Evaluation of Regulated Deficit Irrigation on Grape in Texas and Implications for Acclimation and Cold Hardiness

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ABSTRACT. Deficit irrigation is used increasingly as a vigor management tool and to conserve water in grape vineyards. Several strategies including regulated deficit irrigation (RDI) have emerged, but none has been evaluated in Texas. Deficit irrigation has also been observed to influence vine acclimation and presumably vine cold hardiness. Experiments were established in a commercial 'Cabernet Sauvignon' (*Vitis vinifera*) vineyard in west Texas to evaluate RDI under local conditions and to study the potential for deficit irrigation to induce earlier shoot acclimation and influence cold hardiness. RDI significantly reduced pruning weights by as much as 46% and increased applied water-use efficiency up to 72%, but had little or no effect on yield components or fruit composition, indicating that these strategies could be useful in west Texas. Deficit irrigation was consistently associated with earlier and more rapid development of

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The authors thank Steven Shelby, Graham Brown, and Jesse Gorley for technical assistance and thank Newsom Vineyards of Plains, Texas, and the entire Newsom family for their generous cooperation and helpful assistance with this study.

This research was supported by grants from the Viticulture Consortium and the Lipe Foundation.

International Journal of Fruit Science, Vol. 6(2) 2006
Available online at http://ijfs.haworthpress.com

doi:10.1300/J492v06n02_02

periderm on shoots, but had no effect on bud cold hardiness. doi:10.1300/J492v06n02_02

KEYWORDS. Grape, irrigation scheduling, water deficit, periderm, abscisic acid, *Vitis vinifera*

INTRODUCTION

Deficit irrigation of grapevines has been the subject of recent research to explore its potential to conserve water, reduce vine vegetative growth, and possibly improve fruit and wine quality. Deficit irrigation strategies restrict water application to provide less than the full replacement volume of water consumed by plants and in many cases to impose a water deficit in the vine. Grapevines respond to increasing water deficits by decreasing stomatal aperture and thereby reducing transpirational water loss, but with a concomitant reduction in CO_2 uptake and photosynthesis (Gomez-del-Campo et al., 2002; Düring et al., 1997). Stomatal aperture is at least partially under hormonal control through the synthesis and xylem transport of abscisic acid (ABA) from the roots to the leaves (Zhang and Davies, 1989; Düring et al., 1997; Correia et al., 1995; Stoll et al., 2000). The concept of ABA as a root signal produced under drying soil conditions led to the development of the partial rootzone drying strategy (PRD) of deficit irrigation (Dry et al., 1996; Loveys et al., 1998; Stoll et al., 2000). The PRD strategy attempts to stimulate continuous production of ABA from drying roots by irrigating only half of the rootzone while allowing the other half to dry, rotating the watered half on a 10-14-day cycle (Loveys et al., 1998).

The ultimate effects of water deficit on grapevines are dependent upon the intensity and duration of the deficit and the developmental stage during which the deficit occurs. Severe water deficit during any phase of the fruit development period was shown to reduce yield (Hardie and Considine, 1976); reductions from early deficits were primarily attributable to reduced fruit set while later deficits reduced berry size. Matthews et al. (1987) demonstrated that berry growth is more sensitive to moderate water deficits during the pre-veraison period compared with post-veraison, and smaller berry size is a frequently reported response to water deficit (Matthews et al., 1987; Matthews and Anderson, 1989; Van Zyl, 1984; Ojeda et al., 2002; Kennedy et al., 2002). The

effect of water deficit on berry size is often reflected in reduced yield (Gomez-del-Campo et al., 2002; Matthews et al., 1987; Matthews and Anderson, 1989) and water deficits can also impact the subsequent year's crop (Matthews and Anderson, 1988; Spayd and Morris, 1978) by reducing initiation and development of flower primordia (Buttrose, 1974; Matthews and Anderson, 1989). A smaller berry size results in a higher concentration of fruit phenolic compounds (Matthews and Anderson, 1988; Kennedy et al., 2002; Ojeda et al., 2002), and water deficits may directly affect the biosynthesis of phenolic compounds (Kennedy et al., 2002; Ojeda et al., 2002).

Reports on other aspects of fruit composition (i.e., soluble solids, titratable acidity, pH) have shown varied responses to water deficits (Hardie and Considine, 1976; Matthews and Anderson, 1988; Van Zyl, 1984; Ojeda et al., 2002), which are likely attributable to differences in the timing, duration, and intensity of deficit treatments on different grape varieties. Some effects of water deficit on fruit composition may be a consequence of an improved canopy microclimate resulting from reduced vegetative growth (Van Zyl, 1984; Dry et al., 1996). Water deficits inhibit vegetative growth by reducing leaf number and size, shoot elongation rate, total leaf area, and pruning weights (Van Zyl, 1984; Matthews et al., 1987; Gomez-del-Campo et al., 2002).

Matthews et al. (1987) observed accelerated periderm development on shoots in response to moderate water deficits. Development of periderm is considered to be a good visual indicator of shoot acclimation (Wample and Wolf, 1997), and lateral buds increase in cold tolerance as periderm develops around the node (Goffinet, 2000). Despite the possible connection between water deficit and cold acclimation, few studies have directly investigated the potential relationship between the two. An irrigation study on 'Sauvignon blanc' in Washington reported earlier acclimation of vines subjected to reduced irrigation treatments, suggesting better cold hardiness during late summer and early fall. However, no or few differences among irrigation treatments were detected in bud cold hardiness as measured by low-temperature exotherm analysis (Wample and Wolf, 1997). In a separate study, drought stress was induced in 'Concord' (*V. labruscana*) grapes, but once again no consistent difference in bud cold hardiness was shown between irrigated and stressed vines (Wample and Wolf, 1997). However, field observations of 7 *Vitis vinifera* cultivars following a natural freeze event in Washington demonstrated a consistent reduction in primary bud injury associated with vines that were water-stressed in the previous season compared with those receiving standard irrigation (Wample et al., 2000).

Experimental evidence suggests that abscisic acid may play a central role in the signal transduction of cold acclimation (Howell, 2000; Xin and Browse, 2000). Given the putative dual functions of ABA in signaling drought stress and triggering shoot acclimation, further investigations into a possible relationship between deficit irrigation and cold acclimation and hardiness are warranted.

The regulated deficit irrigation (RDI) strategy withholds water to achieve or maintain some degree of water deficit in grapevines during a specific phenological stage, usually between fruit set and veraison (Caspari et al., 1997; Dry et al., 2001). Appropriate timing and extent of water deficits can have desirable effects in reducing vegetative vigor and improving some components of fruit composition (Dry et al., 2001; Kennedy et al., 2002). RDI has become common practice for wine grape production in Australia, California, and other U.S. wine-growing regions, but has not been adopted by commercial vineyards in Texas. The application of RDI to grape production in Texas may have potential, but it has not been experimentally evaluated under local climatic conditions.

The objectives of this study were as follows: (1) To evaluate regulated deficit irrigation for potential application to grape production in west Texas, and (2) to investigate the potential for deficit irrigation to induce early shoot acclimation and increase grapevine bud cold hardiness.

MATERIALS AND METHODS

Vineyard site and plant materials. Regulated deficit irrigation was evaluated over two seasons (2002-03) in a commercial vineyard at Plains, Texas, located within the Texas High Plains. The region has a semiarid, continental climate with hot summers and mild winters. Rainfall is sporadic, ranging from 385 to 601 mm annually, mostly received during the summer months (National Weather Service, 2001). Growing season degree-days (GDD; 10°C base, April-October) in 2002 and 2003 were 2416 and 2305 GDD. Grapevine phenology dates for 2002 and 2003 are shown in Table 1. Rainfall during the growing season was 211 and 160 mm in 2002 and 2003, respectively, but during the period from budburst to harvest it was 98 and 99 mm, respectively. Reference evapotranspiration (ET_o, grass) was obtained from nearby National Weather Service stations; the season totals were 1553 and 1181 mm in 2002 and 2003, respectively. Estimates of grapevine evapotranspiration

TABLE 1. Phenology dates for 'Cabernet Sauvignon' at Newsom Vineyards in Plains, Texas in 2002, 2003.

Phenology Stage	Date
2002	
Budbreak	15 April
Fruit Set	14 May
Veraison (50%)	15 July
Harvest	24 August
2003	
Budbreak	4 April
Fruit Set	16 May
Veraison (50%)	16 July
Harvest	20 August

(ET_c) were calculated by multiplying ET_o by crop coefficients (Table 2) determined for the study vineyard using the percent shaded area of Williams (2001) based upon the relationship between percent shaded area and the crop coefficient (Williams and Ayers, 2005). All experiments were conducted within a four-hectare block of self-rooted 'Cabernet Sauvignon' grapevines planted in 1986, trained to a bilateral cordon (cordon height 1.2 m) and spur pruned to twelve 2-bud spurs. The vines were planted in north-south-oriented rows, spaced 1.2 m (between vines) and 3.4 m (between rows), with no cover crop in the alley. The vineyard soil is Patricia loamy fine sand, a thermic Aridic Paleustalf with approximately 3.1 to 4.6 m sand depth with sandy clay underneath and available water capacity ranging from 40 to 140 mm/m (National Cooperative Soil Survey, 1999). Vineyard management practices were uniformly applied to all experimental treatments.

The vineyard irrigation system consisted of a subsurface drip installed in 2001 midway between vine rows in the alley center at a depth of approximately 0.3 m, with 2 L/hr emitters spaced 1.2 m apart. The vineyard utilized flood irrigation prior to 2001.

Treatments and experimental design. The vineyard's subsurface drip system was bypassed for the duration of the RDI study and a separate drip system was installed for each treatment plot that enabled individual control of water applications. Water was applied through a drip irrigation system with 2L/hr emitters spaced 1.2 m apart on a drip tube suspended beneath the vines, along the row approximately 0.3 m above the soil surface. Irrigation events were scheduled on the basis of vine water

TABLE 2. Crop coefficients estimated for 'Cabernet Sauvignon' at Newsom Vineyards in Plains, Texas. Vine spacing is 1.2 m × 3.4 m and vines are bilateral cordon trained.

Growing Degree Days[1]	Crop Coefficient (K_c)
71	0.10
167	0.28
301	0.39
472	0.45
676	0.49
903	0.50
1136	0.51
1587	0.50
1805	0.48
2009	0.42

[1]April-October, 10°C base.

status as measured by midday leaf water potential (ψ_l) and varied among the treatment plots due to differences in water use. The RDI strategy was evaluated in an experiment that compared a deficit irrigation treatment imposed for approximately 3 weeks prior to veraison to an irrigation treatment (Control) that applied 100% of estimated ET_c. Water was withheld from the RDI treatment during the treatment period to achieve and maintain midday ψ_l between −1.1 and −1.3 MPa. During nondeficit periods, all treatment plots were irrigated equally. The total water applied for RDI and Control plots in 2002 was 1064 and 1506 L/vine (261 and 369 mm) and 404 and 822 L/vine (99 and 201 mm) in 2003, respectively. Considerably less water was applied to both treatments in 2003 compared with 2002 because of lower ET_o and higher rainfall (84 mm vs. 13 mm) during the fruit set to veraison period in 2003. A randomized complete block design was used consisting of 25-vine plots per treatment, replicated four times. Each plot was bordered by a single-vine row on either side of the plot that was irrigated independently of treatment plots. Data were collected on ten vines in the middle of each plot, except where otherwise reported.

All treatments were repeated in 2003 as previously described in a more compact and heterogeneous area of the vineyard to improve the precision of intensive time-series measurements of stomatal conductance, leaf water potential, xylem sap ABA content, and periderm development. The RDI and Control treatments within the "subsample measurement plots" were conducted and analyzed as a completely ran-

domized design, with ten single-vine replications for each treatment, except where otherwise reported. Fruit yield (kg/vine), fruit composition, dormant primary bud cold hardiness, and pruning weight (kg/vine) data were also collected within the subsample measurement plots. Applied water-use efficiency–fruit yield (g) per unit (L) of water applied–was calculated for each treatment (Loveys et al., 1998). To facilitate attainment of water deficits, both plots were protected from potential water inputs from rainfall by covering the soil with a 0.1 mm black plastic prior to and during the deficit treatment period.

Vine water status. Vine water status was monitored in both years by measurement of midday leaf water potential (ψ_l) with a Scholander pressure chamber (Model 3005; Soil Moisture Equipment Corp., Santa Barbara, CA). A leaf was enclosed in a plastic bag with the petiole protruding and secured with a twist tie. The petiole was cut with a sharp razor blade, quickly ($\leq$ 10 s) placed within the sample chamber, and the chamber was slowly pressurized until a drop of sap was observed to exude from the cut end of the petiole. In 2002, three mature sun-exposed leaves from the west side of each treatment plot were sampled every 7 days. The subsample measurement plots were used in 2003 to measure ψ_l on three mature sun-exposed leaves from the west side of each treatment plot every 4-7 days. Stomatal conductance (g_s) was measured with a porometer (Model LI-1600; LI-COR, Inc., Lincoln, NE) in the subsample measurement plots in 2003 on ten mature sun-exposed leaves from each treatment, five each from the east and west sides of the canopy, between 1100 and 1300 h approximately every 3-7 days.

Yield and fruit composition. All fruit was harvested on the same date from the ten middle vines of each treatment plot in 2002 and from ten random vines within the subsample measurement plots in 2003. Fruit was weighed for an estimate of total yield and a randomly collected subsample of 50 clusters was used to determine the mean cluster weight in 2002; all clusters were counted and weighed in 2003. A random subsample of 300 berries provided a measure of berry weight. The remaining fruits were analyzed for total soluble solids concentration, pH, and titratable acidity with a refractometer (Leica 10430, American Optical, Service-Keene, NH), a pH meter (Accumet 925 pH/Ion meter, Fisher Scientific, Pittsburgh, PA), and manually titrated with 0.1 mol NaOH to an endpoint of pH 8.2.

Pruning weight. Vines in treatment plots were dormant pruned in 2003 and 2004 to twelve 2-bud spurs, the same bud count used at the beginning of this study in 2002. All pruning wood from five vines per treatment plot was collected and weighed in 2003 as a measure of vegetative

growth in the 2002 season. The subsample measurement plots were used to evaluate the 2003 irrigation treatment effects on vegetative growth as measured by 2004 dormant pruning weight. Pruning wood was collected and weighed from ten randomly selected vines (replications) within each treatment plot.

Abscisic acid analysis. Xylem sap was collected from the RDI and Control treatments in the subsample measurement plots in 2003 for quantitative analysis of ABA content following the methods of Correia et al. (1995). Three samples were taken from each treatment periodically starting two weeks after fruit set and continuing through veraison. Each sample was collected at midday from a sun-exposed leaf from one of three random vines per treatment. Approximately 50 µl of xylem sap was obtained per sample by expressing sap with the pressure chamber and collecting it with a pipette. Sap was rapidly transferred to Eppendorf tubes and stored in the dark on ice while in the field. Samples were frozen upon return to the laboratory and stored at −70°C for later analysis.

Quantitative analysis of xylem sap ABA was performed using an ELISA immunoassay kit and protocol (Phytodetek ABA ELISA kit; Agdia Inc., Elkhart, IN). A dilution series of (+)–ABA (Sigma, St. Louis) was prepared to provide a calibration standard curve. Leaf xylem sap samples were analyzed without any previous purification following the method of Correia et al. (1995). Each diluted field sample was divided between two wells for analysis, and standards were included in triplicate within the same microplate. Well color was measured with a microplate reader (ELx800 Microplate Reader, Bio-Tek Instruments, Inc., Winooski, VT) after a 2-hour incubation at 23°C. Readings from the two wells per field sample were averaged to represent each sample replicate. ABA content was determined by calculations based on (+)–ABA calibration standards and a log-logit transformation of data.

Acclimation and cold hardiness analysis. Acclimation was assessed in 2002 by monitoring shoot periderm development every two weeks on five randomly selected vines per treatment plot. Five shoots per vine were visually examined for periderm development; the number of nodes with periderm and total nodes per shoot were counted and the percentage of ripened nodes was calculated for each plot. A final assessment of periderm development was made by counting nodes on all shoots of one cordon on a single vine per treatment plot after leaf fall (Wample and Wolf, 1997). Periderm development was monitored earlier and more frequently within the subsample measurement plots in

2003. Ten random shoots on five vines (replications) per treatment plot were assessed weekly beginning 30 June for the number of nodes with periderm and total nodes per shoot. A final assessment of periderm development was conducted in September 2003 for all treatment plots. The number of nodes with periderm and total nodes per shoot were counted for all shoots on one cordon for one vine per treatment plot.

Primary bud cold hardiness was evaluated by low-temperature exotherm analysis (LTE) using methods adapted from Wolf and Cook (1994) and Lipe et al. (1992). RDI irrigation treatments imposed in 2002 were evaluated every two weeks beginning in December 2002. Evaluation of 2003 irrigation treatments was initiated earlier, starting in October 2003 and continuing weekly through December, and then bi-weekly through January and March 2004.

Dormant canes were randomly collected from treatment plots at each test date; buds at node positions one to seven were used for analysis. Buds were excised with approximately 2 mm of the subtending nodal tissue remaining attached to the bud, and then mounted on thermoelectric modules (MELCOR model 44910-OST, Trenton, NJ). For 2002 irrigation studies, each treatment block was represented by one thermoelectric module (TEM) containing 4 buds for a total of 16 buds per treatment. The subsample measurement block was used to evaluate treatment effects in 2003. Out of 5 randomly selected vines (replications), 4 buds were collected from within each treatment plot. The 4 buds from a single vine were placed together on a TEM for a total of 20 buds per treatment comprising 5 replications.

The TEM were positioned randomly in a programmable freezer (Scientemp, Adrian, MI) set to reduce the temperature from 20°C to −35°C at a rate of 3°C/h. TEM voltage output and corresponding freezer air temperature measured with a thermocouple were recorded every 3 sec with a data logger (CR-10X, Campbell Scientific, Logan, UT). The average of the temperatures at which the median LTEs occurred on each of the 4 or 5 TEMs was used as an estimate of the lethal temperature at which 50% of the buds were killed (LT_{50}), after the method of Wolf and Cook (1994).

Statistical analysis. Data were analyzed with SAS statistical software (SAS 8.2, SAS Institute, Cary, NC). Analysis of variance using the general linear models procedure was used to test main treatment effects. Data were analyzed as a randomized complete block design with 2 treatments and 4 replications in 2002 and as a completely randomized design in 2003 with 10 single-vine replications.

RESULTS

Water status. The RDI treatment established vine water deficits in both years for a period of approximately three weeks prior to veraison. Midday ψ_l in 2002 (Figure 1) was significantly ($\alpha = 0.05$) more negative for RDI plots during the 3 weeks prior to veraison, ranging from −1.11 to −1.17 MPa. Control plots had midday ψ_l ranging from 0.91 to 0.97 MPa during the same period. A more severe deficit was achieved with RDI in 2003; midday ψ_l was between −1.13 and −1.25 MPa during the 3 weeks prior to veraison (Figure 2). The Control plots had significantly higher midday ψ_l than RDI during the same period, ranging from −1.01 to −1.07 MPa. Both treatment plots experienced two brief periods of mild to moderate vine water deficit after veraison due to difficulties with the irrigation system.

Stomatal conductance in 2003 followed a pattern similar to ψ_l, with no difference among treatments prior to the beginning of the deficit period and RDI treatment vines maintaining significantly lower g_s during the pre-veraison deficit treatment period (Figure 3). Following an irrigation event at the end of the deficit treatment period, g_s of RDI vines was significantly higher than Control vines on 18 July. Both RDI and Control vines displayed their highest g_s rate on 24 July following a recent irrigation to both treatment plots; Control vines had significantly higher g_s than RDI on this date.

FIGURE 1. Vine water status in 2002 of 'Cabernet Sauvignon' receiving RDI deficit irrigation or a control irrigation treatment. ANOVA significant at P = .05*.

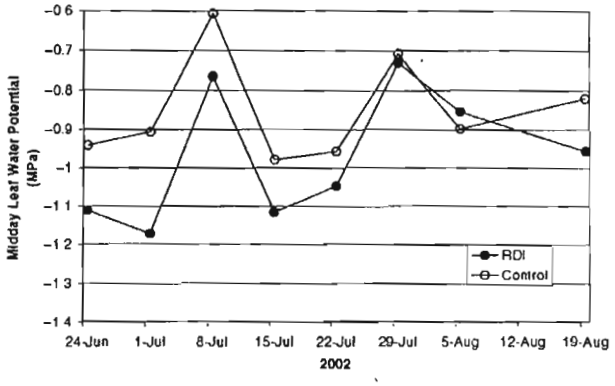
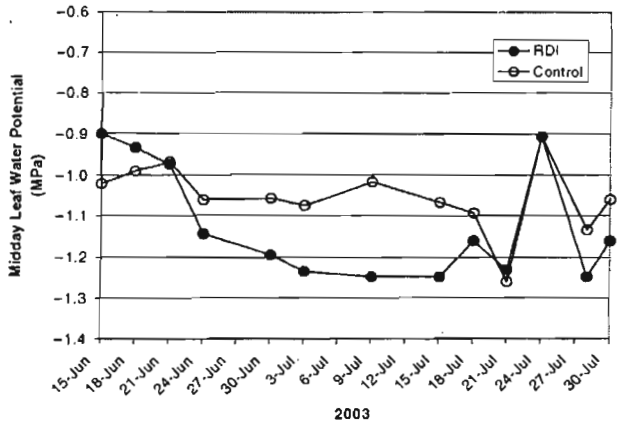


FIGURE 2. Vine water status in 2003 of 'Cabernet Sauvignon' receiving RDI deficit irrigation or a control irrigation treatment. ANOVA significant at P = 0.05* and P = 0.01**.



Yield components. There was no significant effect of RDI on yield, cluster weight, or berry weight in this study, although a consistent trend for higher values was apparent for the Control vines (Table 3). Yield was reduced in all plots by approximately 20% in 2003 due to hail damage.

Pruning weight. Deficit irrigation significantly reduced pruning weights in one of the two years. Pruning weight of RDI plots was 46% less than Control plots in 2002. Yield/pruning weight ratio did not differ between treatments in the two years.

Applied water-use efficiency. Production of similar yields with less applied water led to significantly greater AWUE for RDI in one of two years (Table 3). RDI plots received slightly less than 50% of the water applied to Control plots in 2003, but had 72% higher AWUE.

Fruit composition. Deficit irrigation had no effect on fruit-soluble solids, TA, or pH in both years of this study (Table 3). Fruit composition was typical for this vineyard and somewhat more favorable for both treatments in 2003.

Abscisic acid. Leaf xylem sap ABA of RDI vines reached a peak of 0.396 mmol m^{-3} on 30 June 2003 and was higher than in Control vines during the early portion of the imposed deficit treatment period (Figure 4). Subsequent to the peak for the RDI treatment, a general decline in ABA was observed in both treatments during the period of measurement and ABA of Control vines remained within a fairly narrow range

FIGURE 3. Seasonal stomatal conductance of 'Cabernet Sauvignon' receiving RDI deficit irrigation or a control irrigation treatment. ANOVA significant at P = 0.05* and P = 0.01**.

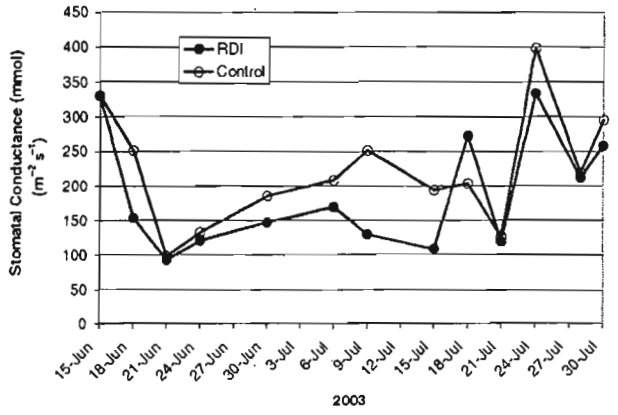


TABLE 3. Effect of RDI and a control irrigation treatment on yield components, pruning weights, applied water-use efficiency, and fruit composition of 'Cabernet Sauvignon' grapevines.

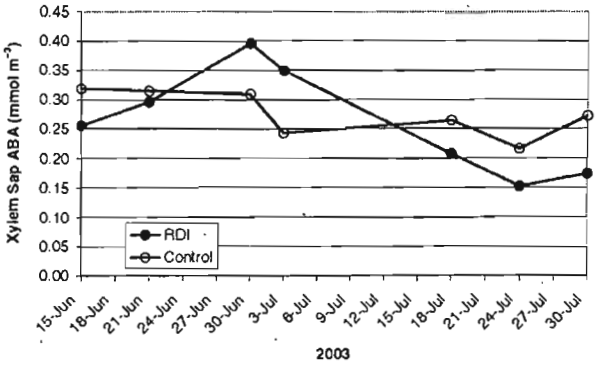
Irrigation Treatment	Yield (kg/vine)	Cluster Wt. (g)	Berry Wt. (g)	Pruning Wt. (kg/vine)	Yield/ Pruning Wt.	Applied Water-Use Efficiency[a] (g/L)	Soluble Solids (%)	Titratable Acidity (g/L)	pH
2002									
RDI	4.53	88.43	1.17	0.56*	9.99	4.8	24.55	4.24	3.88
Control	5.43	97.76	1.25	1.02	5.76	3.7	23.85	4.50	3.87
2003									
RDI	2.76	41.10	–	0.40	7.39	6.8**	23.54	5.14	3.59
Control	3.26	46.96	–	0.50	7.83	4.0	23.63	4.35	3.65

[a]Applied water-use efficiency is the ratio of fruit yield (g) per unit of applied water (L) (Loveys et al., 1998).
*Treatments significantly different by ANOVA at α =.05.
**Treatments significantly different by ANOVA at α =.01.

of 0.216 to 0.319 mmol m^{-3}. The xylem sap ABA concentrations measured in our study are somewhat lower than those reported by Correia et al. (1995) for moderately stressed vines (1.08 and 1.79 mmol m^{-3}).

Acclimation and cold hardiness. RDI consistently resulted in significantly earlier and more rapidly developing periderm compared with

FIGURE 4. Xylem sap ABA concentration of 'Cabernet Sauvignon' receiving RDI deficit irrigation or a control irrigation treatment. ANOVA significant at P = 0.05* and P = 0.01**.



Control vines. Periderm development had already been initiated by the time (24 July) the first measurements were taken in 2002, when 58% of the nodes of the RDI vines had periderm (Figure 5) compared with only 33% for the Control vines. The percentage of ripened nodes in the Control treatment eventually equaled that of RDI vines by the final sampling date.

Periderm assessments were initiated earlier in 2003 and again RDI vines exhibited significantly earlier and more rapid periderm development than Control vines (Figure 6). The most rapid rate of increase in periderm development occurred between 30 June and 21 July, corresponding to the period of vine water deficit conditions as indicated by ψ_l (Figure 2). As in the previous season, periderm development of Control vines eventually equaled RDI by the final sampling date.

Although RDI vines began the acclimation process earlier and developed periderm more quickly, there was no measurable improvement in bud cold hardiness when compared with Control vines (Table 4). Average median LT_{50} values were similar for RDI and Control vines on all sampling dates except 19 November 2003 when the Control treatment was significantly more cold hardy (−14.45°C) than the RDI treatment (−13.69°C). Bud cold hardiness of both treatments followed a typical pattern of increasingly lower LT_{50} values during the fall acclimation period until stabilizing in midwinter, and then increasingly higher LT_{50} values as vines began to deacclimate in late winter and early spring.

FIGURE 5. Periderm formation along the shoot in 2002 of 'Cabernet Sauvignon' receiving RDI deficit irrigation or a control irrigation treatment. ANOVA significant at P = 0.05*.

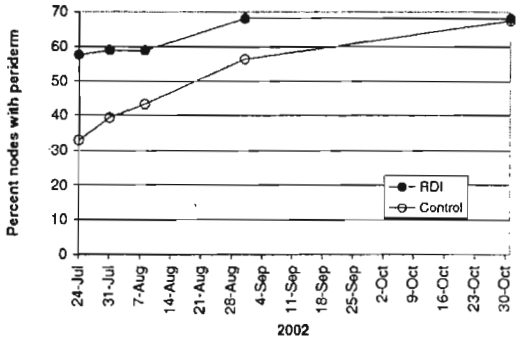
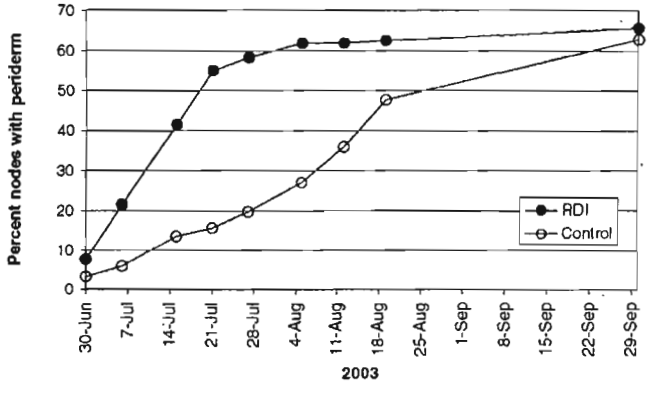


FIGURE 6. Periderm formation along the shoot in 2003 of 'Cabernet Sauvignon' receiving RDI deficit irrigation or a control irrigation treatment. ANOVA significant at P = 0.05* and P = 0.01**.



DISCUSSION

Mild to moderate water deficits were induced for the period three weeks prior to veraison by limiting water applications in RDI treatment plots. Deficit conditions within RDI vines were clearly indicated by higher midday ψ_l of RDI-treated vines during this time period compared with the Control treatment. Midday ψ_l is considered to be a good indicator of vine water status (Matthews et al., 1987; Stoll et al., 2000) and soil water availability (Williams and Trout, 2005) and therefore the pressure

TABLE 4. Effect of RDI and a control irrigation treatment on dormant bud cold hardiness of 'Cabernet Sauvignon' expressed as median LT_{50} values (°C).

Sampling Date	RDI	Control
2002 Treatment Year		
20 December 2002	−23.27	−21.88
03 January 2003	−23.56	−23.90
15 January 2003	−23.04	−21.76
31 January 2003	−24.75	−24.90
16 February 2003	−23.35	−22.93
2003 Treatment Year		
08 October 2003	−11.90	−11.60
15 October 2003	−10.77	−11.32
22 October 2003	−12.22	−13.34
29 October 2003	−11.10	−12.35
05 November 2003	−12.47	−12.97
12 November 2003	−13.22	−13.01
19 November 2003	−13.69	−14.45*
26 November 2003	−17.69	−17.53
03 December 2003	−17.42	−17.01
17 December 2003	−14.40	−16.49
07 January 2004	−17.32	−16.77
21 January 2004	−20.50	−19.62
04 February 2004	−20.24	−21.68
18 February 2004	−21.73	−20.79
03 March 2004	−21.48	−20.18
17 March 2004	−19.53	−17.49
31 March 2004	−9.84	−8.18

*Treatments within rows significantly different by ANOVA at $\alpha = .05$.

chamber has become an important tool for managing deficit irrigation in commercial vineyards. Stomatal conductance (g_s) is another indicator of vine water status and g_s was also reduced compared with Control vines during the three weeks prior to veraison.

Regulation of stomatal aperture and thus g_s has been demonstrated to be influenced by increased ABA synthesis within roots under drying conditions and transport to leaves (Correia et al., 1995; Stoll et al., 2000). In our study, xylem sap ABA content increased in RDI vines during the early portion of the deficit period, coinciding with comparatively low g_s and decreasing midday ψ_l. This agrees with reports that demonstrated higher levels of ABA in roots (Dry et al., 1996; Loveys et al., 1998) and xylem sap (Correia et al., 1995; Stoll et al., 2000) in

water-stressed grapevines. We observed ABA levels of RDI vines reaching a peak relatively early in the deficit period, and then declining. A similar pattern for ABA production in roots was reported by Loveys et al. (1998); ABA initially increased in response to water deficit and then declined despite continued dry soil conditions. The transient nature of ABA production by drying roots is the reason for the 10-14-day rotational irrigation cycle of the partial rootzone drying strategy that attempts to continually maintain a portion of the root system in a drying condition (Loveys et al., 1998). Tardieu and Davies (1992) proposed an explanation for transient ABA production based on increased stomatal sensitivity to ABA at lower ψ_l.

It is interesting to note that a rapid increase in shoot periderm development occurred immediately after the peak level of xylem sap ABA was attained. ABA has been implicated as a signal transducer for initiating the shoot acclimation process (Howell, 2000; Xin and Browse, 2000).

RDI generally resulted in reduced vegetative growth (pruning weights) compared with Control vines in our study. This is consistent with other deficit irrigation reports (Van Zyl, 1984; Matthews et al., 1987; Gomez-del-Campo et al., 2002). Vigor reduction can be an important component of canopy management practices that attempt to improve microclimate conditions for enhanced fruit ripening and more effective disease control.

The overall response of vines to our RDI treatment with respect to growth, yield, and fruit composition was not large, in contrast to other reports of deficit irrigation significantly impacting yield components and fruit composition. This was likely because the comparative Control treatment did not receive a high irrigation rate and vine water status (ψ_l) was often closer to deficit rather than abundant levels. RDI could be expected to have a greater impact when implemented in a vineyard that has previously received high irrigation rates. The results of our study indicate that the RDI strategy can be successfully implemented in west Texas to reduce vine vegetative growth and improve the efficiency of applied water use without sacrificing yield or fruit quality.

Acclimation and Cold Hardiness

Matthews et al. (1987) observed accelerated periderm development on grapevine shoots in response to moderate water deficits, and our deficit irrigation treatment elicited a similar response. RDI was consistently associated with earlier and more rapid vine acclimation as

indicated by shoot periderm development. Earlier vine acclimation indicates better cold hardiness in early fall (Wample and Wolf, 1997), which can be important in years with an exceptionally early frost. Freeze injury resulting from low temperatures prior to adequate vine acclimation in the fall is a major production risk for grapes on the Texas High Plains and other northern production regions (Lipe et al., 1992).

Although earlier acclimation was clearly achieved with the RDI treatment, improved primary bud cold hardiness as measured by controlled freezing LTE methods was not evident. Our controlled freezing apparatus was not functional until December 2002, and so any potential treatment effects prior to this time could not be evaluated. Wample et al. (2000) reported that cane cold hardiness differences resulting from irrigation treatments were detectable early in the dormant season, but not by late December. Similarly, our irrigation treatments had no significant effect on primary bud cold hardiness for the remainder of the 2002-03 dormant season. Both treatments exhibited typical and similar bud hardiness levels at all sampling dates. Irrigation treatments in 2003 again did not influence primary bud cold hardiness even at the earlier evaluation dates conducted in October. All treatments attained adequate and fairly similar levels of primary bud cold hardiness at sampling dates throughout the dormant season. It should be noted again that our comparative Control treatment did not represent excessive application of water, which has been reported to reduce vine cold hardiness (Wample and Wolf, 1997; Wample et al., 2000).

It is well established that cane maturation (ripening) is a prerequisite for vine cold hardiness, and field observations suggest that early shoot acclimation corresponds to better vine cold hardiness (Goffinet, 2000; Matthews et al., 1987; Wample and Wolf, 1997). But such a relationship has not been demonstrated in the laboratory using the LTE bud cold hardiness method. The present study found no differences in primary bud cold hardiness measured by LTE among treatments that produced significantly earlier shoot acclimation. A similar lack of relationship was reported by Wample and Wolf (1997)–earlier shoot acclimation was associated with reduced irrigation rates for 'Sauvignon blanc' in Washington, but no or few differences in bud cold hardiness were detected by the LTE method.

The LTE bud cold hardiness methodology has been demonstrated to agree well with field survival (Wolf and Cook, 1994), but it has also been suggested that disparate results may occur because field injury may be more closely related to cane and trunk tissues than to buds (Wample and Wolf, 1997). Supplemental field observations of relative

cold hardiness could not be obtained in our study because damaging freeze events did not occur in the test vineyard at any time during the study. The LTE method was used in Washington to assess both cane and bud hardiness of 'Cabernet Sauvignon' receiving different irrigation treatments; cane hardiness was increased by low irrigation rates, but no difference in bud hardiness was detectable (Wample et al., 2000). Cane hardiness was not evaluated in the present study, but it appears that continued investigation in this area is warranted.

CONCLUSIONS

Deficit irrigation can be successfully utilized for commercial grape production in west Texas to reduce vegetative growth and improve the efficiency of applied water use. The RDI strategy had beneficial effects without negatively influencing crop yield or fruit composition. These benefits were attained with mild to moderate levels of vine water stress (midday ψ_l between -1.1 and -1.3 MPa) and it should be noted that a greater or a lesser response to deficit irrigation can likely be induced by modification of the timing, duration, or extent of the water deficit. Deficit irrigation could influence shoot acclimation, but did not improve primary bud cold hardiness.

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