Water Management of Irrigated Cabernet Sauvignon Grapevines in Semi-Arid Areas

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Abstract: The effect of four years of deficit irrigation on water savings, yield, crop load, plant growth, and juice composition was determined on Cabernet Sauvignon grapes grown on the Central Coast of California. The growing season was divided into three periods. The first was from budburst to fruit set, during which there was no irrigation. The second was from fruit set to three weeks post-fruit set, during which 75% of calculated crop water use (ET_c) was applied for all treatments. The third began three weeks post-fruit set and continued to harvest, during which irrigation resumed whenever the leaf water potential (LWP) reached -1.2 MPa in one of three sustained deficit irrigation treatments equal to 25/35% (LOW), 50% (MED), and 75/65% (HIGH) of ET_c. The sum of rainfall and irrigation applied during the growing season ranged from 91 to 196 mm, from 145 to 234 mm, and from 198 to 273 mm for the LOW, MED, and HIGH treatments, respectively. Total water use, including soil water during the growing season, ranged from 250 to 359 mm, 288 to 418 mm, and 313 to 378 mm for the LOW, MED, and HIGH treatments, respectively. Yield was linearly related to the sum of irrigation and rain and to the total available water (rain, irrigation, and stored soil water) during the growing season. Yield was consistently lower in the LOW treatment across all years than in the MED and HIGH treatments; while yields in the MED and HIGH treatments were not different. Average pruning weight and cane weight declined in all treatments over the four years of the study, as did average berry size. Berry and wine composition was not affected by irrigation treatment within a given year, but were different across years due to climate, irrigation schedules, and harvest dates. Our results illustrate potential applied water savings during the growing season with moderate deficit irrigation (i.e., MED), with minimal or no significant effect on fruit yield and juice composition, while severe reduction of applied water (i.e., LOW) led to loss of yield without changing juice composition and would not be considered economically sustainable.

Key words: California, drip irrigation, regulated deficit, sustained deficit, water management, yield

An industry-sponsored economic survey estimated that United States grape products are valued at $162 billion annually (MKF Research 2007), making them the highest-valued perennial specialty crop in the U.S. The semiarid regions of California, Oregon, and Washington account for >90% of U.S. grape production and >9% of global grape production (fourth after France, Italy, and Spain). There are currently 319,000 ha of grapes under production in California, of which ~194,000 ha are winegrapes, 33,200 ha are table grapes, and 91,900 ha are raisin grapes. Conservative estimates of the water applied for grape production in California are in the range of 1.56 billion cubic meters per year (Cooley 2015).

In 2015, California was in the fourth year of a severe drought that resulted in agriculture receiving severely reduced surface water allocations and extensive fallowing of agricultural land. Thus, irrigators needed to respond by developing water management practices that contribute to achieving sustainable levels of future use. For perennial crops, improved water management may include refining crop water requirements, improving irrigation scheduling, and adopting deficit irrigation strategies.

Deficit irrigation is routinely practiced in winegrape production for limited time periods to reduce plant vigor and improve grape composition (Edwards and Clingeleffer 2013).

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Acknowledgments: The authors thank J. Lohr Vineyards and Wines for the use of their vineyards, their technical support, and monetary contributions to this project. The authors acknowledge the support of Mr. Richard Schoneman, USDA-ARS-SJVASC, and the students who worked on this project over the years. Partial funding was provided by the NIFA sponsored project "Vineyard water management strategies with limited and impaired water supplies." The authors also thank the AJEV associate editor and the anonymous reviewers for their thorough review and helpful suggestions that improved the manuscript.

Manuscript submitted Mar 2017, revised Mar 2017, Jun 2017, accepted Jul 2017

doi: 10.5344/ajev.2017.17022

A variety of deficit irrigation strategies, including sustained deficit irrigation (SDI), regulated deficit irrigation (RDI), and partial root-zone drying (PRD), have been implemented in winegrape production with minimal effects on yield, depending on the severity of the deficit strategies used (Roby et al. 2004, López et al. 2009, Santesteban et al. 2011, Romero and Martinez-Cutillas 2012, Shellie 2014). RDI has been implemented by researchers to control plant vigor to improve color intensity, sugar, total anthocyanins, and flavonols (Santesteban et al. 2011, Romero et al. 2013), but it has generally not been used as a water-saving measure.

Most deficit irrigation strategies are not applied across an entire growing season, but instead target specific growth stages from budburst to fruit set, fruit set to veraison, and veraison to harvest. These strategies may include changing the volume of water applied within phenological stages, managing the stem water potential (Ψ) during specific phenological stages, or combinations of applied water and managed stem Ψ (Acevedo-Opazo et al. 2010). Maximum yields of Thompson Seedless grapes were achieved with an SDI application equal to 80% of the crop water requirement (ET_c; Williams et al. 2003), and it was demonstrated that watering grapevines to full ET_c reduced wine quality (Williams and Matthews 1990).

The objectives of this research were: (1) to develop alternative deficit irrigation management strategies for winegrapes in California and, (2) to determine the impact of alternative deficit irrigation management strategies on crop yield, fruit composition, and plant response in a commercial vineyard.

Materials and Methods

This research was conducted for four years (2011 to 2014) on a 14-year-old *Vitis vinifera* L. (cv. Cabernet Sauvignon clone 7) on rootstock 5C vineyard located at J. Lohr Vineyards in Paso Robles, CA (35.687´N; -120.662´W; Figure 1). The 31-ha experimental area contained 12 contiguous individual fields divided into two blocks, with each block containing two replications of three irrigation treatments (LOW, MED, and HIGH). The statistical design was a randomized complete block. Ten contiguous vines in the center of each plot were selected based on uniformity of size and lack of disease, and were used each year for data collection. The experiment was located on well-drained sandy loam over clay (San Ysidro series) and sandy loam over gravelly silty clay (Arbuckle series).

The crop was planted in 1997 in a north-south orientation with a 3-m row spacing and a 1.8-m within-row vine spacing. A three-wire vertical shoot-position (VSP) trellis was used and the vines were head-trained, cane-pruned to three canes with 10 to 12 buds/cane, and two to three, two-bud renewal spurs with two canes going in one direction and the third cane going in the opposite direction. The training used in this block is characterized as a modified sprawl. On the east-facing side were two lift wires and the canopy was vertical in the fruit zone. On the west facing side, only one lift wire was used and the canopy was allowed to hang over the fruit zone to provide protection from the afternoon sun. The crop load was thinned in 2011, but not in any year thereafter, by design. The vines were pruned in January each year and the pruning weights were determined. The total number of canes on the 10 vines in each 10-vine plot was counted, and all canes were removed except for three canes saved for the coming year. The canes from each 10-vine plot were bundled and weighed in the field.

A 2-m wide, no-till cover crop of Blando Brome and Zorro fescue was planted between rows prior to the beginning of the experiment. The vine row was sprayed with a pre-emergent herbicide postharvest, and again in late winter. The cover crop was not irrigated, thus rainfall was the only water supply. After pruning, the canes were mulched and the cover crop was mown, with a second mowing occurring in late April after the cover crop had gone to seed. The last fertilization on this field was in 2012, when a banded application of a compost/sulfur/gypsum blend (1.7 T/ha popcorn sulfur, 1.7 T/ha gypsum, 13.3 T/ha treated compost) was applied.

The irrigation treatments were designed to provide different volumes during three periods of the growing season. The first period was from budburst to fruit set, when no irrigation was applied. The second period was from fruit set to three weeks post-fruit set, during which 75% of calculated crop water use (ET_c) was applied to all treatments. The third period began three weeks post-fruit set and irrigation was resumed when the leaf water potential (LWP) reached -1.2 MPa in one of the three SDI treatments. At this time, SDI treatments were implemented that were equal to 25/35% (LOW), 50% (MED), or 75/65% (HIGH) ET_c accumulated following the previous week's irrigation. In 2012, the volume of applied water in the LOW treatment was increased from 25 to 35% ET_c, and the volume of applied water in the HIGH treatment was decreased from 75 to 65% ET_c in consultation with the

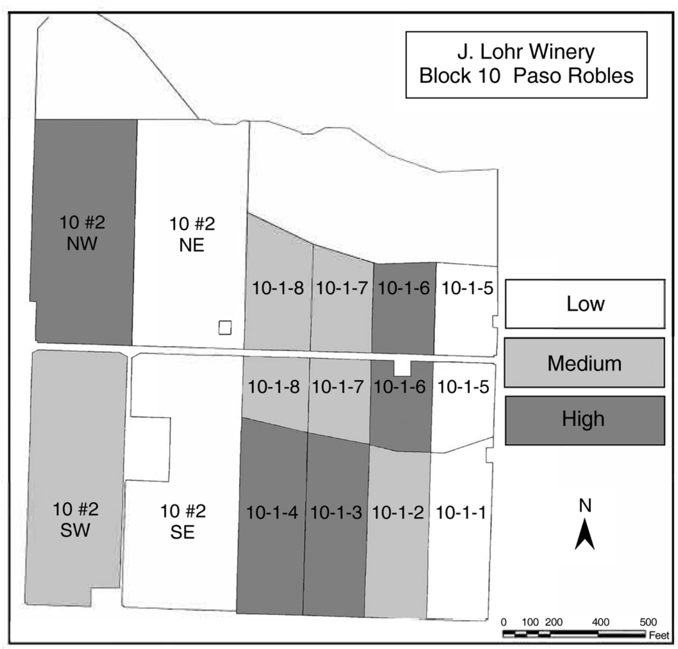

Figure 1 Layout of field plots in the J. Lohr Cabernet Sauvignon vineyard located in Paso Robles, CA. LOW is 25/35% of calculated crop water use (ET_c) applied as sustained deficit postveraison to harvest. MED is 50% of ET_c applied as sustained deficit postveraison to harvest. High is 75% of ET_c applied as sustained deficit postveraison to harvest.

grower cooperator. The different volumes of application were achieved by adjusting the run time of the irrigation system.

The ET_c since the previous week's irrigation was calculated using daily reference evapotranspiration (ET_o) obtained from the Western Weather Group (WWG) (www.westernweathergroup.com) weather station (35.64´N; -120.63´W) located at the Paso Robles municipal airport, ~3.3 km southeast of the vineyard, multiplied by a crop coefficient (K_c). The K_c was determined from a table based on growing degree day (GDD) base 10°C for multiple-row spacing. The cooperator managed the irrigation and used the GDD-K_c for a VSP vineyard with a row spacing of 3 m to compute daily ET_c. The K_c begins at 0.11, increases to 0.49 at a total of 1500 GDD, and remains constant thereafter. The GDD data were taken from the same WWG station as the ET_o.

The crop was drip-irrigated each Tuesday using a single lateral attached to the trellis and positioned ~0.3 m above the ground with 2 L/hr emitters spaced at ~1 m intervals along the drip line. The system was operated manually to apply the previous week's ET_c based on the LOW, MED, and HIGH irrigation treatments. Each treatment had a Signet paddlewheel electronic water meter (Ryan Herco) installed, and the applied water was recorded on a CR 1000 data logger (Campbell Scientific Instruments).

A Puresense irrigation management system (JAIN Irrigation) installed in June 2012 measured soil water content continuously in 30-cm increments to a depth of 1.5 m in one replication of each treatment using capacitance probes. The soil water content was assumed representative of the entire field at that depth. The Puresense system also monitored the irrigation system runtime and collected weather data over the grapevine canopy. The soil water contribution to total ET_c was calculated between budburst and harvest as the sum of the percent change in soil water content for each 30-cm depth increment.

LWP was measured weekly on Monday between 1200 and 1400 hr using a PMS Instrument model 600 pressure chamber (Scholander et al. 1964). One fully expanded, fully sunlit leaf from each of the 10 experimental vines was covered with a plastic bag prior to removal from the vine. The petiole was broken from the vine, cut with a razor, then inserted into the pressure chamber. LWP measurements were begun in May just prior to fruit set and continued through harvest.

Harvest was scheduled when Brix reached ~25. Fruit from the 10 measurement vines in each plot were harvested individually into a single bin per vine. The number of clusters was counted and the bin was weighed in the field. The average cluster weight was determined by dividing the total weight by the number of clusters. The fruit from each plot was subsampled into three separate containers for further analysis. A total of 1.4 kg of fruit from each of the 10 vines (14 kg total) was put into one of the containers and sent to the E&J Gallo Research winery in Modesto, CA, for small-batch winemaking. Two clusters from each vine (20 clusters total) were put into each of the remaining two containers. One of the containers was sent to E&J Gallo for fruit analysis and the other was sent to the J. Lohr laboratory to determine berry weight and color density. Ten berries were removed from each cluster and sent to the J. Lohr laboratory, where three 50-berry samples were selected and weighed to obtain an average weight for each replication. At E&J Gallo, a subsample of berries from each plot was collected, then juice was expressed and analyzed for soluble solids (Brix), pH, titratable acidity (TA), and potassium using standard methods (Iland et al. 2004).

Wines were produced from grape samples from each 10-vine plot at the research winery of E&J Gallo. The grapes were crushed using a destemmer-crusher (Miller Company). Sulfur dioxide (40 mg/L) was added to the grapes at crushing, and must TA was adjusted to between 0.6 to 0.7 g/100 mL, without dropping the pH below 3.5. Commercial yeast strain ICV D254 (Lallemand) was used to inoculate the juice at a pitch rate of 0.18 g/L. The crushed grapes (must) were placed in temperature-controlled stainless-steel fermentation tanks and maintained at 30°C until fermentation was complete. Grape skins rising to the top of the tank during fermentation were punched down twice per day until the must was pressed at 0 Brix using a membrane press (Miller Company). The wines were cold-settled, filtered, then stored in nitrogen-blanketed stainless-steel tanks at 12°C until bottled. Free sulfate concentrations were adjusted to 30 mg/L prior to bottling.

At bottling, the wine lots were analyzed for alcohol percentage (by gas chromatography), TA, malic acid, total phenols, and anthocyanins (using standard analytical methods) (Chapman et. al 2004), and aroma (IBMP, β-damascenone, geraniol, linalool, nerol), color (anthocyanins), and mouthfeel (total C6 compounds, polymeric tannins, quercetin glycosides) compounds.

Analysis of variance was performed and the Tukey test was used to determine significant differences among treatments at $p < 0.05$. Both procedures were performed using SigmaPlot (Systat Software, Inc.).

Results

The phenological stages, average temperature, and accumulated GDDs for the period from budburst to harvest at the Paso Robles site were calculated (Table 1). There was a 14% increase in average annual temperature from budburst to harvest over the project that resulted in a 16% increase in GDDs, and was associated with a 25% increase in annual ET_o (Table 2). Budburst was generally the first two weeks of April except for in 2012, when it occurred in the third week (Table 1). Bloom occurred nearly a month earlier in 2014 than in 2011 (Table 1). After 2011, the coolest year in the project (Table 1), fruit set occurred earlier each year, shifting from the third week in June to the second week in May, nearly a month earlier. As a result, veraison moved from the middle of August to the last week in July, and harvest was in the first one to two weeks of October. The time from fruit set to harvest increased from 107 days in 2011 to 144 days in 2014 (Table 1).

The applied irrigation, rainfall, ET_o, and ET_c data accumulated during the growing season are summarized, along with the rainfall and irrigation from the previous year's harvest to budburst (Table 2). Previous grower practice indicated that

~300 mm was sufficient to fill the soil water in the crop root zone and meet the consumption of water from budburst to fruit set. Thus, the goal was to have at least 300 mm of water from rainfall and irrigation applied prior to budburst. The volume of supplemental irrigation applied prior to budburst was based on the rainfall that occurred post-harvest from the previous year. The change in soil water content (ΔSW) during the growing season was also measured (Table 2).

The ET_o for the growing season varied from a low of 898 mm in 2011 to a high of 1193 mm in 2014. The calculated water consumption (ET_c) ranged from 286 mm in 2011 to 405 mm in 2014. The small ET_c in 2011 reflects that it was the coolest year of the study.

The applied water data by treatment are given for each year along with the sum of the rainfall during the growing season (Table 2). The total applied water (irrigation + precipitation; I+P) summaries ranged from 91 mm (LOW treatment in 2011) to 273 mm (HIGH treatment in 2012). Starting in 2012, the ΔSW was available and was added to the applied water calculation (total). In general, soil water use decreased as applied water increased from the LOW to HIGH water treatments. As a result, the average total available water across all treatments (from LOW to HIGH) increased from an average of 227 to 364 mm in 2012 to an average of 233 to 379 mm in 2013, and from 182 to 283 mm in 2014. This emphasizes the importance of stored soil water as a component of total vineyard water use. The total soil water in the 1.5-m root zone at budburst returned to approximately the same levels (375 to 450 mm) for each treatment during winter in 2013 and 2014, indicating that the soil water profile was filled and there was adequate water to meet crop demands. The data in Figure 2 give the variation in total soil water content to a depth of 1.5 m for each of the treatments from 2012 to 2014.

The applied water savings during the growing season were calculated based on meeting the full calculated ET_c. For the HIGH treatment, the water savings ranged from 75 mm in 2012 to 181 mm in 2014, the year with the highest ET_c. The savings in the MED treatment ranged from 121 mm in 2012

Table 1 Summary of crop phenology dates, average temperature, and accumulated growing degree days (GDD) for the period from budburst to harvest for a Cabernet Sauvignon vineyard located on the J. Lohr Ranch, Paso Robles, CA.

Year	Budburst	50% Bloom	Fruit Set	50% Veraison	Harvest	Avg temp (°C)	GDD Base 10°C
2011	8 April	10 June	21 June	10 Aug	6 Oct	17.9	1484
2012	22 April	26 May	5 June	3 Aug	9 Oct	20.0	1722
2013	13 April	18 May	30 May	27 July	2 Oct	19.7	1710
2014	9 April	14 May	10 May	28 July	1 Oct	19.8	1749

Table 2 Water balance summary from 2011 to 2014 for an irrigation study on a Cabernet Sauvignon vineyard located on the J. Lohr Ranch, Paso Robles, CA, for the growing season defined as budburst to harvest. LOW is 25/35% of ET_c applied as sustained deficit postveraison to harvest. MED is 50% of ET_c applied as sustained deficit postveraison to harvest. HIGH is 75% of ET_c applied as sustained deficit postveraison to harvest.

				Growing season (mm)							
Year	Total (I+P)[a] Harvest to budburst[b]	ET_o[c] (mm) Growing season	ET_c (mm) Growing season	Irrigation treatment	P	I	I + P	Water Savings[d]	ΔSW[e]	Total (I+P+SW)	Water Savings[f]
2011	325	898	286	LOW	39	52	91	195	ND	–	–
				MED	39	106	145	141	ND	–	–
				HIGH	39	159	198	88	ND	–	–
2012	168	998	348	LOW	4	177	181	167	178	359	0
				MED	4	223	227	121	148	375	0
				HIGH	4	269	273	75	85	358	0
2013	208	1091	363	LOW	0	196	196	167	145	341	22
				MED	0	234	234	129	184	418	0
				HIGH	0	269	269	84	109	378	0
2014	298	1193	405	LOW	0	138	138	267	112	250	155
				MED	0	180	180	225	108	288	117
				HIGH	0	224	224	181	89	313	92

[a]I: applied irrigation water; P: precipitation.
[b]Harvest to budburst means from harvest of the previous year to budburst of the current year.
[c] ET_o: reference evapotranspiration.
[d]Water savings based on meeting the full crop water requirement (ET_c), with only irrigation and rainfall applied during the growing season.
[e]ΔSW: change in soil water content.
[f]Water savings based on meeting the full crop water requirement (ET_c), with irrigation and rainfall applied during the growing season and stored soil water.

to 225 mm in 2014, while the savings in the LOW treatment ranged from 167 mm in 2012 and 2013 to 267 mm in 2014. When the savings are averaged by treatment across the four years of the project, there was a savings of 199 mm in the LOW treatment, 154 mm in the MED treatment, and 109 mm in the HIGH treatment. Compared to the average ET_c during this period of 350 mm, there was 56, 44, and 30% savings in the LOW, MED, and HIGH treatments, respectively (Table 2). However, when the ΔSW during the growing season is added to irrigation and precipitation, ET_c was fully met in 2012, but not in the LOW treatment in 2013, and not in any treatment in 2014. This emphasizes the importance of rainfall and supplemental irrigation in replenishing the soil water in the crop root zone during fallow periods.

In each year, the LWP was ~ -1.0 MPa in early June prior to fruit set, indicating that the vines were not under stress (Figure 3). There was a gradual increase in stress in 2011, reaching a max in September after crop development was completed, with a LWP at veraison of ~ -1.2 MPa. By the end of the growing season (2011), the difference in LWP between the LOW treatment and the remaining treatments was sufficient to justify a change in the irrigation treatment strategy. The percentage ET_c in the LOW treatment was increased and that of the HIGH treatment decreased (Figure 3). In 2012, the LWP decreased from -1.0 MPa in mid-June to -1.7 MPa by August at veraison, after which there was some recovery to ~ -1.5 MPa. In 2013, the LWP decreased from -1.2 MPa at the start of the irrigation treatments to -1.4 MPa at veraison and ~ -1.5 MPa until mid-September, when it decreased to -1.7 MPa at harvest (Figure 3). The LWP response in 2014 differed from the previous years. The irrigation treatments began at -0.8 MPa and reduced to -1.2 MPa. There was brief recovery in stress followed by a gradual decrease to ~ -1.4 MPa at veraison, which remained at that level until harvest (Figure 3). There was very little separation in the stress values among treatments except

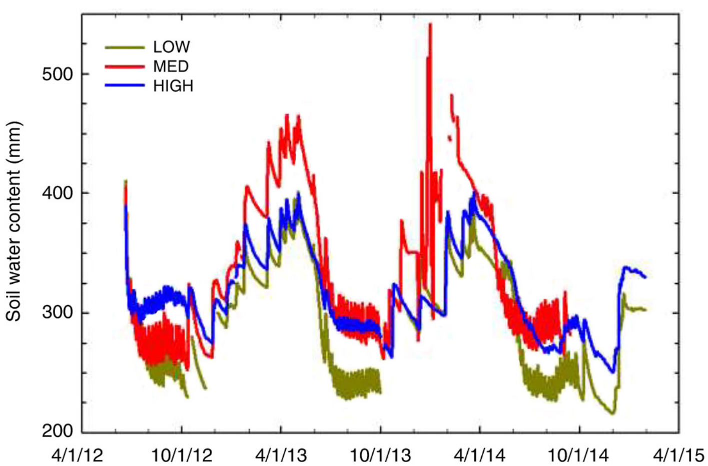

Figure 2 Total soil water content to a depth of 1.5 m for LOW, MED, and HIGH deficit irrigation treatments in a J. Lohr Cabernet Sauvignon vineyard located in Paso Robles, CA. LOW is 25/35% of calculated crop water use (ET_c) applied as sustained deficit postveraison to harvest. MED is 50% of ET_c applied as sustained deficit postveraison to harvest. HIGH is 75% of ET_c applied as sustained deficit postveraison to harvest.

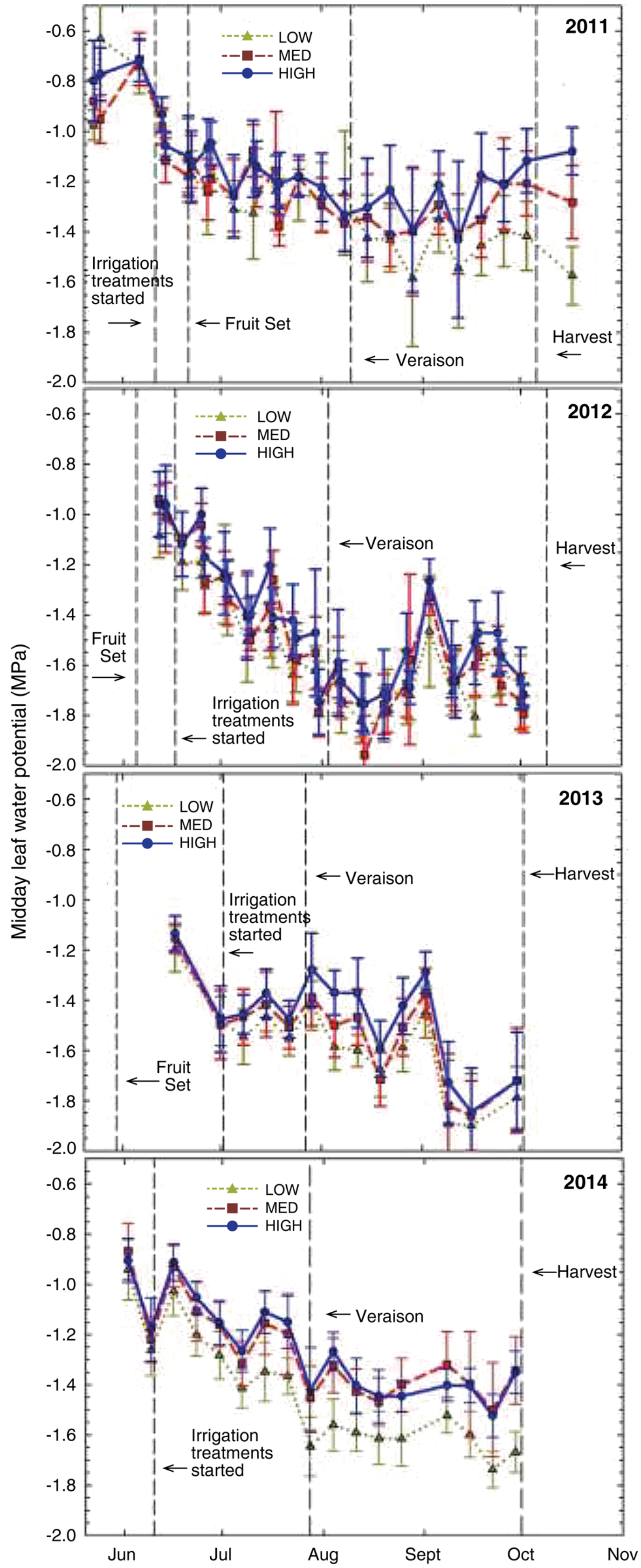

Figure 3 Leaf water potential from 2011 to 2014 for LOW, MED, and HIGH deficit irrigation treatments in a J. Lohr Cabernet Sauvignon vineyard located in Paso Robles, CA. LOW is 25/35% of calculated crop water use (ET_c) applied as sustained deficit postveraison to harvest. MED is 50% of ET_c applied as sustained deficit postveraison to harvest. HIGH is 75% of ET_c applied as sustained deficit postveraison to harvest.

in 2014, when the LOW treatment was separated from the other treatments throughout the growing season.

The fruit yields, berry weight, fruit per vine, clusters per vine, and cluster weight were compared by treatment within each year of the study (Table 3). In 2011 and 2014, the LOW treatment had lower berry weights than the MED and HIGH treatments, while no difference was observed between the MED and HIGH treatments. There were differences in berry weight between all treatments in 2012 and no difference in berry weight across treatments in 2013 (Table 3). Except in 2011, the weight of the fruit per vine was different between the LOW treatment and the other two treatments, with no differences between the MED and HIGH treatments. The clusters per vine differed between the LOW to HIGH treatments in 2012 and 2013. There were no differences in the number of clusters per vine in 2014. Within a year, the cluster weight increased with increased water consumption, with differences between the LOW and MED and HIGH treatments, but not the MED and HIGH treatments. The net effect is that yields were higher in the MED and HIGH treatments than in the LOW treatment, but with no difference between the MED and HIGH treatments. The exception was in 2011, where the MED was different from the HIGH and LOW treatments (Table 3).

The berry weight, clusters per vine, fruit per vine, cluster weight, and yield were also studied across years within an irrigation treatment (Table 3). With the exception of the fruit per vine in the LOW treatment, there were differences in the variables across the years for each irrigation treatment. There is no distinct pattern of response for these variables across the years. Thus, the responses are fully independent of the irrigation management.

The pruning weight per vine, canes per vine, weight per cane, and yield to pruning ratio (Ravaz index) are given for each irrigation treatment within a year and for each irrigation treatment across years (Table 4). There were differences in pruning weight per vine, with weights increasing as the applied water increased, except in 2013 (Table 4). While there were differences between the LOW treatments and other treatments, there were none between the MED and HIGH treatments. In 2011 and 2014, there were no differences across treatments in the canes per vine. In 2012, there were differences in the canes per vine between the LOW and other treatments, but not between the MED and HIGH treatments. In 2013, the difference was between the LOW and MED treatments and the HIGH treatment, with HIGH having the lowest number of canes.

Table 3 Summary of berry weight and yield per vine, clusters per vine, cluster weight, and total yield for four years and three irrigation strategies on a Cabernet Sauvignon vineyard located on the J. Lohr Ranch, Paso Robles, CA. Data are compared across treatments within a year and across years by treatment. LOW is 25/35% of calculated crop water use (ET_c) applied as sustained deficit postveraison to harvest. MED is 50% of ET_c applied as sustained deficit postveraison to harvest. HIGH is 75% of ET_c applied as sustained deficit postveraison to harvest.

Irrigation treatment	Berry wt (g)	Clusters/ vine	Fruit/vine (kg)	Cluster wt (kg)	Yield (T/ha)
2011					
LOW	0.98 a[a] e[b]	37 a e	4.3 a	0.12 a e	7.6 a e
MED	1.05 b e	47 b ef	6.4 b e	0.14 b e	11.5 b ef
HIGH	1.12 b e	41 a e	5.1 a e	0.12 ab e	9.2 a e
2012					
LOW	0.78 a f	57 a f	5.2 a	0.09 a f	9.4 a e
MED	0.87 b f	64 ab eg	7.8 b f	0.12 b f	13.9 b eg
HIGH	1.00 c f	68 b e	8.9 b f	0.13 b e	15.9 b f
2013					
LOW	0.80 f	77 a e	6.8 a	0.09 a fg	12.2 a f
MED	0.79 g	87 ab g	8.6 b g	0.10 b g	14.7 b g
HIGH	0.79 f	88 b g	8.8 b f	0.10 b f	15.3 b f
2014					
LOW	0.63 a g	64 f	4.8 a	0.08 a g	8.7 a e
MED	0.71 b h	62 f	6.4 b g	0.10 b g	11.4 b f
HIGH	0.75 b g	67 g	7.2 b g	0.11 b f	12.9 b f

[a]Analysis of variance (ANOVA) was performed and the Tukey test was used to determine significant differences among treatments at $p < 0.05$. Means within years not followed by the same letter differ statistically by the Tukey test.
[b]ANOVA was performed and the Tukey test was used to determine significant differences among treatments at $p < 0.05$. Means across years within a treatment not followed by the same letter differ statistically by the Tukey test.

Table 4 Summary of yield, pruning weight per vine, and ratio of yield to pruning weight (Ravaz index) and canes per vine as a function of irrigation treatments in a Cabernet Sauvignon vineyard located on the J. Lohr Ranch, Paso Robles, CA. Data were compared across treatments within a year and across years by treatment. LOW is 25/35% of calculated crop water use (ET_c) applied as sustained deficit postveraison to harvest. MED is 50% of ET_c applied as sustained deficit postveraison to harvest. HIGH is 75% of ET_c applied as sustained deficit postveraison to harvest.

Irrigation treatment	Pruning wt/vine (kg)	Ravaz index (kg/kg)	Canes/ vine	Wt/cane (g)
2011				
LOW	1.1 a[a] e[b]	4.2 a e	27.9 e	39.2 e
MED	1.3 ab e	6.4 b e	30.7 e	42.2 e
HIGH	1.4 b e	4.1 a e	29.7 e	48.9 e
2012				
LOW	0.8 a f	7.1 a e	21.2 a f	29.4 a f
MED	0.9 ab e	10.2 b f	28.9 b e	33.1 a fg
HIGH	1.1 b f	8.5 ab f	28.8 b e	39.2 b f
2013				
LOW	0.6 fg	13.1 f	25.0 ab ef	23.4 a f
MED	0.6 f	15.8 g	25.6 a f	25.7 a g
HIGH	0.7 f	13.2 g	22.7 b f	31.5 b g
2014				
LOW	0.5 a g	12.4 f	21.3 f	23.4 a f
MED	0.7 b g	10.9 f	21.8 g	30.6 b fg
HIGH	0.6 b g	13.0 g	20.8 f	31.9 b g

[a]Analysis of variance (ANOVA) was performed and the Tukey test was used to determine significant differences among treatments at $p < 0.05$. Means within years not followed by the same letter differ statistically by the Tukey test.
[b]ANOVA was performed and the Tukey test was used to determine significant differences among treatments at $p < 0.05$. Means across years within a treatment not followed by the same letter differ statistically by the Tukey test.

There were no differences across treatments in weight per cane in 2011. In the remaining years, weight per cane increased as the applied water increased. In 2012 and 2013, there were differences between the HIGH and other treatments, with no differences between the LOW and MED treatments. In 2014, the difference was between the LOW and other treatments, with no difference between the MED and HIGH treatments.

The Ravaz index was calculated for each year. There were no differences across treatments in 2013 and 2014, but there were differences across treatments in 2011 and 2012, where the MED treatment was greater than the LOW and HIGH treatments. The comparison across years within an irrigation treatment (Table 4) demonstrated a general trend toward reduction in the number of canes per vine, pruning weight per vine, and weight per cane across the years. The result was an increase in the Ravaz index within an irrigation treatment across the years.

A regression analysis of the yield and applied water data from budburst to harvest determined that there was a linear response for the yield relative to the applied water. The resulting equation for the yield and applied water is

$$Y = 0.056\ x + 0.66 \qquad \text{(Eq. 1)}$$

where yield is Y and x is the sum of the applied irrigation and rainfall during the growing season ($R^2 = 0.92$). When the stored soil water is added to the applied irrigation and rainfall and used in the yield regression, the resulting equation is

$$Y = 0.034\ x + 1.05 \qquad \text{(Eq. 2)}$$

where Y is yield and x is the total water ($R^2 = 0.47$; Figure 4).

As water becomes limiting, there is increased interest in quantifying the yield as a function of the applied water, including irrigation and rainfall. Water productivity (WP) is a measure used to characterize yield as a function of applied water and can be extended to include ΔSW. An alternative characterization is the crop water footprint (CWFP), which is the water used per mass of yield; this formulation includes blue, green, and grey water. Green water is rainfall stored as soil water, blue water is irrigation, and grey water is that required for pollution amelioration associated with final processing of the commodity. We did not consider grey water in the calculation of the CWFP. The WP and the CWFP are based on the applied irrigation water and total water use, including irrigation, rainfall, and ΔSW (Total) (Table 5). The WP was calculated as the ratio of yield to mega-liters of water used, and the CWFP is the ratio of cubic meters of water used per ton of yield. The CWFP calculation included blue and green water (Mekonnen and Hoekstra 2011).

Since WP is a ratio of yield to applied water from budbreak to harvest, the value typically decreases as applied water increases without increasing yield, which is the case in 2011 (i.e., WP I+P only). However, in 2013 and 2014, the WP values for the LOW and MED treatments were equal, and both were greater than the HIGH treatment. This pattern changed when the contribution of soil water was included in the calculation. When stored soil water makes a significant contribution to yield, it can be misleading to consider only the applied water and rainfall when calculating WP and CWFP. The LOW treatment had poorer water productivity than the MED and HIGH treatments, with HIGH treatments having the highest water productivity value in 2012 to 2014. When considering the CWFP values using only the applied water, more water was required per unit of yield as the treatments went from LOW to HIGH (Table 5). When the CWFP calculation included the ΔSW, that trend reversed and less total water was required per unit of yield as treatments went from LOW to MED to HIGH (Table 5).

Juice composition variables were analyzed across treatments within a year and across years within an irrigation treatment (Table 6). There were no irrigation treatment differences in Brix, TA, yeast assimilable nitrogen (YAN), or anthocyanins within any year; however, there were year-to-year differences for several of these variables (Table 6). There was a difference in the potassium concentrations between the LOW and MED and the HIGH treatments in only 2011, and there were year-to-year differences in the potassium concentrations in each of the treatments (Table 6). There were differences in malic acid concentrations across treatments in 2012 and 2014, but not in 2011 or 2013. There were differences in malic acid concentrations across the years within the LOW and MED treatments, but not the HIGH treatment (Table 6). There were differences in pH across the years within an irrigation treatment (Table 6), and differences between treatments in 2011 and 2014. Within treatments, there were year-to-year differences in TA in the LOW and MED treatments. The only differences in anthocyanin concentrations occurred across years in the MED treatment (Table 6). There were no differences in the remaining comparisons across years and

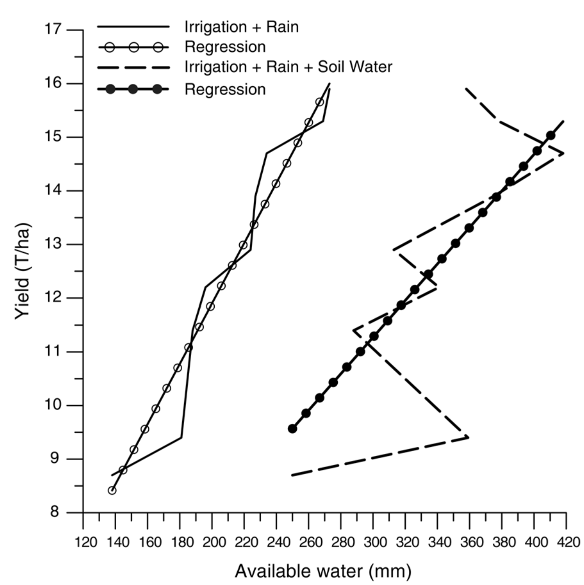

Figure 4 Total yield of Cabernet Sauvignon grapes grown in a J. Lohr vineyard located in Paso Robles, CA, plotted as a function of sum of irrigation and rainfall during the growing season and a function of sum of irrigation, rainfall, and change in stored soil water during the growing season (budburst to harvest).

treatments, except for increased values of β-damascenone in the HIGH treatment. The total C6 compound values were different from year-to-year within a treatment, but did not vary across treatments within a year, and the same pattern existed for polymeric tannins and quercetin glycosides (Table 6).

Discussion

By incorporating components of various irrigation strategies into our experimental management scheme, we identified potential avenues for water savings (MED) that resulted in moderate stress with limited effects on grape yield and

Table 5 Water productivity (WP) and crop water footprint (CWFP) summary as a function of irrigation treatments in a Cabernet Sauvignon vineyard located on the J. Lohr Ranch, Paso Robles, CA. LOW is 25/35% of calculated crop water use (ET_c) applied as sustained deficit postveraison to harvest. MED is 50% of ET_c applied as sustained deficit postveraison to harvest. HIGH is 75% of ET_c applied as sustained deficit postveraison to harvest.

Year/Irrigation Treatment	Yield (T/ha)	Growing Season I+P[b] (mm)	Growing Season Total (I+P+SW)[b] (mm)	WP (T/ML^a) I+P	WP (T/ML^a) Total	CWFP (m^3/T) I+P	CWFP (m^3/T) Total
2011							
LOW	7.6 b[c]	91	–	8.4	–	119.7	–
MED	11.5 ab	145	–	7.9	–	126.0	–
HIGH	9.2 a	198	–	4.6	–	215.0	–
2012							
LOW	9.4 a	177	359	5.3	2.6	188.3	381.9
MED	13.9 b	227	375	6.2	3.7	160.4	269.8
HIGH	15.9 b	273	358	5.9	4.4	169.2	225.2
2013							
LOW	12.2 a	196	341	6.2	3.6	160.7	279.5
MED	14.7 b	234	418	6.3	3.5	159.2	284.4
HIGH	15.3 b	269	378	5.7	4.0	175.8	247.1
2014							
LOW	8.7 a	138	250	6.3	3.5	158.6	287.4
MED	11.4 b	180	288	6.3	4.0	157.9	252.6
HIGH	12.9 b	224	313	5.8	4.1	173.6	242.6

[a]ML: megaliters.
[b]I: irrigation during the growing season; P: rainfall during the growing season; SW: change in soil water.
[c]Analysis of variance was performed and the Tukey test was used to determine significant differences among treatments at $p < 0.05$. Means within the irrigation treatment within years not followed by the same letter differ statistically by the Tukey test.

Table 6 Summary of juice composition parameters within an irrigation treatment across years in a Cabernet Sauvignon vineyard located on the J. Lohr Ranch, Paso Robles, CA. LOW is 25/35% of calculated crop water use (ET_c) applied as sustained deficit postveraison to harvest. MED is 50% of ET_c applied as sustained deficit postveraison to harvest. HIGH is 75% of ET_c applied as sustained deficit postveraison to harvest.

	LOW				MED				HIGH			
	2011	2012	2013	2014	2011	2012	2013	2014	2011	2012	2013	2014
Soluble solids	25.88 ab[a]	24.85 b	26.50 ab	26.60 a	24.1 ab	23.925 a	26.3 b	25.45 ab	23.58	23.43	26.13	25.33
Potassium (mg/L)	1616.75 a	1593.5 a	1324.75 b	NA	1469 a	1555.75 a	1302 b	NA	1412.3 ab	1570.0 b	1346.5 a	NA
Malic acid (mg/L)	1636 a	1118 b	1186 ab	1653 a	1914 a	1512 ab	1178 b	1949 a	2050.00	1807.00	1326.00	2081.00
pH	3.72 ab	3.77 a	3.68 b	3.59 c	3.60 a	3.73 b	3.67 ab	3.68 ab	3.57 a	3.75 b	3.70 b	3.69 ab
TA[b] (g/100mL)	0.36 a	0.38 ab	0.41 b	0.46 c	0.40 ab	0.37 a	0.40 ab	0.43 b	0.43	0.39	0.41	0.43
YAN[b] (mg/L)	133.75	151.75	149.00	123.00	124.50	152.50	144.25	110.25	128.50	154.00	135.00	101.25
Anthocyanins (mg/g berry)	1.18	1.12	1.24	1.14	1.06 ab	0.91 a	1.19 b	0.99 ab	0.98	0.85	1.11	1.05
Total C6 compound (μg/L)	4464.0 ac	3783.5 a	2561.3 b	5566.1 c	4946.8 a	4562.0 a	2618.0 b	5240.0 a	4272.25 a	4420.50 a	2383.86 b	5223.92 a
β-damascenone (μg/L)	NA	NA	51.69	48.57	NA	NA	49.76	49.18	NA	NA	44.59 a	48.60 b
Linalool (μg/L)	NA	NA	0.52 a	2.18 b	NA	NA	0.64 a	2.00 b	NA	NA	0.54 a	2.17 b
Polymeric tannins (mg/L)	2964 a	1957 b	3325 ac	3654 c	2472 ab	2127 a	2987 bc	3065 c	2433	2295	2923	3033
Quercetin glycosides (mg/L)	63.00	93.00	73.00	89.75	62.75 a	95.25 b	62.25 a	86.25 b	70.00 a	106.75 b	65.50 a	81.00 a

[a]Analysis of variance was performed and the Tukey test was used to determine significant differences among treatments at $p < 0.05$. Treatment means within the same year not followed by same letter differ statistically by the Tukey test.
[b]TA: titratable acidity, YAN: yeast assimilable nitrogen.

composition. Severe stress consistently resulted in reductions in yield across the experiment without increasing fruit composition variables and would not be recommended as the optimal irrigation strategy for this commercial setting, given the production goals for this vineyard. Our results were promising enough that the grower cooperator reduced irrigation amounts in the HIGH treatment (from 75 to 65% ET_c) during the course of the study.

There was no irrigation from budburst to fruit set. Instead, rainfall and supplemental irrigation were used to fill the soil profile prior to budburst. This supply was adequate to support crop growth until fruit set, at which time irrigation was initiated at 75% ET_c. At fruit set, irrigation was applied for three weeks to ensure fruit development and maintain soil water supply. Berry growth during Stage I (during cell division and cell elongation) is more sensitive to water deficits than during Stage III (after veraison), when only cell elongation takes place (Matthews and Anderson 1989, Williams and Matthews 1990). After three weeks, irrigation was suspended and LWP was monitored until a level of ~ -1.2 MPa was attained, and irrigation was initiated without regard to phenological stage. At this time, a sustained deficit was maintained without regard to the LWP, where other studies irrigated to control the max stress to -1.4 MPa (Santalucia et al. 2007, Acevedo-Opazo et al. 2010, Intrigliolo et al. 2012). In 2013, the stress in all treatments ranged from ~ -1.2 MPa to -1.5 MPa, and ultimately to ~ -1.7 MPa. This stress had no greater effect on yield than in other project years with lower sustained stress levels.

The Ravaz index is used as a measure of vine balance or crop load and is typically in the range of five to 10 for winegrapes (Bravdo et al. 1985, Hepner et al. 1985). That goal was met in 2011 and 2012, and was exceeded in all treatments in 2013 and 2014 as a result of the reduced pruning weight per vine, which increased the value of the ratio. Fruit composition of winegrape is generally not adversely affected until the Ravaz index reaches 10 (Bravdo et al. 1985). Ravaz index values that consistently exceeded 10 had limited effect on raisin grape quality, suggesting that these values may not apply across all grape commodities (Williams et al. 2010). Other researchers noted that grape yields are linearly related to total applied water (Fereres and Soriano 2007, Williams et al. 2010, Shellie 2014). In this study, the cluster weights reduced with time as a result of reduced berry size, as noted in other studies (Williams et al. 2010, Junquera et al. 2012, Shellie 2014). The number of clusters per vine was lower in 2011 than in any other year of the experiment as a result of thinning, which was true for the yield as well. With the lower yields, the Ravaz index ranged from 4.1 to 6.4 kg/kg. The lack of thinning after 2011 resulted in larger crop loads and higher Ravaz index than might otherwise have occurred. We opted not to include thinning in our experimental design. As a consequence, there may be reduced growth in subsequent seasons as indicated by the declining pruning weights.

The cooperator typically uses ~170 to 400 mm irrigation during the growing season for all the Cabernet Sauvignon vineyards on this ranch. The average applied water across the ranch for 2011 to 2014 was ~280 mm, which corresponds to the 15-year average for the ranch (Perry, personal communication, 2015). The experimental plots used less water than that ranch average in all the years of the experiment (Table 3). The average applied irrigation across the treatments for the four years were 230 mm for HIGH, 185 mm for MED, and 140 mm for LOW. This represents an average reduction in applied irrigation water of 50 to 140 mm compared to the ranch average. The MED treatment had 95 mm less water applied than the ranch average.

Even though there was a reduction in total yield, the resulting yields were in the range of the grower yield goal of ~12.3 T/ha. The experimental plots were in the range of those production goals, using ~35% less water than the grower would typically use. As noted above, deficit irrigation is often used in winegrape production to improve fruit composition. The irrigation treatments did not result in differences in fruit and juice composition within a given year, but there was year-to-year variation not associated with the irrigation treatments. The fruit composition variables can be subdivided and categorized as basic, aromas (good and bad), color, and mouthfeel. These variables are affected by region, climate, soil, harvest date, irrigation, and crop load, so comparison with other research is problematic. There are also the owner management objectives related to yield and irrigation strategies that will affect these variables. The Brix, potassium, malic acid, pH, TA, and YAN will fall into the basic variables category and will be affected by the harvest date. The harvest date was determined by the cooperator when the Brix was in the range of 25°. This level of Brix was met in 2013 and 2014 in all treatments. The average across treatments was 24.5, 24.0, 26.3, and 25.7 in 2011, 2012, 2013, and 2014, respectively. The aroma chemistry included the C6 compounds, β-damasceone, and linalool. These variables are affected by region and treatment. Year-to-year variation in these data are evident within an irrigation treatment, but not between treatments within a year. It appears that the deficit strategies did not impact the aroma composition within a year and the variation was year-to-year. It is important to note that there was an increase in the average temperature over the course of this experiment. The color and mouthfeel variables include anthocyanins, polymeric tannins, and querctin glyscosides. There were no differences in the values of these variables between irrigation treatments within a given year, but there were year-to-year differences within irrigation treatments in some of the variables.

Conclusion

The MED and HIGH deficit irrigation strategies resulted in water savings relative to the study ranch's standard practices, while maintaining the grower's yield goals. We confirmed results from other studies that the yield was linearly related to total applied water from budburst to harvest. These strategies relied on full soil water content in the root zone at budburst. The reduced individual cane weight led to a decrease in the total pruning weight per vine. The general trend toward lower cane weight and yield with time suggests that these approaches to deficit irrigation as a component of a drought water management strategy are potentially not sustainable. The consistent values of water productivity captured over several years in this study suggest that the MED and HIGH strategies should be sustainable. The irrigation treatments did not affect within-year fruit composition variables.

Literature Cited

Acevedo-Opazo C, Ortega-Farias S and Fuentes S. 2010. Effects of grapevine (*Vitis vinifera* L.) water status on water consumption, vegetative growth and grape quality: An irrigation scheduling application to achieve regulated deficit irrigation. Agr Water Manage 97:956-964.

Bravdo B, Hepner Y, Loinger C, Cohen S and Tabacman H. 1985. Effect of irrigation and crop level on growth, yield and wine quality of Cabernet Sauvignon. Am J Enol Vitic 36:132-139.

Chapman DM, Matthews MA and Guinard JX. 2004. Sensory attributes of Cabernet Sauvignon wines made from vines with different crop yields. Am J Enol Vitic 55:325-334.

Cooley H. 2015. California agricultural water use: Key background information. ISBN-10:1893790657, pp. 1-9. Pacific Institute, Oakland,CA.

Edwards EJ and Clingeleffer PR. 2013. Interseasonal effects of regulated deficit irrigation on growth, yield, water use, berry composition and wine attributes of Cabernet Sauvignon grapevines. Aust J Grape Wine Res 19:261-276.

Fereres E and Soriano MA. 2007. Deficit irrigation for reducing agricultural water use. J Exp Bot 58:147-159.

Hepner Y, Bravdo B, Loinger C, Cohen S and Tabacman H. 1985. Effect of drip irrigation schedules on growth, yield, must composition and wine quality of Cabernet Sauvignon. Am J Enol Vitic 36:77-85.

Iland P, Bruer N, Edwards G, Weeks S and Wilkes E. 2004. Chemical Analysis of Grapes and Wine: Techniques and Concepts. Patrick Iland Wine Promotions, Pty. Ltd., Campbelltown, SA.

Intrigliolo DS, Perez D, Risco D, Yeves A and Castel JR. 2012. Yield components and grape composition responses to seasonal water deficits in Tempranillo grapevines. Irrigation Sci 30:339-349.

Junquera P, Lissarrague JR, Jiménez L, Linares R and Baeza P. 2012. Long-term effects of different irrigation strategies on yield components, vine vigour, and grape composition in cv. Cabernet-Sauvignon (*Vitis vinifera* L.). Irrig Sci 30:351-361.

López MI, Sánchez MT, Ramírez P and Morales J. 2009. Effect of a deficit irrigation regime on the quality of wines made from white grapes (*Vitis vinifera* L.) grown in semiarid areas. J Food Qual 32:481-503.

Matthews MA and Anderson MM. 1989. Reproductive development in grape (*Vitis vinifera* L.): Responses to seasonal water deficits. Am J Enol Vitic 40:52-60.

Mekonnen MM and Hoekstra AY. 2011. The green, blue and grey water footprint of crops and derived products. Hydrol Earth Sys Sci 15:1577-1600.

MKF Research. 2007. The impact of wine, grapes, and grape products on the American economy 2007: Family business building value. The Wine Business Center, St. Helena, CA. https://www.wineinstitute.org/files/mfk_us_econ_report07.pdf.

Roby G, Harbertson JF, Adams DA and Matthews MA. 2004. Berry size and vine water deficits as factors in winegrape composition: Anthocyanins and tannins. Aust J Grape Wine Res 10:100-107.

Romero P and Martinez-Cutillas A. 2012. The effects of partial rootzone irrigation and regulated deficit irrigation on the vegetative and reproductive development of field-grown Monastrell grapevines. Irrigation Sci 30:377-396.

Romero P, Gil-Muñoz R, del Amor FM, Valdés E, Fernández JI and Martinez-Cutillas A. 2013. Regulated deficit irrigation based upon optimum water status improves phenolic composition in Monastrell grapes and wines. Agr Water Manage 121:85-101.

Santalucia G, Barbagallo MG, Constanza P, Di Lorenzo R and Pisciotta A. 2007. Vegetative and reproductive behaviour of Vitis vinifera L. (cv. 'Cabernet Sauvignon') vines growing under non-irrigated conditions and moderate water stress induced by different irrigation systems. *In* International Workshop on Advances in Grapevine and Wine Research. Nuzzo E and Giulivo C (eds.), pp. 754:323-328. ISHS Acta Hortic.

Santesteban LG, Miranda C and Royo JB. 2011. Regulated deficit irrigation effects on growth, yield, grape quality and individual anthocyanin composition in Vitis vinifera L. cv. 'Tempranillo'. Agr Water Manage 98:1171-1179.

Scholander PF, Hammel HT, Hemmingsen EA and Bradstreet EA. 1964. Hydrostatic pressure and osmotic potential in leaves of mangroves and some other plans. Proc Natl Acad Sci USA 52:119-125.

Shellie KC. 2014. Water productivity, yield, and berry composition in sustained versus regulated deficit irrigation of Merlot grapevines. Am J Enol Vitic 65:197-205.

Williams LE and Matthews MA. 1990. Grapevine. *In* Irrigation of Agricultural Crops, Agronomy Monograph No. 30. Stewart BA and Nielsen DR (eds), pp. 1019-1055. ASA-CSSA-SSSA Madison, WI.

Williams LE, Phene CJ, Grimes DW and Trout TJ. 2003. Water use of young Thompson Seedless grapevines in California. Irrigation Sci 22:1-9.

Williams LE, Grimes DW and Phene CJ. 2010. The effects of applied water at various fractions of measured evapotranspiration on reproductive growth and water productivity of Thompson Seedless grapevines. Irrigation Sci 28:233-243.