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ORIGINAL PAPER

Interaction of applied water amounts and leaf removal in the fruiting zone on grapevine water relations and productivity of Merlot

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Abstract A study was conducted in the San Joaquin Valley of California on Merlot to determine the interaction of applied water amounts [at 0.4, 0.8, and 1.2 of estimated vineyard evapotranspiration (ET_c)] and leaf removal (at berry set or veraison) in the fruiting zone on productivity. Shaded area was measured beneath the canopy of the 1.2 irrigation treatment at solar noon throughout the study to provide an estimate of seasonal crop coefficients (K_c). Vine water status was assessed across treatments and years by measuring midday leaf water potential (Ψ_l). The maximum K_c determined from the percent shaded area was 0.7 at the row spacing of 3.66 m and canopy type that developed a "California Sprawl." Irrigation treatment had a significant effect on midday Ψ_l and no such effect for leaf removal. Clusters exposed to direct solar radiation had significantly higher temperatures and lower cluster Ψ than clusters in the shade. Irrigation treatment had a significant effect on berry weight, soluble solids, and titratable acidity. Yields of vines significantly increased as applied water amounts increased. In this wine grape production area, profitability is dependent upon yield. This study provided a reliable estimate of ET_c and applied water amounts to maximize yield.

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Introduction

Many of the effects of deficit irrigation (versus excess irrigation) on berry characteristics mimic the effects of light (more exposed versus shaded clusters) on the same parameters. Most of the studies examining the effects of canopy management practices on fruit composition and wine quality have failed to quantify their effects on vine water status. Conversely, most irrigation studies conducted to date have failed to quantify how soil or vine water status affects canopy characteristics or microclimate of the vine with a few exceptions (Chaves et al. 2007; dos Santos et al. 2003, 2007). Soil water deficits will reduce vegetative growth of grapevines resulting in smaller canopies and less leaf area per vine (Williams et al. 2010a) and a fruiting zone less congested with foliage (dos Santos et al. 2003, 2007). Therefore, some of the effects of deficit irrigation may result from a "better" microclimate within the fruiting zone similar to those resulting from canopy management practices. Canopy management practices that divide the canopy (either horizontally or vertically) or allow for greater penetration of light into the fruiting zone (resulting in higher fruit temperature and increased evaporative potential) may influence water relations of the entire vine or of individual clusters. For example, trellis type will influence water use of a grapevine (van Zyl and van Huyssteen 1980; Williams and Ayars 2005b) and consequently fruit and vine water status (van Zyl 1987). Higher fruit temperatures (which increases the berry to air vapor pressure difference) and greater evaporative potential within the fruiting zone may increase water use of the berries, which could change the berries' water potential (cluster water status). It has been demonstrated that transpiration of grape clusters increased in response to higher temperatures and changes in vapor pressure deficits around the fruit (Rebucci et al. 1997).

The majority of the wine grapes produced in the central/southern portions of the San Joaquin Valley of California are used for bulk wine production. Fruit used to make red wines from these areas typically have low acid, color, and tannins but more veggie taste and aroma. In recent years, efforts have been made to increase the quality of the grapes produced in this area. While irrigation studies (particularly the use of deficit irrigation) have been conducted on wine grapes in the coastal grape growing regions of California (Matthews and Anderson 1988; Williams 2010) or in raisin vineyards in the San Joaquin Valley (Grimes and Williams 1990; Williams et al. 2010a, b), no such studies have been conducted on wine grapes in the San Joaquin Valley. In addition, canopy management practices used in cooler grape growing regions (Downey et al. 2006; Smart and Robinson 1991) have not been tried in the San Joaquin Valley as cluster exposure to prolonged, direct sunlight may decrease berry quality in this hot growing region (Bergqvist et al. 2001).

A study was conducted across five growing seasons to investigate the interaction of different applied water amounts and leaf removal in the fruiting on vine and cluster water status, canopy size, and productivity of Merlot grown in the San Joaquin Valley of California. The three irrigation treatments consisted of applied water amounts at 0.4, 0.8, and 1.2 of estimated vineyard evapotranspiration (ET_c). Vineyard ET_c was estimated by measuring the amount of shade cast on the soil surface at midday and using the relationship between percent shaded area and the crop coefficient (K_c) given in Williams and Ayars (2005b) and then using the equation: $ET_c = K_c * ET_o$ where ET_o is reference ET (Allen et al. 1998). Irrigation amounts at a particular fraction less than that of ET_c applied throughout the growing season have been termed "sustained deficit irrigation" (SDI) (Fereres and Soriano 2007). Vine water status was used as a tool to determine whether applied water amounts resulted in midday leaf water potential (Ψ_l) values similar to those obtained by Williams et al. (2010a) for vines irrigated at 100 % of ET_c determined with a weighing lysimeter. Within each irrigation treatment, leaves were removed in the fruiting zone of the vines either at berry set or veraison. The control canopy management practice was no leaf removal at either time.

Materials and methods

Vineyard site and cultural practices

This study was conducted in a mature, *Vitis vinifera* L. cv. Merlot vineyard located near the city of Madera (lat. 36°55′N; long. 120°9′W) in the San Joaquin Valley of California from 2001 to 2005. The majority of the soil within the experimental portion of this vineyard was a Traver loam with a small portion of it a Grangeville fine sandy loam. The vines were planted on their own roots with 2.13 m between vines down the row and 3.66 m between rows (1,282 vines ha^{-1}). Vineyard rows were approximately east/west. The vines were trained to a bilateral cordon and pruned to 2-bud spurs. All treatments were pruned during the dormant portion of the growing season to the same number of spurs each year. The trellis was a cordon wire at a height of 1.28 m and a foliage catch wire 0.3 m above that. The canopy that develops using this training/trellis system with no shoot positioning has typically been referred to as the "California sprawl."

Irrigation treatments

Vines were drip-irrigated at 0.4, 0.8, or 1.2 of estimated ET_c once irrigation commenced. The three irrigation treatments were achieved using different numbers of emitters or emitters with different discharge rates. Vineyard ET_c was estimated as the product of reference ET (ET_o) and seasonal crop coefficients (K_c) (Allen et al. 1998). The seasonal K_cs used to schedule irrigations at this site were developed by measuring the shade cast on the ground beneath the canopy of vines being irrigated at the 1.2 treatment amount at solar noon at various intervals throughout the growing season each year of the study and then using the relationship between the percentage of shade and the K_c given in Fig. 10 of Williams and Ayars (2005b). The shaded area beneath the canopy was determined with a digital camera as outlined in Williams and Ayars (2005b). It was assumed that the K_c remained constant after full canopy had been reached since the vines were continually irrigated up to the end of October, similar to that found by Williams and Ayars (2005a). Reference ET was obtained from the California Irrigation Management Information System (CIMIS) weather station (#145) located ~15 km from the vineyard. Variables measured and calculations used to determine daily ET_o from CIMIS can be found in Synder and Pruitt (1992). Temperature data used in calculating degree-days were obtained from the same CIMIS weather station. Degree-days were calculated using the sine method with a lower threshold of 10 °C (see University of California Statewide Integrated Pest Management Project's Web site (www.ipm.ucdavis.edu) for details).

Irrigation treatments each year in this vineyard were not imposed until midday leaf water potential (Ψ_l) reached approximately −1.0 MPa for vines in the 1.2 irrigation treatment. Vines were irrigated once weekly from 2001 to 2004 beginning on Friday and generally ending by Sunday, with applied water amounts estimated to equal that required for the coming week. This was the schedule used by the cooperator to minimize pumping costs as electricity was cheaper on the weekend than during the week. The vineyard changed ownership in 2005 and the new managers irrigated the vineyard 2–3 times a week. Applied water amounts in each of the irrigation treatments were measured with inline (in the drip line) water meters. The meters had been calibrated prior to their use in this study.

Canopy management treatments

Canopy management practices included the manual removal of leaves and lateral shoots in the fruiting zone shortly after berry set or veraison (leaves in the control treatment were not removed) across all years of the study. Leaves and lateral shoots were removed from the base of the primary shoot up to the uppermost cluster on each. In most cases, the primary shoots were devoid of foliage up to node positions 6–8 from the base of the shoot after leaf removal took place. The earliest date across years in which leaves were removed from vines for the berry set treatment was May 26, 2004 and the latest date was June 25, 2002. The earliest date in which leaves were removed for the veraison treatment across years was July 7, 2004 and the latest date was July 27, 2002. The amount of shade cast on the ground as a function of both irrigation and canopy management treatments was quantified as described above after the removal of the leaves at set and veraison in 2002, 2003, and 2004. Leaf area per vine for the 0.8 treatment (vines growing in border rows) was estimated in 2004 by removing all shoots per unit length of row (0.5 m), taking the shoots back to the laboratory and measuring leaf area of all shoots with a LI 3100 area meter (LiCor Biosciences, Lincoln, NE). Total vine leaf area was estimated by multiplying leaf area of the subsample by 4.26 (distance between vines down the row/0.5). Area of the leaves removed at berry set in 2003 for the three irrigation treatments was determined by collecting all leaves removed from an individual vine and measuring their area as described above.

Measurement of vine water status

Leaf (Ψ_l) and stem (Ψ_{stem}) water potentials were measured as described by Williams and Araujo (2002). Occasionally, pre-dawn leaf water potential (Ψ_{PD}) was measured with data collected prior to sunrise. All water potential measurements were taken with a pressure chamber (model 1000; PMS Instrument, Corvallis, OR) on fully expanded, mature leaves. Leaf Ψ was determined on leaves exposed to direct sunlight at the time of measurement. Leaf blades for Ψ_l and Ψ_{PD} determinations were covered with a plastic bag, quickly sealed and petioles then cut within 1 to 2 s. The time between leaf excision and chamber pressurization was generally less than 10 to 15 s. Approximately 60 min before measurements, leaves for the determination of Ψ_{stem} were enclosed in plastic bags covered with aluminum foil. The plastic bag and aluminum foil enclosing the leaf blades were also inserted into the chamber during pressurization. Leaves chosen for Ψ_{stem} were selected from shoots on the shaded side of the canopy. Midday measurements were generally taken one-half hour on either side of solar noon (1300 h Pacific daylight time [PDT]) across dates and years measuring a single leaf from 3 individual vines per treatment in blocks 1, 3, and 5. Midday measurements of Ψ_l were measured on a weekly and occasionally a biweekly basis throughout the study. The first and last midday Ψ_l measurement dates in 2001, 2002, 2003, 2004, and 2005 were 16 May and 30 August, 3 May and 22 August, 13 May and 11 September, 13 April and 19 August, and 24 May and 11 September, respectively. Cluster water potential was determined similarly to that described by Greenspan et al. (1996). Clusters were enclosed in a plastic bag and then the peduncle severed within 1–2 s. The same pressure chamber used to measure Ψ_l was used to measure cluster Ψ. A daily time course of Ψ_l, Ψ_{stem}, and cluster water potential were measured on August 15, 2001 using 4 individual leaf or cluster replicates from a single vine in blocks 1, 2, 3, and 4.

Temperature and light measurements within the canopy

Temperature and relative humidity were measured in the vineyard with two temperature/relative humidity probes (model DM-84 Multimeter with MultiMeterMateRH/T probe, A.W. Sperry Inst., Inc., Hauppauge, NY) and on occasions a Pocket Sling Psychrometer (Cole-Parmer, Vernon Hills, IL). The probes were positioned just below the fruiting zone of vines, making sure they were completely in the shade. The probes were placed in two different treatment plots. Measurements with the sling psychrometer were taken between rows at a height of ~2 m. The probes were routinely calibrated in the laboratory and the outputs from the two were within 1 °C and 2 % relative humidity of calibration values. Cluster temperatures were measured with a portable infrared thermometer with laser pointer (Model # 39650-04, Cole Parmer Instruments, Co., FChicago, IL.) on two separate occasions. The thermometer was held approximately 35 cm from the surface of the cluster with the sun to the back for the measurements of clusters exposed to direct sunlight. Temperatures of clusters in the shade were fully shaded at the time of measurement. Photon flux density in the fruiting zone was measured with a Sunfleck Ceptometer (Decagon, Pullman, WA, USA) on a single date after leaf removal at berry set and again after leaves had been removed at veraison in 2002, 2003, and 2004. The light bar was inserted horizontally into the fruiting zone of the five center vines in each treatment plot.

Individual values within each plot were used for data analyses ($n = 25$).

Yield and components of yield

Vegetative growth was determined by taking pruning weights during the dormant portion of the growing season. Yield and cluster number per vine were measured at harvest. Pruning weights, yield, and cluster numbers were taken on the five middle vines in each leaf removal subplot. The yield components measured were berry and cluster weights, berries per cluster, and cluster number per vine. Berries (150 berries per sample) were sampled on a common date across treatments (prior to the actual harvest date) each year. Dates of berry sampling ranged from August 18, 2004 to August 30, 2005. Berries were sampled from each of the nine vines in the leaf removal subplots. Cluster weights were calculated by dividing total cluster weight per vine by cluster number per vine. Berries per cluster were calculated by dividing cluster weight by berry weight. Soluble solids (Brix), pH, and titratable acidity were measured on the juice of the berry samples using a temperature-compensating refractometer, pH meter, and titrating to an end point of pH 8.2 with 0.1 N NaOH, respectively. Irrigation treatments (and their leaf removal subplots) were harvested on the same date in 2001 and 2005 and from one to two weeks apart from 2002 to 2004. Yield was determined on the 5 center vines within each subplot.

Experimental design and data analyses

The experimental design was a split-plot factorial using completely randomized blocks. Blocks were imposed across rows with irrigation treatments randomly assigned to a specific row within each block. Each block was replicated 5 times. An individual block consisted of 6 rows (3 irrigation treatment data rows and 3 border rows; the border rows were between each irrigation treatment row) with each irrigation treatment row consisting of 30 contiguous vines. The border rows were irrigated at the 0.8 level. The leaf removal subplots were randomly assigned down each irrigation treatment data row with 1 border vine between subplots. Each plot consisted of 9 data vines. The berry composition, yield, yield components, and pruning weight data were analyzed as a split, split-plot ANOVA with irrigation treatment the main plot, leaf removal treatment a subplot and year a sub–subplot using CoStat v. 6.400 (CoHort Software, Monterey, CA, USA). There were significant interactions between irrigation treatment and year and leaf removal treatment and year but they will not be reported herein. Data collected on specific dates during a growing season were analyzed as a two-way ANOVA with irrigation the main plot and leaf removal the subplot. Duncan's multiple range test was used to separate means. Differences were considered significant at $P < 0.05$.

Results

Environmental data

Degree-day (DD) accumulation and estimated ET_c started each year on 15 March as this date is close to the beginning of budbreak for vines grown in the San Joaquin Valley. Degree-days from 15 March to 31 October ranged from 2177 in 2005 to 2417 in 2001 with a mean of 2298. The DDs accumulated here would indicate that this location was a Region V (Hot), based upon the classification of Amerine and Winkler (1944) using a base temperature of 10 °C. Degree-days from 15 March to 31 August averaged 1731 across years. Reference ET (ET_o) was fairly uniform across years and averaged 1250 mm from 15 March to 31 October (Table 1). Rainfall during 2001 was the least while that from 2005 the greatest, both prior to 15 March and during the growing season, across years. Dates of anthesis, veraison, and harvest ranged from 16–20 May, 15–26 July, and 25 August to 27 September, respectively, across years.

Table 1 Reference ET (ET_o) and estimated ET_c from 15 March to 31 October each growing season across the duration of the study

Years		Estimated	Rainfall		Irrigation treatment		
					Applied H_2O (% of ET_c)		
	ET_o (mm)	ET_c (mm)	Before 15/3 (mm)	After 15/3 (mm)	0.4	0.8	1.2
2001	1,261	729	137	40	33	64	92
2002	1,257	708	174	42	34	65	92
2003	1,241	714	183	42	31	63	94
2004	1,289	760	161	2	36	69	103
2005	1,204	663	191	83	41	78	124

Rainfall from 31 October the previous year up to 15 March in the current growing season and rainfall during the growing season (after 15 March) are also given. Applied water amounts as a percent of estimated ET_c are given in the rightmost columns

Calculation of ET_c

The percent of shade cast on the ground at solar noon beneath the canopy of vines irrigated at the 1.2 level was highly uniform across growing seasons (Fig. 1). In general, the amount of shade increased from early in the season until the canopy reached maximum size, approximately 750 DDs after 15 March, and thereafter leveled off. The maximum K_c used in this study was 0.7 (Fig. 2). Estimated ET_c of this vineyard, characterized by vines having a "California Sprawl"-type canopy and a row spacing of 3.66 m, was ~715 mm from 15 March to 31 October (Table 1). Estimated vineyard water use as a percent of the seasonal estimated ET_c from budbreak (15 March) to anthesis, budbreak to veraison, and budbreak to harvest was 10, 52, and 82 %, respectively, when averaged across years. Applied water amounts to all treatments the first 4 years of the study were less than the respective designated irrigation treatment acronyms. This was due in part to the fact that irrigation did not commence until midday Ψ_l reached a value of ~ -1.0 MPa for vines in the 1.2 irrigation treatment (Table 2) and that the cooperator applied less water than requested on several occasions. Applied water amounts in 2005 were actually close to the 0.4, 0.8, and 1.2 designated treatments due to the fact that the new owner applied more water than requested on numerous occasions once irrigation commenced.

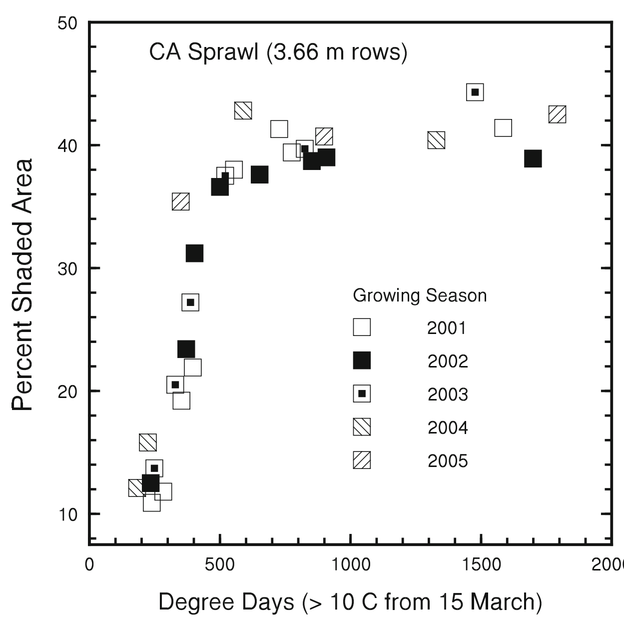

Fig. 1 The percent shaded area measured beneath Merlot grapevines over five growing seasons as a function of degree-days. Shaded area was determined on vines that had been irrigated at 1.2 of estimated ET_c Each data point is the mean of 3–5 individual measurements

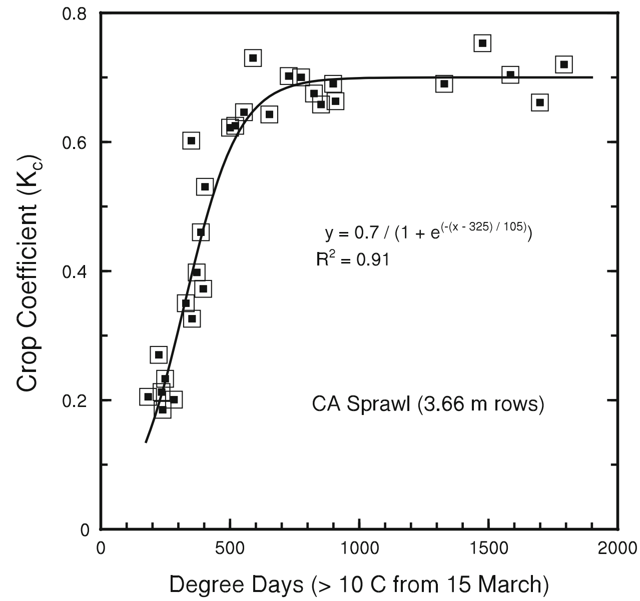

Fig. 2 The seasonal crop coefficient for a California Sprawl canopy on 3.66 m rows as a function of degree-days from 15 March. The individual values of the K_c are derived from the percent *shaded area* data in Fig. 1 using the following equation: $K_c = 0.017$ * percent *shaded area*

Table 2 Date of irrigation each year and midday leaf water potential (MPa) measured prior to that date

Years	Date of 1st irrigation	Irrigation treatment		
		0.4	0.8	1.2
2001	16 May	−1.03	−1.03	−1.03
2002	30 May	−1.16 b	−0.99 a	−0.93 a
2003	22 May	−1.18 b	−1.08 a	−1.04 a
2004	27 May	−1.04 c	−0.96 b	−0.89 a
2005	10 June	−1.06 c	−1.00 b	−0.94 a

Values of Ψ_l within a given year followed by a different letter are significantly different at the $P < 0.05$ level. The year 2001 was the first year of the study

Effects of irrigation treatments on vine water status

Midday Ψ_l of the 0.4 treatment from 2002 to 2005 prior to the initiation of the first irrigation of the year was significantly lower than that of the 1.2 treatment, while midday Ψ_l of the 0.8 treatment was significantly lower than that of the 1.2 treatment the last 2 years of the study (Table 2). The daily time course of leaf and stem Ψs was examined late in the 2001 growing season to determine whether one or the other was more discriminatory is assessing vine water status (Fig. 3). Pre-dawn Ψ of the 0.4 treatment on that date was approximately −0.3 MPa, while that of the 1.2 treatment was greater than −0.1 MPa. The only other

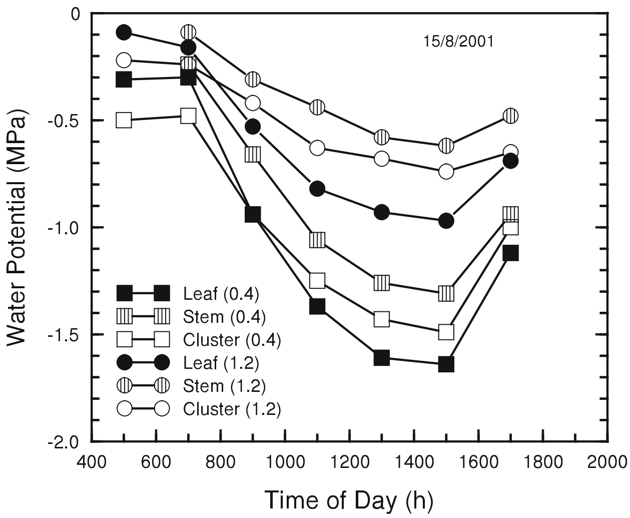

Fig. 3 The time course of leaf, stem, and cluster water potentials of Merlot grapevines irrigated at the 0.4 and 1.2 irrigation levels during the day on August 15, 2001. Each value is the mean of four individual measurements. The measurements of each leaf, stem, and cluster water potential were taken on an individual vine in four of the blocks in the 0.4 and 1.2 irrigation treatments

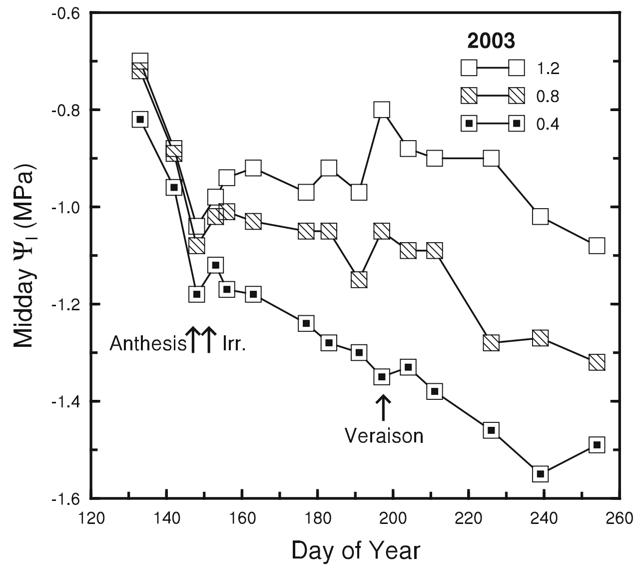

Fig. 4 The seasonal course of midday leaf water potential (Ψ_l) of Merlot grapevines irrigated at three fractions (0.4, 0.8 and 1.2) of estimated ET_c. Each value is the mean of 9 individual leaf replicates (3 leaves chosen from each of the defoliation treatments within the specific irrigation treatment). Weekly measurements of midday Ψ_l generally took place on Thursday or on Friday before irrigation started. The *first arrow on the left* denotes the approximate date of anthesis, the *second arrow* denotes the day when irrigations commenced and the *third arrow* is the approximate date of veraison. Harvest took place on days of year 262 for the 0.4 irrigation treatment and 270 for the remaining two irrigation treatments in 2003

time Ψ_{PD} was measured in this study was on July 29, 2004 where Ψ_{PD} for the 0.4, 0.8, and 1.2 irrigation treatments were −0.27, −0.17, and −0.1 MPa, respectively. The diurnal course of both leaf and stem Ψ followed the same patterns for both treatments with the daily minimum reached around 1500 h (PDT); however, those values were not significantly different from values obtained at 1300 h. Both leaf and stem Ψs were highly correlated with one another ($R^2 > 0.95$) using the data from this date (it should be noted that data for the 0.8 treatment were collected on that date but not included in Fig. 3 for the clarity of presentation). The daily pattern of cluster Ψ followed those of leaf and stem Ψs except it was lower than Ψ_{PD} of both treatments.

The seasonal pattern of midday Ψ_l for all irrigation treatments during 2003 (Fig. 4) is representative of those for the other growing seasons with the exception of the first year (data not given). Midday Ψ_l of the 0.4 irrigation treatment was significantly different from those of the other two irrigation treatments from the first measurement of the season onwards. Midday Ψ_l of the 0.8 irrigation treatment was significantly different from those of the 1.2 treatment from day of year 160 throughout the remainder of the 2003 growing season. Midday Ψ_l of the 1.2 irrigation treatment was greater than −1.0 MPa once irrigation commenced and remained such until late in the 2003 growing season. Seasonal, mean midday Ψ_l across the five-year study averaged −1.09, −0.93, and −0.82 MPa for the 0.4, 0.8, and 1.2 irrigation treatments, respectively (Table 3).

Table 3 Seasonal mean, midday leaf water potential (MPa) of Merlot grapevines as a function of irrigation treatment each year of the study

Years	Irrigation treatment		
	0.4	0.8	1.2
2001(11)	−1.04	−0.86	−0.78
2002(12)	−1.08	−0.92	−0.81
2003(15)	−1.24	−1.06	−0.91
2004(18)	−1.08	−0.91	−0.82
2005(15)	−1.11	−0.92	−0.78

The values within parentheses following year are the number of dates data were collected

Effects of leaf removal on canopy size, PFD in the fruiting zone, and water relations

Estimated leaf area per vine for vines irrigated at the 0.8 amount on May 12 and July 1, 2004 were 11.5 (±0.4 [SE]) and 14.3 (±1.0) m^2 $vine^{-1}$, respectively. The amount of leaf area removed at berry set in 2003 was 2.36, 4.40, and 4.32 m^2 $vine^{-1}$ ($n = 1$) for the 0.4, 0.8, and 1.2 irrigation treatments, respectively. Estimated leaf area per vine for vines irrigated at the 0.8 amount on the same date was 11.6 m^2 $vine^{-1}$ (±0.3, $n = 4$). The PFD measured in the

Table 4 The effects of date and irrigation and leaf removal (LR) treatments on photon flux density (PFD) measured in the fruiting zone of Merlot grapevines in 2003

Date	Leaf removal treatment	Photon flux density (μmol m^{-2} s^{-1})			
		Irrigation treatment			Ave. effect
		0.4	0.8	1.2	LR trtmnt.
12 June	Control	158 c	65 d	54 d	92
	LR:set	352 a	276 b	216 bc	281
	Ave. effect irr.	255	171	135	
11 August	Control	375 cd	223 ef	107 f	235
	LR: set	520 b	397 c	291 de	403
	LR: ver	616 a	454 bc	365 c	478
	Ave. effect irr.	504	358	254	

Each value is the mean of 25 individual measurements. Ambient PFD was 1718 and 1666 μmol m^{-2} s^{-1} on 12 June and 11 August, respectively. Leaf removal at berry set took place on 9 June and that at veraison took place on 23 July that year. Values of individual treatments followed by a different letter for each date are significantly different at the $P < 0.05$ level

Table 5 The effects of date and irrigation and leaf removal treatments on percent shaded area measured below Merlot grapevines on two dates in 2003

Date	Leaf removal treatment	Percent shaded area			
		Irrigation treatment			Ave. effect
		0.4	0.8	1.2	LR trtmnt.
2 July	Control	26.0	33.9	38.8	32.9
	LR:set	25.4	32.9	38.9	32.4
	Ave. effect Irr.	25.7 c	33.4 b	38.9 a	
14 August	Control	36.5	42.0	44.7	41.1
	LR: set	37.7	41.0	43.8	40.8
	LR: ver	34.0	40.7	43.5	39.4
	Ave. effect Irr.	36.1 c	41.2 b	44.0 a	

Each value is the mean of 6 individual measurements taken at solar noon. The percent shaded area was determined by dividing the total shade per vine by the area allocated per vine in the vineyard (7.8 m^2). The percent shaded areas for the cooperator's vineyard on 2 July and 14 August were 39.7 and 44.3, respectively. Other information is as given in Table 4

fruiting zone of the control vines (no leaf removal) at solar noon increased as irrigation amount decreased whether measured at berry set or veraison in 2003 (Table 4). This pattern was similar to those measured in 2002 and 2004 (data not given). There was a significant interaction between irrigation and leaf removal treatments for PFD measured in the fruiting zone at both phenological dates (Table 4), and this was also observed in 2002 and 2004 (data not given). Irrigation treatment had a significant effect on the amount of shade cast on the soil surface beneath the vines but the leaf removal treatments did not in 2003 (Table 5) or in 2002 and 2004 (data not given). The amount of shade cast on the soil surface for the 0.4 treatment at berry set and veraison was 66 and 82 %, respectively, that of the 1.2 treatment. Lastly, leaf removal had no significant effect on midday Ψ_1 measured on 4 dates in 2003 (Table 6) or on other dates in 2002 and 2004 (data not given).

Effects of irrigation amount and exposure on cluster Ψ and cluster temperature

The effects of irrigation treatments and cluster exposure (shaded or exposed to direct sunlight) on cluster temperature and water potential were examined on several dates (with results similar to those presented herein). Both irrigation treatment and cluster exposure had a significant effect on cluster temperature but there were no significant interactions (Table 7). There was a significant interaction between irrigation treatment and cluster exposure on cluster Ψ (Table 8). Shaded clusters always had the higher Ψ within an irrigation treatment compared to the sunlit clusters.

Effects of treatments on vine productivity and pruning weights

Year had a significant effect on berry weight, soluble solids, pH, and titratable acidity but there were no significant interactions among the irrigation and leaf removal treatments and year on those berry parameters (data not given). With the exception of berry weight, the leaf removal treatments had no significant effect on basic juice composition (Table 9). Berry weights of the 0.4 and 0.8 irrigation treatments were 81 and 96 % those of vines irrigated at the 1.2 level and berries of vines in which the leaves were removed at berry set or veraison were significantly smaller than those of the control (Table 9). Soluble solids were significantly affected by the irrigation treatments with vines irrigated at the 0.8 and 1.2 levels having lower sugar concentrations than berries of the 0.4 irrigation treatment when sampled on the same date. Titratable acidity (TA) decreased as applied water increased. Juice pH was unaffected by the irrigation treatments.

Year had a significant effect on yield, yield components, and pruning weights but there were no significant interactions among irrigation and leaf removal treatments and year on those parameters (data not given). Both irrigation and leaf removal treatments had a significant effect on yield of these vines but there was no significant interaction (Table 10). Irrigating vines at the 0.4 and 0.8 levels reduced yields by 35 and 13 % compared to the 1.2 treatment, respectively. The reduction in yield of the 0.4 irrigation treatments was due to fewer clusters per vine, lower cluster weight, and fewer berries per cluster compared to

Table 6 Midday leaf water potential (MPa) of Merlot grapevines measured as a function of date and irrigation and leaf removal treatments in 2003

Date	Leaf removal treatment	Irrigation treatment			Ave. effect LR Trtmnt.
		0.4	0.8	1.2	
12 June	Control	−0.99	−0.79	−0.67	−0.82
	LR: set	−0.99	−0.77	−0.65	−0.80
	Ave. effect Irr.	−0.99 c	−0.78 b	−0.66 a	
2 July	Control	−1.28	−1.09	−0.94	−1.10
	LR: set	−1.28	−1.08	−0.90	−1.09
	Ave. effect Irr.	−1.28 c	−1.09 b	−0.92 a	
24 July	Control	−1.34	−1.07	−0.91	−1.11
	LR: set	−1.32	−1.14	−0.89	−1.12
	LR: ver	−1.32	−1.07	−0.85	−1.08
	Ave. effect Irr.	−1.33 c	−1.09 b	−0.88 a	
27 August	Control	−1.56	−1.28	−1.04	−1.29
	LR: set	−1.53	−1.29	−1.00	−1.27
	LR: ver	−1.55	−1.25	−1.02	−1.27
	Ave. effect Irr.	−1.55 c	−1.27 b	−1.02 a	

Irrigation treatments were applied water amounts at 0.4, 0.8, and 1.2 of estimated ET_c. Canopy management treatments consisted of leaf removal (LR) in the fruiting zone either at berry set (set) or veraison (ver) or no leaf removal (control). There were no significant interactions between the irrigation and leaf removal treatments on any date. Values within the (Ave. Effect Irr.) rows followed by a different letter are significantly different at the $P < 0.05$ level

Table 7 The effects of irrigation treatment and exposure (sunlit vs. shaded) on cluster temperature (°C) measured on Merlot grapevines

Time of day (h)	Exposure	Irrigation treatment			Ave effect exposure
		0.4	0.8	1.2	
1500	Sunlit	39.7	38.8	38.1	38.8 a
	Shaded	32.8	31.3	31.1	31.7 b
Ave. effect irrigation		36.3 a	35.1 b	34.6 b	

Measurements were taken on July 8, 2002. Irrigation treatments were 0.4, 0.8, and 1.2 of estimated vineyard ET_c. Cluster temperature was measured with a hand-held infrared thermometer. Ambient temperature at the time of measurement was 34.5 °C. Each value is the mean of 14 individual replicates

the 1.2 treatment. Yield of the 0.8 treatment was reduced due to significant reductions in berry weight, cluster weight, and berries per cluster when compared to that of the 1.2 irrigation treatment. Yield of the berry set leaf removal treatment was significantly lower than the control leaf removal treatment due to fewer clusters per vine (Table 10).

Pruning weights were significantly reduced as applied water amounts decreased (Table 10). Pruning weights of the 0.4 and 0.8 irrigation treatments were reduced by 33 and 16 %, respectively, when compared to the 1.2 irrigation treatment. While the yield to pruning weight ratio differed significantly between the 0.4 and 0.8 irrigation treatments, the differences were rather small. The leaf removal treatments had no significant effects on pruning weights or the yield to pruning weight ratio.

Discussion

Estimates of vineyard ET_c

The maximum K_c utilized in this study, based upon the percent shaded area measured at solar noon, was 0.7. This is the same mid-season K_c recommended by Allen et al. (1998) for wine grape vineyards. That the two values are the same is probably fortuitous. Other typical row spacings for wine grape vineyards in the San Joaquin Valley with similar canopy sizes include 3.05 and 3.35 m. If this vineyard had been planted on a 3.35 m row spacing and the amount of shade cast on the soil surface at solar noon been similar to that measured in this study, the maximum K_c would have been 0.76. It would have been 0.84 for a 3.05 m row. Williams et al. (2003) reported that the

Table 8 The effect of irrigation amount and exposure (sunlit vs. shaded) on cluster water potential (MPa) of Merlot grapevines measured on July 5, 2002 at 1500 h

Irrigation treatment	Sunlight cluster	Shaded cluster	Ave. effect irrigation
1.2	−0.96 c	−0.79 a	−0.88
0.8	−1.06 d	−0.90 b	−0.98
0.4	−1.30 f	−1.19 e	−1.25
Ave. effect exposure	−1.11	−0.96	

There was a significant interaction between exposure and irrigation treatments on cluster water potential ($n = 5$). Other information is as given in previous tables

maximum K_c, determined with a weighing lysimeter, was 0.98 for vines using a 0.6 m cross-arm trellis and planted with a row spacing of ~3.35 m. Williams (2010) reported that the maximum estimated K_c for a vineyard employing a vertical shoot positioning (VSP) trellis and rows planted 3.05 m apart was 0.52. The above would indicate that the maximum K_c is a function of trellis and/or canopy type (Williams and Ayars 2005b) and row spacing and that the common mid-season, maximum K_c as proposed by Allen et al. (1998) for wine grape vineyards would not be appropriate in all circumstances. In addition, the value of the K_c used in this study remained at 0.7 up to the end of the growing season (October 31) since the vineyard was irrigated up to that date. It should be pointed out that the K_c values are for non-stressed crops cultivated under excellent agronomic and water management conditions and achieving maximum crop yield (i.e., standard conditions) (Allen et al. 1998). It had previously been shown that the K_c will remain almost constant up to the end of the growing season if the vines are irrigated at ET_c and the canopy remains functional, that is, there is no pest or disease damage (Daane and Williams 2003; Williams and Ayars 2005a). The only reason that the K_c value would decrease after harvest under most circumstances in the San Joaquin Valley is if irrigation is either reduced or terminated after that time, as shown by Williams et al. (2012).

Validation of the seasonal crop coefficients estimated for use in this study was done indirectly. Mean, midday Ψ_l measured throughout and at the end of the growing season across years for the 1.2 irrigation treatment was greater than −1.0 MPa. It has been demonstrated that values of midday $\Psi_l > -1.0$ MPa ($\Psi_{stem} > -0.7$ MPa; $\Psi_{PD} \geq -0.1$ MPa) indicate that vines are being irrigated at or greater than ET_c (Girona et al. 2006; Grimes and Williams 1990; Marsal et al. 2008; Williams and Baeza 2007; Williams et al. 1994, 2011: Williams and Trout 2005). It was also demonstrated in this study that berry weight of the 0.8 irrigation treatment was 96 % that of the 1.2 treatment. It has been shown that berry weight of Thompson Seedless was maximized at applied water amounts equivalent to 0.8 of measured ET_c (Williams et al. 2010b) while berry weights of Cabernet Sauvignon vines irrigated at 0.75 of estimated ET_c were 95 % of those of vines irrigated at 1.0 of estimated ET_c (Williams 2010). Therefore, both measurements of midday Ψ_l and final berry weights of the three irrigation treatments would indicate that applied water amounts, based upon estimated K_c values used in this study, provided a good estimate of ET_c.

Effects of leaf removal on PFD in the fruiting zone, canopy size, and water relations

The PFD measured in the fruiting zone of vines in the control leaf removal treatment and irrigated at the 0.8 and 1.2 levels were ~3 and 4 % at berry set and 6 and 13 % after veraison, respectively, compared to that measured above the canopy across years. These values are similar to those measured by Dokoozlian and Kliewer (1995) in the fruiting zone for dense canopies at berry set and veraison, respectively. The increase in PFD in the fruiting zone

Table 9 The effects of irrigation and leaf removal treatments on berry composition of Merlot grapevines grown in the San Joaquin Valley of California measured across the duration of this study (2001–2005)

Irrigation treatments			Leaf removal treatments		
0.4	0.8	1.2	Control	Berry set	Veraison
Berry weight (g berry^{-1})					
1.32 c	1.56 b	1.63 a	1.54 a	1.49 b	1.49 b
Soluble solids (Brix)					
22.8 a	21.8 b	20.9 c	21.9	21.9	21.7
pH					
3.70	3.70	3.69	3.68	3.70	3.71
Titratable acidity (g L^{-1})					
4.81 c	5.20 b	5.57 a	5.29	5.19	5.11

Berry samples generally were taken two weeks prior to harvest each year

Table 10 The effects of irrigation and leaf removal treatments on yield, components of yield, and pruning weights of Merlot grapevines grown in the San Joaquin Valley of California

Irrigation treatments			Leaf removal treatments		
0.4	0.8	1.2	Control	Berry set	Veraison
Yield (kg vine^{-1})					
11.7 c	15.7 b	18.1 a	15.8 a	14.6 b	15.2 ab
Clusters (# vine^{-1})					
80 b	92 a	95 a	92 a	85 b	91 a
Cluster weight (g)					
151 c	182 b	206 a	181	182	176
Berries cluster^{-1}					
113 b	113 b	122 a	120 a	115 b	114 b
Pruning weight (kg vine^{-1})					
1.04 c	1.31 b	1.57 a	1.35	1.26	1.29
Yield/Pruning weight (kg kg^{-1})					
11.3 b	12.1 a	11.5 ab	11.7	11.5	11.8

Values were averaged across all years of the study

reported here from berry set to veraison for all treatments is probably due to the increase in the weight of the shoots and clusters during that time period, pulling the basal portion of the shoots apart from one another, therefore providing more light into the center of the canopy. Light measured in the fruiting zone of the control leaf removal treatment for vines irrigated at 0.4 of estimated ET_c was significantly greater than those for the other two irrigation treatments on both dates. This is similar to that reported by dos Santos et al. (2007) when the PFD measured in the fruiting zone of their non-irrigated and deficit irrigated (applied water amounts at 50 % of their full irrigation treatment) treatments were compared to their full irrigation control. Leaf removal at berry set or veraison significantly increased PFD in the fruiting compared to the control leaf removal treatment across irrigation treatments. In several cases, PFD measured in the fruiting zone of vines in which leaves have been removed at berry set or veraison and irrigated at 0.8 and 1.2 of estimated ET_c were similar to the PFD measured for the control leaf removal treatment for vines irrigated at the 0.4 level. This would indicate that canopy management practices would be useful on increasing PFD in the fruiting zone while maximizing yield of vines irrigated with more water.

Irrigation treatment had a significant effect on the amount of shade cast on the ground at solar noon in this study. Such would be an indirect measure of canopy size due to vegetative growth and may be an appropriate means to assess light interception by grapevine canopies. Marsal et al. (2008) measured the fraction of light intercepted (FIR) at midday of vines irrigated with differing amounts of water as a measure of canopy size. dos Santos et al. (2003) measured canopy width in the fruiting zone of vines trained to a VSP trellis to characterize the effects of their irrigation treatments on growth and their possible effects on light in the fruiting zone. Despite a considerable amount of leaf area removed from the vines at berry set (estimated to be ~35 % of the total leaf area for the 0.8 irrigation treatment) or veraison in this study, there were no significant effects of the leaf removal treatments on the amount of shade cast on the ground at solar noon on either date. This would appear to be opposite to what one would assume based upon the PFD values measured in the fruiting zone in response to the leaf removal treatments. It should be pointed out that PFD in the fruiting zone was measured ~1.5 m above the soil surface, whereas shaded area was measured at the soil surface. Shaded area measured at solar noon would include shade cast on the soil surface by the vine's south facing canopy curtain. In addition, light also would have been absorbed by the fruit or leaves on the north facing canopy before reaching the soil surface. The fact that only irrigation treatment significantly affected midday values of Ψ_l measured at solar noon would support the contention that leaf removal did not affect the amount of light intercepted by the canopy (i.e., amount of canopy shade measured).

Effects of irrigation amount and light exposure on cluster water potential and temperature

It has been reported that clusters exposed to direct sunlight may be upwards of 10 °C greater than those in the shade at the time of measurement (Bergqvist et al. 2001; Spayd et al. 2002). In this study, temperatures of clusters exposed to direct sunlight were 7.1 °C greater than those in the shade at an ambient temperature was 34.5 °C. Irrigation treatment did have a significant effect on cluster temperatures but those differences were much less than those measured as a function of cluster exposure. Grape berries will transpire (Greenspan et al. 1996; Rebucci et al. 1997). Accordingly, cluster water potential will undergo a daily fluctuation, highest values prior to sunrise, and lowest from midday to later in the afternoon and that the absolute values during the day are a function of soil water availability (Greenspan et al. 1996). Such was found in this study (Fig. 3). Transpiration of grape berries will also respond to changing the vapor pressure deficit around the fruit via manipulation of temperature and relative humidity (Rebucci et al. 1997). Increased temperature of exposed clusters would increase the cluster (berry) to air vapor pressure difference resulting in greater berry transpiration. Therefore, transpiration of exposed fruit would be greater than that of shaded fruit, perhaps resulting in clusters on the same vine with differing values of water potential. Such has been recently found where the water potentials of clusters exposed to direct sunlight were lower than those in the shade at the time of measurement (Koch et al. 2012). In this study, there was a significant interaction between irrigation and exposure treatments on cluster water potential. Cluster water potentials of vines irrigated at the 0.4 amount were the lowest across treatments, while cluster water potentials of fruit exposed to direct sunlight on vines in the other two irrigation treatments were lower than those of their shaded cohorts. The above would indicate that canopy management practices allowing greater fruit exposure to sunlight, such as leaf removal or shoot positioning, can also affect the water status of clusters independent of the water status of the entire vine.

Effects of treatments on reproductive growth

The effects of the irrigation treatments on berry weight and composition were similar in many respects to those previously reported and summarized in Williams and Matthews (1990) and Williams et al. (1994). Berry weight significantly decreased as applied water amounts decreased, 4 % for the 0.8 treatment and 31 % for the 0.4 treatment compared to the 1.2 irrigation treatment. Soluble solids increased as applied water amounts decreased when berries were sampled on a common date. The irrigation treatments had no significant effect on berry juice pH but titratable acidity (TA) significantly increased as applied water amounts increased. The differences in TA among the irrigation treatments may have been due to differences in berry maturity when sampled on a common date. However, when fruit was harvested at similar soluble solids concentrations to make wine, TA values of the must were similar among the irrigation treatments in 2 out of 3 years (data not given).

There were significant effects of the leaf removal treatments on berry weight with weights of the berry set and veraison treatments lower than the control. Bergqvist et al. (2001) found that berry weights of Grenache and Cabernet Sauvignon grown in the San Joaquin Valley generally increased as exposure increased and then decreased with further increases in exposure (PFD measured at midday > 100 μmol m^{-2} s^{-1}) depending upon the side of the vine the clusters were located (north or south side of vines in east/west rows). The slightly smaller berries in the two leaf removal treatments compared to the control may be due to differences in cluster water potential with the more exposed clusters having a lower water potential. A similar explanation for the smaller berry size in the Bergqvist et al. (2001) study as light exposure increased may apply. The above results differ from those of Crippen and Morrison (1986) and Rojas-Lara and Morrison (1989) who found that berries of sun-exposed fruit were heavier than those grown in the shade. Differences among studies may be due to the fact that the two latter studies (Crippen and Morrison 1986; Rojas-Lara and Morrison 1989) were conducted in Napa Valley, a much cooler grape growing region compared to the San Joaquin Valley.

The leaf removal treatments had no significant effects on soluble solids, pH, or TA of the berries in this study. Bergqvist et al. (2001) found that soluble solids initially increased as light increased and subsequently decreased with further increases in light exposure. They also reported that TA generally decreased as PFD increased for both Grenache and Cabernet Sauvignon regardless cluster position (north or south side of the vine). The comparison of the effects of light exposure on the above three berry composition parameters in the Bergqvist et al. (2001) study may not be directly applicable to the results from this study. Many of the responses of soluble solids, pH, and TA to light exposure they described were maximized or started to decrease at PFD values > 100 μmol m^{-2} s^{-1} when PFD was measured perpendicular to the cluster's plane at midday. In this study, PFD was measured on a horizontal plane in the fruiting zone at midday and therefore values obtained may not be the representative of values actually measured on any particular cluster. It should also be pointed out that cluster exposure was transitory in this study; clusters were exposed to direct sunlight on and off throughout the day as leaves on the shoots above the clusters intermittently shaded them. Therefore, the data reported here would indicate that changes in PFD due to leaf removal in the fruiting zone and resulting changes in berry or cluster temperatures and duration of those changes were not different enough to affect those berry parameters.

The greatest yield for an individual treatment in this study across years was equivalent to 28.6 t ha^{-1}. The greatest and lowest mean yields as a function of year were equivalent to 24.3 (2002) and 15.7 t ha^{-1} (2004), respectively. Yield decreased as applied water decreased in this study, 35 and 13 % for the 0.4 and 0.8 irrigation treatments, respectively, compared to the 1.2 irrigation treatment. The reduction in yield by the two lower applied water treatments compared to the 1.2 treatment were due to fewer clusters per vine, lower cluster weights, and fewer berries per cluster. It has been demonstrated that yields of grapevines are a linear function of applied water amounts up to a certain point where it will level off (Grimes and Williams 1990; Marsal et al. 2008; Netzer et al. 2009; Salón et al. 2005; Williams et al. 2010b). It would appear that yields of the 1.2 irrigation treatment in this study were close to or had reached the yield to applied water ratio plateau.

The leaf removal treatments had a significant effect on yield. Cluster number per vine was the primary yield component affected with the control having more clusters per vine compared to the berry set leaf removal treatment, less so for berries per cluster. During several years of the study (2002–2004), the numbers of clusters per vine were counted when shoot length was approximately 30 cm and at that time, there were no significant difference among the leaf removal treatments (data not given). It is concluded that the reduced numbers of clusters at harvest for the berry set treatment was due to the inadvertent removal of clusters during the manual leaf removal process. It would appear that once the clusters were of considerable size (weight), such as at veraison, the inadvertent removal of clusters was less of a problem.

Pruning weights were significantly reduced as applied water amounts decreased. This is similar to that reported in numerous other studies (Williams and Matthews 1990; Williams et al. 1994). While there were significant differences in the yield to pruning weight ratios among the irrigation treatments, these differences were small. The ratios reported here were much higher (they averaged 18 and 17 in 2002 and 2003, respectively, across treatments) than normally assumed to be ideal for wine grapes, 4–7 (Smart and Robinson 1991). However, the yield to pruning weight ratios found in this study is similar to those of Thompson Seedless grown in the San Joaquin Valley (Williams et al. 2010b). This may indicate that the above "ideal ratio" suggested by others may not apply uniformly across grape growing regions.

Conclusions

Estimating ET_c as done in this study, measuring the amount of shade beneath the canopy at midday proved a reliable technique in calculating seasonal crop coefficients. The appropriateness of the crop coefficients were based upon the measurements of vine water status (midday Ψ_l). The midday values of Ψ_l were similar to those in other studies where vines were irrigated at full ET_c. In addition, berry size and productivity of the Merlot vines used in this study appeared to approach values of maximum size and yield at the highest irrigation level.

Leaf removal in the fruiting zone did not significantly affect vine water status as measured by midday Ψ_l. This is not unexpected as the amount of shaded area measured beneath the vines at solar noon was not different among the canopy management treatments. However, midday Ψ_l was significantly affected by applied water amounts. Cluster exposure did affect cluster water status; clusters exposed to direct sunlight at the time of measurement had lower Ψ values than those in the shade. This would indicate that increasing light in the fruiting zone via canopy management practices may affect berry composition as a result of their effect on cluster water status.

Despite an increase in yield per unit applied water as applied water amounts decreased in this study (3.2, 4.1, and 6.0 t ML^{-1} across years for the 1.2, 0.8, and 0.4 irrigation treatments, respectively), a grower's profitability is still based upon the quantity of fruit produced. Therefore, while sustained deficit irrigation (SDI) may be one means to increase fruit quality, the significant reductions in yields measured in this vineyard indicate that deficit irrigation is not economically sustainable in this grape growing region. While regulated deficit irrigation was not employed in this study, the author has found that deficit irrigating vines with applied water amounts at similar fractions of ET_c used in this study (0.4 and 0.8) from either berry set to veraison or from veraison to harvest will reduce yields of Cabernet Sauvignon grown in a hot region to the same extent as SDI at those fractions (L. E. Williams, unpublished data).

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