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ORIGINAL PAPER

The effects of applied water at various fractions of measured evapotranspiration on reproductive growth and water productivity of Thompson Seedless grapevines

Larry E. Williams · D. W. Grimes · C. J. Phene

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Abstract The reproductive growth and water productivity (WP_b) of Thompson Seedless grapevines were measured as a function of applied water amounts at various fractions of measured grapevine ET_c for a total of eight irrigation treatments. Shoots were harvested numerous times during the growing season to calculate water productivity. Berry weight was maximized at the 0.6–0.8 applied water treatments across years. As applied water amounts increased soluble solids decreased. Berry weight measured at veraison and harvest was a linear function of the mean midday leaf water potential measured between anthesis and veraison and anthesis and harvest, respectively. As applied water amounts increased up to the 0.6–0.8 irrigation treatments there was a significant linear increase in yield. Yields at greater applied water amounts either leveled off or decreased. The reduction in yield on either side of the yearly maximum was due to fewer numbers of clusters per vine. Maximum yield occurred at an ET_c ranging from 550 to 700 mm. Yield per unit applied water and WP_b increased as applied water decreased. The results from this study demonstrated that Thompson Seedless grapevines can be deficit irrigated, increasing water use efficiency while maximizing yields.

Introduction

Grapes are the single largest agricultural commodity in California with greater than 340,000 ha under cultivation (Anonymous 2008). Grapes are produced for use as raisins (dried fruit), table grapes (fresh fruit), concentrate and wine in California with gate receipts in excess of $3 billion (Anonymous 2007). The largest grape production area in California is within the San Joaquin Valley where all four grape types are produced with vineyard acreage in excess of 206,000 ha. Within this valley vineyards are irrigated either using groundwater or water that had been stored in reservoirs with snow melt from the Sierra Nevada Mountain range (Williams and Matthews 1990). Irrigation is required due to the fact that rain generally falls during the dormant portion of the growing season and that water storage in the soil profile is insufficient to meet vineyard evapotranspiration (ET_c).

In general, vines receiving no supplemental water or that are deficit irrigated will have less vegetative growth, smaller berries and lower yields than vines that are irrigated or irrigated with greater amounts of water (Williams and Matthews 1990; Williams et al. 1994). Deficit irrigation and/or moderate vine water stress has been associated with increased fruit quality, especially for grape cultivars used in wine production (Williams and Matthews 1990; Williams et al. 1994).

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L. E. Williams (✉)
Department of Viticulture and Enology,
University of California, Davis, CA, USA
e-mail: williams@uckac.edu

D. W. Grimes
Department of Land, Air and Water Resources,
University of California, Davis, CA, USA

L. E. Williams · D. W. Grimes
Kearney Agricultural Center, 9240 S. Riverbend Ave.,
Parlier, CA 93648, USA

C. J. Phene
Water Management Research Laboratory,
USDA-ARS, Parlier, CA 93648, USA

The relationship between yield and applied water amounts has been termed the crop water production function (CWPF) (Helweg 1991). More recent articles have emphasized the relationship between dry plant biomass production (or yield) per unit of water used (either plant transpiration or ET), termed water productivity (WP_b) (Fereres and Soriano 2007; Steduto et al. 2007). It has been shown that CWPF and WP are linearly related to applied water amounts and ET/transpiration, respectively, up to a certain point at which time the function levels off with further increases in applied water (Helweg 1991; Fereres and Soriano 2007). There are a few studies in which such functions have been developed for grapevines. Marsal et al. (2008) reported that yield of Tempranillo grapevines increased linearly with increased applied water amounts. Van Rooyen et al. (1980) reported similar results. Grimes and Williams (1990) concluded that there was a curvilinear relationship between relative yield of Thompson Seedless grapevines and relative crop ET. Yield was maximized at 100% of estimated ET_c in that study.

Williams et al. (2009) had previously demonstrated the effects of applied water amounts at various fractions of grapevine ET_c, measured with a weighing lysimeter, on soil water content, vine water relations and vegetative growth of Thompson Seedless grapevines grown in the San Joaquin Valley of California. This paper will report how the above described irrigation treatments affected the reproductive development and WP of the same Thompson Seedless grapevines. The irrigation treatments ranged from no applied water to applied water amounts at 1.4 of ET_c (a total of 8 treatments). It was anticipated that the range and number of irrigation treatments and duration of the study, which exceeded those of Grimes and Williams (1990), would provide us with enough data points to operate beyond the linear portion of the CWPF (Helweg 1991) and/or WP (Fereres and Soriano 2007). The inclusion of applied water amounts in excess of ET_c led to conclusions concerning possible negative effects of over-irrigation on grapevine productivity as has been shown for other crops (Helweg 1991).

Materials and methods

The *Vitis vinifera* L. (cv. Thompson Seedless, clone 2A) grapevines and treatments used herein were the same as those described previously (Williams et al. 2009). Grapevine water use for the 0.2, 0.6, 1.0 and 1.4 irrigation treatments throughout each growing season was calculated by summing the amount of applied irrigation water and the amount of water depleted in the soil profile up to the date measurements were taken. Grapevine water use from budbreak to harvest for the above-mentioned irrigation treatments was determined by adding the values presented in Tables 2 and 3 of Williams et al. (2009).

Bud fruitfulness was determined by dissecting buds using a compound microscope in January of 1991. Subsequently, the percent of the total buds that grew (percent budbreak) was determined by marking a single vine in each irrigation treatment replicate using the 0.6 m cross-arm trellis, counting the total number of shoots and dividing by the total number of buds ($n = 8$) in 1992, 1993 and 1994. The percent bud fruitfulness was determined on the same vines by counting the number of shoots with a cluster when the shoots were approximately 30 cm in length. Shoots were recorded as fruitful regardless the number of clusters per shoot. Subsequently, these values (percent bud fruitfulness) were calculated by dividing by the number of shoots per vine.

All shoots and clusters of individual grapevines were harvested at various times throughout the course of the study for the 0.2, 0.6, 1.0 and 1.4 irrigation treatments. The vines used were border vines separating the different trellises within a given irrigation treatment plot. Shoots were removed from the vines, taken to the lab and separated into leaves, stems (main axis of the shoot) and clusters. Fresh weights of the different organs were measured and then sub-sampled. Leaves and stems were dried at 60°C in forced air ovens for a minimum of 3 days or until no further decrease in weight was measured. The same procedure was used to dry clusters up until veraison (berry softening). Subsequent to veraison, clusters were dried in forced air ovens held at a temperature of 40°C, to minimize carmelization of the berries, until no further decrease in weight was measured.

Berries were sampled numerous times during each growing season using 50 berry samples per irrigation treatment. The last berry sample prior to harvest consisted of 100 berries per irrigation/trellis treatment. Soluble solids (°Brix), pH and titratable acidity (TA) were also measured on the juice of the berry samples using a temperature compensating refractometer (Model 10471 AO Abbe digital refractometer, American Optical Co., Buffalo, New York), pH meter (Orion Research Model 701A Digital Ionanalyzer, Ontario Research and Innovation Optical Network, Toronto, Canada) and titrating to an end point of pH 8.2, respectively. Fruit harvest took place at an acceptable soluble solids concentration and when it was possible to sell the fruit from this vineyard to a local winery for use as concentrate. The weights of the four center vines of each six-vine irrigation/trellis sub-plot were used for data analysis.

Data were analyzed via regression analysis using linear, quadratic, and cubic terms. Regressions with the best fit are presented. Reproductive growth and yield were analyzed using analysis of variance for either irrigation or trellis treatments and means separated using Duncan's multiple range test. The homogeneity of linear regression slopes was tested for all data sets in which slopes were compared. CoStat statistics software (CoHort Software, Monterey, CA, USA) was used for data analyses.

Results

Grapevine ET_c for the 1.0 irrigation treatment ranged from 574 to 829 mm across years (Table 1). Crop ET for grapevines in the 0.2, 0.6 and 1.4 irrigation treatments were 41, 69 and 125%, respectively, that of the 1.0 irrigation treatment.

Significant differences in berry weights among the irrigation treatments could occur as early as the first week in June (data not given). Berry weights among treatments at veraison were significantly different from one another, but year had a major effect as to the degree of separation (Table 2). Berry weights at harvest from 1990 to 1992 were remarkably similar at a particular irrigation treatment (Fig. 1). Berry weight increased from no applied water to the 0.8 irrigation treatment and then leveled off at greater applied water amounts. All berry weights for a particular irrigation treatment in 1993 were greater than those from previous years. Berry weight that year was maximized at the 0.6 irrigation treatment and it leveled off thereafter.

Table 1 Grapevine ET_c (mm)[a] calculated from budbreak until harvest for the 0.2, 0.6, 1.0 and 1.4 irrigation treatments across four years of the study

Year	Irrigation treatments (applied water at specific fractions of lysimeter water use)			
	0.2	0.6	1.0	1.4
	(mm)			
1990	266[a]	417[a]	574[a]	649[a]
1991	266	480	673	869
1992	244	405	638	758
1993	339	582	829	1119

The data in this table are derived from Tables 2 and 3 in Williams et al. (2009)

[a] Surface area per vine of 7.55 m^2

Table 2 Effect of irrigation treatments (applied water at various fractions of lysimeter water use) on berry weight (g 100 berries^{-1}) measured shortly after veraison each year of the study

Date	Irrigation treatment							
	0.0	0.2	0.4	0.6	0.8	1.0	1.2	1.4
7/17 90	60 c	77 b	90 a	99 a	104 a	99 a	94 a	96 a
7/21/91	82 b	83 b	87 b	95 ab	104 a	103 a	105 a	97 a
7/1/92	66 e	82 d	88 cd	96 b	106 a	100 b	94 bc	94 bc
7/13/93	102 c	118 ab	119 ab	123 a	116 ab	117 ab	114 b	114 b

The 0 treatment was irrigated at the 0.2 amount in 1991. Means followed by a different letter within a given year are significantly different at $P < 0.05$

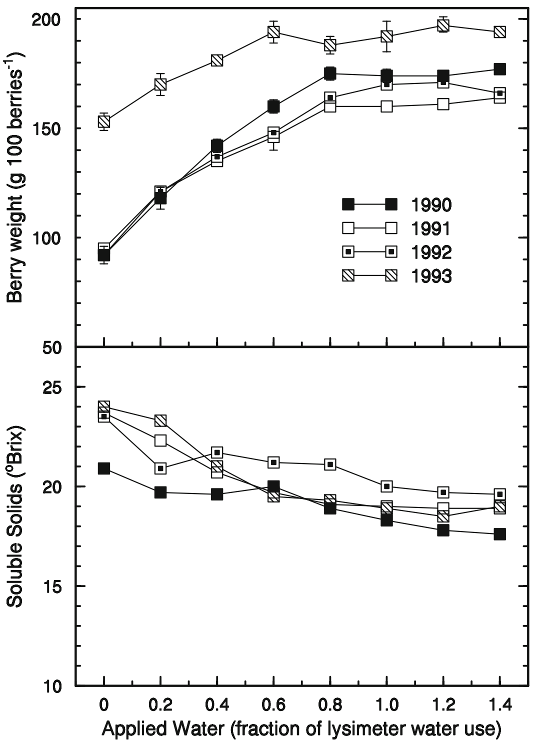

Fig. 1 Berry weights and soluble solids measured prior to harvest across all years of the study. *Values* represent the mean values of the irrigation treatments (a composite of all trellis treatments). *Bars* represent one SE and are shown when larger than the symbol

Berry weight at veraison was a linear function of the mean midday Ψ_l measured from anthesis to veraison (Fig. 2). It should be pointed out that berry weights of the 1.4 irrigation treatment in 1991 and 1992 and berry weights of the 1.0 and 1.4 irrigation treatments in 1993 were less at veraison than some of the treatments receiving less applied water amounts (Table 2). Berry weights measured at harvest were also a linear function of mean midday Ψ_l measured from anthesis to harvest. Finally, the increase in berry weight from veraison to harvest was a linear function of mean midday Ψ_l measured from veraison to harvest. The greater berry weights measured in 1993, compared to data from 1991 and 1992, were reflective of the higher Ψ_l values measured that year.

Soluble solids generally decreased as applied water amounts increased and there was some variation from year to year for a particular treatment (Fig. 1). As applied water amounts increased, titratable acidity in the juice of the berries increased (data not given).

With the exception of 1991 data, in which clusters abscised early in the growing season on vines in the 0 and 0.2

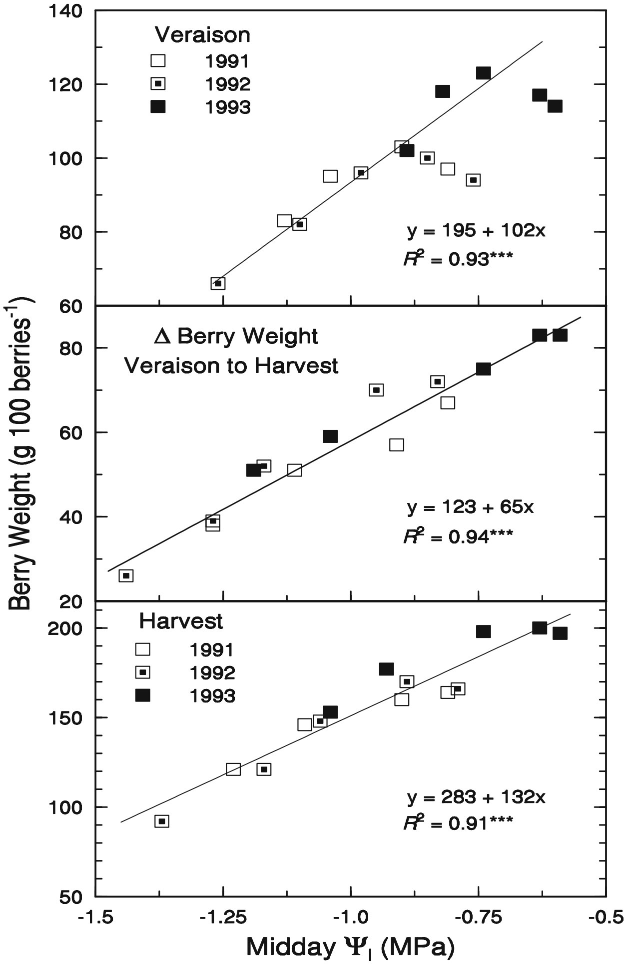

Fig. 2 Berry weight at veraison and at harvest as a function of mean midday Ψ_{l} measured between anthesis and veraison and between anthesis and harvest, respectively. Also included is the difference in berry weight between veraison and harvest each year as a function of mean midday Ψ_{l} measured between veraison and harvest. In the *top* graph, berry weights for the 1.4 irrigation treatment in 1991 and 1992 and for the 1.0 and 1.4 irrigation treatments in 1993 are not included for determining the relationship between berry weight and mean midday Ψ_{l} measured from anthesis to veraison

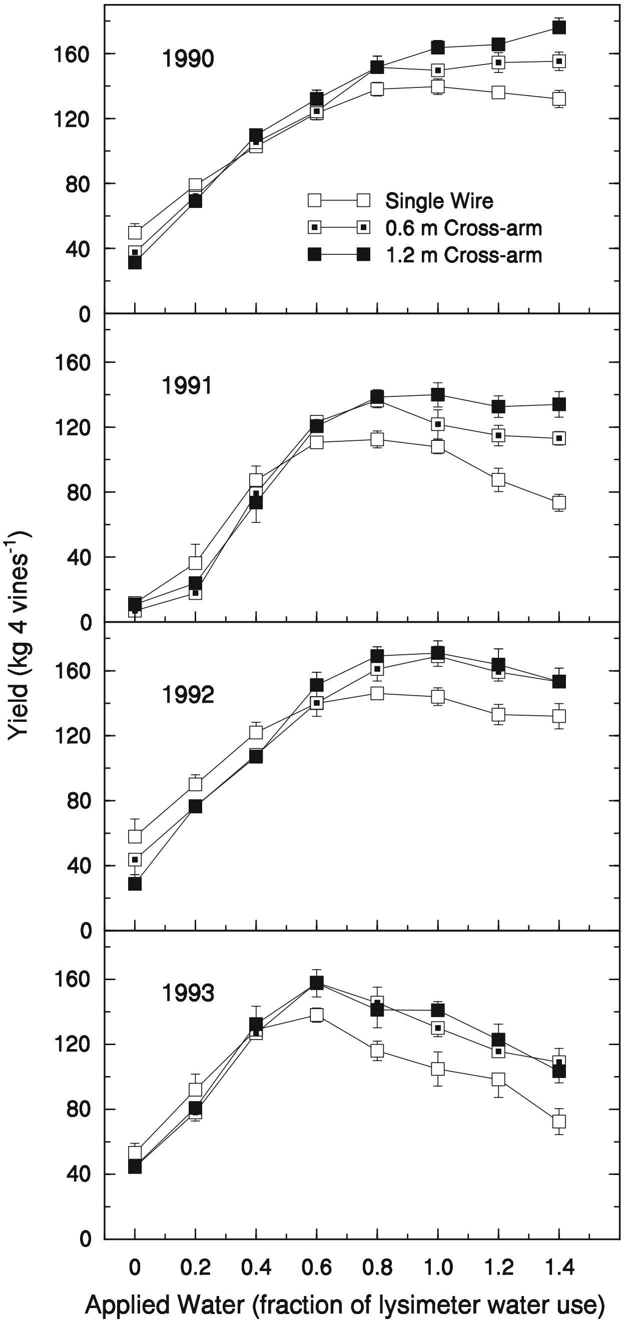

Fig. 3 Yield of Thompson Seedless grapevines as a function of irrigation and trellis treatments measured each year of the study. There were 1,326 vines per hectare. Individual data points within the figure multiplied by 0.331 are equivalent to metric tonnes per hectare. *Bars* represent one SE

irrigation treatments and less so for the 0.4 treatment, yield generally increased linearly as applied water amounts increased across all trellis treatments (Fig. 3). Yields were maximized at the 0.8 irrigation treatment for the 0.6 and 1.2 m cross-arm trellis treatments from 1990 to 1992. Applied water amounts greater than that for the 1.0 treatment reduced yields for the single wire cross-arm across all years compared to the other two trellises. Yields were maximized at the 0.6 irrigation treatment in 1993 with greater applied water amounts reducing yields for the remaining treatments. Reduced yields at the lower irrigation treatments were due in part to fewer clusters per vine (Fig. 4). With the exception of cluster abscission in 1991, fewer clusters per vine for those treatments were due to shorter shoots, fewer canes to choose from at pruning and a decrease in bud fruitfulness some of the years (Table 3). The reduction in cluster number per vine for the higher irrigation treatments was due to fewer buds that pushed and lowered bud fruitfulness when compared to the other treatments.

Yield was linearly related to mean, midday Ψ_{l} measured from anthesis to harvest from 1991 to 1993, excluding the

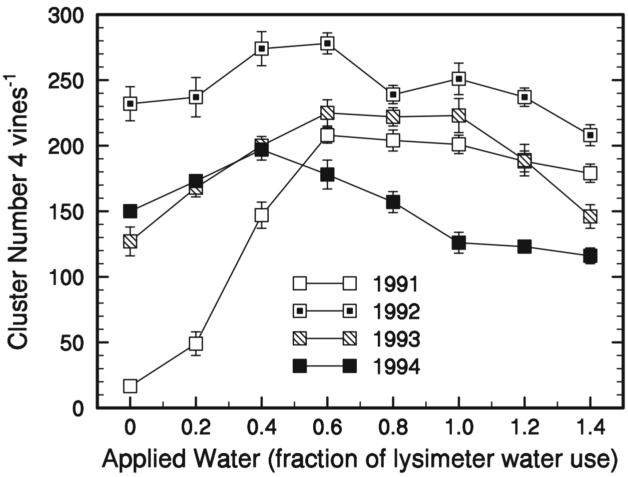

Fig. 4 The number of clusters per vine counted when shoots were approximately 30 cm in length within the 0.6 m cross-arm trellis subplot of each irrigation treatment. The data from 1994 is presented since it represents the effects of the previous year's (1993) treatments on bud fruitfulness. The *bars* represent one SE

yield data from the 1.0 and 1.4 irrigation treatments from 1993 (Fig. 5). Yields decreased rapidly as Ψ_{PD}, measured close to harvest each year, decreased from −0.1 to −0.2 MPa. Yields from 1992 and 1993 at a Ψ_{PD} value of −0.2 MPa were half those of the yields in treatments having higher values of Ψ_{PD}.

The fruit to pruning weight ratios generally increased from the no applied water to the 0.4 to 0.6 irrigation treatment across years (Fig. 6). For all higher irrigation treatments the ratio decreased.

The best fit between yield and grapevine ET was a second order polynomial (Fig. 7). This was regardless whether yields were expressed in absolute or relative values. Based upon the regression, yields were maximized at grapevine ET between 550 and 700 mm of water with increased applied water amounts reducing yield for this cultivar.

With the exception of 1991, yield per unit applied water decreased as applied water increased across years (Table 4). Yield per unit ET$_c$ was greatest for the 0.6 irrigation treatment, compared to the other three treatments, all four years. The WP$_b$ slopes of the Thompson Seedless grapevines differed significantly among the 0.2 (1992 data only), 0.6, 1.0 and 1.4 irrigation treatments based upon 2 years of data (Fig. 8). The slopes of the WP$_b$ also differed significantly between years for the 0.2 irrigation treatment.

Discussion

In this study applied water amounts in excess of ET$_c$ generally reduced the number of clusters per vine for those treatments due to fewer buds that broke and lowered bud fruitfulness compared to the other treatments. The decrease in bud fruitfulness for those treatments was probably due to increased shade within the canopy due to excessive leaf area (Williams et al. 2009). The reduction in the number of buds that grew in response to high amounts of applied water may have been due to primary bud necrosis and therefore a lack of primary bud growth at budbreak (Morrison and Iodi 1990; Perez and Kliewer 1990). Primary bud necrosis is thought to result from bud shading (Perez and Kliewer 1990) and/or increased shoot vigor (Lavee et al. 1981), both of which would have occurred in this study for vines receiving applied water amounts in excess of ET$_c$.

The percentage of buds that grew for the no applied water, 0.2 and 0.4 irrigation treatments were greater than those for treatments in which applied water amounts were in excess of ET$_c$ while bud fruitfulness of the former

Table 3 The percentage of buds that broke in 1992, 1993 and 1994 as a function of irrigation treatment for the 0.6 m cross-arm trellis and the percent fruitfulness of the buds that actually broke for the previously mentioned years

Irrigation treatment	1991	1992		1993		1994	
	% Fruitful	% Break	% Fruitful	% Break	% Fruitful	% Break	% Fruitful
0	87 a	93 ab	86 bc	93 ab	64 c	93 a	77 abc
0.2	78 ab	96 a	88 abc	95 a	69 bc	89 ab	86 a
0.4	–	88 b	94 a	99 a	80 ab	85 abc	82 ab
0.6	–	89 b	93 ab	97 a	84 a	81 bcd	70 bc
0.8	–	88 b	89 abc	84 cd	73 abc	77 cd	70 bc
1.0	70 b	90 b	93 ab	89 bc	78 ab	80 bcd	73 bc
1.2	–	80 c	83 c	85 cd	70 bc	75 cd	64 cd
1.4	–	79 c	82 c	81 d	77 ab	72 d	54 d

The percent fruitfulness of the three treatments in 1991 represents fruitfulness of buds that were dissected in January of 1991. The basal three nodes on each 15-node cane were not included in the analyses. Means followed by a different letter within each column are significantly different at the $P < 0.05$ level ($n = 20$)

– Data not collected

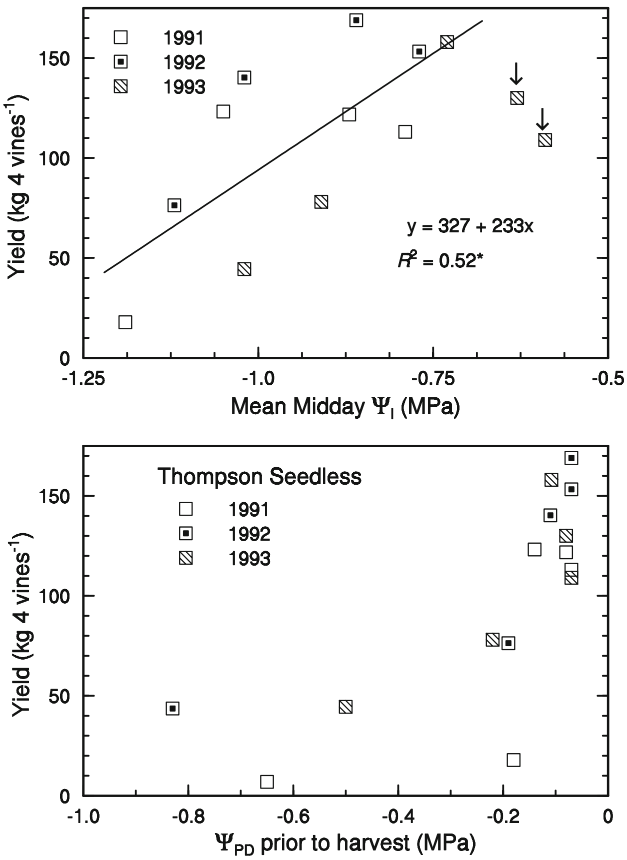

Fig. 5 The relationship between yield and mean, anthesis to harvest midday Ψ_l and Ψ_{PD} measured prior to harvest on grapevines in the 0.2, 0.6, 1.0 and 1.4 irrigation treatments from 1991 to 1993. Values from the no applied water treatment were included in the 1993 data set in the *upper graph* and for the same treatment across all years in the *lower graph*. Two data points (*arrows* above *symbols*) were not included in the regression analysis of yield versus mean Ψ_l

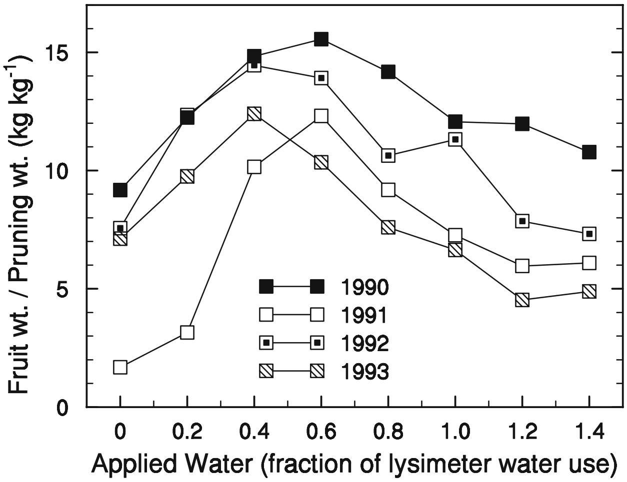

Fig. 6 The relationship between the fruit to pruning weight ratios as a function of applied water amounts measured only for vines in the 0.6 m trellis subplots. (n = 8)

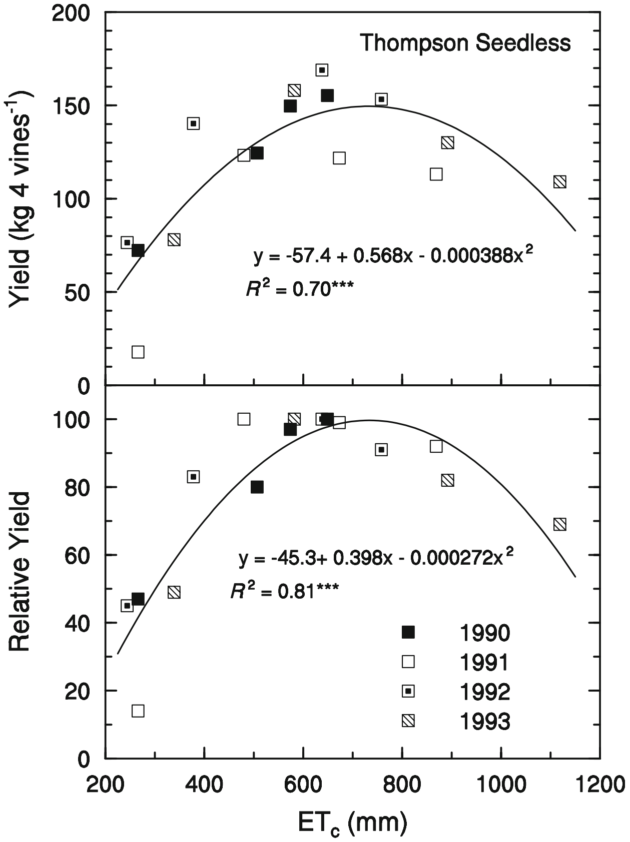

Fig. 7 Yield as a function of grapevine water use (ET$_c$) for the 0.2, 0.6, 1.0 and 1.4 irrigation treatments. Water use values were taken from Table 1. Relative yields represent the yield of each treatment divided by the highest yield recorded for a particular irrigation treatment within a given year

Table 4 Yield as a function of applied water amounts for all irrigation treatments and yield as a function of grapevine ET$_c$ for four (0.2, 0.6, 1.0 and 1.4) of those irrigation treatments

Year	Irrigation treatment (fraction of lysimeter water use)						
	0.2	0.4	0.6	0.8	1.0	1.2	1.4
Yield per applied water amounts (kg fresh weight m^{-3})							
1990	96.3	82.8	69.3	61.6	47.8	41.7	36.7
1991	17.8	40.2	42.5	34.6	25.6	21.9	16.9
1992	89.9	76.9	66.9	57.5	46.9	37.7	30.6
1993	69.3	62.5	48.4	34.5	24.7	17.8	14.4
Yield per ET$_c$ (kg fresh weight m^{-3})							
1990	35.9		39.4		34.6		31.6
1991	9.0		33.9		24.0		17.2
1992	43.0		45.8		35.1		26.9
1993	30.5		36.0		19.3		12.9

treatments were similar, less than or greater than the latter treatments in 1992, 1993 and 1994, respectively. It was reported that bud fruitfulness of severely water-stressed Shiraz vines was higher than vines within the other irrigation

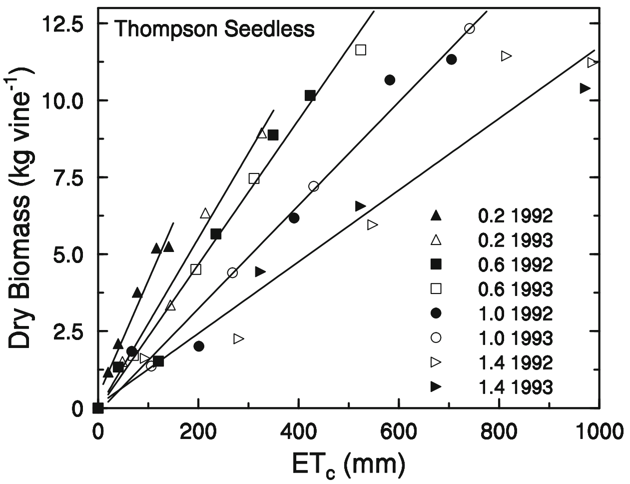

Fig. 8 Water productivity calculated for grapevines in four of the eight irrigation treatments. The regression equations found in the graph for a particular irrigation treatment and year are as follows: 0.2/1992, $y = 0.373 + 0.0385x$, $R^2 = 0.97$; 0.2/1993, $y = -0.025 + 0.0277x$, $R^2 = 0.99$; 0.6/1992 and 1993, $y = -0.033 + 0.0235x$, $R^2 = 0.98$; 1.0/1992 and 1993, $y = -0.133 + 0.0168x$, $R^2 = 0.98$; 1.4/1992 and 1993, $y = -0.097 + 0.0116x$, $R^2 = 0.97$. All regressions were significant at the $P < 0.001$ level

treatments in a study conducted in Australia (Smart et al. 1974). The increase in the percentage of buds that broke and bud fruitfulness for the deficit irrigated vines compared to vines receiving more applied water may be an indirect one since foliage and shoot density was less for those treatments resulting in greater light reaching the buds. As mentioned previously (see references cited above), shading has been associated with increased primary bud necrosis and decreased bud fruitfulness. The reduction in bud fruitfulness for the no and 0.2 applied water treatments compared to the other treatments in 1993 is similar to that demonstrated for Cabernet franc vines receiving no applied water over three growing seasons (Matthews and Anderson 1989) or Shiraz vines being deficit irrigated subsequent to veraison (Petrie et al. 2004). It has been shown that shoot internode diameter is correlated with bud fruitfulness across different grape cultivars, the smaller the diameter the lower the bud fruitfulness (Sánchez and Dokoozlian 2005). The lowest irrigation amounts employed in this study did reduce stem diameter compared to those irrigated at 0.6 of ET_c or greater (data not given).

Early on in the 1991 growing season, prior to the initiation of irrigation, cluster desiccation and/or abscission occurred on vines in the no applied water, 0.2 and 0.4 irrigation treatments. At this time shoot growth on vines in the 0.2 irrigation treatment had slowed considerably and midday Ψ_l was approximately −1.2 MPa at that time. The desiccation of whole or parts of clusters has been reported for container grown Cabernet franc (Hardie and Considine 1976) and Sultana (syn. Thompson Seedless) (Alexander 1965) grapevines. This occurred when the vines were exposed to severe water stress at or shortly after anthesis (up to 3 weeks later). Concurrent with a reduction in shoot growth in response to water stress young tendrils of grapevines have been reported to abscise (Alexander 1965; Winkler et al. 1974). Tendrils and clusters of grapevines are homologous organs, both derived from anlagen formed at the apices of primary buds during their development (Mullins et al. 1992). Therefore, the desiccation/abscission of clusters early in the growing season reported herein was probably due to water stress at that time, similar to that reported previously for tendrils on grapevines stressed for water.

Berry size is an important yield component in the production of raisins (Christensen 2000). Applied water amounts at 80% of grapevine ET_c maximized berry weight from 1990 to 1992 with no further significant increase with greater applied water amounts. Berry weight was maximized at the 0.6 irrigation treatment in 1993, a year in which SWC was greater at budbreak and thereafter than SWC measured in previous years (Williams et al. 2009). The greater availability of soil water in 1993 resulted in berries that were ~15% larger prior to harvest for treatments irrigated at the 0.8 level or greater than in previous years but ~60 and 35% larger for the no applied water and 0.2 irrigation treatments, respectively, for the same yearly comparisons. It has been shown that water stress during Stage I of berry growth, when cell division and cell elongation takes place, is more sensitive to water deficits than during Stage II of berry growth (subsequent to veraison) when only cell elongation takes place (Matthews and Anderson 1989; van Zyl 1984; Williams and Matthews 1990). The greater berry size across irrigation treatments at veraison and harvest and the greater percent increase for the no applied water and the 0.2 irrigation treatments in 1993 compared to the three previous years would indicate that this may have been the reason for the yearly differences reported in this study.

Berry weight at harvest has previously been shown to be a linear function of applied water amounts (Salón et al. 2005), a fruit stress index based upon the summation of root weighted soil matric potential from anthesis to harvest (Stevens et al. 1995) and mean Ψ_{PD} (Medrano et al. 2003). In this study berry weight at harvest was a linear function of applied water amounts for vines in the 0.6 m cross-arm trellis up to the applied water amounts received by the 0.8 irrigation treatment from 1990 to 1992 and up the 0.6 irrigation treatment in 1993. In addition berry weight at veraison and harvest and the difference in weight between veraison and harvest were linearly related to the mean, midday Ψ_l measured during those specific phenological events. The greater relationship between midday Ψ_l and berry weight reported in this study (R^2 values in excess of 0.9) than that reported by Medrano et al. (2003) using Ψ_{PD} as the independent variable ($R^2 = 0.48$) would indicate that midday Ψ_l is a better indicator of vine water status, especially when deficit irrigation was being used. The increase in berry weight subsequent to veraison across the 4-year study was ~30, 30, 35 and 40% of the final berry weight for the no applied water, 0.2, and 0.4 irrigation treatment and treatments with applied water amounts at 0.8 of ET_c or greater, respectively. It was reported that 75% of berry growth occurred during Stage I for Cabernet franc (Matthews and Anderson 1989) somewhat higher than found in this study for the lowest applied water amount treatments. Using the data in Fig. 2, a decrease in the mean midday Ψ_l from −0.75 to −1.25 MPa during the period from anthesis to veraison resulted in a 57% reduction of berry weight while a similar decrease in midday Ψ_l from veraison to harvest reduced berry weight (Δ berry weight) by almost the same percentage. This would indicate that a similar amount of vine water stress results in similar relative decreases in berry growth regardless the time in which the stress was imposed.

It is interesting to point out that berry weights for the 1.2 and 1.4 irrigation treatments were significantly less than the maximum weight recorded in other treatments at veraison in 1992 and 1993. A possible explanation for a reduction in berry weight due to over-irrigation in this study may be competition from excessive vegetative growth by those treatments for carbohydrates or a water-logging effect on growth of the berries in those treatments similar to that shown for shoot growth (Williams et al. 2009).

The maximum yield in this study was in excess of 50 t ha^{-1} for the 0.6 and 1.2 m trellis treatments, 3 out of the 4 years while that in 1991 was greater than 45 t ha^{-1}. Maximum yield of Thompson Seedless reported by Grimes and Williams (1990) was 30 t ha^{-1} while that in a commercial Thompson Seedless vineyard was estimated (yields were reported in dry raisin weights) to range from 25 to 30 t ha^{-1} (Peacock et al. 1987). One possible explanation for the higher yields reported here compared to the other two was that a new clone (2A) of Thompson Seedless, certified free of tested viral pathogens, was used in this vineyard. Thompson Seedless clone 1A was used in the Grimes and Williams (1990) study and probably in the Peacock et al. (1987) study. Another reason could be the high frequency of daily drip irrigations (irrigation occurred whenever the lysimeter used 2 mm of water).

Yield increased linearly as a function of applied water amounts up to the 0.6 or 0.8 irrigation treatments, depending upon trellis treatment. The exception was in 1991 when clusters abscised from vines in the no applied water treatment and the 0.2 and 0.4 irrigation treatments. Marsal et al. (2008), Netzer et al. (2009), Salón et al. (2005) and van Rooyen et al. (1980) also reported that yields of grapevines increased linearly with increasing applied water amounts. The CWPF is generally assumed to be linear up to a certain point at which time yield either levels off or starts to decrease due to excessive water in the soil profile (Helweg 1991). Yields of the 0.6 and 1.2 m cross-arm trellis treatments generally leveled off at applied water amounts in excess of the 0.8 irrigation treatment the first 3 years of the study. It was only in the fourth year of the study that yields decreased significantly at applied water amounts in excess of the 0.8 irrigation treatment. It is assumed that the reduction in yield by over-irrigating the vines was due to fewer buds that broke (perhaps due to primary bud necrosis or bud death) and lowered bud fruitfulness.

Yield of vines using the 0.6 m cross-arm trellis in this study was a linear function of the mean midday Ψ_l measured from anthesis until harvest. The coefficient of determination for this relationship (R^2) was 0.52. Grimes and Williams (1990) also found that yield of Thompson Seedless was a linear function of midday Ψ_l with a similar R^2 value (0.58). Marsal et al. (2008) found a linear relationship ($R^2 = 0.94$) between yield and average midday stem water potential (Ψ_{stem}). It is felt that the greater coefficient of determination found in the Marsal et al. study for this relationship compared to our study was not due the method of measuring vine water status (Ψ_{stem} vs. Ψ_l, respectively). It has been found that Ψ_l and Ψ_{stem} are highly correlated with one another (Stevens et al. 1995; Williams and Araujo 2002; Williams and Trout 2005), therefore the relationship between yield and Ψ_{stem} in this study would probably have been no greater than that for yield and Ψ_l reported here. Marsal et al. (2008) also regressed the mean value of yield and midday Ψ_{stem} collected over a 3-year period, which may have smoothed out the data. In this study yields varied considerably from year to year for vines irrigated in excess of ET_c, which may have decreased the reliability of the relationship. Finally, the data obtained in this study indicates that the irrigation treatment in the previous year had a large influence on final yield in the current growing season. Therefore, the measurement of leaf or stem Ψs would only provide an estimate of the water status of vines in the current season and how those deficits affected yield components that developed in the current year, such as that found for berry weight.

If is often assumed that Ψ_{PD} is a better indicator of grapevine water status than that of midday Ψ_l (Medrano et al. 2003). Williams and Trout (2005) though demonstrated that both Ψ_l and Ψ_{stem} were more highly correlated with soil water content, soil matric potential and applied water amounts than Ψ_{PD}. While Ψ_{PD} was not measured routinely in this study it was measured prior to harvest from 1991 to 1993 and at various times during the 1992 and 1993 growing seasons (Williams et al. 2009). It was shown that Ψ_{PD} measured close to harvest was the lowest value of the year for vines in the irrigation treatments receiving no applied water or that were deficit irrigated. Medrano et al. (2003) found that yields of Tempranillo and Manto Negro were a linear function of Ψ_{PD} but with a R^2 value of only 0.26. In this study, we found large decreases in yield with Ψ_{PD} decreasing from −0.1 to −0.2 MPa when measured at harvest. Similar results were found when berry weight was expressed as a function of Ψ_{PD} (data not given). The data presented in this study and the low correlation between yield and Ψ_{PD} found by Medrano et al. (2003) would indicate that the measurement of Ψ_{PD} may not truly reflect vine water status when deficit irrigation is being used in the study. It would also indicate that a Ψ_{PD} value of ≥ -0.2 MPa does not indicate little or no stress as proposed by Deloire et al. (2004).

The fruit weight to pruning weight ratio has been used as a measure of vine balance or crop load (Bravdo et al. 1984, 1985; Salón et al. 2005). Fruit quality of wine grapes was generally not adversely affected until this ratio exceeded 10 (Bravdo et al. 1984, 1985). In the present study, this ratio exceeded 10 for nearly all irrigation treatments in 1990 and for irrigation treatments ranging from 0.2 to 0.8 the remaining years. Sugar concentration in the fruit at harvest is one of the primary factors determining quality of raisins (Christensen 2000). The lower soluble solids concentrations in the fruit of vines irrigated in excess of ET_c occurred even though yields were less than those of the treatments receiving lower applied water amounts. Thus, despite the irrigation treatments that were being deficit irrigated having a higher fruit to pruning weight ratio than those being irrigated at ET_c or greater, soluble solids for the former treatments were generally significantly greater than those in the latter treatments. This would indicate that the fruit to pruning weight ratio may not apply uniformly across different grape commodities, especially when deficit irrigation is being used.

Actual or relative yield of Thompson Seedless grapevines trained to the 0.6 m cross-arm trellis were generally maximized at an ET_c (measured between budbreak and harvest) ranging from 550 to 700 mm in this study. Yield decreased significantly when grapevine water use was less than 400 mm. When grapevine water use exceeded 800 mm, yields also decreased significantly. The best fit of the data (using actual or relative yield) was a second order polynomial. Grimes and Williams (1990) reported that relative yield increased linearly as a function of relative ET_c. When the Grimes and Williams data was expressed as relative yield versus actual ET_c yields increased linearly up to an ET_c of 400 mm and leveled off at ET_c values between 600 and 800 mm (Williams and Matthews 1990). While maximum yields obtained in this study were much greater than those reported by Grimes and Williams (1990) the relative yields as a function of ET_c were similar.

Deficit irrigation is being touted as one means to increase water use efficiency, particularly for woody perennial crops (Fereres and Soriano 2007). The objective would be to reduce ET without a significant reduction in crop productivity. In this study vine productivity as a function of applied water amounts and ET_c were calculated as well as biomass WP_b (Steduto et al. 2007). Yield as a function of applied water amount increased as applied water amounts decreased (with the exception of 1991 when clusters abscised on vines in the 0.2 and 0.4 irrigation treatments early in the season). However, yield as a function of ET_c was greatest when applied water amounts were 60% of ET_c each year of the study. It would appear that one could increase water use efficiency of Thompson Seedless grapevines using a trellis system with either the 0.6 or 1.2 m cross-arm using the seasonal K_c developed for the 0.6 m cross-arm trellis (Williams et al. 2003) and then apply water at amounts from 60 to 80% of calculated ET_c across the growing season, reducing water use while maximizing economic return. Sustained deficit irrigation (SDI) used in this study has been shown to be least detrimental to yield of almond trees when compared with regulated deficit irrigation techniques (Goldhamer et al. 2006).

Many studies have shown that the relationship between biomass produced and water used (either expressed a transpiration or ET_c) is highly linear (Steduto et al. 2007). Such was found in this study with grapevines grown in the San Joaquin Valley of California and water use expressed as ET_c. The WP_b function was increased in this study by decreasing the amount of water applied to the vines. It should be pointed out that the slope of the WP_b decreased significantly for the 0.2 irrigation treatment from 1992 to 1993 due to an increase in water used by vines in that treatment due to extra water in the soil profile resulting in an increase in ET_c.

Conclusions

Reproductive growth of Thompson Seedless grapevines farmed for use as raisins or to be crushed for concentrate was determined in response to applied water amounts at various fractions of grapevine ET_c measured with a weighing lysimeter, over four growing seasons. The CWPF (yield per unit applied water) was best expressed as a curvilinear function similar to that shown for other crops. Yields of vines in this study were maximized at ET_c values ranging from 550 to 700 mm (measured between budbreak and harvest). Maximum yields were recorded across years with applied water amounts between 60 and 80% of ET_c. Yields were reduced at ET_c values less than 400 mm and greater than 800 mm. Over-irrigation of these vines reduced the number of buds that grew and bud fruitfulness. Berry weight increased linearly as applied water amounts increased up to the 0.6–0.8 irrigation treatment. The application of more water did not significantly increase berry weight further. Berry weight and yield were a linear function of mean midday Ψ_l while there was no obvious relationship between the two and Ψ_{PD} measured just prior to harvest.

Yield per unit applied water increased as applied water decreased across all irrigation treatments. This would indicate that one could increase the water use efficiency of grapevines just by reducing applied water amounts. However, yield per unit ET_c was maximized at the 0.6 irrigation treatment. The WP_b was linear across the four irrigation treatments and increased as ET_c decreased. The results indicate that water use efficiency in Thompson Seedless vineyards can be increased with sustained deficit irrigation while maintaining yields of high quality. Further research is needed to determine whether this can be achieved without high frequency drip irrigation.

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