Effect of Irrigation Amount and Preharvest Irrigation Cutoff Date on Vine Water Status and Productivity of Danlas Grapevines

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Abstract: An irrigation study was conducted in a *Vitis vinifera* L. (cv. Danlas) table-grape vineyard in Morocco with vines receiving no applied water (NI treatment) or one of two applied water amounts with subplots composed of three irrigation cutoff dates: early cutoff (EC) at berry set, late cutoff (LC) at veraison, and no cutoff (traditional irrigation, TI; based on grower practice). Midday leaf water potential (Ψ_l), canopy temperature (T_C), and soil water content were measured in several of the treatments. Midday Ψ_l was significantly correlated with soil water content (r = 0.89), ambient temperature (r = -0.71), and vapor pressure deficit (r = -0.62). The highest yield and berry weights were measured in TI vines followed by LC vines. NI vines had the lowest soluble solids at harvest. No significant differences were observed for fruit pH and titratable acidity among treatments. A comparison of NI and TI treatments indicated that yields increased as T_C - T_A (ambient temperature) and Ψ_l increased. Under the conditions of this study, an average T_C - T_A of -2.5°C or a Ψ_l of -1.0 MPa would be sufficient to maintain yield and fruit quality, while a Ψ_l value of -1.2 MPa would indicate water stress. Estimated vineyard evapotranspiration was much greater than the amount of water normally applied to vines in this region, and values of Ψ_l and temperature differentials indicated such. However, since grapes produced in this region are destined for the early table-grape market, results indicate that vines could be deficit irrigated or water applications could be terminated at veraison without a significant yield loss.

Key words: grapevines, irrigation, leaf water potential, canopy temperature, water status, growth, yield

Most studies conducted on grapevines have indicated that water deficits affect vegetative growth to a greater degree than fruit growth (Williams and Matthews 1990, Williams et al. 1994). Therefore, it is important not to stress grapevines during canopy development to protect the berries from sunburn, particularly in hot grapegrowing regions (Bergqvist et al. 2001). Vegetative growth of grapevines is much more affected by water deficits than is photosynthesis (Williams and Matthews 1990, Williams et al. 1994). After the canopy has developed sufficient leaf area, moderate water deficits can be imposed such that leaves remain functional while the rate of shoot growth is much reduced (Williams 1996, Williams et al. 1994).

The degree to which berry growth is affected by water deficits depends upon the time when the water stress is imposed and the severity of stress (Matthews et al. 1987). Withholding water between budbreak and veraison resulted in a 60% reduction in the maximum berry weight compared with berries from nonstressed vines (Smart et al. 1974). Berry growth is most susceptible to water stress during stage I of berry growth (between bloom and 4 to 5 weeks later) (McCarthy 2000). During this time cell division takes place in the berry (Mullins et al. 1992), and the smaller size of berries is due to a reduced number of cells per berry (Matthews et al. 1987). Differences in vine water status before veraison has been shown to have no effect on the onset of veraison, while withholding water after veraison can delay the accumulation of soluble solids under severe water deficits (Matthews and Anderson 1988).

An objective irrigation management strategy requires information on yield loss associated with quantified field water deficits and the ability to assess the adequacy of irrigation amount and frequency during the growing season (Grimes and Williams 1990, Williams 2000b). Seasonal (budbreak to the end of October) water requirements (crop evapotranspiration, ET_c) of a mature Thompson Seedless vineyard in the San Joaquin Valley of California varied from 700 to ~800 mm (Williams et al. 2003), depending on canopy size and how grapevines are farmed, such as for table-grape production (Williams and Ayars 2005a,b). Rainfall during the dormant portion of the growing season may provide 75 to 150 mm of the water requirement in semiarid grapegrowing regions depending on the timing of the rainfall, water-holding capacity of the soil, and rooting depth.

It is important to detect onset of vine water stress and subsequent decrease in turgor to a level that interferes with normal plant functioning in commercial vineyards (van Zyl 1987). There are various means of determining

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the water status of grapevines, such as the measurement of predawn leaf and midday leaf and stem water potentials; these methods are highly correlated with one another and with measures of soil water availability and leaf physiology (Grimes and Williams 1990, Williams and Araujo 2002, Williams and Trout 2005). It has also been shown that seasonal mean midday measurements of leaf water potential (Ψ_l) and stomatal conductance (g_s) are highly correlated with yield of Thompson Seedless grapevines (Grimes and Williams 1990).

Numerous studies have used canopy temperature to detect water stress in crops, including grapevines (Nielsen 1994, Sepaskhah and Kashefipour 1994, Grimes and Williams 1990). Investigators have standardized this procedure by determining the difference in canopy temperature (T_C) with that of ambient temperature (T_A) (Idso et al. 1977). Throughout the greater portion of the daylight period, T_C - T_A was a linear function of vapor pressure deficit (VPD) for plants transpiring at their potential rate, irrespective of other environmental parameters except cloud cover and wind (Idso et al. 1981). This linear relationship was defined as a nonstressed baseline. As soil water was depleted from the root zone or as the evaporative demand increased, a point would occur where the crop could no longer transpire at its potential rate, and T_C - T_A versus VPD would be located above the non-water-stressed baseline. In one study, canopy temperature of grapevines irrigated at various fractions of full ET_c differed throughout the day (Williams et al. 1994). Vines that were not irrigated or deficit irrigated at 0.2 of ET_c had canopy temperatures greater than ambient temperature, while those given applied water amounts at full ET_c or greater had canopy temperatures less than that of ambient on a hot day (ambient temperature ranged from 22°C at 0730 hr to 39°C at 1500 hr). Canopy temperature of vines irrigated at 0.6 of ET_c was equal to or slightly less than ambient temperature throughout the diurnal period. It is unknown if similar results would have been obtained on cooler days. It has been demonstrated that canopy temperature of grapevines was linearly correlated with soil water content (van Zyl 1986). Lastly, the Crop Water Stress Index (CWSI), which uses the canopy/ambient temperature differential departure from the nonstress baseline, was linearly related to yield of Thompson Seedless grapevines (Grimes and Williams 1990).

This study was conducted to evaluate the effect of various irrigation treatments, applied water amounts, and strategies (cutoff dates) on grapevine productivity in Morocco. This study also correlated various methods of determining vine water status with climatic conditions to derive objective criteria to be used in a vineyard irrigation management scheme in this table-grape production region.

Materials and Methods

The study was conducted in a commercial vineyard located in Skhirate (33°75’north; 7°8’west), south of Rabat, near the Atlantic coast of Morocco. This region is known for its early production of table grapes. *Vitis vinifera* L. used in this study were 12-year-old Danlas grapevines grafted onto the rootstock 110R. The vineyard soil was about 1 m in depth and composed of 70% sand, 6% silt, and 24% clay. Vine and row spacing were 1.5 and 3.0 m, respectively, with a row direction northwest to southeast. Vines were head-trained and pruned to four canes of 5 to 7 buds each. The trellis system was a double T (locally called a Pergolette). The lower cross arm was 0.4 m wide, and located 0.8 m aboveground. The upper cross arm was 0.8 m wide, and located 0.4 m above the lower one. The fruiting canes were tied to the wires on the lower cross arm and the current season’s shoots were positioned over the uppermost wires.

The vines were drip-irrigated using pressure compensating emitters (one emitter per vine). Four irrigation strategies were used in the study: no irrigation (NI), early irrigation cutoff at berry set (EC), late irrigation cutoff at veraison (LC), and irrigation the entire season (TI, traditional irrigation). The TI treatment represented the amount of water the cooperator normally would apply to vines in the vineyard. Within irrigated treatments, two applied water amounts were obtained by using different emitter sizes (2 and 4 L h^{-1}). Subsequent to harvest, all treatments were irrigated at the 2 or 4 L h^{-1} rate, depending upon treatment, to the end of August, amounting to 108 (24 mm) and 120 (26.7 mm) L $vine^{-1}$ in 2000 and 2001 for 4 L h^{-1} emitter treatments and half that for 2 L h^{-1} emitter treatments. Seasonal irrigation timing and length during an irrigation event was determined by the grower-cooperator. Reference evapotranspiration (ET_o) was estimated according to the Hargreaves and Samani (1985) formula using weather data (daily maximum and minimum temperature) obtained from an Institut Agronomique et Vétérinaire Hassan II weather station located 20 km from the vineyard. The crop coefficients (K_c) used to calculate ET_c (where $ET_c = K_c * ET_o$) were from Doorenbos and Pruitt (1986).

Vine water status and soil water content were simultaneously measured over two growing seasons in selected treatments (2000 and 2001). Soil samples from each block were taken weekly from the wetted zone to gravimetrically determine soil water content to a depth of 0.2 m. Seasonal midday leaf water potential (Ψ_l) was determined weekly with a pressure chamber as previously described (Ezzahouani and Williams 1995). Two to three leaves per replicate plot were measured on each sample date. Canopy temperature (T_C) was measured with a hand-held infrared thermometer (model 2010; Appareillage Industriel et Scientifique, Stockholm, Sweden). The infrared thermometer was held perpendicular to the upper portion of the sun-exposed canopy for a distance of 3 to 4 m (by walking along the row). Readings were always taken with the sun behind the operator, care being taken not to include sky, soil, or clusters in the field of view. Vapor pressure deficit (VPD) was calculated from ambient air temperature (T_A) and relative humidity determined with a ventilated psychrometer held 2 m above the soil surface. The Crop Water Stress Index (CWSI) was determined by a published empirical procedure (Idso et al. 1981). The CWSI is the ratio of the deviation of the measured T_C - T_A from a lower nonstressed baseline to the range between the nonstressed baseline and a zero transpiration baseline at a given VPD. The nonstress baseline in this study was determined with data collected from vines in the TI treatment (4 L h^{-1} water application rate) early in the growing season both years, as the amount of water supplied by the cooperator to the treatments used in the study later in the season was considerably less than estimated ET_c. During this time frame, the vines were still actively growing and it was assumed they were not stressed for water. The equation for the nonstressed baseline was $T_C - T_A = 0.80 - 3.25*VPD$ ($R^2 = 0.95$, n = 8).

Shoot length was measured weekly in 2001 on the same eight shoots in each plot until the shoots were hedged the second week of May. Cluster number and yield per vine were measured at harvest. Samples of 100 berries per replicate were randomly collected and analyzed for weight, soluble solids, titratable acidity (determined by titration with 0.133 N NaOH using phenolphthalein as indicator), and pH. Pruning weights were measured during the dormant portion of the growing season.

The experimental design was a split-plot replicated four times with irrigation amount as the main plot and irrigation strategy as the subplots. Each irrigation amount (rate) was randomly established within each block down a single row with 24 vines. Individual plots (strategy treatment) consisted of six vines within an irrigation amount treatment row leaving two buffer vines between plots. Data collected from the middle four vines were analyzed using analysis of variance and linear regression. Mean separations were determined using the Student-Newman-Keuls test. Means were averaged across years, as there was only one (soluble solids) significant year-by-treatment interaction.

Results

Anthesis, berry set, and veraison occurred earlier in 2000 than in 2001, with harvest taking place one week earlier in 2000 (Table 1). The mean March through July high and low temperatures in 2000 were 23.6 and 17.1°C in 2000 and were 22.6 and 15.2°C in 2001, respectively. During the period between budbreak and harvest, rainfall amounted to 73 and 21 mm in 2000 and 2001, respectively (Table 2).

Table 1 Dates of anthesis (bloom), berry set, veraison, harvest, and early and late cutoff for Danlas grapevines over a two-year period.

					Cutoff	
Year	**Anthesis**	**Berry set**	**Veraison**	**Harvest**	**Early**	**Late**
2000	Apr 18	May 04	Jun 29	Jul 14	May 04	Jun 29
2001	Apr 12	Apr 21	Jun 09	Jul 07	Apr 21	Jun 20

Table 2 Rainfall during the growing season in 2000 and 2001 and estimated ET_c and applied water amounts from budbreak to harvest in 2001 for Danlas grapevines grown in Morocco. Reference ET (ET_o) calculated according to Hargreaves and Samani (1985). The seasonal crop coefficients (K_c) taken from Doorenbos and Pruitt (1986).

Month/ period[a]	2000 rain (mm)	2001 rain (mm)	2001 ET_o (mm d^{-1})	K_c	2001 ET_c (mm d^{-1})	2001 ET_c (L $vine^{-1}$ 10 d^{-1})	2001 applied water (L $vine^{-1}$ 10 d^{-1})
March							
P1	0	0	3.3	0.25	0.82	37	8
P2	0	0	2.9		0.72	32	8
P3	0	23	3.6		0.90	40	8
April							
P1	45	0	4.4	0.45	1.98	89	8
P2	10	0	4.4		1.98	89	8
P3	13	2	4.8		2.16	97	8
May							
P1	5	16	4.8	0.6	2.88	130	24
P2	0	0	3.5		2.10	94	24
P3	0	0	4.7		2.82	127	24
June							
P1	0	0	5.4	0.7	3.78	170	36
P2	0	0	6.2		4.34	150	36
P3	0	0	7.0		4.90	220	36
July							
P1	0	0	6.0	0.7	4.20	189	24
P2	0	0	6.4		4.48	211	24
P3	0	0	7.0		4.90	220	24

[a] Periods represent approximate 10-day intervals.

Rainfall from September the previous year (1999 and 2000) until March 2000 and 2001 was 271 and 314 mm, respectively. Estimated ET_c between budbreak to the end of the month of harvest for the 2001 growing season was 430 mm. The amount of water applied to the TI treatment (with 4 L h^{-1} emitters) was ~200 and 300 L $vine^{-1}$ (44 and 67 mm) the first and second years, respectively. Estimated applied water amounts for the EC, LC, and TI treatments (irrigated with 2 L h^{-1} emitters) were 20, 114, and 150 L $vine^{-1}$ (4.5, 25, and 33 mm, respectively) in 2001. Estimated applied water amounts for the EC and LC treatments using the 4 L h^{-1} emitters in 2001 were 40 and 228 L $vine^{-1}$ (9 and 51 mm). Soil water content in the top 0.2 m the first and the second seasons ranged from 2.8 to 12.6% and from 2.8 to 16.8%, respectively, across all treatments.

Shoot length measured during the 2001 growing season was consistently greater for TI vines compared with EC and NI vines. The difference in shoot length between the TI and EC treatments was detected one week after the EC treatment was imposed, resulting in a significant difference in shoot length between the treatments two weeks later. On 2 May 2001, average shoot lengths for TI vines ranged from 131 to 127 cm depending on the rate of applied water. On the same date, shoot length was similar for the EC (114 cm) and NI (112 cm) vines. The rate of applied water had only a slight effect on shoot length. Shoots in all treatments were hedged the second week of May.

Midday Ψ_l declined throughout the season for all treatments both years. Early in each year, Ψ_l ranged from -0.7 to -0.8 MPa regardless of treatment. When subsequently measured on 8 Jul 2000, Ψ_l decreased to -1.4 and -1.7 MPa for the TI and EC treatments, respectively (Figure 1). On 6 Jun 2001 midday Ψ_l for the TI and EC treatments was -1.0 and -1.4 MPa, respectively, and for the NI treatment it was -1.2 MPa (Figure 2). Midday Ψ_l of the TI treatment was significantly ($p < 0.05$) correlated with soil water content (r = 0.89), ambient temperature (r = -0.71), and VPD (r = -0.62).

Canopy temperatures of the vines were generally cooler than those of ambient temperature regardless of treatment. During the first growing season the absolute values of ambient and canopy temperatures ranged from 19.8 to 36.5°C and 20.5 to 32.4°C, respectively. During the second growing season, ambient temperature ranged from 20.7 to 28.7°C while canopy temperatures of the TI vines ranged from 15.5 to 26.5°C. Canopy temperatures for the EC vines measured the first and second growing seasons ranged from 22.5 to 32.8°C and from 16.1 to 27.0°C, respectively. Canopy minus air temperature differentials (T_C - T_A) averaged -2.60 and -1.81°C in 2000 and -2.45 and -1.52°C in 2001 for the TI and EC treatments, respectively. Canopy temperatures for the NI vines ranged from 18.3 to 29.3°C during the 2001 growing season, with a mean T_C - T_A value of -0.17°C.

The T_C - T_A values of the TI treatment (4 L h^{-1} rate) subsequent to shoot hedging across two growing seasons were located above the nonstress baseline (Figure 3), indicating that even vines receiving the most applied water were not receiving enough to meet vineyard ET requirements. The seasonal, mean CWSI was 0.47 and 0.65 in 2000 and 0.39 and 0.58 in 2001 for TI and EC vines, respectively. The seasonal, mean CWSI for the NI treatment in 2001 was 0.93. Based upon the CWSI where the vines are no longer transpiring at their potential rate, Y_l corresponded to a value of -1.2 MPa.

The LC and TI vines had the highest yields, averaging ~14 kg $vine^{-1}$, and NI vines had the lowest yield (~11 kg $vine^{-1}$) (Table 3). TI vines had a 30% higher yield than NI vines and a 19% higher yield than EC vines. Doubling the amount of applied water had no significant effect on yield. There was a significant difference in yield per vine between the first and second growing seasons, 13.0 versus 12.3 kg $vine^{-1}$, respectively. However, there were no signifi-

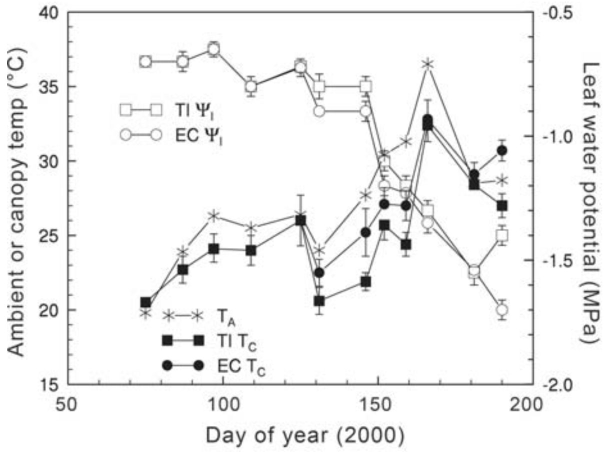

Figure 1 Effect of irrigation cutoff date (EC = early cutoff; TI = no cutoff; applied water amount = 4 L h^{-1} for both) on the seasonal values of leaf water potential (Ψ_l) and canopy temperature (T_C) in 2000. Ambient temperature at the time of measurement is shown. Measurements began on 15 Mar and concluded on 8 Jul. Irrigations were terminated for the EC treatment on 4 May (DOY 125). Values of Ψ_l and T_C are the means of at least eight individual measurements. Bars represent one standard error and are shown when larger than the symbol.

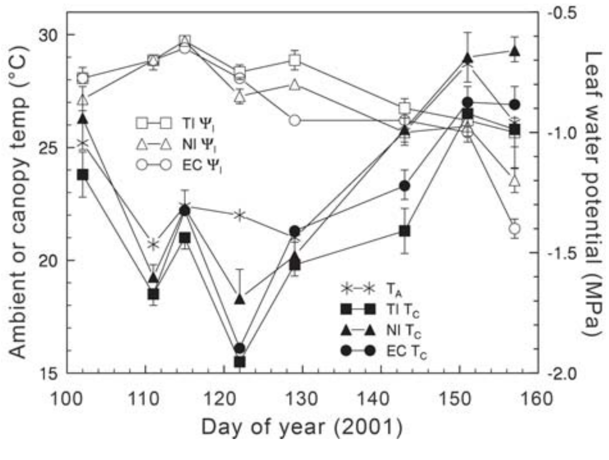

Figure 2 Effect of irrigation cutoff date on the seasonal values of leaf water potential (Ψ_l) and canopy temperature (T_C) in 2001. Measurements began on 12 Apr and concluded on 6 Jun. The early cutoff date was 21 Apr (DOY 111). Other information as given in Figure 1. NI denotes the nonirrigated treatment.

cant interactions among treatments. There were no significant differences in cluster number per vine related to irrigation treatments, interaction among treatments, or growing seasons. Lastly, there was a significant negative correlation (r = -0.92) between seasonal, mean CWSI of selected treatments and yield across the two-year study.

The highest and lowest berry weights were measured on the TI and NI vines (4.32 versus 3.21 g berry^{-1}) (Table 4), corresponding to a 34% increase in berry size because of irrigation. Withholding water at berry set significantly reduced berry weight ~16% relative to the TI vines. Withholding water at veraison had no significant effect on berry weight when compared with the TI treatment. There were no significant effects of irrigation amount or significant interaction among treatments on berry weight.

The number of berries per cluster was not significantly affected by treatments, but there was a significant difference between the two growing seasons. Averaged across all treatments, the number of berries per cluster was 134 and 150 the first and second year, respectively.

There was a significant difference in soluble solids between the NI and LC vines, while the EC and TI vines were intermediate (Table 5). There was no significant effect of the amount of applied water on soluble solids. However, year had a significant effect on soluble solids, the first year attaining higher soluble solids than the second. There was a significant interaction between irrigation cutoff treatments and growing seasons.

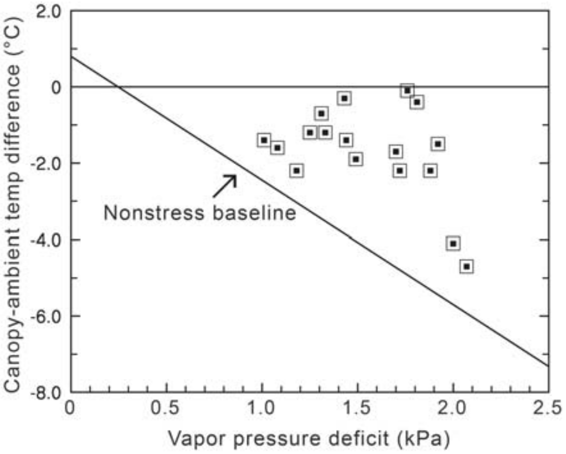

Figure 3 Effect of vapor pressure deficit on the canopy to ambient temperature difference of the TI (4 L h^{-1}) treatment in 2000 and 2001, midseason onward. Nonstress baseline is also shown (see Materials and Methods for equation).

Table 3 Average effect over two years (2000 and 2001) of irrigation treatments on yield (kg/vine) of Danlas grapevines. Data collected at harvest (14 Jul 2000, 7 Jul 2001). The NI treatment did not receive any water.

Applied water amount rate	Irrigation cutoff NI	EC	LC	TI	Avg effect of irrig amt.
2 L h^{-1}	10.80	11.55	13.24	14.33	12.48
4 L h^{-1}	10.94	12.26	14.06	13.95	12.80
Avg effect of irrig cutoff	10.87c[a]	11.91b	13.65a	14.14a	

[a]Means followed by a different letter within this row are significantly different at the 5% level using the Student-Newman-Keuls test.

Titratable acidity and pH of the fruit did not differ among treatments (data not given). However, these two parameters were significantly affected by year. Titratable acidity was 0.336 and 0.514 g 100 mL^{-1} for the first and second seasons, respectively, while pH was 3.04 and 3.23.

NI vines had the lowest pruning weight, TI and LC vines had the highest, and EC vines were intermediate (Table 6). Greater applied water significantly increased pruning weight. There was a significant ($p < 0.05$) negative correlation (r = -0.87) between seasonal, mean CWSI of the selected treatments and pruning weights across the two years.

Table 4 Average effect over two years (2000 and 2001) of irrigation treatments on berry weight (g berry^{-1}) of Danlas grapevines. Data collected at harvest (14 Jul 2000, 7 Jul 2001). The NI treatment did not receive any water.

Applied water amount rate	Irrigation cutoff NI	EC	LC	TI	Avg effect of irrig amt.
2 L h^{-1}	3.20	3.63	3.96	4.23	3.76
4 L h^{-1}	3.21	3.82	4.09	4.40	3.88
Avg effect of irrig cutoff	3.21c[a]	3.73b	4.02a	4.32a	

[a]Means followed by a different letter within this row are significantly different at the 5% level using the Student-Newman-Keuls test.

Table 5 Average effect over two years (2000 and 2001) of irrigation treatments on berry soluble solids (Brix) of Danlas grapevines. Data collected at harvest (14 Jul 2000, 7 Jul 2001). The NI treatment did not receive any water.

Applied water amount rate	Irrigation cutoff NI	EC	LC	TI	Avg effect of irrig amt.
2 L h^{-1}	13.9	14.6	14.6	14.1	14.3
4 L h^{-1}	13.7	13.9	14.3	14.4	14.1
Avg effect of irrig cutoff	13.8b[a]	14.2ab	14.4a	14.2ab	

[a]Means followed by a different letter within this row are significantly different at the 5% level using the Student-Newman-Keuls test.

Table 6 The average effect over two years (2000 and 2001) of irrigation treatments on pruning weights (kg vine^{-1}) of Danlas grapevines. Vines were pruned in December of 2000 and 2001. Data collected at harvest (14 Jul 2000, 7 Jul 2001). The NI treatment did not receive any water.

Applied water amount rate	Irrigation cutoff NI	EC	LC	TI	Avg effect of irrig amt.
2 L h^{-1}	1.90	2.61	2.64	2.70	2.46b[a]
4 L h^{-1}	2.90	3.10	3.60	3.70	3.32a
Avg effect of irrig cutoff	2.40c	2.85b	3.12a	3.20a	

[a]Means followed by a different letter within column are significantly different at the 5% level using the Student-Newman-Keuls test.

Discussion

Based on the climate data of 2001, estimated ET_c resulted in a seasonal (budbreak through the month of harvest) water requirement of 420 mm (~2000 L $vine^{-1}$). Seasonal (15 Mar to 31 Oct) water requirements (ET_c) of mature Thompson Seedless grapevines measured with a weighing lysimeter in the San Joaquin Valley of California can range from 718 to 865 mm and K_c may be greater than 1.0 (Williams et al. 2003). In one study, water use of Thompson Seedless grapevines for table-grape production ranged from 700 to 840 mm, with a maximum K_c of 0.95 (Williams and Ayars 2005a); water use between budbreak and harvest (18 Aug) in 1995 was 495 mm. While estimated water use in our study was less than that found in the San Joaquin Valley between budbreak and harvest, the differences are not that great. One reason for the difference could be the date of harvest, which occurred earlier in Morocco than in California. Differences in ET_o between the two locations could be another factor contributing to differences in vineyard ET. Reference ET as calculated in this study between 1 Mar and 31 Jul 2001 was 744 mm (Table 1), while historical ET_o at the Parlier site in San Joaquin Valley is 790 mm. Therefore, reference ET at the Morocco site was ~6% less than that at the San Joaquin Valley site. Lastly, the K_c used in this study at midseason to estimate ET_c was 0.7, less than that reported for table grapes (Williams and Ayars 2005a) Subsequent experiments by the senior author indicate that the maximum K_c used in this study was appropriate based upon the amount of shade measured beneath similar vines and estimating the K_c using the relationship between the K_c and percent shaded area (Williams and Ayars 2005b).

Leaf water potential has been found to decrease throughout the season even for vines that are well-watered (Williams and Matthews 1990), perhaps because Ψ_l of well-watered grapevines is a linear function of both ambient temperature and VPD, decreasing as both environmental parameters increase (Williams and Trout 2005, Williams and Baeza 2007). However, in this study the reduction in Ψ_l was probably associated with increased water stress, as the applied water amounts were much less than estimated ET_c. With the exception of early season measurements taken both years, reported Ψ_l (Figures 1 and 2) would be lower than predicted Ψ_l derived from the well-watered or fully irrigated baseline of the relationship between Ψ_l and ambient temperature or VPD reported by Williams and Baeza (2007), indicating that the vines were stressed for water. Water amounts applied to the vines in this study (TI treatment, 4 L h^{-1} emitters) are typical for commercial vineyards at this location in Morocco, where there is minimal water available for irrigation.

Assessing plant water status with the measurement of leaf or canopy temperature has long been used (Tanner 1963). Subsequently, the measurement of plant or canopy temperatures has been normalized with respect to environmental factors concomitant with the development of the CWSI (Idso et al. 1981, Jackson et al. 1988). The CWSI requires a non-water-stressed baseline describing the linear relationship between VPD and the canopy-air temperature difference. However, it has been demonstrated that this nonstressed baseline can be influenced by site selection for ambient temperature and VPD measurements (Idso et al. 1990) and crop type and its development (Nielsen 1994, Wanjura et al. 1990, Stockle and Dugas 1992, Sepaskhah and Kashefipour 1994). In fact, the non-water-stressed baseline (T_C - T_A versus VPD) found in this study differs from that reported elsewhere (Grimes and Williams 1990). The intercept and slope found in this study was 0.8 and -3.25, while that in the Grimes and Williams study was 0.7 and -1.57. These intercepts and slopes for grapevine also differ from those cited above in studies on different crops. Therefore, the non-water-stressed baseline used in this study may be site, cultivar, and/or trellis specific.

It was suggested in one study that canopy-air temperature differentials might be used in scheduling vineyard irrigation (van Zyl 1986); temperature differentials were significantly correlated with the change in soil water content (r = 0.65), stomatal resistance (r = 0.78), and midday Ψ_l (r = -0.68). Another study found that the seasonal values of the CWSI and midday Ψ_l were highly correlated (r = -0.87) (Grimes and Williams 1990), but in the current study there was only a weak relationship between the CWSI and midday Ψ_l (r = -0.56, p = 0.07). A nonsignificant relationship between CWSI and Ψ_l for sweet lime (*Citrus limetta*, Swing) has also been reported; however, the authors found that the inclusion of VPD in a multiple regression doubled the correlation coefficient for that relationship (Sepaskhah and Kashefipour 1994).

Vegetative growth is generally more sensitive to water deficits than is reproductive growth (Williams et al. 1994, Williams and Matthews 1990). The decrease in the rate of shoot growth was the first to be affected by the irrigation treatments in this study. Differences found here may have been more pronounced if shoots had not been hedged just before the period of active shoot growth (during May and June), which also coincided with higher ambient temperatures. Growth of lateral shoots, measured in the pruning weight data, reflected the effect of irrigation with an increase proportional to the duration and also the rate of irrigation. The greatest increase in pruning weights between the two application rates (2 versus 4 L h^{-1} emitters) occurred for the NI treatment, due to the NI treatment receiving postharvest irrigation along with the other treatments. In another study it was reported that an early irrigation cutoff of Thompson Seedless grapevines was accompanied by reduced shoot growth (Christensen 1975). Under the conditions of this experiment, with a limited supply of irrigation water, withholding water at berry set (EC treatment) did not result in a significant difference in shoot length when compared with the NI treatment.

Irrigation rate had no significant effect on yield or berry weight probably because the amount of applied water early in the growing season (March and April) was much less than estimated ET_c. It was during April in this study that potential berry size for this year's crop was determined (berry set) and cluster primordia differentiation for next year's crop begins (Williams 2000a). The low amount of applied water during this time (6% and 12% of estimated ET_c for the 2 and 4 L h^{-1} rates) and the lack of differences in midday Ψ_l among treatments early on would indicate that the availability of water to all treatments was the same during this period. Therefore, great differences in reproductive growth between the two irrigation rates would not be expected, especially when harvest takes place at relatively low sugar levels. However, the increase in yield per vine in this study was proportional to the duration of irrigation as it was related to irrigation cutoff treatments. Yield and berry weights of TI vines were significantly greater than those of NI vines (30 and 34% greater, respectively). The yield increase was mainly due to berry weight ($r = 0.59$) and less so to cluster number per vine ($r = 0.38$). The increase in berry weight caused a significant increase in cluster weight for TI vines compared with NI vines (data not given). There was a negative correlation between berry weight and the number of berries per cluster ($r = -0.60$). In a study on Thompson Seedless grapevines, there was a linear increase in yield as applied water increased from 0 to 100% of estimated ET_c (Grimes and Williams 1990). In another study on Thompson Seedless, yield and berry weight increased as applied water increased from 0 to 80% of ET_c (Williams 2000b). Berry weight leveled off at 80% ET_c applied water, while yield for some of the trellis treatments actually decreased with more applied water. Season-long applied water to the TI treatment (with 4 L h^{-1} emitters) in the current study was 10% and 16% of estimated ET_c from budbreak to harvest the first and second years of the study, respectively. Data from other studies would indicate that the highest applied water amount in this study was probably less than the amount that may have maximized yield of these vines (Grimes and Williams 1990, Williams 2000b).

Comparison of the NI, EC, and TI treatments showed that as yields increased, their $T_C - T_A$ values increased (-0.17, -1.52, and -2.45, respectively) and their minimum Ψ_l values decreased (-1.4, -1.2, and -1.0 MPa, respectively). Both yield and pruning weights in this study were significantly (negatively) correlated with the seasonal, mean CWSI of the selected treatments. In a study on Thompson Seedless grapevines, a linear relationship between vine productivity and the CWSI and midday Ψ_l was found (Grimes and Williams 1990).

Withholding water at berry set also affected yield components, with significant reductions in yield per vine and berry weight compared with the FI treatment. Berry weight has reported to be most sensitive to water stress subsequent to anthesis (McCarthy 1997, 2000). Results from this study are similar to one in which the early irrigation cutoff date reduced berry size, possibly because of the low water-holding capacity of the vineyard soil, which was 70% sand (Christensen 1975). A reduction in Syrah berry weight and sugar accumulation in the fruit occurred when vines were deficit irrigated from berry set to veraison and veraison to maturity, respectively (Ojeda et al. 1998). Withholding water at veraison (late cutoff date) did not significantly reduce yield when compared with the TI vines. Waiting until veraison to terminate the irrigation resulted in significantly greater yield and a slight increase in berry weight when compared with the berry set cutoff treatment.

Soluble solids were significantly affected by irrigation treatments while pH and titratable acidity were not. The lowest berry fruit soluble solids concentration and content were measured on fruit from the NI vines, averaging 13.8 Brix and 0.44 g $berry^{-1}$, respectively. Relative to the NI vines, withholding water at berry set did not affect significantly soluble solids concentration; however, there was a significant difference in sugar per berry for the EC and NI vines (0.53 versus 0.44 g soluble solids $berry^{-1}$, respectively). Even though fruit soluble solids were highest for the LC vines, indicating earlier maturity, soluble solids per berry were highest for the TI vines. Another study reported that deficit irrigation after veraison affected fruit composition but not the size of berries (Ojeda et al. 1998). Under the conditions of this study, in an early table-grape production region, irrigating beyond veraison may be not advisable since grapegrowers want earlier ripening even if there may be some yield loss.

Yield of Thompson Seedless was reduced when seasonal values of midday Ψ_l and the CWSI were less than -0.9 MPa and greater than 0.2, respectively (Grimes and Williams 1990). Under the conditions of this study, it is necessary to have moderate vigor early on for the production of early Danlas table grapes, which could be accomplished by limiting the CWSI to ~0.4, corresponding to a Ψ_l of -0.8 MPa and a $T_C - T_A$ of -2.5°C. Since Ψ_l can decrease throughout the season, a minimum value of -1.2 MPa would correspond to the maximum CWSI (0.7) recorded in this study.

Conclusions

Estimated daily water use at a table-grape vineyard in Morocco ranged from 3 to 22 L $vine^{-1}$ while estimated vineyard water requirements from budbreak to harvest averaged 2000 L $vine^{-1}$ (420 mm). This study demonstrated that commercially grown grapevines at this location are generally underirrigated with regard to estimated vineyard ET. The use of an infrared thermometer was a sensitive and rapid technique to determine vine water status. Under the conditions of this study, a $T_C - T_A$ of less than -2.5°C or a CWSI greater than 0.4 could be considered a value to indicate initial vine water stress. A midday Ψ_l of -1.0 MPa could also be considered a threshold value when grapevines initially experience water stress. Given these criteria, either technique could be used to determine when to initiate irrigations early in the growing season. They could also be used to determine the interval between irrigation events or serve as a baseline in production areas where grapegrowers do not want to stress their vines and there is ample water for irrigation purposes. Under limited water reserves and based upon the treatments imposed in this study, an irrigation cutoff at veraison would conserve water and minimize any yield reduction. This treatment may also accelerate the accumulation of sugar in the berries and possibly prompt an earlier harvest and thus better market conditions.

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