Interaction of rootstock and applied water amounts at various fractions of estimated evapotranspiration (ET_c) on productivity of Cabernet Sauvignon

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Abstract

Background and Aims: It is commonly thought that grapevine rootstocks vary in their tolerance to drought. This study examined the interaction between various applied water amounts and productivity of Cabernet Sauvignon grafted onto five rootstocks.
Methods and Results: The commercial vineyard used in this study was located along the central coast of California. The rootstocks used were Teleki 5C, 110 Ricter, 140 Ruggeri, 1103 Paulson and Freedom. Irrigation amounts ranged from 0.25 up to 1.25 of estimated vineyard evapotranspiration. Midday leaf water potential (Ψ_l), was significantly affected by irrigation treatment but not by rootstock. There was a significant effect of irrigation treatment and rootstock on berry weight, number of bunches per vine and yield but no interaction between those two factors. The rootstock 5C had the lowest yield compared with the other rootstocks. Yield at the 0.25 irrigation level was approximately 62% of the yield at the 1.25 irrigation level across rootstocks. Irrigation treatment was the only factor that significantly affected soluble solids in the fruit. There was a significant interaction between rootstock and irrigation amount on pruning weights. Berry weight, yield and pruning weights were linearly correlated with midday Ψ_l across rootstock and year.
Conclusions: The results indicate that the rootstocks producing greater yields at the highest applied water amounts also produced greater yields when deficit irrigated.
Significance of the Study: Under both stressed and non-stressed conditions, the rootstocks with the highest yield were those with the greatest number of bunches.

Keywords: *evapotranspiration, grapevine, irrigation, rootstock*

Introduction

Grapevines are the number one horticultural crop grown in California with acreage greater than 340 000 ha (Anonymous 2008). Much of this acreage utilises *Vitis vinifera* L scions grafted onto rootstocks that possess resistance to soil-borne pests, primarily phylloxera (*Daktulosphería vitifoilia* Fitch) (Mullins et al. 1992) and nematodes (McCarthy and Cirami 1990). In addition to such resistance, rootstocks may affect salt tolerance of the scion (Walker et al. 2002) and vegetative and reproductive growth of the scions and the ability to maintain productivity under varying soil and environmental conditions (Ezzahouani and Williams 1995, 2005).

Increasing competition for water resources from environmental and urban users may limit its availability to agriculture. Vineyard water use is similar to that of other agricultural crops (Williams et al. 2003, Williams and Ayars 2005a, 2005b). Studies have been conducted to determine the drought tolerance of *Vitis* species, *V. vinifera* cultivars and/or commercial rootstocks using various screening methods (During and Scienza 1980, Carbonneau 1985, Padgett-Johnson et al. 2003). This was done in order to select cultivars and/or rootstocks more suited to grow in areas where water is limiting. Galet (1979), Pongracz (1983) and Southey (1992) have each ranked the ability of commercial rootstocks to withstand drought based upon observations in the field under dry-land farming conditions (no irrigation). A couple of studies were conducted by Ezzahouani and Williams (1995, 2005) in which the performance of three tablegrape cultivars grafted onto eight rootstocks under dry-farmed conditions in Morocco were evaluated. There were clear differences among the rootstocks regarding vine water relations, as determined by measuring midday leaf water potential (Ψ_l), berry weight and productivity. The observations by Ezzahouani and Williams (1995, 2005) may be more meaningful for commercial grape production than those of Galet (1979), Pongracz (1983) and Southey (1992) where no data were presented. As suggested by Jones (1992) and Passioura (1996) drought tolerance in agriculture and horticulture should be defined in terms of yield in relation to limiting water supply.

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Most vineyards in California are irrigated. It is unknown if the rankings of rootstocks for drought tolerance by Galet (1979), Pongracz (1983) and Southey (1992) would be applicable in vineyards using deficit irrigation. Therefore, a study was conducted to determine the response of Cabernet Sauvignon, grafted onto five different rootstocks and irrigated with different amounts of water in a vineyard near Paso Robles, California.

Materials and methods

A *V. vinifera* cv. Cabernet Sauvignon (clone 8) vineyard was planted with certified nursery material in 1993 near Paso Robles, California (35° 41′ N, 120° 39′ W). Vine and row spacings were 1.83 and 3.05 m, respectively, with an east/west row direction. The vines were grafted onto five rootstocks: 110 Richter (110R) a cross between *V. berlandieri* Ressequier no. 2 × *V. rupestris* Martin, Teleki 5C (5C), a cross between *V. berlandieri* × *V. riparia*, Freedom, a cross of a seedling of Dog Ridge × a seedling of 1613, and 1103 Paulsen (1103P) and 140 Ruggeri (140Ru), both being a cross between *V. berlandieri* Ressequir no. 2 × Rupestris du Lot. All vines were trained to unilateral cordons and were spur pruned. A survey in March of 2001 indicated there were from 16 to 18 spur positions per vine within the vineyard across irrigation treatments and rootstocks. Buds per vine (excluding the basal bud on the spur) after pruning ranged from 26 to 31. A vertical wire trellis system (vertical shoot positioning (VSP) trellis) was used. Canopy management consisted of moving the wires and positioning the shoots. The shoots were hedged once they grew beyond the upper wires of the trellis (cut approximately 0.3 m above the uppermost wire). Leaves were removed within the fruiting zone on the north side of the canopy. No leaf removal took place on the south side of the canopy. The only bunches that were removed during the study were those developing on lateral shoots.

The soil was a Cropley clay (fine, smectitic, thermic Aridic Haploxerert) to a depth of 1.2 m (26, 32 and 42% sand, silt and clay, respectively). Below this depth, the soil consisted of sand. Soil pH and ECe (EC of the saturated soil paste extract) down to the 1.2 m depth were 7.7 and 2.61 dS/m, respectively, with the latter value above the yield reduction threshold for grapevines (Christensen 2000). Soil samples were taken in blocks II and V for each rootstock irrigated at the highest and lowest amounts of water with a 5 cm (diameter) soil auger slightly off centre from the vine row to determine rooting depth in 2000. No roots were detected for soil samples taken between 1.2 and 2.0 m depths at the above mentioned locations.

Estimated vineyard evapotranspiration (ET_c) was calculated as follows:

$$ET_c = ET_o \times K_c \quad (1)$$

where ET_o is reference *ET* and K_c is the crop coefficient. It should be pointed out that 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). The seasonal K_c values used were those for a VSP trellis at a row width of 3.05 m (Figure 1). The seasonal K_c had been developed previously in a VSP trellised Chardonnay vineyard, on a 2.13-m row spacing in the Carneros district of Napa Valley using the water budgeting method (unpublished data). The seasonal K_c values developed in Carneros were adjusted (lowered) at this location for the wider row spacing. During the 2000 growing season, the amount of shade cast on the ground at solar noon was measured across rootstocks irrigated at the 1.0 level in this study several times. That value was converted to a K_c using the equation given in figure 10 of Williams and Ayars (2005b) and compared with the K_c being used in the study during that week. For example, the percentage of shaded areas (means ± standard error, $n = 5$) on 20 May and 15 September were 13.7 (±0.5) and 27.0 (±0.8), respectively. Converting those shaded areas to a K_c (where the K_c = % shaded area * 0.017) resulted in values of 0.23 and 0.46, respectively, while the K_c being used at those times were 0.22 and 0.49, respectively. Therefore, the K_c values being used in the study were similar to those calculated by the shaded area method. Reference *ET* was obtained from the PR1 weather station operated by the Paso Robles Wine Country Alliance (PRWCA), located approximately 10 km from the vineyard. Vines were irrigated one to three times weekly, depending upon the estimated required amounts.

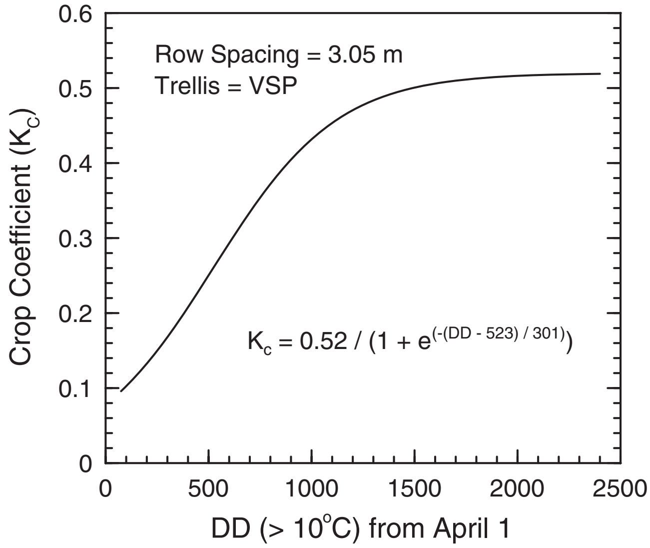

Figure 1. The seasonal crop coefficients as a function of degree-days (DD) used in the study to estimate ET_c. The seasonal K_c values are for a vertical shoot positioning (VSP) trellis on a 3.05-m row spacing.

Variables measured and calculations used to determine daily ET_o can be found in Synder and Pruitt (1992). Temperature data used in calculating degree-days were obtained from the PRWCA PR1 weather station. Degree-days were calculated using the single sine method with a lower threshold of 10°C (see University of California Statewide Integrated Pest Management Project's website (http://www.ipm.ucdavis.edu) for details).

The experimental design was a split-plot with randomised blocks. The main plots (rootstocks) were randomised within a block across rows with each main plot

Table 1. The accumulation of DDs, rainfall amounts, reference *ET* (ET_o), estimated vineyard *ET* (ET_c), date of the first irrigation and applied water amounts during the 5 years the study was conducted at Paso Robles.

Year	DD	Rainfall			Estimated	Date of	Applied
		Seasonal (mm)	From 4/1 (mm)	ET_o (mm)	ET_c (mm)	1st irrigation	H_2O (mm)
1997	1950	—	0	1178	411	17 June†	202
1998	1611	545	86	995	307	22 June	265
1999	1640	158	31	1046	315	30 May	287
2000	1800	266	37	1116	377	11 May	323
2001	1909	348	17	1257	432	31 May	367

The DDs, ET_o and ET_c are for the periods from 1 April to 31 October each year. Seasonal rainfall is for the period beginning 1 November from the previous year until 31 October in the current year. Rainfall in the column 'From 4/1' is the amount that fell subsequent to 1 April that year. †The study was not initiated in 1997 until after anthesis. The vines had been irrigated twice by the vineyard manager prior to the initiation of the study that year. DD, degree-day.

consisting of 11 contiguous rows, or a total of 55 rows for the five rootstocks in each block. Blocks were replicated five times down all rows with each block nine vines in length. Two border vines separated blocks. Irrigation treatments were sub-plots within each main plot and consisted of water applications at various fractions (0.25, 0.5, 0.75, 1.0 and 1.25) of estimated vineyard ET_c from the time irrigations commenced each season until the last irrigation of the year. The season-long application of water amounts at fractions less than ET_c has been termed 'sustained deficit irrigation' or SDI (Fereres and Soriano 2007). Within each individual rootstock plot, the irrigation treatments were set up as a line source in which each row received more or less water depending on the direction the irrigation treatments within the plot were assigned. This design is similar to that used in previous irrigation studies by the author (Grimes and Williams 1990, Williams et al. 2010a). For example, if the first irrigation data row within a specific rootstock plot was irrigated at 0.25 of ET_c, both rows bordering it were irrigated with the same amount of water. The next irrigation data row (proceeding to the right, the direction randomly assigned within each rootstock plot) would be irrigated with applied water amounts at 0.5 of ET_c. The border row to its left would be irrigated with applied water at 0.25 of ET_c while that to its right would be irrigated with 0.5 of ET_c. This procedure was then repeated for the three remaining irrigation treatments within each rootstock plot. Therefore, the row on either side of an irrigation data row were either irrigated with the same amount of water as the data row or with water amounts less than that designated for the specific irrigation treatment. Six border vines were used to separate an individual rootstock/irrigation treatment down the row, two vines from a row within a rootstock/irrigation treatment assigned to the preceding block and two vines in the next block and two border vines between blocks.

Water was applied to the vines irrigated at estimated ET_c (the 1.0 applied water amount) using two, 4 L/h emitters per vine, one on either side of the trunk. Vines irrigated at 1.25 of ET_c had two, 4 L/h emitters and one, 2 L/h emitter per vine (two emitters on one side of the trunk and one on the other). Those irrigated at 0.75 of ET_c had one, 4 L/h emitter and one 2 L/h emitter per vine (one on either side of the trunk). Vines irrigated at 0.25 and 0.5 of ET_c had one and two, 2 L/h emitters per vine, respectively, the latter treatment had one emitter on either side of the trunk. In-line water metres in several rows measured actual applied water amounts for each irrigation treatment. The water metres were calibrated prior to the study. Because the experimental vineyard site was part of a much larger vineyard, the initial irrigations each year were scheduled in liaison with the vineyard manager and continued until the third week of October each year (Table 1). An exception was the first year of the study in which treatments were not imposed until after the cooperator had already initiated his seasonal irrigation.

Leaf water potential (Ψ_l) was measured as described by Williams and Araujo (2002). Briefly, Ψ_l was measured with a pressure chamber (Model 1000, PMS Instrument Co., Corvallis, OR) on fully expanded, mature leaves exposed to direct solar radiation located on the outside of the canopy. Leaf blades for Ψ_l 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 pressurisation was generally less than 10 to 15 s. A single leaf from the centre vine of each irrigation sub-plot in all five blocks was measured and used for data analyses in 1997 and 1998. In subsequent years, an individual leaf from two of the three middle data vines in each irrigation sub-plot from the first three blocks was used for data analyses. Midday Ψ_l measurements were taken frequently in 1997 and 1998 and in subsequent years at least at veraison and close to harvest (generally in September). Predawn leaf (Ψ_{PD}) and midday stem water potentials (Ψ_{stem}) were measured as described by Williams and Araujo (2002) just prior to harvest in 2001 along with midday Ψ_l.

Vine phenology (budbreak, anthesis and veraison) was monitored and estimated visually. Budbreak was considered to have occurred when green tissue was visible among the bud scales. Vegetative growth was determined by taking pruning weights during the dormant portion of the growing season. Yield and bunch number per vine were measured at harvest. Pruning weights, yield and bunch numbers were taken on the three middle vines of each irrigation sub-plot. The yield components measured were berry and bunch weights, berries per bunch and bunch number per vine. Berries (100 berries per sample) were sampled on 9 September 1997, 9 October 1998, 4 October 1999, 13 September 2000 and 12 September 2001 to determine fruit composition prior to harvest. Berries were sampled from the middle five vines in each irrigation sub-plot. Bunch weights were calculated by dividing total bunch weight per vine by bunch number per vine. Berries per bunch were calculated by dividing bunch 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 0.2 N NaOH, respectively. Harvest took place at a predetermined soluble solids level in the fruit based upon the grower/cooperator's standards.

Data were analysed via a three-way analysis of variance (ANOVA) with randomised blocks. The first factor was rootstock, the second was irrigation treatment and the third was year. The data were also analysed as a split, split-plot ANOVA with rootstock the main plot, irrigation treatment a sub-plot and year a sub-sub-plot to determine if results differed from the three-way ANOVA. Results of the analyses were similar to that of the three-way ANOVA except that the *F* and *P*-values were slightly different. Means were separated with the Tukey-Kramer test and considered significant at $P < 0.05$. In the first year of the study, data were only collected from the first four blocks, while in 2001, data were only collected from the first three blocks.

Results

The estimated dates of budbreak for Cabernet Sauvignon at the trial location occurred the last week of March in 1998 and 2000 and the first week of April in 1999 and 2001. The estimated dates of anthesis ranged from the third week of May in 2000 to the second week of June in 1998 while the dates of veraison ranged from the third week of July 1997 to the third week of August 1998. The accumulation of degree-days (DDs) from 1 April to 31 October was lowest in 1998 and 1999 and highest in 1997 (Table 1). The accumulation of DDs in 1997 was approximately 20% greater than those in 1998 and 1999. Anthesis, veraison and harvest dates were reflective of the differences among years in DDs with vines harvested on 18 September 1997 but not until 27 October 1998.

Seasonal rainfall was greatest in 1998 (Table 1). This amount was almost 3.5 times greater than the amount that fell in 1999. With the exception of 1998, precipitation that fell subsequent to 1 April was minimal. The last date of significant rainfall subsequent to 1 April was a total of 40 mm the first and second weeks of May 1998, 14 mm on 6 April 1999, 30 mm on 17 April 2000, and 5 mm on 20 April 2001. Reference *ET* was lowest in 1998 and highest in 2001. Estimated ET_c ranged from 307 to 432 mm (equivalent to 1713 and 2411 L/vine, respectively) across years. Estimates of ET_c ranged from 30 (in 1999) to 35% (in 1997) of ET_o. Applied water amounts to the 1.0 treatment were from 85 to 91% of estimated seasonal ET_c, excluding the amount applied in 1997 because of the lateness in which the study was initiated. Across the duration of the study, applied water amounts for the 0.25, 0.5, 0.75 and 1.25 irrigation treatments were 21, 47, 74 and 122% the amount of water the 1.0 irrigation treatment received, respectively.

Mean midday Ψ_l was measured six times prior to the last measurement date during each of the 1997 and 1998 growing seasons was significantly ($P < 0.001$, $R = 0.97$) correlated with midday Ψ_l measured close to harvest both years (data not given). In addition, midday Ψ_l measured at veraison in 1999 and 2000 was significantly ($P < 0.001$, $R = 0.99$) correlated with midday Ψ_l measured close to harvest each of those years. Irrigation treatment had a significant effect on midday Ψ_l measured prior to harvest (Figure 2). There was no significant effect of rootstock on midday Ψ_l measured prior to harvest, nor was there a significant interaction between rootstock and irrigation treatment on midday Ψ_l measured at that time. Midday Ψ_{stem} for the 0.25, 0.5, 0.75, 1.0 and 1.25 irrigation treatments measured close to harvest in 2001 were −1.19, −1.04, −0.94, −0.76 and −0.72 MPa, respectively. Midday Ψ_l and Ψ_{stem} were significantly correlated with one another ($R = 0.96$, $P < 0.001$, $\Psi_l = -0.37 + 0.86\Psi_{stem}$) on that date across irrigation treatments and rootstocks. Both midday Ψ_l and Ψ_{stem} were significantly ($P < 0.001$) correlated with Ψ_{PD} when measured on that date (Ψ_{PD} ranged from −0.15 to −0.45 MPa).

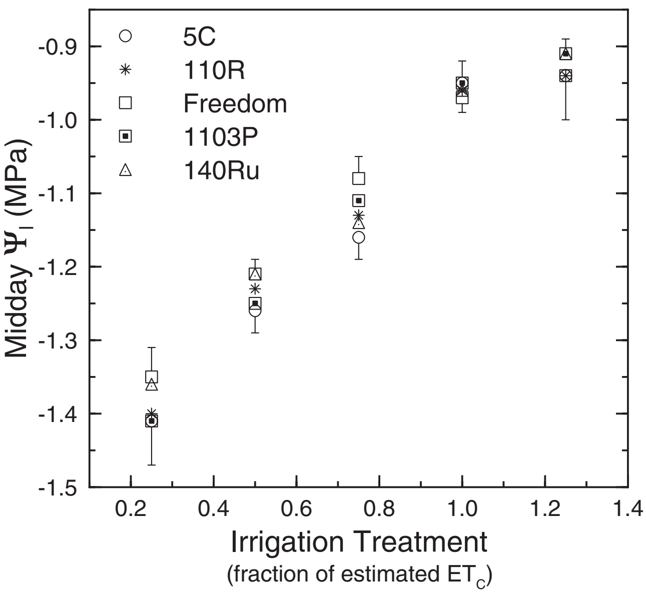

Figure 2. Midday leaf water potential (Ψ_l) of Cabernet Sauvignon as a function of rootstock and applied water amounts. Values are the means of measurements taken close to harvest each year of the study. Bars represent one standard error.

Table 2. The effect of year on various parameters measured throughout the course of the study on Cabernet Sauvignon grapevines grown near Paso Robles. Values are the means measured across irrigation treatments and rootstocks.

Parameter†	Year				
	1997	1998	1999	2000	2001
Berry weight (g/berry)	1.06[c]	0.99[d]	1.03[c]	1.20[b]	1.25[a]
Soluble solids (°Brix)	22.8[a]	21.9[b]	23.0[a]	21.9[b]	20.4[c]
pH	3.61[b]	3.51[c]	3.48[c]	3.55[c]	3.87[a]
TA (g/L)	5.64[c]	7.17[a]	7.32[a]	6.29[b]	6.50[b]
Number of bunches per vine	—‡	54[b]	50[c]	57[b]	66[a]
Bunch weight (g)	—‡	146[b]	93[d]	129[c]	161[a]
Number of berries per bunch	—‡	149[a]	93[d]	108[c]	133[b]
Yield (kg/vine)§	6.8[c]	7.9[b]	4.8[d]	7.6[b]	10.7[a]
Pruning weight (kg/vine)	1.32[a]	1.35[a]	0.95[b]	0.95[b]	—¶
Yield per pruning weight (kg/kg)	5.15[c]	5.85[b]	5.05[c]	8.00[a]	—¶

†Values within a given parameter row followed by a different letter are significantly different. ‡Values in these three rows in 1997 were not calculated as bunch numbers were not determined at harvest. §Yield given above multiplied by 1.791 is equivalent to t/ha. ¶Pruning weights were not measured in 2001.

Year had a significant effect on many of the measured parameters. Berry and bunch weights, bunch number per vine and yield was greatest in 2001 when compared with the other years (Table 2). Juice titratable acidity was highest and pH lowest in 1999. Some of the differences in soluble solids across years may have been because of the date in which the final berry sample of the season took place. Pruning weights were greatest in 1998 while the yield to pruning weight ratio was highest in 2000.

There were no significant interactions among rootstock, irrigation treatment and year for any of the measured parameters. Therefore, the data presented in the remainder of the results section were analysed only as a function of rootstock and irrigation treatment. Berry weight increased from the lowest irrigation treatment up to 1.0 of estimated ET_c, at which point it leveled off (Table 3). Freedom had the largest berries while 5C the smallest. The number of bunches per vine increased as applied water increased. The numbers of bunches per vine for the 140Ru and 1103P rootstocks were approximately 10% greater than the number per vine for the 5C rootstock. Yield of vines on the1103P rootstock was ~16% greater than that measured for 5C. Freedom and 140Ru had the largest bunches and 140Ru also had the greatest number of berries per bunch (Table 4). While there were significant differences among irrigation treatments for the number of berries per bunch, they were rather small. Lastly, as applied water increased, soluble solids decreased. Rootstock had no significant effect on soluble solids.

There was a significant interaction of irrigation treatment and rootstock on pruning weights (Table 5). Pruning weights of both 140Ru and 1103P at all irrigation amounts were greater than the pruning weights of 5C and 110R when irrigated at the 1.25 irrigation amount. The 5C rootstock had the highest yield to pruning weight ratio and 1103P the lowest.

Berry weight and yield were linear functions of midday Ψ_l measured close to harvest (Figures 3 and 4). While there was a significant relationship between pruning weight and midday Ψ_l measured close to harvest, there was much greater variation (lower *r*-value) for this data set compared with berry weight and yield because of the large differences in pruning weights among rootstocks at all irrigation levels (Figure 5).

Discussion

Estimates of vineyard ET *and measures of vine water status*

The numbers of irrigation treatments and years this study was conducted provided a wide range of water statuses the vines experienced as well as differing environmental conditions including large variations in rainfall from season to season. Applied water amounts were various fractions of estimated ET_c and these fractional water amounts were imposed from the first irrigation of the season until the middle of October. Applied water amounts at fractions less than ET_c season long has been termed 'sustained deficit irrigation' or 'SDI' (Fereres and Soriano 2007). This irrigation technique would be similar to 'partial rootzone drying' (PRD) (McCarthy et al. 2000, Marsal et al. 2008) except there would be no alteration in applying water from one side of the vine's trunk to the other on a regular basis.

The low and high values of estimated ET_c from 1 April to 21 October were 265 mm in 1998 and 367 mm in 2001, 27 and 29% of ET_o, respectively. These relatively low estimates of ET_c were because of the trellis used (VSP – with a narrow canopy) and the wide row spacing (3.05 m) in this vineyard. The highest K_c used during the season was only 0.52, much less than that proposed for winegrape vineyards at mid-season (0.7) in Allen et al. (1998) and the maximum K_c (0.8) used by Marsal et al. (2008) to estimate ET_c for VSP-trained vines planted on a

Table 3. The effects of irrigation treatment and rootstock on berry weight and yield of Cabernet Sauvignon grapevines measured from 1997 to 2001. Bunches per vine are means of data collected from 1998 to 2001.

Rootstock	Irrigation treatment (fraction of ET_c)					Average effect rootstock†
	0.25	0.5	0.75	1.0	1.25	
			Berry weight (g/berry)			
5C	0.87	1.02	1.10	1.13	1.18	1.06[b]
110R	0.96	1.07	1.12	1.22	1.23	1.11[ab]
Freedom	0.98	1.07	1.22	1.26	1.28	1.16[a]
140Ru	0.93	1.07	1.16	1.23	1.18	1.12[ab]
1103P	0.93	1.05	1.16	1.22	1.19	1.11[ab]
Ave. eff. irrigation†	0.94[d]	1.06[c]	1.14[b]	1.20[a]	1.21[a]	
			Bunches (number/vine)			
5C	46	50	55	55	55	52[c]
110R	38	51	56	58	63	55[b]
Freedom	45	51	55	58	63	54[bc]
140Ru	52	52	58	62	66	58[a]
1103P	55	54	59	57	67	58[a]
Ave. eff. irrigation	49[c]	52[c]	57[b]	58[b]	63[a]	
			Yield (kg/vine)‡			
5C	5.3	6.3	7.4	7.5	8.1	6.9[b]
110R	5.7	6.5	8.5	8.7	9.1	7.7[a]
Freedom	5.2	6.5	7.6	8.6	9.6	7.5[a]
140Ru	6.3	6.7	7.9	8.3	9.6	7.8[a]
1103P	6.2	7.1	8.4	9.2	10.1	8.2[a]
Ave. eff. irrigation	5.7[e]	6.6[d]	8.0[c]	8.4[b]	9.3[a]	

†Values within the ave. eff. irrigation rows and the average effect rootstock column for a given parameter followed by a different letter are significantly different. ‡Yield given above multiplied by 1.791 is equivalent to t/ha.

3.1 m row spacing. The seasonal K_c used in this study did not decrease after mid-season, as given in Allen et al. (1998), because it was shown that the K_c for grapevines does not decrease if the vines are irrigated until the end of the season and the canopy is still in good condition (Daane and Williams 2003, Williams and Ayars 2005a). In addition, it is felt that the estimate of ET_c using the seasonal crop coefficients found in Figure 1 were appropriate because mean midday Ψ_l measured throughout and at the end of the growing season across years and rootstocks for the 1.0 irrigation treatment was greater than −1.0 MPa and most of the time is not significantly different from the 1.25 irrigation treatment. It has been demonstrated that values of midday $\Psi_l > -1.0$ MPa ($\Psi_{stem} > -0.7$ MPa) indicate that vines are being irrigated at or greater than ET_c (Grimes and Williams 1990, Williams and Matthews 1990, Williams et al. 1994, Williams and Trout 2005, Girona et al. 2006, Williams and Baeza 2007, Marsal et al. 2008).

Applied water amounts for the SDI treatments (the 0.25, 0.5 and 0.75 of estimated ET_c treatments) averaged across years were 65, 146 and 230 mm, respectively. These values were only 6, 13 and 21%, respectively, of ET_o. Midday Ψ_l decreased linearly as applied water amounts decreased and the values of Ψ_l for the deficit-irrigated treatments were significantly different from one another across rootstocks and from those measured for the 1.0 and 1.25 irrigation treatments. The lowest values of midday Ψ_l measured at the end of the growing season for the 0.25 irrigation treatment across rootstocks ranged from −1.4 to −1.55 MPa while that for midday Ψ_{stem} near harvest in 2001 was −1.2 MPa (vines irrigated at the 1.25 level had a Ψ_{stem} of −0.7 MPa). The values of midday Ψ_l at harvest for the 0.25 irrigation treatment were similar to those reported for Cabernet Sauvignon, grafted onto four of the same rootstocks used in this study, in a dry-farmed vineyard in Napa Valley at harvest in 1998 (Nuzzo and Matthews 2006). Values of midday Ψ_{stem} for vines irrigated at 50% of estimated ET_c at harvest averaged −1.04 MPa in this study while those taken at the end of the growing season for vines irrigated at 50% of estimated ET_c in the study by Marsal et al. (2008) ranged from −1.1 to −1.3 MPa.

Because the irrigation treatments used in this study were based upon estimates of ET_c, they resulted in vine water status values (midday Ψ_l) that were fairly uniform from year to year and highly correlated with measurements taken earlier in the growing season. Similar results

Table 4. The effects of irrigation treatment and rootstock on calculated bunch weight and berries per bunch of Cabernet Sauvignon grapevines from 1998 to 2001. Soluble solids (°Brix) were measured each year of the study.

Rootstock	Irrigation treatment (fraction of ET_c)					Average effect rootstock†
	0.25	0.5	0.75	1.0	1.25	
			Bunch weight (g)			
5C	111	122	129	133	143	128[c]
110R	112	120	132	139	145	130[bc]
Freedom	115	122	134	147	151	134[ab]
140Ru	116	133	142	146	153	138[a]
1103P	119	124	132	146	144	133[ab]
Ave. eff. irrigation†	115[d]	124[c]	134[b]	140[a]	143[a]	
			Number of berries per bunch			
5C	127	120	118	116	121	118[ab]
110R	116	113	112	114	121	115[b]
Freedom	117	111	111	115	119	115[b]
140Ru	126	126	123	122	123	124[a]
1103P	126	116	114	119	116	118[ab]
Ave. eff. irrigation	122	117	116	117	120	
			Soluble solids (°Brix)			
5C	22.4	22.0	21.8	21.8	21.9	22.0
110R	22.4	21.9	22.0	21.5	21.5	21.9
Freedom	22.9	22.1	21.7	21.5	21.4	21.9
140Ru	22.2	22.4	21.9	21.2	21.7	21.9
1103P	22.7	22.2	22.3	22.0	22.0	22.2
Ave. eff. irrigation	22.5[a]	22.1[b]	22.0[bc]	21.7[c]	21.6[c]	

†Means within the average effect rootstock column or ave. eff. irrigation rows not followed by any letters are not significantly different from one another at the $P < 0.05$ level. Other information is as given in Table 3.

have been obtained with Thompson Seedless grapevines grown in the San Joaquin Valley of California using the SDI irrigation strategy with ET_c being determined with a weighing lysimeter (Williams et al. 2010a). This irrigation strategy may also explain the high correlation between berry weight, yield and pruning weight and vine water status as measured by midday Ψ_l in this study and those of Williams et al. (2010a,b). Midday Ψ_l has previously been shown to be highly correlated with soil water content, soil matric potential and applied water amounts using the SDI strategy (Williams and Araujo 2002, Williams and Trout 2005).

Rootstock

The rootstocks used in this study had previously been classified with varying degrees of drought tolerance although, the basis for such classification was not always given. Galet (1979) suggested that 110R and 140Ru are best in very dry soils followed by 1103P. It was also reported that the 5C rootstock was much less resistant to drought and Freedom was sensitive to drought. Southey (1992) ranked 110R and 140Ru as resistant to drought while 1103P moderately susceptible to drought. In that study Southey indicated that Dog Ridge (a parent of Freedom) was susceptible to drought. Carbonneau (1985) ranked 110R and 140Ru as highly drought resistant and 1103P as resistant to drought.

While irrigation treatments had a significant effect on midday Ψ_l in this study, there was no significant effect of rootstock or a significant interaction between irrigation treatment and rootstock on vine water status. This differs from that reported by Ezzahouani and Williams (1995) where rootstock significantly affected average midday Ψ_l of dry-farmed Ruby Seedless grapevines in Morocco. Of the rootstocks used in that study and this one, average Ψ_l of 1103P was significantly greater than those of 110R and 140Ru. Nuzzo and Matthews (2006) reported that there were no significant differences in midday Ψ_l of Cabernet Sauvignon grafted onto 5C, 110R, 140Ru and 1103P in the first year of their study. However, midday Ψ_l measured at harvest the second year was significantly lower for 1103P compared with 110R and 140Ru and they were significantly lower than that of Cabernet grafted onto 5C. The lack of a rootstock effect on midday Ψ_l in this study is similar to that reported by Stevens et al. (2008). Little variation in midday Ψ_l across rootstocks in this study at any particular irrigation treatment is not surprising for two reasons: (i) While pruning weights did differ among

Table 5. The effects of irrigation treatment and rootstock on pruning weight and the yield to pruning weight ratio of Cabernet Sauvignon grapevines from 1997 to 2000.

Rootstock	Irrigation treatment (fraction of ET_c)					Average effect rootstock
	0.25	0.5	0.75	1.0	1.25	
	Pruning weight (kg/vine)					
5C	0.74^{i}	0.83^{hi}	0.92^{fghi}	0.81^{hi}	0.95^{efgh}	0.82
110R	0.82^{hi}	0.82^{hi}	0.91^{fghi}	0.95^{efgh}	1.09^{defg}	0.95
Freedom	0.89^{ghi}	0.95^{efgh}	1.01^{efgh}	1.29^{cd}	1.23^{d}	1.10
140Ru	1.09^{defg}	1.12^{def}	1.22^{d}	1.45^{c}	1.68^{b}	1.34
1103P	1.22^{d}	1.15^{de}	1.42^{c}	1.48^{c}	1.90^{a}	1.45
Ave. eff. irrigation	0.94	0.98	1.11	1.22	1.37	
	Yield per pruning weight (kg/kg)					
5C	6.60	6.82	7.28	8.35	8.16	7.62^{a}
110R	6.24	7.36	7.29	7.54	7.23	7.30^{a}
Freedom	5.78	6.23	6.57	6.12	6.87	6.53^{b}
140Ru	5.75	5.99	5.49	5.33	5.07	5.69^{c}
1103P	4.81	5.16	5.01	5.15	4.47	5.07^{d}
Ave. eff. irrigation	5.94^{b}	6.46^{ab}	6.76^{a}	6.62^{a}	6.49^{ab}	

There was a significant interaction between rootstock and irrigation treatment on pruning weights. Other information is as given in Table 3.

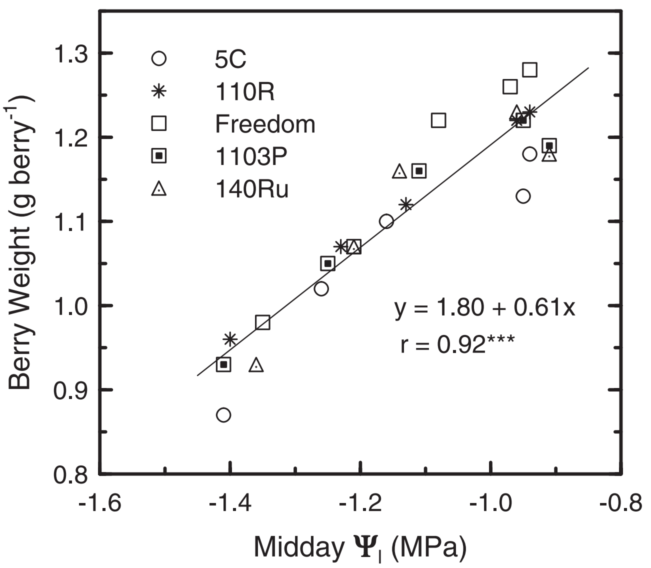

Figure 3. Berry weight of Cabernet Sauvignon as a function of midday leaf water potential (Ψ_l) measured close to harvest. Each data point represents the mean across irrigation treatment, rootstock and year ($n = 25$).

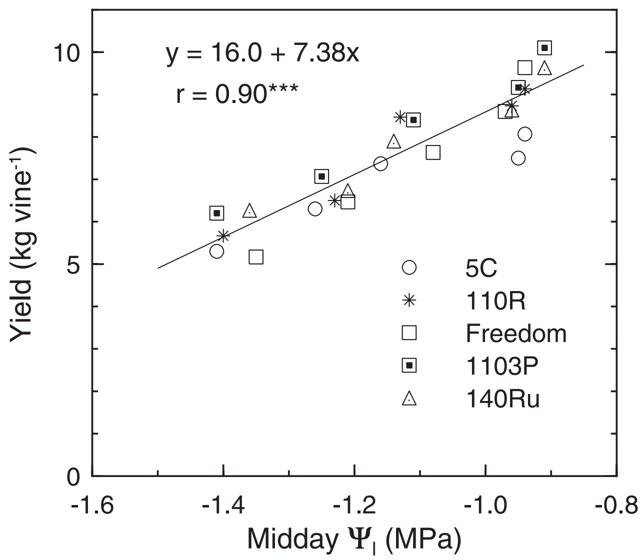

Figure 4. Yield of Cabernet Sauvignon as a function of midday leaf water potential (Ψ_l) measured close to harvest each year. Each data point represents the mean across irrigation treatment, rootstock and year ($n = 25$).

rootstocks, and for a rootstock at any particular applied water amount, canopy size was fairly uniform among rootstocks and among irrigation treatments. This was because of the fact that shoots were vertically positioned and they were hedged once they grew above the top trellis wire. (ii) It is assumed that the roots of the vines across rootstocks in this study were limited to a depth of 1.2 m as no roots were detected at depths between 1.2 and 2.0 m (see Materials and Methods section). Therefore, the volume of soil the vines' roots were able to explore for each rootstock and in each of the irrigation treatments would be the same. Drought tolerance of plants in natural ecosystems (Monneveux and Belhassen 1996) and grapevine cultivars and/or rootstocks (Smart and Coombe 1983) has often been attributed to the exploration of greater soil depths by roots. Under the conditions of this study, rooting depth appeared to have been limited and therefore the rooting characteristics of a particular rootstock would probably have only had a minimal effect on water extraction from the soil profile.

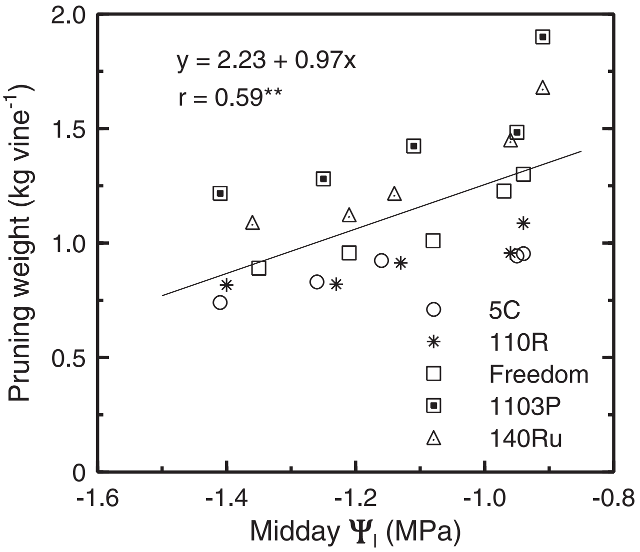

Figure 5. Pruning weights of Cabernet Sauvignon as a function of midday leaf water potential (Ψ_l) measured close to harvest. Data were collected from 1997 to 2000. Each data point represents the mean across irrigation treatment, rootstock and year ($n = 25$).

There was a significant effect of irrigation and rootstock on yield and components of yield but no significant interaction between the two for those measured parameters. Increasing applied water amounts from 0.25 to 1.25 of estimated ET_c increased yields by 62% across rootstocks and years (10.3 to 16.6 t/ha). Yields of Cabernet Sauvignon grafted onto 5C were significantly lower than the yields of the other rootstocks in this study. The rootstock 1103P had the highest overall mean yield and the highest yield at each irrigation treatment in this study followed by 140Ru. The lowest per cent increase in yield for an individual rootstock comparing the 0.25 and 1.25 irrigation treatments was that for 5C (52%) while the greatest was that for Freedom (86%). McCarthy et al. (1997) reported that mean yields doubled in a Shiraz rootstock trial comparing an irrigated treatment with a non-irrigated treatment. The yield of Freedom almost tripled when comparing the non-irrigated and irrigated treatments, less so for the other rootstocks. In that study, Shiraz grafted onto 110R had significantly lower yields in the non-irrigated plots compared with the 1103P, Freedom and 140Ru grafted vines. Stevens et al. (2008) reported that yields of Chardonnay grapevines in response to a 35% reduction in irrigation amount were not modified by rootstock. They did find that yields were significantly greater for vines grafted onto 1103P compared with vines grafted onto 140Ru and 110R. Dry-farmed Cabernet Sauvignon grafted onto 5C had the lowest yields compared with the rootstocks 110R, 140Ru and 1103P in the first year of a 2-year study conducted in Napa Valley (Nuzzo and Matthews 2006). The second year of that study, which received more seasonal rainfall than the first year, Cabernet Sauvignon grafted onto 5C had the highest yields when compared with the other three rootstocks. Yields of dry-farmed Dattier de Beyrouth grafted onto 1103P and 140Ru were significantly greater than that of 110R while yields of Alphonse Lavellée didn't differ significantly among the three rootstocks the second of a 2-year study (Ezzahouani and Williams 2005). In an earlier study, Ezzahouani and Williams (1995) reported that yield of dry-farmed Ruby Seedless grapevines grafted onto 140Ru and 110R were significantly greater than that of 1103P. The results from the above-mentioned studies and those obtained herein would indicate that under most circumstances, yields of scions grafted onto 1103P and 140Ru would be greater under water-limiting conditions than either 5C or Freedom. Scions on the rootstock 110R would give intermediate results.

The increased yields for Cabernet Sauvignon when grafted onto 1103P and 140Ru and the lowered yield of 5C across irrigation treatments in this study were primarily because of the number of bunches per vine and to a lesser extent berry weight. The per cent reduction in yield of Cabernet Sauvignon (going from the 1.25 to the 0.25 irrigation treatment) was similar for 5C, 110R, 140Ru and 1103P. This would indicate that the rootstocks classified at being more drought tolerant (110R, 140Ru and 1103P) were similarly affected by water deficits as was the 5C rootstock, considered much less resistant to drought. Therefore, the only reason the former rootstocks may have been classified as drought tolerant was because of the fact that they produced higher yields regardless the amount of applied water or available soil moisture. One could also have come to this conclusion with the data presented in the study by Stevens et al. (2008). It has been pointed out that the selection for yield in the absence of drought is an effective way to limit yield reductions because of water stress (Richards 1996).

There was a significant interaction between irrigation treatment and rootstock on pruning weights in this study. Interestingly, the pruning weight of Cabernet Sauvignon grafted onto 1103P and irrigated at 0.25 of estimated ET_c was significantly greater than the pruning weights of 5C and 110R irrigated at 1.25 of estimated ET_c. Pruning weights of 140Ru and irrigated at the 0.25 level were significantly greater than those of 5C across all irrigation treatments and 110R irrigated at 1.0 of estimated ET_c or less. It would appear that the ability of Cabernet Sauvignon (clone 8) grafted onto 5C and 110R to produce vegetative mass was minimal regardless the amount of applied water at this location. The pruning weights of Shiraz grafted onto 1103P and 140Ru were significantly greater than that of 110R (Stevens et al. 2008). Pruning weights of Cabernet Sauvignon grafted onto 1103P and 140Ru were greater than those of 5C and 110R in the 2-year study of Nuzzo and Matthews (2006) with absolute differences among the four rootstocks dependent upon year. Ezzahouani and Williams (1995) reported that there were no significant differences in pruning weights of Ruby Seedless grafted onto 110R, 140Ru and 1103P under dry-farmed conditions in Morocco. Therefore, scions on the rootstocks 140Ru and 1103P would have a larger canopy under most vineyard situations (from non-water limiting or standard conditions to water limiting conditions). After reviewing the literature, Stevens et al. (2008) concluded that the primary effect of rootstocks on vine performance under well-watered and deficit conditions may be the effect of rootstock on vine vigour. However, it was shown that excessive vegetative growth increased bud necrosis of the grapevine cultivar Queen of Vineyard compared with less vigourous vines (Lavee et al. 1981). Excessive vegetative growth has been found to reduce yields in the field because of reduced bud fruitfulness (Williams et al. 2010b). Because the shoots of the vines were vertically positioned in this study, reduced fruitfulness and/or necrosis of the basal buds because of excessive shading (May 1965, Perez and Kliewer 1990) by the canopy across treatments was probably negligible.

The yield to pruning weight ratio has been used to assess crop load with a range from 4 to 7 reported as ideal (Smart and Robinson, 1991). In this study Cabernet Sauvignon grafted onto 5C had the highest ratio while that for 1103P the lowest. The rankings of the yield to pruning weight ratios of 5C, 110R, 140Ru and 1103P (highest to lowest) in this study is the same as that found by Nuzzo and Matthews (2006) for the same rootstocks. It would appear that the differences in this ratio across rootstocks had no significant effect on sugar accumulation in the fruit of Cabernet Sauvignon in this study because the canopies of the vines were similar across rootstocks because of the trellis used (vertical shoot positioned with shoot hedging above the top wire).

Water use efficiency

Greater emphasis is being placed upon increased water use efficiency in agro-ecosystems and deficit irrigation is one means to improve it (Fereres and Soriano 2007). Firstly, this study demonstrated that water use efficiency can be increased by using rootstocks that will produce more with less water, i.e. 1103P versus 5C. Secondly, yield per unit applied water in this study across rootstocks and years was 15.8, 8.1, 6.2, 4.8, and 4.4 t/ML for the 0.25, 0.5, 0.75, 1.0 and 1.25 irrigation treatments, respectively. Similar results were obtained in a Thompson Seedless vineyard located in the San Joaquin Valley of California (Williams et al. 2010b). This would indicate that anytime one deficit irrigates, whether using SDI, other deficit irrigation techniques such as PRD and regulated deficit irrigation (McCarthy et al. 2000, Marsal et al. 2008), or plant-based deficit irrigation scheduling (Girona et al. 2006), grapevine water use efficiency will increase. It should be pointed out that yield did decrease linearly as applied water amounts decreased and that the increase in water use efficiency because of deficit irrigation may not provide sufficient economic return in all grape production areas.

Conclusions

Irrigation amount and grapevine rootstock significantly affected yield of Cabernet Sauvignon, but there was no significant interaction between the two on yield under the conditions of this study. The number of bunches per vine was the primary component of yield affected by either irrigation amount or rootstock. Cabernet Sauvignon grafted onto 1103P and 140Ru had the highest yields across irrigation treatments when compared with the other three rootstocks. There was a significant interaction between irrigation amount and rootstock on pruning weights of the scion with 1103P and 140Ru having greater pruning weights at the lowest applied water amount treatment than either 110R and 5C irrigated with the greatest amount. Further study is needed to determine if a trellis system other than the VSP used here would have affected the results. A trellis system allowing a larger canopy and therefore greater water demand by the more vigourous rootstocks may have negatively affected vine water status at the lower applied water amounts and adversely affected productivity to a greater extent than would a low vigour rootstock such as 5C.

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