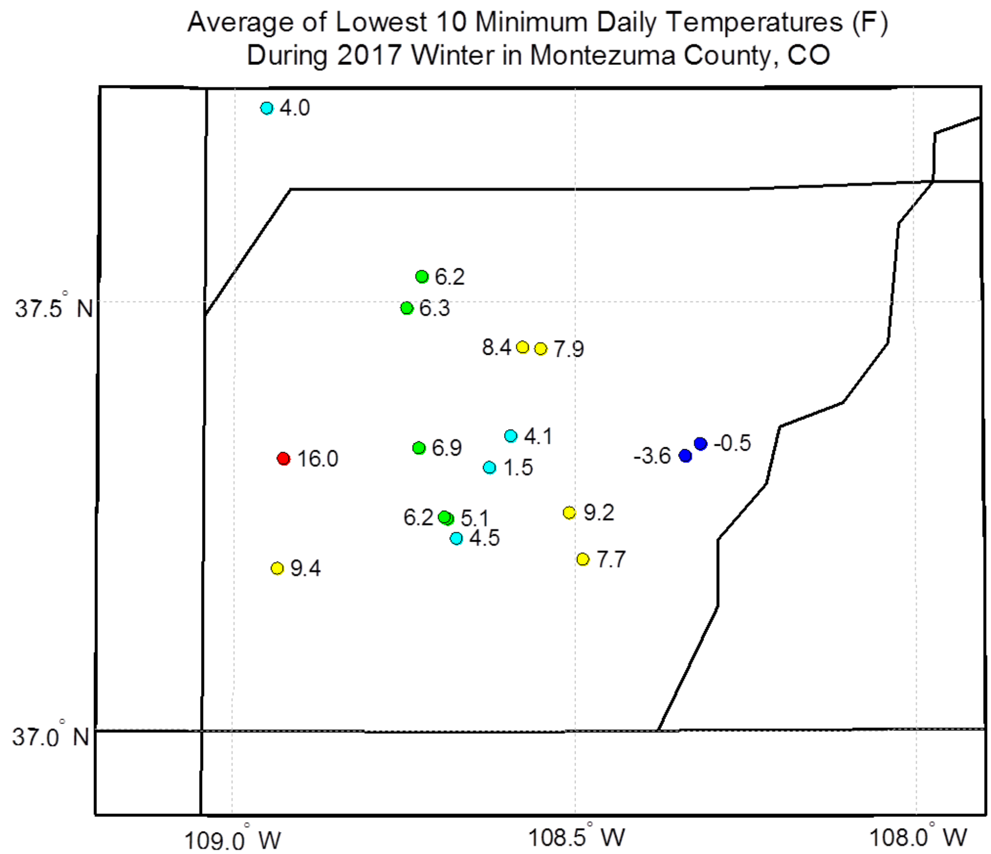


Fig. 2: Average minimum temperature of the 10 coldest days from December 21, 2016 to March 30, 2017 for 17 locations in SW Colorado. County and state boundaries are shown in black, the focal point being Montezuma County.

Despite what thermometer behavior immediately surrounding the city of Cortez would suggest, higher elevation did not guarantee warmer winter nights than lower elevation on a county-wide scale. At an elevation of 5242 ft, the Schuster property was the warmest property on average by 6.6 F. Here the average of the 10 lowest minimum daily temperatures for winter 2016-2017 was 16 F. This suggests that cold air must commonly drain away from the property on cold winter nights. The Towac reservation CoAgMET station was the second warmest station on average at 9.4 F. It is also the second lowest elevation station used in the study.

The coldest temperature of winter 2016-2017 for all stations used in this study occurred on the morning of January 27, 2017. It is likely not the case that all stations would synchronize so nicely every winter. The temperature differences across the county from this event were wide. The CoAgMET-operated Mancos station registered the coldest temperature of 17 degrees below zero (Fig. 3). This station also registered the coldest average from the winter's lowest ten temperature events. The Schuster property stayed the warmest at 10 F. This station registered the warmest ten event average. For this individual day, the average pattern for winter 2016-2017 cold events held nicely. The Cortez city and airport COOP stations were colder than their surroundings in all directions.

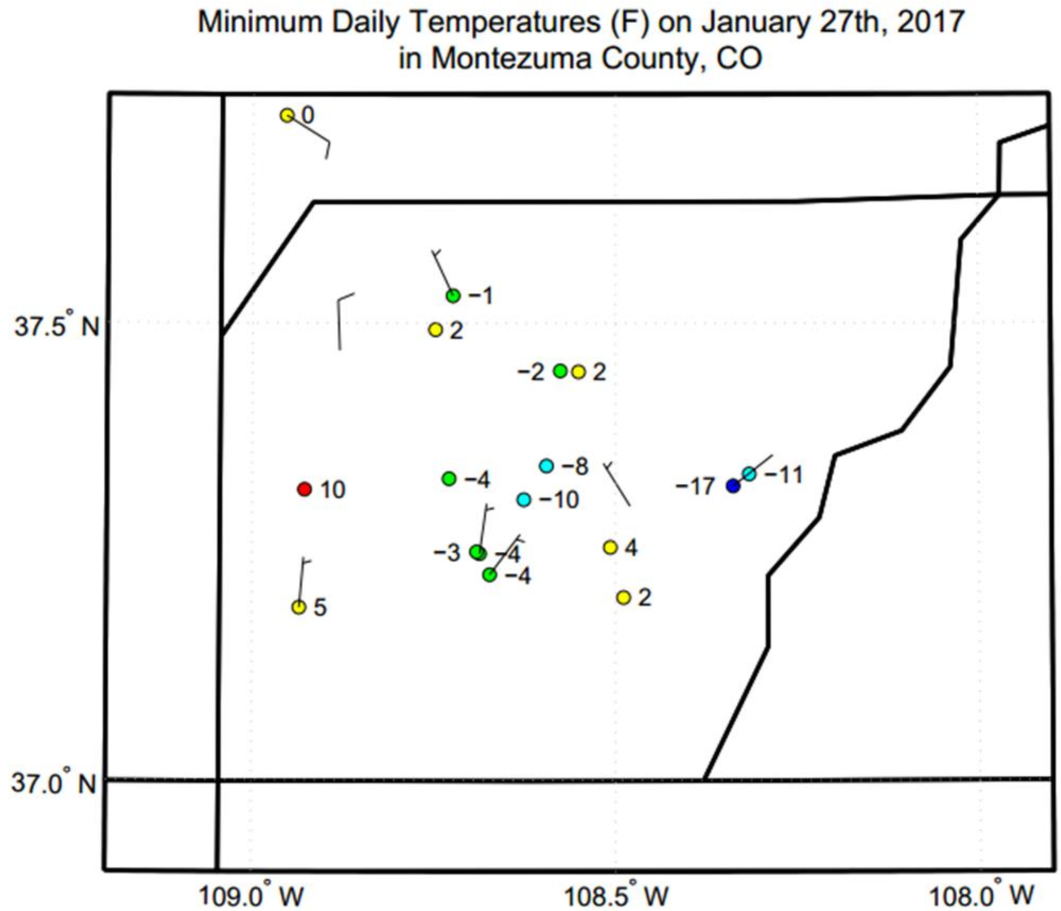


Fig. 3: Minimum temperature of 17 sites in SW Colorado on January 27, 2017. County and state boundaries are shown in black, the focal point being Montezuma County. The skinny, black lines attached to station locations are wind barbs, indicating average wind speed and direction of the hour of coldest temperature. The direction of the wind barb indicates the direction from which wind is coming. The side notches on each barb indicate its speed. No notch: 0-2.5 mph. Half notch: 2.5-7.5 mph. Full notch: 7.5-12.5 mph. Two wind barbs were included from the RAWS network. This network was not used to collect temperature measurements.

January 27, 2017 was a day of deep snow cover for Cortez. The COOP station in the city reported 7” of snow depth that morning. Two nearby Community Collaborative Rain, Hail, and Snow (CoCoRaHS) Network stations reported 8” and 9” of snow depth. This morning came on the heels of a persistent snowfall pattern. Cortez reported measurable snowfall every day between January 20 and 25 for a total of 18.1”. Snow-covered surfaces reflect sunlight during the day rather than absorbing it, and efficiently radiate away infrared energy, so it is no surprise that the coldest temperatures come with snow on the ground. Six of Cortez' ten coldest daily minimum temperatures occurred between January 22 and 29. All of these events were below 10 F. Wine grapes should be considered to be at higher risk during times of deep snow cover unless the vines are insulated by the snow.

From a large-scale perspective, the coldest air of winter 2016-2017 hit Montezuma County when a polar high pressure airmass was overhead (Figs. 4, 5). This airmass originated up in the Yukon. High pressure is a key ingredient in many winter cold events as high pressure causes calm surface winds. Lack of large-scale airflow can prevent air from mixing in the lower atmosphere. Mixing keeps nighttime temperatures warmer.

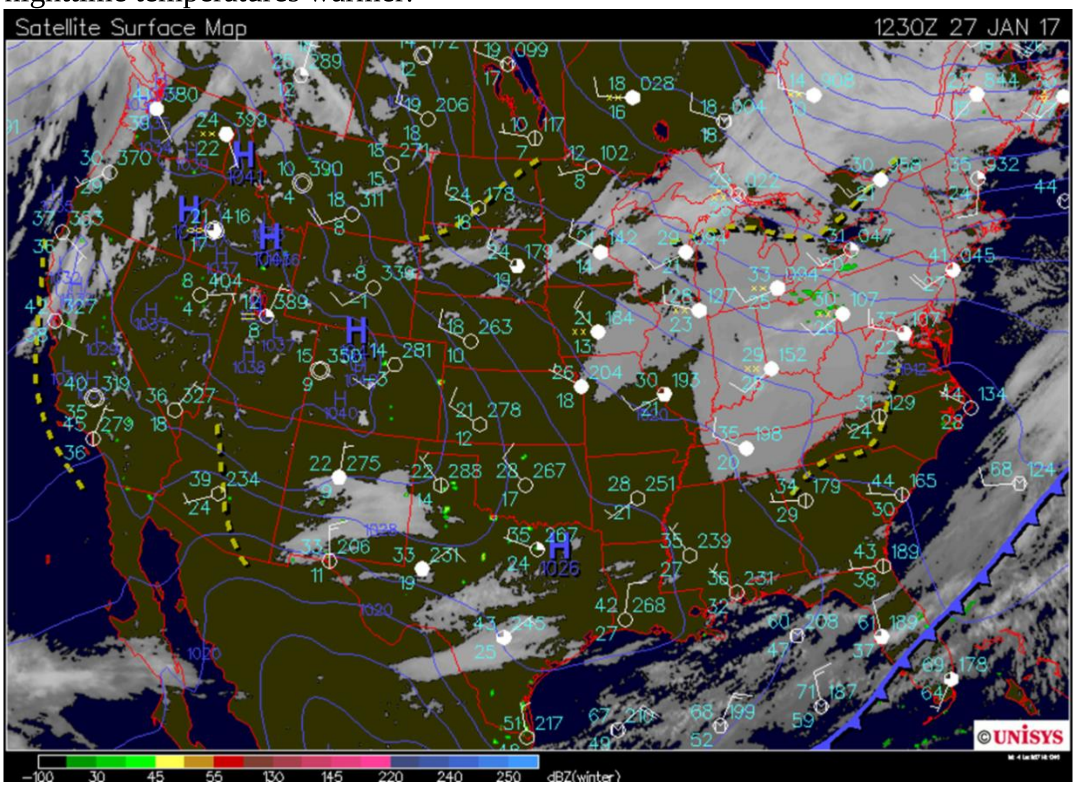


Fig. 4: Map of atmosphere pressure and wind analysis for the morning of January 27, 2017. An "H" marks an area of high pressure. An "L" marks an area of low pressure. The thick blue line with triangle-shaped attachments indicates a cold front. Each skinnier blue line indicates a line of constant pressure.

Daily low temperature maps and surface analyses were also produced using the stations in Table 10 for January 6 and 7, January 26 to 29, and March 2, 2017. These dates were chosen as they represent the coldest air outbreaks of winter 2017. Some of the key similarities between the days for which a surface analysis was conducted were: All days analyzed occurred with high atmospheric surface pressure according to Unisys satellite data; all days analyzed were directly following a snow event; for all days analyzed, a measurable snow depth was recorded by the Cortez Cooperative Observing Network station. Surface wind observations from CoAgMET and Remote Automated Weather Stations (RAWS) were generally consistent among days analyzed as well. Night time wind speeds were slow, and followed a drainage pattern. Air flowed from high elevations to low elevations, and then along valley bottoms and canyons. This is a typical pattern even on warm nights, but can be disrupted by storm activity. None of the coldest temperatures of winter 2016-2017 occurred under actively stormy conditions for Montezuma County, but if such an event were to occur, both the wind and temperature patterns outlined here would be significantly disrupted.

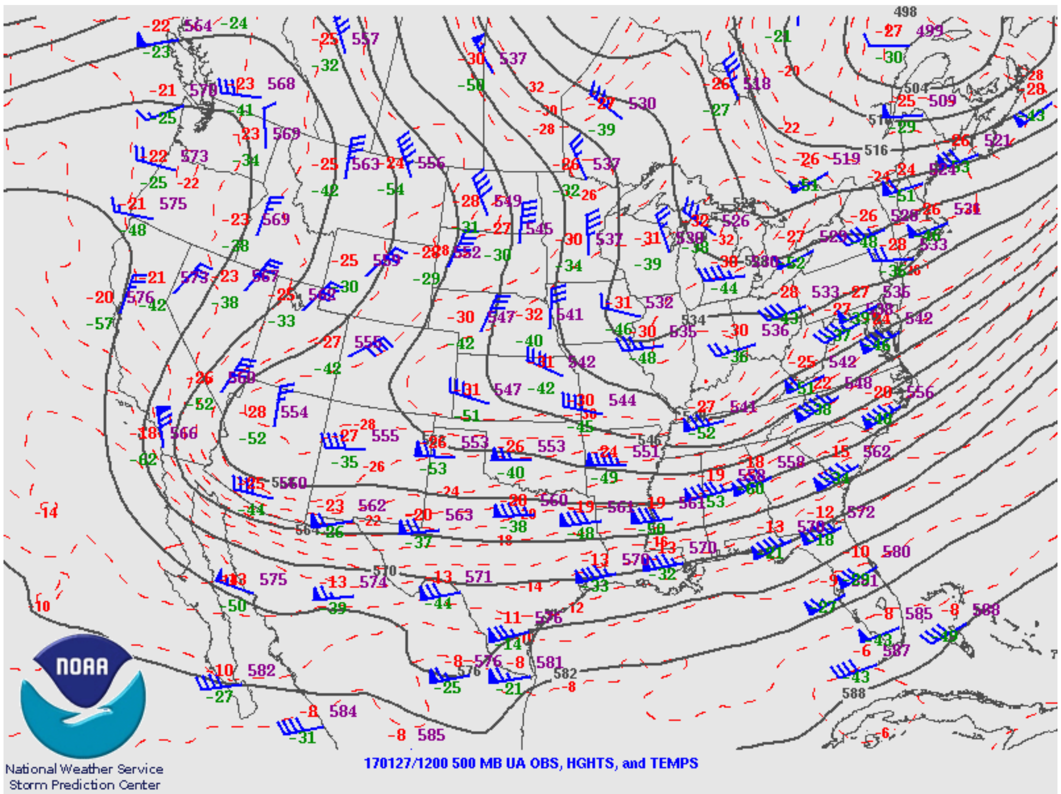


Fig. 5: Upper troposphere wind analysis for January 27, 2017. The map shows the height, temperature, and wind speed of the atmosphere at the 500 mb pressure level. The solid black lines indicate a line of constant height. The dashed red lines indicate a line of constant temperature. Each blue line is a wind barb. The stem of each wind barb indicates the direction from which the wind is blowing. The lines on the side of each barb give winds speed. ½ notch = 5 knots. 1 notch = 10 knots. 1 flag = 50 knots. (1 knot = 1.15 mph) Add the flags together to find the wind speed at each station.

Temperature patterns on each of these mornings showed similarities, but there were subtle differences. The Schuster property did not always record the warmest minimum temperature. On January 26, 2017, the warmest minimum daily temperature was recorded by the Montezuma Orchard Restoration Project property at 25 F. The next warmest was the Schuster property at 17 F. On January 28, the Schuster property tied with the Cortez 8SE station for the highest daily min at 14 F. Interestingly, this tie occurred between the highest and lowest elevation stations. On January 29, the warmest station was Cortez 8SE again. Every day analyzed showed the valley where Cortez sits reaching cooler temperatures than all surrounding directions. In most days the Cortez airport station was the coldest. This temperature pattern was least pronounced for March 2, 2017. On this day, the airport was warmer than the city station, warmer than the Drew property north of town, and nearly as warm as the grape growing property to the southwest.

Section 4 – Continued local long term trend analysis: In order to expand our understanding of where further growth will be possible in Montezuma County, CO it is important not only to gain an understanding of which parts of the county are most ideally situated for growth spatially (see section 3), but also to investigate the area's observed historic record of climate variability and change. In FY 2016's report (Caspari et al., 2016), this was done using the long-standing Cooperative Observing Network Station in the city of Cortez. Figure 6 is included as a reminder of these findings.

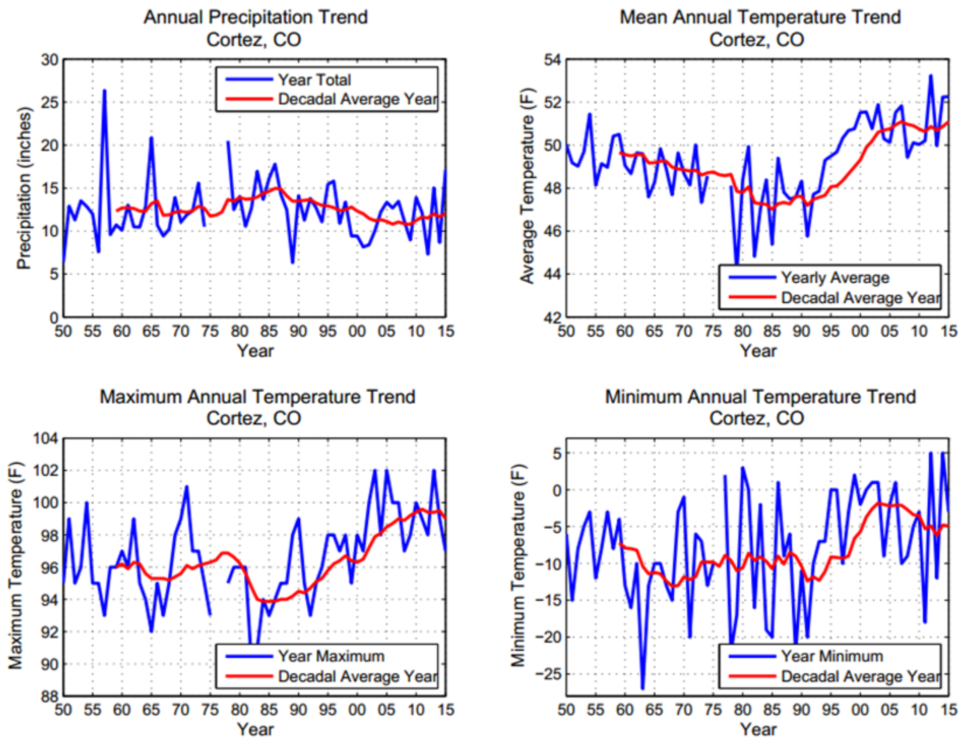


Fig. 6: Annual precipitation (top left), average temperature (top right), maximum temperature (bottom left), and minimum temperature (bottom right) for the Cortez Cooperative Observing Network Station. Blue lines show yearly values. Red lines show decadal averages. Data are plotted for 1951-2015.

A long term climate trend analysis was conducted based on observed temperature and precipitation records from Mesa Verde, CO. This station is southeast of potential grape growing locations. It was chosen because of its long data record. Daily observations used in this investigation span 1931-2016. Daily precipitation accumulation, average temperature, maximum temperature, and minimum temperature data were gathered for this station from the SC ACIS Climate Services Portal.

Yearly and seasonal precipitation accumulation, average temperature, maximum temperature, and minimum temperature were computed and plotted for each year in the period of record. Ten-year (decadal) average yearly and seasonal precipitation accumulation, average temperature, maximum temperature, and minimum temperature were computed and plotted for each 10-year period from 1931-1940 to 2007-2016. Seasons in this study are defined as follows: spring (March-May), summer (June-August), fall (September-November), and winter (December-February).

Decadal trends in yearly and seasonal precipitation accumulation, average temperature, maximum temperature, and minimum temperature were computed. Significance of trends was assessed using a Mann-Kendall test for monotonic increases or decreases. This analysis method is more sophisticated than a linear trend analysis. Because linearity is not assumed, the results are not easily thrown off by outlying data. Significance of trends was analyzed for 1931-2016, and for 1981-2016.

Two types of events that are potentially detrimental to wine grape growth had previously been identified: extreme cold early in the winter, and anomalous cold snaps in the late spring following the onset of the growing season. These events were searched for in the Mesa Verde data record. The problematic events were sorted into not two, but three types where early winter cold was categorized two separate ways: temperatures below 0 F that occurred prior to January 1, and early cold season-extreme minimum temperatures that are both below 10 F and at least 10 F below the season’s previous lowest temperature. Spring killing events were represented by temperatures below 28 F occurring after May 1. The number of years in which each of these three event types occurred/decade was recorded.

While the Mesa Verde Cooperative Observing Network station does have a longer period of record than the Cortez station, it has endured several changes over the years that have the potential to throw off trends. These changes included:

1. Aug 1930: station relocation
2. Sept 1941: station relocation
3. Nov 1959: station relocation
4. May 1982: observation time corrected to 0800
5. July 1985: station relocation
6. November 1988: new thermometers

Maximum summer temperatures appear to change significantly following the 1941 station move. This data discontinuity could be an artifact of the station move, or a reflection of the warm temperatures experienced by much of the United States during the 1930s. From these data alone, it is difficult to say.

Mean annual temperature for Mesa Verde has decreased significantly since the 1930s, but has increased significantly since the 1980s (Fig. 7). The dip in mean annual temperature of over 2 F from the 1950s to the 1980s is indeed consistent with what has been observed in the city of Cortez, and reported in FY 2016. For Mesa Verde, temperatures have since rebounded to 1950s levels. For Cortez, temperatures in recent years are warmer than the 1950s. Mesa Verde has warmed less over the past 30 years than the statewide average of 2 F (Lukas et al, 2014). Minimum annual temperatures are of special importance for wine grape growth. There are no significant trends in minimum winter annual temperatures for Mesa

Verde. Annual precipitation has decreased by 0.26"/decade since the 1930s, and 1.09"/decade since the 1980s. These trends are not significant with respect to the background interannual variability.

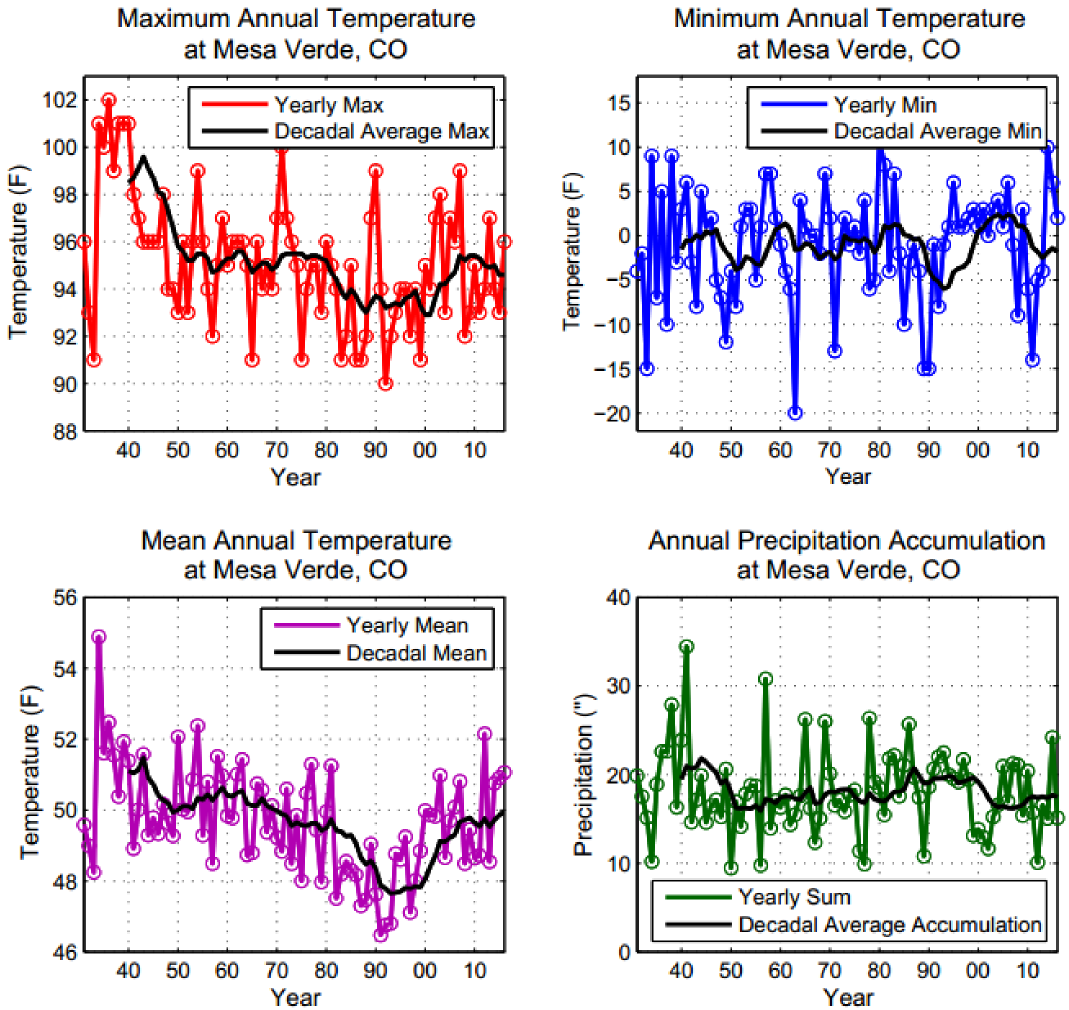


Fig. 7: Annual maximum temperature (top left), minimum temperature (top right), mean temperature (bottom left), and precipitation accumulation (bottom right) for the Mesa Verde Cooperative Observing Network Station. Colored lines show yearly values. Black lines show decadal averages. Data are plotted for 1931-2016.

Average winter temperatures at Mesa Verde have actually come down over the years, both since the 1930s and 1980s (Fig. 8). Minimum winter temperatures have varied from year-to-year, but held roughly steady on longer timescales. Maximum winter temperatures, however, have trended downwards with an odd level of consistency that is unlikely to be explained by any of the recorded station relocations or reinstrumentations. Winter precipitation has varied from under 2" to over 12", but the trends are insignificant.

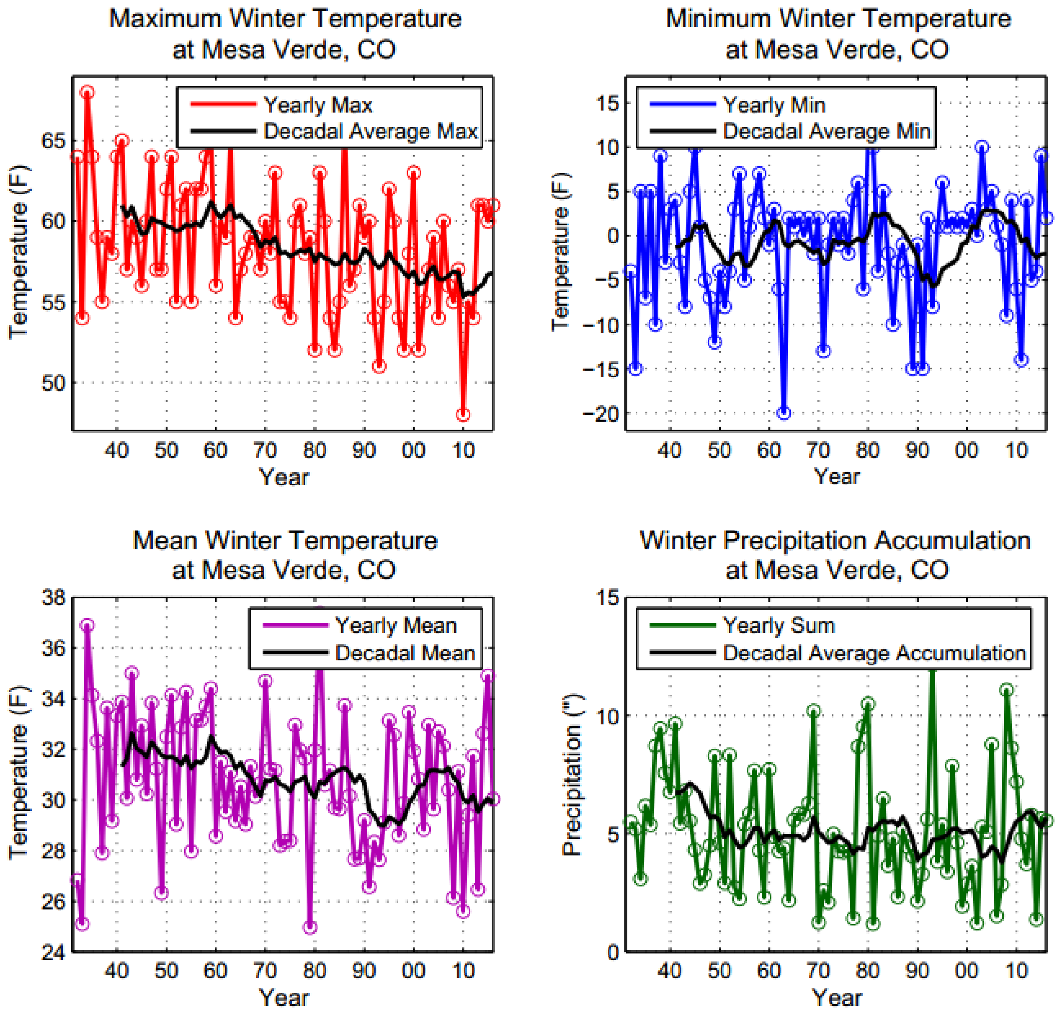


Fig. 8: Wintertime (December, January, February) maximum temperature (top left), minimum temperature (top right), mean temperature (bottom left), and precipitation accumulation (bottom right) for the Mesa Verde Cooperative Observing Network Station.. Colored lines show yearly values. Black lines show decadal averages. Data are plotted for 1931-2016.

Average spring temperatures went down markedly from 1930-1950, but have been steady long-term since with a dip in the 1980s and early 1990s (Fig. 9). Spring precipitation was also higher during these cooler years. Maximum spring temperatures decreased from the 1930s to the 1980s and have come back up since. Minimum spring temperature is trending up, 0.93 F/decade since the 1980s. For the period 1950-2016, spring temperature and precipitation patterns for Mesa Verde are very similar to what was shown for Cortez in last year's report, which lends confidence that these local variations are indeed real, and not an artifact of changing station location, equipment, or observers.

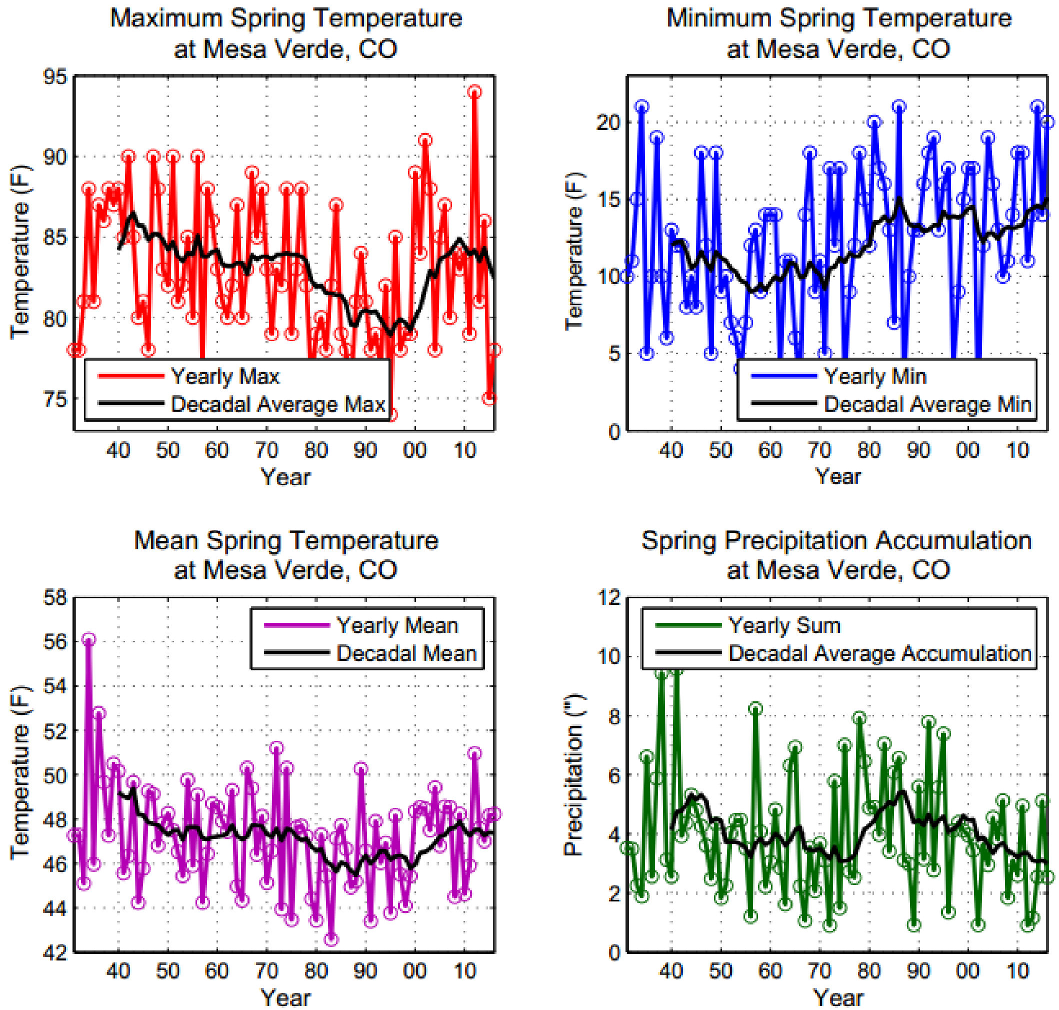


Fig. 9: Springtime (March, April, May) maximum temperature (top left), minimum temperature (top right), mean temperature (bottom left), and precipitation accumulation (bottom right) for the Mesa Verde Cooperative Observing Network Station.. Colored lines show yearly values. Black lines show decadal averages. Data are plotted for 1931-2016.

Average summer temperatures at Mesa Verde, CO have trended down by 0.2 F/decade since the 1930s (Fig. 10). The 30s were the warmest decade measured over summer in the period of record with an average temperature of 73.7 F. Again, it is possible the station move of 1941 had something to do with this. Summer temperature varied from year-to-year, but does not display any long-term trend behavior from the 1940s through the 1970s. Summer temperatures dropped again from the early 1980s to the mid-1990s by over 3 F, and rebounded thereafter. The Cortez Station also showed this trend. Maximum summer temperature at Mesa Verde has trended down by 0.5 F/decade since the 1930s. Most all of this cooling occurred between 1931 and 1950. Minimum summer temperatures display interannual and interdecadal variability, but are stable over longer measurable timescales. Summer precipitation is highly variable. It has been below one inch (1962), and above 9.5" (1969), but there is no long-term trend.

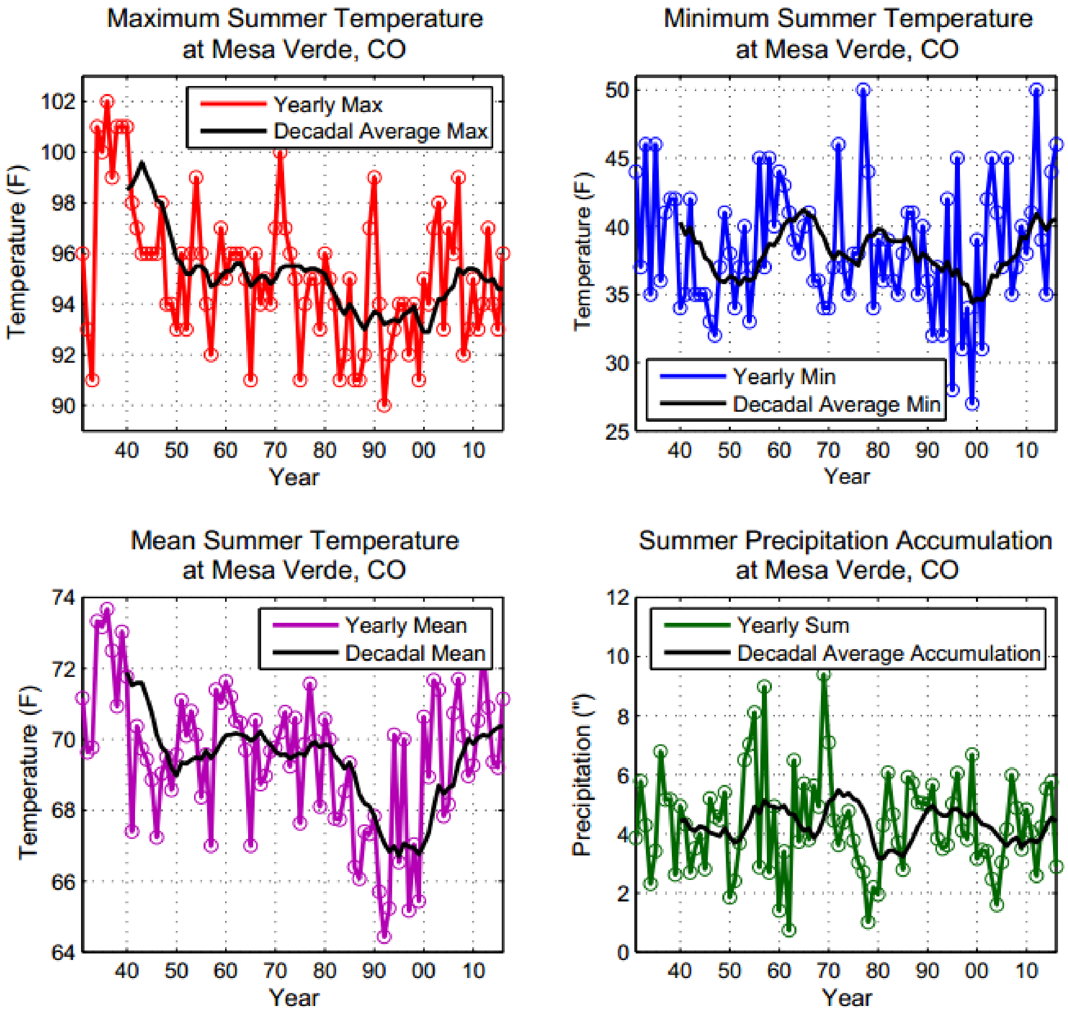


Fig. 10: Summertime (June, July, August) maximum temperature (top left), minimum temperature (top right), mean temperature (bottom left), and precipitation accumulation (bottom right) for the Mesa Verde Cooperative Observing Network Station.. Colored lines show yearly values. Black lines show decadal averages. Data are plotted for 1931-2016.

As shown in last year's report (Caspari et al., 2016), the Cortez COOP station showed significant warming during the fall from 1950s to present date. Fall trends at Mesa Verde have not been the same (Fig. 11). The rise in temperature of 0.84 F/decade from the 1980s to present date is significant at 99% confidence, but there is no trend in fall temperature from the 1930s to present date. Maximum fall temperatures are down 0.26 F/decade since the 1930s and 0.13 F/decade since the 1980s. These trends are opposite in sign from Cortez. Minimum fall temperature is mostly steady over time, but with large year-to-year variability. Minimum fall temperature has been as low as -3 F and as high as 26 F. Decadal average fall precipitation peaked in the early 1990s. There is no significant trend in precipitation over time.

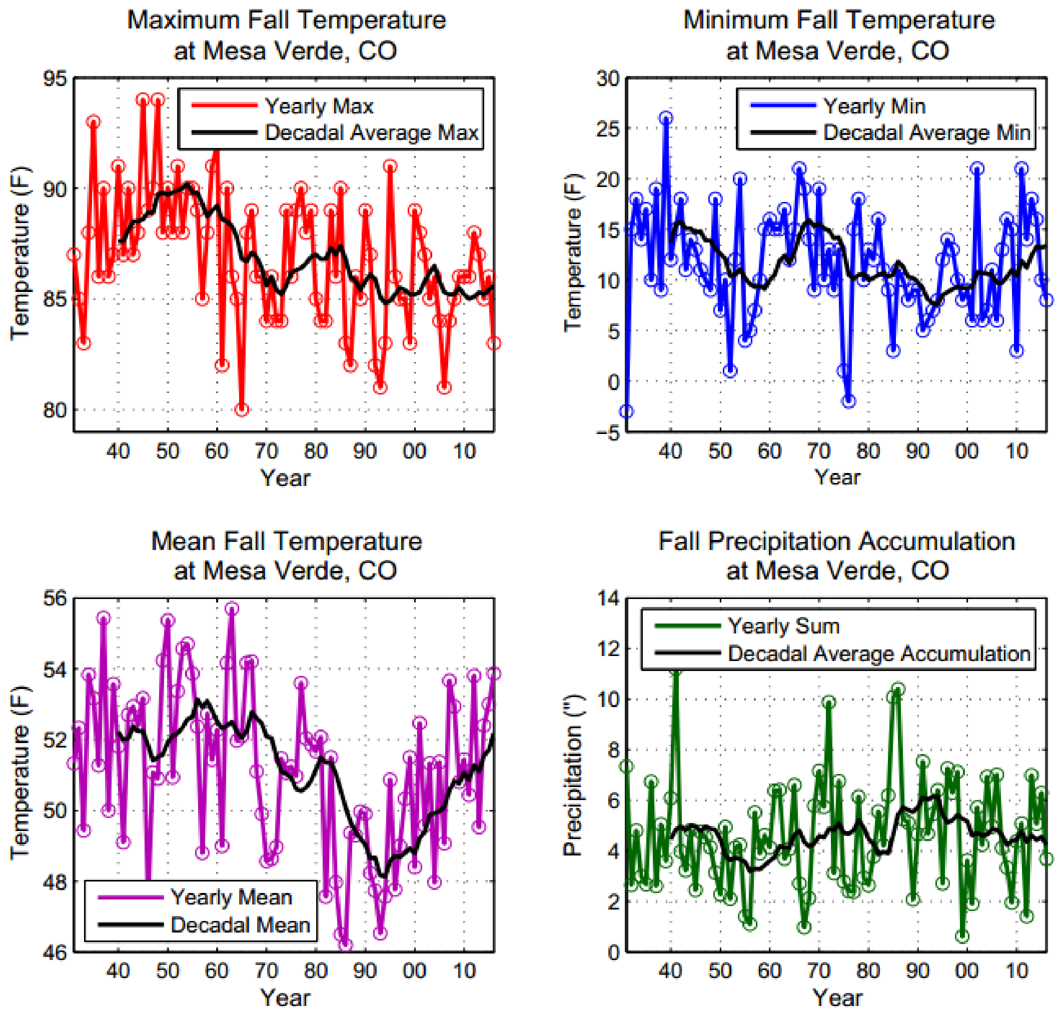


Fig. 11: Fall (September, October, November) maximum temperature (top left), minimum temperature (top right), mean temperature (bottom left), and precipitation accumulation (bottom right) for the Mesa Verde Cooperative Observing Network Station.. Colored lines show yearly values. Black lines show decadal averages. Data are plotted for 1931-2016.

The seasonal cycle in precipitation has not changed appreciably from the 1930s to present date (Fig. 12). August through October is the wet season. This is driven by the North American Monsoon. August averages 2.25” of precipitation. Through the winter season, 1.50-2.00” of precipitation is expected per month. The dry season is late spring through early summer. June is the driest month of the year. Mid-monsoon precipitation has been higher in recent years, but peak intensity of the monsoon has also been shorter lived.

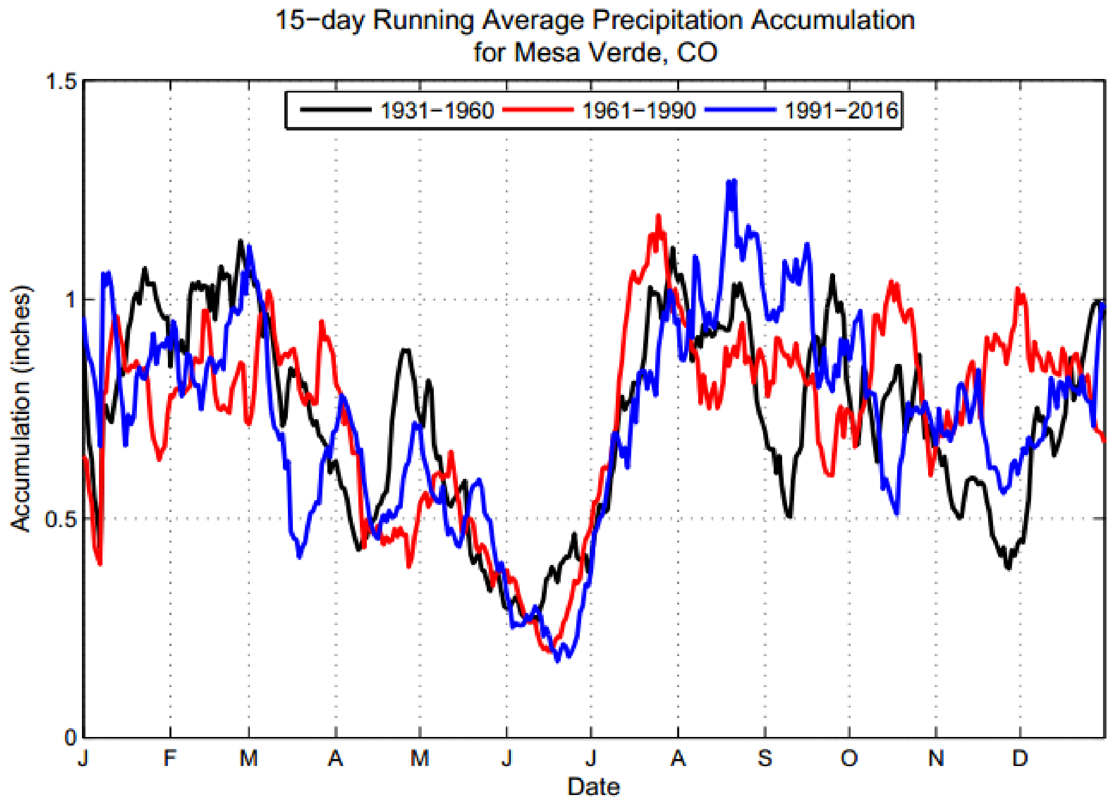


Fig. 12: Fifteen-day running average precipitation accumulations averaged over three separate periods for the Mesa Verde Cooperative Observing Network Station.. The running 15-day average precipitation accumulations are shown in black for years 1931-1960, red for 1961-1990, and blue for 1991-2016.

The warm temperatures of the 1930s have a marked impact on the observed long-term trends from 1931-2016. Average temperature at Mesa Verde has fallen significantly in every season other than fall (Table 11). The trends are significant at 95% confidence for winter and spring, and 99% confidence for summer. Maximum annual temperatures have decreased with 99% confidence for all seasons including fall. Minimum annual temperatures have been nearly steady. Winter, which is the most important season for inspecting minimum temperature trends, shows a drop in minimum temperature of 0.09 F/decade. Annual precipitation has not changed significantly, though it is down slightly for winter and spring.

The sign of temperature trends since the 1980s is opposite the trends since the 1930s (Table 12). In recent years, the Mesa Verde COOP station has recorded significant warming. Trends in annual average temperatures, summer average temperature, and fall average temperature are significantly upwards at 99% confidence. There is greater than 95% confidence that increases in spring temperatures are not random. Winter has actually cooled at a rate of 0.42 F/decade since the 80s, but the trend is not significant. Maximum temperatures have not changed significantly since the 1980s. Summer and fall minimum temperature are up significantly. Unfortunately, winter and spring minimum temperatures are more likely to have adverse impacts on grape yield, and these trends are not significant. Winter minimum temperatures are actually down 0.87 F/decade since the 1980s.

Precipitation accumulations are down slightly since the 1980s, but the 1980s were the wettest decade on record, and these decreases are not statistically significant.

Table 11: Trends in average annual temperature, maximum annual temperature, minimum annual temperature, and precipitation for 1931-2016 for the Mesa Verde Cooperative Observing Network Station.. If the trend is positive, and statistically significant, it is highlighted in red to represent 99% confidence in the trend direction. If the trend is negative, and statistically significant, it is highlighted in purple (blue) to represent 99% (95%) confidence in the trend direction.

	Average Temperature	Maximum Temperature	Minimum Temperature	Total Precipitation
Annual	-0.15	-0.51	-0.04	-0.26
Winter	-0.19	-0.55	-0.09	-0.14
Spring	-0.24	-0.23	0.40	-0.15
Summer	-0.20	-0.51	0.03	0
Fall	0	-0.26	-0.04	-0.03

Table 12: Trends in average annual temperature, maximum annual temperature, minimum annual temperature, and precipitation for 1981-2016 for the Mesa Verde Cooperative Observing Network Station.. If the trend is positive, and statistically significant, it is highlighted in red (orange) to represent 99% (95%) confidence in the trend direction.

	Average Temperature	Maximum Temperature	Minimum Temperature	Total Precipitation
Annual	0.43	0.43	-0.43	-1.09
Winter	-0.42	-0.23	-0.87	-0.02
Spring	0.56	0.93	0.30	-0.81
Summer	0.64	0.43	0.73	0.20
Fall	0.84	-0.13	0.70	-0.50

None of the three identified dangerous cold weather scenarios appear to be decreasing with any certainty. The first seven years of the 2010s have actually been anomalously harsh for wine grape growth based on the dangerous event categories listed in Table 13. Three years were identified in which the minimum temperature has gone below 28 F after May 1 (type 1), the temperature has dropped below 0 F before January 1 in two years (type 2), and there have been four years where the temperature has dipped below 10 F in combination with dipping over 10 degrees lower than any previous day in the late fall or early winter (type 3). The average number of occurrences/decade of each of these scenarios historically is 3.3, 1.1, and 0.8 respectively. All three event types occurred with lower frequency than the long-term average in the 2000s, but all three types are out–pacing the long-term average since 2010. Scenario three, “years with a new most extreme minimum > 10 F cooler than the previous extreme minimum, and below 10 F,” can be thought of as hazardous because grape vines are more abruptly exposed to extreme cold. The frequency of years in which vines are "startled" in to winter mode, so to speak, has been anomalously high in the most recent decade.

Table 13: The number of years/decade when three different types of events that are potentially dangerous to wine grape growth occurred.

	Temperature below 28 F after May 1	Temperature below 0 F Before January 1	New most extreme minimum > 10 F cooler than the previous extreme minimum, and < 10 F
1930s	2	1	0
1940s	2	0	0
1950s	4	1	2
1960s	4	2	1
1970s	5	2	1
1980s	3	0	0
1990s	5	2	1
2000s	2	0	1
2010s*	3	2	4

* indicates incomplete data record

Section 5 – Projected trends: While long-term temperature trends at Mesa Verde are somewhat out of alignment with long-term temperature trends for the globe as a whole, the area should be thought of as likely to warm. This assertion is not based on the local observed temperature records, but on the fundamental physics involved in adding greenhouse gasses to the atmosphere. Data from the Coupled Model Intercomparison Project (Taylor et al., 2012), which is run by the Intergovernmental Panel on Climate Change (IPCC), shows that Montezuma County is likely to warm significantly in coming decades (Fig. 13). The amount of warming will depend in part on how humans choose to alter their greenhouse gas emissions. The direst of projections, in which no action is taken, produce a model mean of 9 F warming in the winter, and 14 F warming in the summer. This would allow much less hardy plants to grow in Montezuma County, but only if there was a concomitant increase in the minimum winter temperature as well as a decrease in the frequency of extreme temperature drops in late fall and early winter (type 3 events), and a reduction in spring freeze events. Such warming trend would also have significant and unresolved implications on irrigation demand, and water availability.

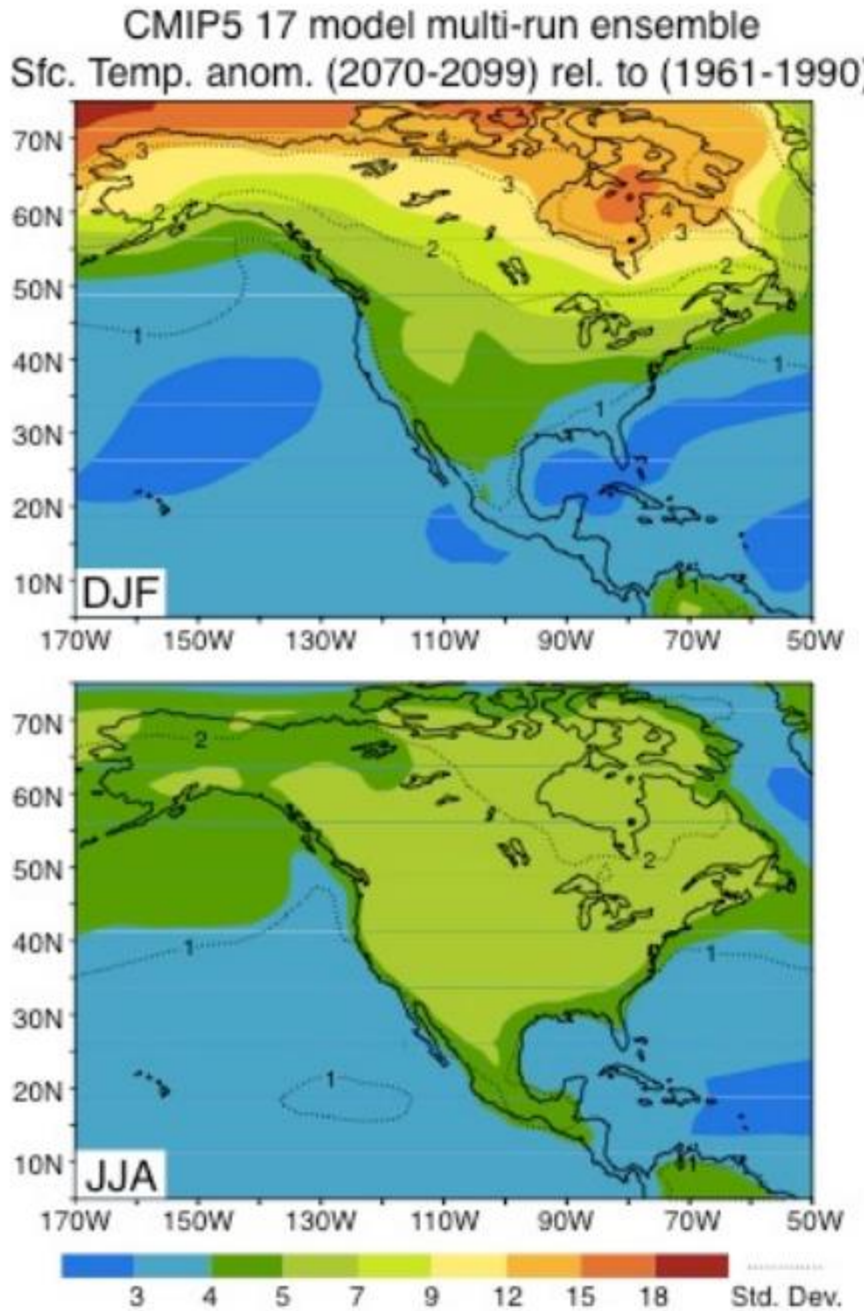


Fig. 13: Multi-model projected warming in North America by the end of the 21st century. Colored lines give the mean projected warming, and dashed lines give the standard deviation. The top panel shows projections for winter (December-February), and the bottom panel shows projections for summer (June-August). This figure is courtesy of the IPCC 2013 report. Temperature values are in Celsius.

Warming rates over the arctic and northern Canada are greater than global average warming rates (Fig. 13), and have been shown to lead to higher yearly minimum temperatures in the lower 48.

Section 6 – Summary: This study provides evidence that nocturnal winter air temperatures stay warmer on the hillsides to the north of Cortez and locations in McElmo Canyon on the coldest of nights than they do in the city of Cortez. The warmest area, and therefore likely the least vulnerable to freeze damage, was the Schuster property. This property did not receive any low temperatures below 10 F in winter 2016-2017. This property is roughly 17 miles from the canyon entrance. Using the Cortez Municipal Airport as a reference, it appears that wintertime low temperatures get warmer from east to west in McElmo Canyon. More data points would help draw more clear conclusions.

The hills north of Cortez near Road T between Lebanon Road and Highway 145 may also serve as a potential location for expansion of grape growth. This was an area identified by local growers as a successful former fruit basket. The two participating producers with land here did record higher wintertime low temperatures for the average of the ten coldest winter days than the town of Cortez to the south, and the nearby Colorado State Agricultural Experiment Station to the northwest. 2016-2017 winter minimum temperature was higher in this area than Cortez, the valley to the south of Cortez, and the Montezuma Orchard Restoration property near the mouth of McElmo Canyon.

Determining which areas will become suitable for grape growth in the future is less clear. Records from both the Cortez and Mesa Verde Cooperative Observing Network stations indicate that the area has warmed significantly since the 1980s. Temperatures at Cortez, as shown in the FY 2016 report, are higher than temperatures in any previous decade. This record goes back to the 1950s. The Mesa Verde station has been reporting since the late 1920s. This station shows annual temperatures were warmer in the 1930s than present levels by 1-2 F. Minimum winter temperature trends are not significant for the long-term Cortez or Mesa Verde COOP stations. Extreme cold in winter, and early frosts have not gone away. It appeared that these harmful events were on the decline in the previous decade, but the trend did not continue in the 2010s despite additional warming.

Projections indicate warming is highly likely in future decades. Using future climate projections to plan future grape growth activities is difficult since projections are dependent on human decisions, and since climate models run at too coarse a resolution to capture the spatial pattern of warming in full detail. Given that cold damage is the limiting factor for grape growth, more potential growing locations are likely to emerge adjacent to currently successful plots in McElmo Canyon and north of Cortez.

II. Development of Integrated Wine Grape Production

1. Sustainable resource use

An Integrated Vineyard Production System requires a sustainable use of all resources, including soil, water, and air. The projects listed below are the continuation of our long-term program.

- Water use by young grapevines. (Caspari and Sterle)

  There is a lack of understanding of the water needs for grapevines in the Colorado climate. Irrigation inputs vary widely from too little to grossly excessive watering. An understanding of grapevine water use is needed to develop sound irrigation practices. In addition, irrigation management can influence both grapevine growth and fruit quality. In previous studies using the heat-pulse technique, we determined peak daily water use to be ~8 L per day for mature grapevines trained to VSP and spaced 5’ in the row. However, no data are available on vine water use of newly-planted vines throughout the first growing season.

In 2016, we planned to continue a study initiated in 2015 on water use of young vines using potted vines to determine water use by a mass balance approach. However, high salt concentration in an aged compost used to make a 50:50 soil/compost blend caused half the potted vines to die shortly after planting in spring 2016. The remaining vines had poor growth and the experiment was terminated. The experiment is now being repeated in 2017.

Water use of four young potted Chambourcin vines was determined by a mass balance approach. During May and June of 2017, vines were watered once per week until water drained freely from the pots, pot weights were determined when drainage had ceased, and weights determined again prior to the next irrigation. Shortly after bud break, shoot number was reduced to 2 shoots per vine. Shoots were trained upwards supported by bamboo inserted to the pots. Shoot lengths and leaf numbers were determined weekly so that water use could be related to canopy development. All laterals were removed as soon as they emerged. Severe winds on 12 June, 2017 caused some leaf loss and leaf damage, as well as shoot breakage. Broken shoots resumed growth within two weeks from prompt buds. Photos 1 and 2 show one of the vines on 5 and 23 June, 2017, respectively.

Photo 1 (left): Appearance of potted Chambourcin vine on 5 June, 2017. Mean shoot length approximately 0.8 m.

Photo 2 (right): Appearance of potted Chambourcin vine on 23 June, 2017. Shoot on the left was broken by excessive wind on 12 June, 2017. Mean shoot length approximately 1.2 m. Note the broken shoot on the left and tattered leaves.

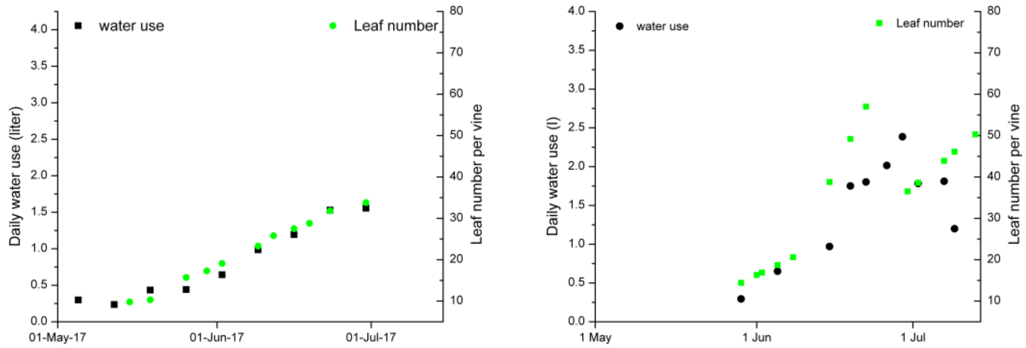


Fig. 14: Leaf number and water use of potted Chambourcin (left) and Noiret (right) vines growing at the Western Colorado Research Center – Orchard Mesa during the 2017 and 2015 season, respectively.

Similar to the results from the 2015 season with Noiret, early season water use of Chambourcin vines in 2017 was linearly related to leaf area (Fig. 14). A direct comparison between the two years shows that vine water use was slightly higher until mid-June in 2017 than in 2015, but lower afterwards. The slightly higher water use early in the 2017 season is due to an earlier bud break and thus higher leaf number until about mid-June (Fig. 15), and also a slightly higher evaporative demand (data not shown). After mid-June, leaf number (area) and water use were higher in 2015 as lateral leaves of Noiret did not get removed in 2015 until 30 June, whereas in 2017 laterals of Chambourcin were removed as soon as they emerged. As mentioned in last year's report (Caspari et al., 2016), approximately 35 % of the leaves of Noiret were on lateral shoots and the main leaf number declined to 37 leaves per vine when laterals were removed on 30 June, 2015. Lateral leaf removal resulted in a significant drop in vine water use (Fig. 14, right). In 2017, the average number of leaves on Chambourcin was 34 on 30 June. It should be noted that leaf area development of Chambourcin has been slowed due to the leaf and shoot damage from the severe winds on 12 June, 2017. Nonetheless, overall the two sets of data show very good agreement during the early part of the season.

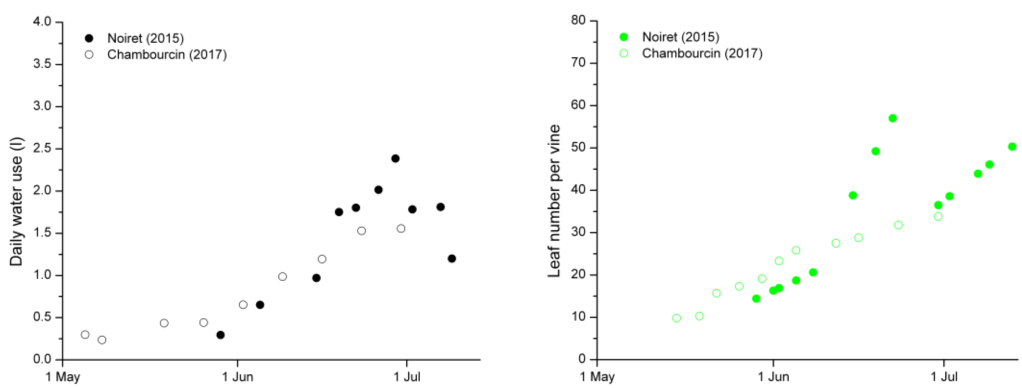


Fig. 15: Water use (left) and leaf number (right) of potted Chambourcin and Noiret vines growing at the Western Colorado Research Center – Orchard Mesa during the 2017 and 2015 season, respectively.

- Vineyard floor management - soil health, fertility, and water requirements (Caspari, Sterle, Schipanski, and Stromberger)

  Approximately 40% of the vineyards in Colorado are drip irrigated. While drip and sub-surface drip irrigation are the most water efficient methods of irrigation, the question arises how to manage the inter-row area. Precipitation in Colorado's semi-arid climate is generally insufficient to maintain a green cover crop. Many older vineyards were set up with drought tolerant grasses sown in the inter-row area, but over the years those grasses have died out and been replaced by weeds. Some growers opt to clean-cultivate the inter-row, others maintain bare soil through the use of herbicides or mow the resident vegetation. Bare soil or minimal vegetation cover in the inter-row is likely to degrade soil quality that potentially has negative impacts on vine performance. Results from the variety trial at Rogers Mesa (see Viticulture Webpage) show a very strong effect of soil condition and irrigation system on yield and fruit quality[4].

  To further investigate the effects of different soil and irrigation management on long-term vineyard productivity and vine and soil fertility, an experiment was initiated in the fall of 2013 in the Chardonnay block at the Orchard Mesa site that was planted in 1992. These vines have been drip irrigated since planting, with initially a crested wheatgrass cover crop planted in the inter-row area. Over time the grass has been replaced by weeds and/or bare soil. Vine vigor is low in many areas of the block - a situation not uncommon in older commercial vineyards. After the 2013 harvest, the irrigation system was changed from drip to sprinkler, and four replicated cover crop treatments established: two different grass-only cover crops; one grass-legume mix; and one legume mix. During the 2014 growing season the vineyard was sprinkler irrigated to optimize the establishment of the cover crops. In spring 2015 one of the grass-only treatments ("Hycrest" crested wheatgrass) was returned to drip irrigation (the "standard" situation since planting in 1992).

  In 2016, cover crops were kept short by mowing in early spring to reduce the risk of damage from late spring frosts. After the risk of frost had passed, the cover crops were allowed to grow tall. Cover crops were mowed four times during the remainder of the season, and each time fresh and dry weight of the cover crop biomass was determined. Seasonal cover crop biomass production was two to four times higher in the sprinkler-irrigated plots than in the drip-irrigated crested wheatgrass plots (Fig. 16; Photo 3, 4).

  Soil samples for microbial analysis were taken in May, June, July, August, and October from both the inter-row areas and immediately under the vines. Samples were kept refrigerated overnight and then send to a commercial laboratory (Ward Laboratories Inc., Kearney, NE) for a soil microbial community analysis using Phospholipid Fatty Acid Analysis (PLFA). Resin strips were placed in the inter-row areas and in the vine row five times during the season, each time keeping them in place for approximately one month.

[4] Sprinkler-irrigated vines with a grass cover crop growing in the inter-row area have produced on average 2.8 times more yield than drip irrigated vines with a bare soil inter-row area. Fruit maturity was almost always enhanced (berries higher in soluble solids and pH, and lower in titratable acidity) under drip irrigation and bare soil. An analysis of data from the 2012 grape grower survey also suggests higher yields with furrow or sprinkler irrigation versus drip irrigation.

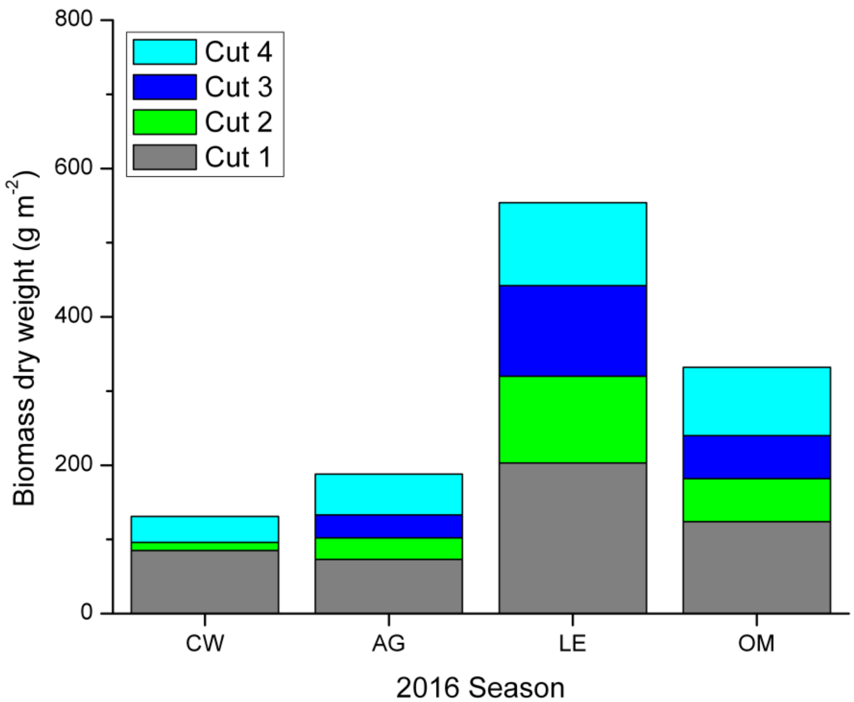


Fig. 16: Seasonal biomass production of cover crops in a Chardonnay vineyard at the Western Colorado Research Center – Orchard Mesa. Note that the CW was mowed only three times due to lack of regrowth in the middle of summer (see Photo 1).

CW, AG, LE, OM: crested wheatgrass, Aurora Gold hard fescue, legume mix, and orchard mix, respectively. Vines in the CW plots are drip irrigated, vines in AG, LE, and OM are irrigated by micro-sprinklers.

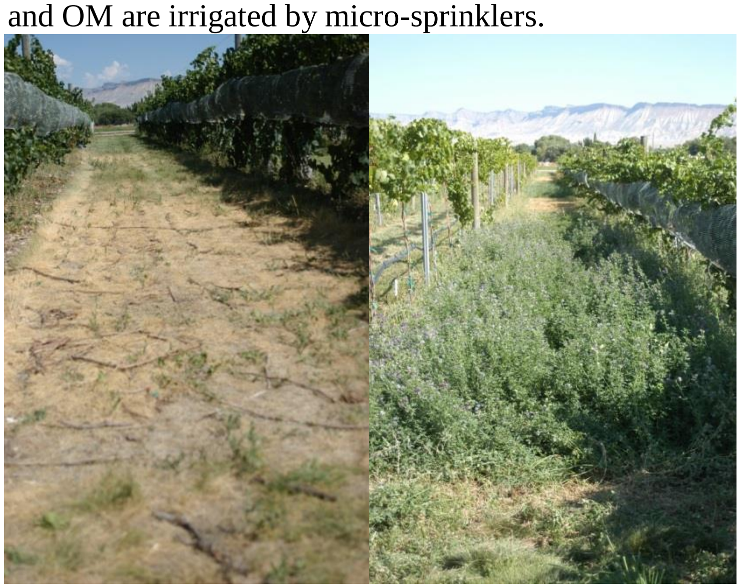


Photo 3 (left): A crested wheatgrass plot on 24 August, 2016.
Photo 4 (right): A legume mix plot right before mowing on 24 August, 2016.

Regardless of cover crop species or sampling date, cover cropped soils from the alleys had significantly greater biomass of arbuscular mycorrhizal (AM) fungi than soils from the vine rows. The average concentration of the PLFA biomarker for AM fungi, 16:1ω5c, was 99 nmol g^{-1} soil in the alley, compared to 85 nmol g^{-1} soil in the vine row.

The ratio of monounsaturated:polyunsaturated PLFAs varied significantly over the growing season, regardless of cover crop presence or species. The ratio was significantly lower in June than in May, July, and October (Fig. 17). The ratio of monounsaturated:polyunsaturated fatty acids can be interpreted as an indicator of microbial community stress. A higher ratio indicates less stress, while a lower ratio (as occurred in June) would depict higher levels of prolonged stress due to conditions related to soil temperature, moisture, pH, or nutrient availability (starvation).

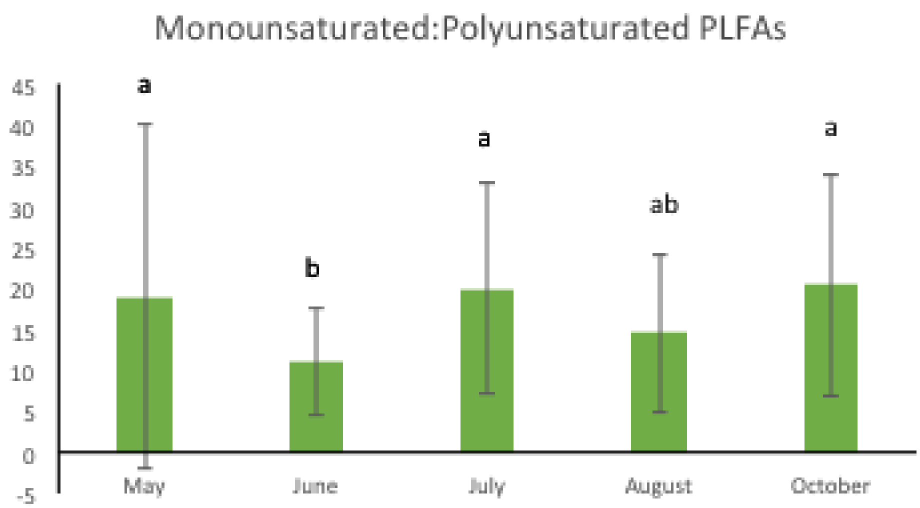


Fig 17: The ratio of monounsaturated:polyunsaturated PLFAs in soils collected from vine rows and alleys planted to cover crops during the 2016 growing season. Error bars represent ± 1 standard deviation (n=32). Bars labeled with different letters are significantly different ($P<0.05$).

Total microbial biomass and biomass of Gram-positive bacteria, Gram-negative bacteria, and protozoa were significantly affected by the two-way interaction of cover crop presence (alley vs. vine row) and sampling date. Also affected were the ratio of fungal:bacterial biomass, Gram-positive:Gram-negative bacterial biomass, and the ratio of saturated:unsaturated PLFAs. Regardless of the cover crop species planted, biomass values and the ratio of fungal:bacterial biomass were greater in cover-cropped soil from alleys compared to soil within the vine rows in July, 2016 (Table 14). The ratio of Gram-positive:Gram-negative bacterial biomass was significantly lower in alley soil compared to soil from the vine row, indicating that growth of Gram-negative bacteria was stimulated to a greater degree than growth of Gram-positive bacteria in alley soils planted to cover crops.

Communities under stressed conditions will increase their proportion of unsaturated fatty acids. This will likely occur most often as a result of low soil moisture or large fluctuations in soil temperature. In general, a lower value of saturated:unsaturated PLFAs (as occurred in alley soil compared to vine row soil in July) indicates a community undergoing some type of environmental stress.

Table 14: Mean biomass concentrations (± 1 standard deviation; nmol PLFA g^{-1} soil) and ratios of microbial groups in soil collected from alleys or vine rows in July, 2016. Values are averaged across cover crop treatments (n=16). Means labeled with different letters are significantly different (P<0.05).

	Alley	Vine
	-------------- nmol PLFA g^{-1} soil	---------------
Total microbial biomass	3,500 (1,270) a	2,260 (743) b
Gram-positive bacteria	964 (380) a	676 (277) b
Gram-negative bacteria	724 (270) a	367 (142) b
Protozoa	27.8 (21.7) a	12.6 (17.6) b
Fungi:Bacteria	0.22 (0.09) a	0.18 (0.09) b
Gram-positive:Gram-negative bacteria	1.36 (0.32) a	1.94 (0.85) b
Saturated:Unsaturated PLFAs	1.74 (0.35) a	2.56 (0.94) b

Biomass of total bacteria, actinomycetes, total fungi, and saprophytic fungi were significantly affected by the three-way interaction of cover crop treatment, sampling location, and sampling date. Specifically, biomass values in July 2016 were significantly greater in alley soil compared to vine row soil when the cover crop species were the orchard mix (for total bacteria total fungi, and saprophytic fungi) or alfalfa (for actinomycetes) (Fig. 18).

Vineyard alleys planted to cover crops, regardless of the cover crop species, supported a greater abundance of AM fungi throughout the vine growing season. In addition, cover cropped alleys promoted greater microbial biomass, biomass of Gram-positive and Gram-negative bacteria, protozoan biomass, and a greater ratio of fungal:bacterial biomass in July. Furthermore, orchard mix and legume cover crops enhanced biomass of total bacteria, total fungi, actinomycete, and saprophytic fungal biomass in alley soils in July.

Thus, cover crops planted to vineyard alleys have the potential to increase microbial biomass, including biomass of bacteria, fungi, AM fungi, and soil fauna (protozoa). With greater microbial and faunal biomass, there is potential for increased microbial and soil food web activities, including N mineralization. Vines whose roots extend into the alleys could also benefit from enhanced root-microbial interactions, including symbioses with AM fungi and associations with plant-growth promoting bacteria and actinomycetes.

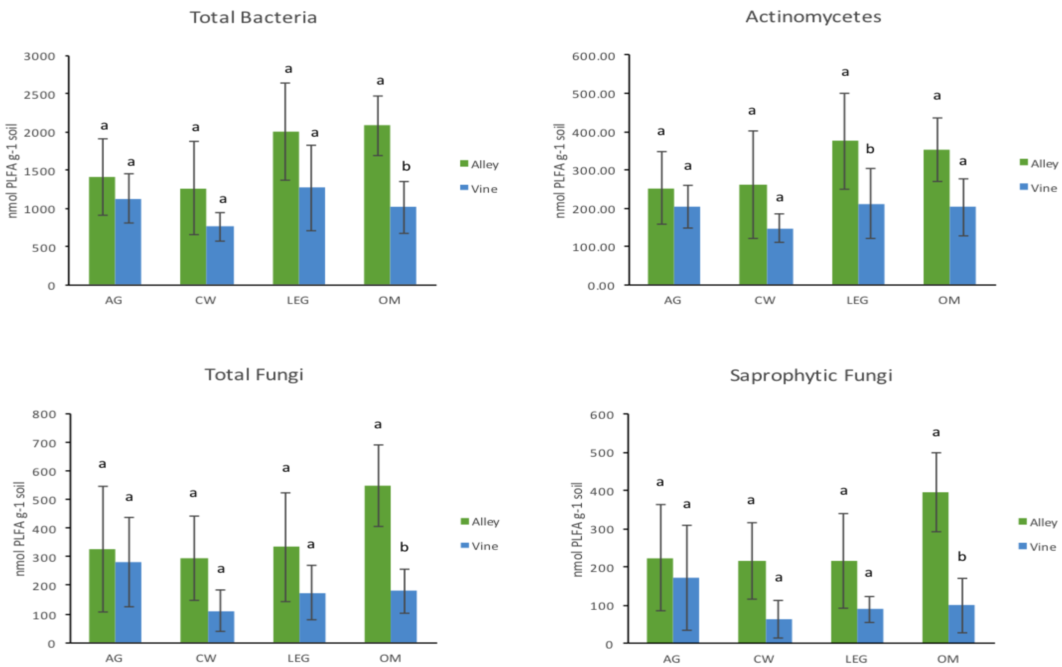
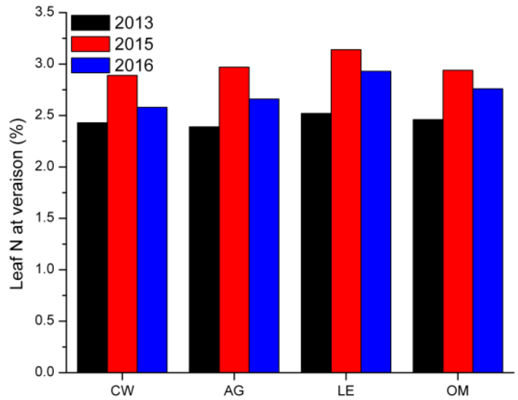


Fig. 18: Biomass of total bacteria, actinomycetes, total fungi, and saprophytic fungi in soil cropped to different cover treatments. Soil samples were collected either in the cover crop alley way or within the vine row, in July 2016. Cover crop treatments were "Aurora Gold" hard fescue (AG), crested wheatgrass (CW), alfalfa (LEG), and orchard mix (OM). Error bars represent ± 1 standard deviation (n=4). Within a cover crop treatment, bars labeled with different letters are significantly different ($P<0.05$).

Chardonnay leaf samples were taken at veraison and send to a commercial laboratory for analysis (Ward Laboratories Inc., Kearney, NE). The results are consistent with those from the 2015 season and indicate that the vine nutritional status is being affected by the type of cover crops. Specifically, the nitrogen concentration in leaf blades was again slightly higher with a legume cover crop than with the other treatments (Fig. 19). A higher availability and/or uptake of nitrogen by vines with a legume cover crop is also implied by much higher nitrogen levels in the musts in both the 2015 and 2016 season (Fig. 20). Further, and consistent with the differences in nutrient concentrations in the cover crop biomass, phosphorus and potassium were lower while iron, calcium, and magnesium were higher with crested wheatgrass than with the other cover crops. However, there was no cover crop effect on the sulfur concentration of Chardonnay leaves at veraison (data not shown).

Since the initiation of this study in 2013 there has been a trend for increased concentrations of sulfur, calcium, magnesium, and iron in leaves taken at veraison. It is worth noting that there has been no application of sulfur fungicides or any fertilizer applications over the past two seasons. In contrast, concentrations of zinc and boron are trending downwards. These trends have been observed in all treatments. While leaf concentrations of nitrogen, phosphorus, potassium, manganese and boron have fluctuated between the years there are no clear trends. Leaf samples for mineral analysis will again be collected at veraison in 2017.



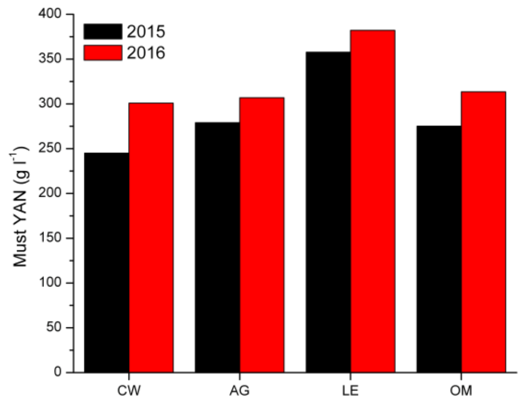


Fig. 19 (left): Effect of cover crops on nitrogen concentration of Chardonnay leaf blades at veraison. Data for 2013 represent nitrogen concentrations prior to the establishment of the cover crops.

Fig. 20 (right): Effect of cover crops on the yeast-assimilable nitrogen (YAN) concentration of Chardonnay musts in 2015 and 2016.

Drip-irrigated vines received 12.5” of irrigation water during the 2016 season whereas a total of 31.1” was applied in the micro-sprinkler irrigated plots. The irrigation volumes applied were much higher than the previous season; however the vineyard received only 4.1” of precipitation between 15 April and 31 October, 2016, compared to 11.7” for the same period the previous year. Approximately one third of the irrigation volume was applied post-harvest to ensure that the soil profile was wet going into the dormant season.

In December 2016, phylloxera was discovered in the Chardonnay block used for the cover crop study. As three out of four replications are planted with own-rooted vines the presence of phylloxera may already have influenced vine performance. The presence of phylloxera also raises questions about the long-term viability of this project.

ENGAGEMENT / OUTREACH / COMMUNICATIONS

The ever-increasing number of growers and wineries in the state means that individual consultations are a very inefficient, and costly way of providing information. We therefore try to conduct our engagement / outreach primarily through industry workshops / seminars, formal presentations (e.g at VinCO), and field days. However, on an annual basis we respond to hundreds of phone and thousands of email inquiries.

1. Field demonstrations/workshops/tours

We provided several tours of the research vineyard and/or the research facilities to individual growers, visiting scientists, and extension staff. Common topics covered included cover crops and irrigation, trellis/training systems with Syrah, crop thinning, powdery mildew management, and vineyard irrigation management.

A “Crush Readiness” workshop was held at WCRC-OM on 28 July, 2016. The workshops was repeated at Kingman Estate Winery in Denver on 29 July, 2016. Nichola Hall and Michael Jones from Scott Labs and Stephen Menke were the instructors at both workshops.

Stephen Menke organized and conducted a “Berry Sensory Evaluation and Harvest Readiness” workshops at WCRC-OM in Grand Junction on 15 September, 2016. Stephen Menke was the instructor. Included in the evaluations were grapes from several cultivars from the WCRC-OM variety trial, as well as some grapes from a variety of cultivars brought by attendees.

As part of the activities during the Colorado Mountain Winefest, Horst Caspari conducted a “Grape growing for beginners” workshop at WCRC-OM on 18 September, 2016.

Stephen Menke assisted with organizing the multi-state wine tasting and formal evaluation of NE-1020 project wines, including wines from several cultivars in the CSU NE-1020 test vineyards, at the NE-1020 annual review meeting in Burlington, VT (16-18 November, 2016). This data will be pooled with data from previous evaluations and shared by outreach.

Horst Caspari assisted with the organization of, and presented at two workshops on phylloxera. The first, half-day workshop in mid-January 2017 prior to VinCO was attended by >100 people. There were approximately 60 participants at the “Phylloxera Seminar” organized by CAVE and held at the Western Colorado Community College in Grand Junction on 26 March, 2017.

Horst Caspari conducted a “Grape Pruning Workshop” attended by >30 growers in Canon City on 9 April, 2017.

We continue to use our web site and other internet resources such as our “Fruitfacts” messages to provide information resources for Colorado growers. Also, as part of the “Application of Crop Modeling for Sustainable Grape Production” project, current weather information from seven vineyard sites in the Grand Valley is accessible to grape growers and the public via the internet. In December 2016, as part of system maintenance, we raised the height of the antenna at WCRC-OM which has resulted in much improved signal reception from the weather stations that are furthest removed (Redlands, Grand Junction North). We will continue to service both the software and hardware for this weather station network.

2. *Off-station research and demonstration plots*

The uptake of new research results and new production techniques is fastest when growers are directly involved in their development. One way of involving growers in research is to establish research plots on grower properties. Since 2013, we have established two replicated variety trials in grower vineyards. At both sites, vines were trained by CSU student interns. The Fort Collins vineyard was also used for formal education of CSU students during the fall term. The replicated clonal study with Cabernet Franc (see above) is another example where the research is sited in a commercial vineyard. Buds from this Cabernet Franc vineyard are used for cold hardiness evaluations. And in spring 2017 we planted a replicated rootstock trial with Cabernet Sauvignon in a grower vineyard in Mesa County. Another example of industry collaboration are three different vineyard sites where we monitor temperature profiles. We will continue to use the vineyard at the Western Colorado Research Center at

Orchard Mesa in the first or early stages of testing of new methods and/or trials that carry a high risk of crop damage.

3. Colorado Wine Grower Survey

Colorado State University has conducted this annual survey for over 20 years. Survey forms were send out in November. The majority of forms were send electronically. By 30 June, 2017 we had received 86 responses (representing 146 vineyard sites) totaling 642 acres. The main results of the survey are:

- Potentially a new record grape production in 2016, surpassing 2015
- 1,960 ton production reported so far
- Expected total production >2,200 ton
- Maybe as much as 10 % of production did not get sold
- Average yield of ~3.25 ton/acre; almost identical to 2015
- Average price of $1,636/ton, virtually unchanged from 2015
- The average grower farms 7.5 acres
- Average vineyard size is 4.4 acres
- The median vineyard size is 2.9 acres
- More than half the new plantings in 2016 were with cold-hardy varieties
- There is a continued expansion of vineyard area outside of Colorado's main growing areas

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