Responses of *Vitis vinifera* L. cv. Sultanina to Water Deficits During Various Pre- and Post-Harvest Phases Under Semi-Arid Conditions

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Performance of Sultanina grapevines irrigated at 60% plant-available water depletion (T1) were compared to situations where water deficits were induced at budbreak (T2), before flowering (T3), after flowering (T4), at pea size (T5) and during ripening (T6). The field trial was performed on a fine sandy soil at Upington in the Lower Orange River region in South Africa. Treatments T1 to T6 were irrigated at 60% plant-available water (PAW) depletion during the post-harvest period and winter. A further four treatments were irrigated at 60% PAW depletion from budbreak until irrigation was terminated three weeks (T7), seven weeks (T8), eleven weeks (T9) and fifteen weeks (T10) after harvest, respectively. The periods of water stress induced during the various pre-harvest phenological phases were too short to have a significant effect on vegetative growth. Water deficits during the early season (T2, T3 and T4) tended to affect yield more negatively than deficits applied between pea size and harvest (T5 and T6). Yield reduction was associated with tendencies toward reduced bunch differentiation, berry shed and smaller berries. Berry size was significantly reduced by water deficits induced after flowering (T4). Water deficits had no significant effect on juice sugar content or on total titratable acids. No choice-grade sun-dried raisins could be produced when grapevines were subjected to water deficits during ripening (T6). In comparison to continued irrigation at 60% PAW depletion and water deficits induced up to pea size, significant browning of dipped raisins produced from T5 and T6 grapevines occurred during some seasons. In combination with low relative humidity, water deficits between pruning and budbreak (T7 to T10) reduced yields significantly compared to continued irrigation at 60% PAW depletion throughout the post-harvest period. Low relative humidity and dry soil also induced delayed budbreak and stimulated excessive shoot growth after harvest to such an extent that cane mass was significantly higher compared to irrigation at 60% PAW depletion. Neither water deficits nor significant shoot re-growth during the post-harvest period had any effect on cane starch content at pruning.

Irrigation is an essential practice for grape production in the semi-arid Lower Orange River region of the summer rainfall region in South Africa. Sultanina (Sultana or Thompson's Seedless) is the most important cultivar in this region. Dark-coloured sun-dried raisins and dipped raisins are the two most important dried-grape products. Dipped raisins remain yellow-green due to rapid drying induced by removal of the wax layer on the berries (Grncarevic & Radler, 1971). Optimum balance between growth, yield and quality of dipped raisins in the Lower Orange River region was obtained when Sultana grapevines were irrigated at 60% plant available water (PAW) depletion throughout the growing season (Myburgh, 2003a). However, optimum balance for sun-dried raisins was obtained with wetter soil conditions by maintaining PAW depletion at 30%. Water allocation for irrigation is limited and water restrictions are common during dry summers. Since the 30% and 60% PAW depletion levels remained constant over the season, there is still some uncertainty about the effects of water deficits at critical phenological phases under the specific climatic conditions of this particular region.

Water deficits during critical phenological phases can influence grapevine yield and quality. Severe water stress after flowering can induce cluster abscission (Hardie & Considine, 1976), whereas mild water stress will reduce vegetative vigour, possibly improving canopy light penetration and increasing yield (Williams *et al.*, 1994 and references therein). Water deficits induced during fruit set will restrict cell division and reduce berry size (Hardie & Considine, 1976; Van Zyl, 1984a; Matthews & Anderson, 1989; McCarthy, 1997). Sugar accumulation, which is crucial for quality-raisin production (Saayman & Albertse, 1984), can be reduced if severe water stress during ripening results in leaf senescence, but may be increased when mild water stress reduces vegetative growth (Smart & Coombe, 1983). Practical experience showed that a luxurious water supply before or during harvest may reduce sugar content and, consequently, induce poor raisin quality due to lower drying ratios (Goosen, 1956). Scientific knowledge concerning the effect of water deficits on raisin quality is, however, limited. Water deficits induced by terminating irrigation *ca* ten weeks prior to harvest reduced sun-dried Sultanina raisin quality significantly compared to a cut-off five weeks before harvest (Christensen, 1975). However, this effect was not consistent over seasons. Fresh berry mass and raisin size tended to be larger when irrigation was terminated

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only *ca* 5 weeks before harvest. Recently, it was shown that water deficits induced by irrigation at 90% PAW depletion throughout the season significantly reduced the quality of sun-dried raisins (Myburgh, 2003a). Browning or darkening of dipped raisins, which reduces marketing grade, occurred when Sultanina grapevines that were well watered over the first part of the season were subjected to water stress during ripening (Nagarajah, 1992).

The Lower Orange River is a summer rainfall region. Vineyards along the Lower Orange River therefore require irrigation during winter (Goosen, 1956). Since irrigation guidelines in South Africa were developed more specifically under winter rainfall conditions, knowledge of water relations and of the irrigation requirements of grapevines during the post-harvest period and dry winters is limited. In fact, Van Zyl (1984b) reported that efforts to induce water deficits during the post-harvest period in a field trial at Robertson under winter rainfall conditions failed due to untimely rain. Injudicious irrigation of Sultanina during the post-harvest period, in combination with high temperatures at that stage, may induce excessive vegetative re-growth (Goosen, 1956). On the other hand, field observations showed that too dry conditions during dormancy can be detrimental to growth at the beginning of the new season. However, it should be borne in mind that these observations were relevant to vineyards that were mainly established on the fertile, alluvial soils along the Lower Orange River at that stage. In California budbreak in Perlette table grapevines occurred earlier when irrigation was cut off early in the post-harvest period (15 September) compared to the normal, later cut off on 1 December (Williams *et al.*, 1991).

The aim of this study was to determine the effect of pre-harvest as well as post-harvest water deficits on growth, production and raisin quality of Sultanina in the Lower Orange River region.

MATERIALS AND METHODS

Experiment vineyard

The field trial was performed in a twelve-year-old ungrafted Sultanina (Clone H4) vineyard on the SADOR farm of the South African Dried Fruit Co-operative near Upington. This locality is in a class V climatic region (Winkler, 1962) at 28° 27' South latitude. The soil belonged to the Plooysburg form (Soil Classification Work Group, 1991) and consisted of 600 mm to 900 mm deep red sand on undulating, cemented limestone. Before planting commenced, the soil was deep ripped to a depth of 800 mm. Grapevines were planted at 3.0 m x 2.0 m intervals, trained onto a gable trellis (Zeeman, 1981) and cane pruned, allowing 12 to 18 nodes per cane. Twelve canes were allowed per grapevine. The vineyard was irrigated by means of 32 L/h micro-sprinklers. Soil water matric potential was measured once a week, as well as before and after irrigations, by means of tensiometers. The latter were installed on the vine row *ca* 500 mm from a vine at 300 mm, 600 mm and, where possible, at 900 mm depths. Myburgh (2003a) presented details of the soil texture, soil water retention, irrigation scheduling and meteorological data collection.

Experiment layout

A control treatment (T1) was irrigated from budbreak until harvest at 60% plant-available water (PAW) depletion, where PAW is soil water retained between -0.01 MPa and -1.50 MPa. Water deficits were induced after budbreak (T2), before flowering (T3), after flowering (T4), at pea size (T5) and during ripening (T6). Depending on the meteorological conditions during these periods, irrigation was withheld for two to three weeks to obtain soil matric potentials lower than -0.07 MPa. All these treatments were irrigated at 60% PAW depletion throughout winter. A further four treatments were irrigated at 60% PAW depletion from budbreak until irrigation was terminated three weeks (T7), seven weeks (T8), eleven weeks (T9) and fifteen weeks (T10) after harvest, respectively. All treatments were irrigated just before budbreak. Treatments were replicated three times in a randomised block design. Experiment plots consisted of twelve experiment vines with two buffer vines at each end and a buffer row on each side. Each plot covered 216 m^2. Treatments T2 to T6 were applied from the 1994/95 season until 1997/98. Application of treatments T7 to T10 only began during the post-harvest period of the 1994/95 season and they were in effect applied from 1995/96 until 1998/99. Irrigation at 60% PAW depletion (T1), which served as a mutual control, was applied from 1995/96 until 1998/99.

Plant parameters

Vegetative growth was quantified by measuring cane mass at pruning (July). To assess the reserve status of the dormant grapevines, starch content of canes bearing the next season's crop was determined at pruning on all replications of T1, T7, T8, T9 and T10 using the enzymatic procedure described by Hunter *et al.* (1995). Yield was determined by measuring total grape mass per plot at harvest (end January). Single berry mass was assessed by picking five berries from each of twenty bunches from each plot. Berries were picked at different positions along the longitudinal bunch axis. After determining berry mass, samples were macerated using a mortar and pestle and squeezed through cheesecloth to obtain juice samples. Total soluble solids and total titratable acidity were determined on juice samples from all replications of each treatment using standard Nietvoorbij laboratory procedures. Juice was not analysed during the 1998/99 season.

Sun-dried as well as dipped raisins were produced and their quality grading determined on all replications of T1 to T6 as described by Myburgh (2003a). To quantify browning of dipped raisins, representative *ca* 250 g samples were obtained from the bulk sample by means of a sample splitter. After weighing, brown and yellow raisins were separated by hand. Brown raisins were weighed and their mass was expressed as a percentage of the total sample mass. During the 1995/96 season P, Ca, Mg, K and Na concentrations in skins and flesh of normal yellow dipped raisins as well as those that turned brown upon drying were determined on all replications of T1 (control) and T5, *i.e.* the treatment where the highest percentage of browning occurred during that particular season. Fifty raisins were counted from the brown and yellow raisin samples after the percentage browning was determined as explained above. After soaking raisin samples for three hours in 100 mL de-ionised water, skins and flesh were carefully separated. Samples were placed in folded filter paper (Whatman No. 2) and dried on a sand bath to remove free water. Following this, samples were dried in an oven at 60°C until constant mass was attained. After weighing, samples were ashed in porcelain crucibles by means of a gas flame and ground to a fine powder using a mortar and pestle. Total P, Ca, Mg, K and Na were determined using an inductively coupled plasma atomic emission spectrometer (Liberty 200 ICP AES, Varian, Australia), following digestion with nitric acid/perchloric acid.

Grapevine fertility was quantified by determining total number of bunches per grapevine for each treatment at harvest. Bud fer-

tility at pruning of T1, T7, T8, T9 and T10 was determined during the 1996/97 and 1997/98 seasons. Ten 80 mm-long cane cuttings, each bearing a single bud, were sampled at pruning on all plots. Samples were stored at 4°C for 8 weeks before they were transplanted to mist beds in a greenhouse. Due to malfunctioning of the mist beds, almost no budding occurred and fertility could not be determined during the first season. During the 1997/98 season, however, cuttings were inserted through holes in a 15 mm polystyrene sheet that floated on a Hoagland nutrient solution in a 150 mm-deep container placed in a greenhouse. The nutrient solution was replaced weekly to avoid algae growth. Number of bunches per bud was determined when shoots were *ca* 150 mm long. Bud fertility was calculated by dividing the actual number of bunches by an assumed maximum of two bunches per shoot. Bud fertility was also determined at flowering by counting the number of flower bunches per shoot and dividing by an assumed maximum of two bunches per shoot. Due to logistical problems, bud fertility was not determined during the 1998/99 season.

During the 1996/97 season cane water content was determined just before budbreak (late August) on T1, T7, T8, T9 and T10 plots. Cane samples (*ca* 50 g) were collected and weighed to obtain fresh mass. Dry mass was obtained by drying samples at 60°C until constant mass was attained. Cane water content of the fresh samples was calculated as the percentage water loss. Soil water content was determined gravimetrically over 0-300 mm and 300-600 mm depth increments on the day that canes were sampled. Soil water content was related to matric potential using soil water retention curves as described by Myburgh (2003a).

Statistical analysis

The data were subjected to an analysis of variance. Tukey's least significant difference (LSD) values were calculated to facilitate comparison between treatment means. Means which differed at $p \leq 0.05$ were considered to be significantly different. Statgraphics® was used to determine relationships between parameters by means of linear regression.

RESULTS AND DISCUSSION

Pre-harvest water deficits

Soil water content

An example of the extent to which soil water content in the deficit treatments was depleted in comparison to continued irrigation at 60% PAW depletion is presented in Figure 1. After irrigation was cut off to induce water stress during a specific phenological phase, the initial rapid soil matric potential decrease was followed by a period of considerably slower water depletion. This depletion pattern between irrigations was primarily a result of decreasing evaporation losses from the soil (Myburgh, 1998). On average, minimum soil matric potential obtained during the various phenological phases amounted to *ca* –0.070 MPa, which is slightly lower than –0.064 MPa that is presumed to induce the onset of water stress in grapevines (Van Zyl, 1987). Since evapotranspiration in the Lower Orange River region is relatively low during late winter and early spring (Myburgh, 2003a), it was not possible to induce water deficits in the case of T2 to the same extent as for the rest of the deficit treatments.

Vegetative growth and yield

Water deficits during the various phenological phases had no significant effect on vegetative growth in comparison to T1 (Table 1). When Sultanina grapevines were subjected to water deficits under similar conditions throughout the season, vegetative growth was significantly reduced (Myburgh, 2003a). Hence, exposure to water stress during the various phenological phases was probably too short to reduce shoot growth in the present study. According to Schultz & Matthews (1988), vegetative growth of container-grown White Riesling was inhibited at soil matric potentials below –0.065 MPa and ceased completely at –0.540 MPa.

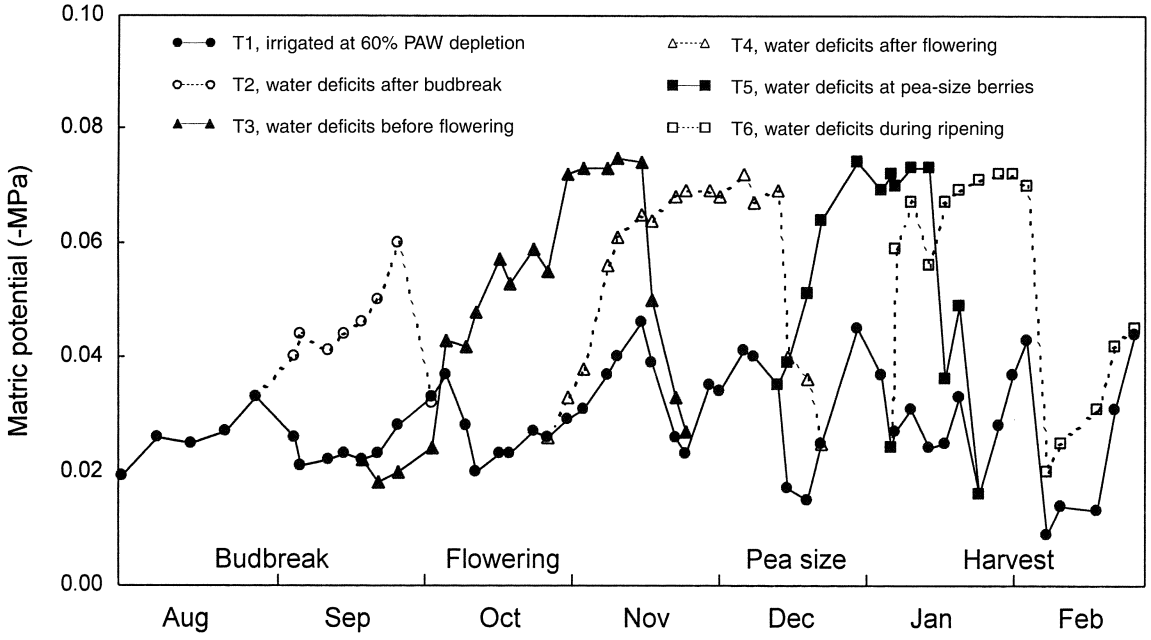

FIGURE 1

Soil water matric potential where water deficits were induced at various pre-harvest phenological phases of Sultanina as measured during the 1995/96 season in a field trial at Upington.

In general, yield showed considerable variation from season to season (data not shown). This seasonal variation, which is typical for Sultanina vineyards (May, 1961), is probably caused by variation in meteorological conditions at the time of flowering, which influences bunch initiation and differentiation (Williams *et al.*, 1994 and references therein). Under the conditions along the Lower Orange River seasonal yield variation occurred irrespective of the degree of soil water depletion between budbreak and harvest (Myburgh, 2003a). Water deficits induced during the various phenological phases had no significant effect on number of bunches per grapevine in comparison to irrigation at 60% PAW depletion throughout the pre-harvest period (T1) (Table 1). According to Buttrose (1974), continuous exposure to water deficits from budbreak until harvest significantly reduced bud fruitfulness. This suggests that duration of water stress in the present study was too short to induce a negative effect on bud fruitfulness. In the case of water deficits induced at budbreak (T2), and before flowering (T3), a tendency toward smaller bunches (Table 1) was the primary cause for the 17% and 15% lower yields, respectively, compared to T1. Bunch differentiation, which occurs around budbreak (Pratt, 1971), was probably limited by the mild water deficits in the case of T2. Although not quantified as such, visual observation revealed that berry shed, which occurred more readily after flowering from bunches of T3, could have reduced bunch mass compared to the other treatments. A tendency towards smaller berries also contributed to lower bunch mass of T2 and T3 (Table 2).

Where water deficits were induced after flowering, significantly reduced berry size caused the 9% yield decrease in comparison to T1 (Table 1). The smaller berries were probably due to limited cell division. Mean yield of grapevines subjected to water deficits at pea size was only 4% lower than yield of T1 grapevines. Water deficits during this phenological phase also tended to reduce berry size in comparison to T1. Furthermore, visual observation revealed that dried berries (waterberries) occurred during some seasons on bunch tips where water deficits were induced at pea size. This possible effect of water deficit is contrary to the presumption that development of waterberries is associated with insufficient hormone production in the fruit and that the most critical period is at flowering and fruit set (Morrison & Iodi, 1990). Although not quantified, it was unlikely that the limited occurrence of waterberries in the present study would have had a meaningful effect on yield or grape quality. Water deficits during fruit ripening tended to reduce mean yield in comparison to T1 (Table 1). This trend was probably also related to a tendency towards smaller berries (Table 2). Yield reductions due to water deficits during ripening were also reported by Van Zyl (1984a) and Matthews *et al.* (1987).

In general, water deficits induced early in the season tended to have a more pronounced negative effect on yield than deficits induced between pea size and harvest. Hardie & Considine (1976) and Matthews *et al.* (1987) reported similar results. In a parallel study, yield of Sultanina grapevines subjected to continued water deficits by irrigation at 90% PAW depletion from budbreak until harvest was significantly lower than yields of grapevines irrigated at 30% depletion (Myburgh, 2003a). This confirms that, under the conditions of this study, significant yield losses will only result from combined negative effects if water deficits are induced during all the phenological phases up to harvest.

TABLE 1

Effect of water deficits during various phenological phases on mean cane mass, number of bunches per grapevine, bunch mass and yield of Sultanina as measured over four seasons at Upington.

Treatment number	Phases when water deficits were induced	Cane mass (t/ha)	Bunches per grapevine	Bunch mass (g)	Yield (t/ha)
T1	No water deficits	2.10	76	348	45.8
T2	At bud break	1.98	81	266	38.0
T3	Before flowering	2.23	78	274	38.8
T4	Flowering to pea size	2.18	78	306	41.7
T5	Pea size to veraison	2.13	84	298	43.8
T6	Veraison to harvest	2.01	80	320	43.0
	LSD ($p \leq 0.05$)	NS*	NS	NS	NS

* NS = Not significant.

TABLE 2

Effect of water deficits during various phenological phases on mean berry mass, total soluble solids (TSS) and total titratable acids (TTA) of Sultanina as measured over four seasons at Upington.

Treatment number	Phases when water deficits were induced	Berry mass (g)	TSS (°B)	TTA (g/L)
T1	No water deficits	1.65	20.3	5.4
T2	At bud break	1.54	20.9	5.3
T3	Before flowering	1.56	21.7	5.3
T4	Flowering to pea size	1.48	21.2	4.9
T5	Pea size to veraison	1.55	21.4	5.1
T6	Veraison to harvest	1.54	21.3	5.1
	LSD ($p \leq 0.05$)	0.17	NS*	NS

* NS = Not significant.

Total solublal solids and total titratable acidity

For logistic reasons grapes could not always be harvested at optimum ripeness, *i.e.* at 22°B as proposed by Saayman & Albertse (1984). In general, water deficits induced during the different phenological phases only tended to increase sugar accumulation and decrease acid content in comparison to T1 (Table 2). This suggests that periods of water stress were probably too short to induce any significant differences in sugar or acid contents. During the 1996/97 season, when yields from all treatments were exceptionally high (> 58 t/ha), sugar accumulation was significantly higher for the treatments with the lowest yields, *i.e.* T2, T3 and T6, in comparison to T1 (data not shown). This indicated that crop load played a more significant role than water deficits with respect to sugar accumulation. High yields generally delay ripening (Smart & Coombe, 1983 and references therein).

Raisin quality

During the first season (1994/95) over-drying of the raisin samples occurred. Consequently, quality-grading values for these raisins were unrealistic and were ignored in this study. Water deficits had no significant effect on quality-grading of dipped or sun-dried raisins. Quality of sun-dried raisins from all treatments, including continued irrigation at 60% PAW depletion, was generally lower than dipped raisin quality (data not shown). In a parallel study it was shown that water deficits applied by irrigation at 90% PAW depletion from budbreak until harvest also had a pronounced negative effect on sun-dried raisin quality compared to that of dipped raisins (Myburgh, 2003a). The fact that no choice-grade sun-dried raisins were produced when grapevines were subjected to water deficits during ripening (data not shown) suggests that sun-dried raisin quality is particularly sensitive to water deficits during ripening. According to the evaluation results, the low quality was due to poor raisin texture. Since there is no explanation for the poor quality in relation to water deficits, this aspect needs to be clarified by further research.

Visual observation revealed that dipped raisins from some treatments turned brown two to three days after they were spread on the drying racks. At the end of the drying process, a relatively large percentage of these discoloured raisins were dark brown to almost black. Browning or blackening of raisins can be caused by enzymatic oxidation of polyphenols to tannins (Grncarevic & Radler, 1971). In grapes catechins are naturally-occurring polyphenolic substrates for enzymatic oxidation (McBean *et al.*, 1971). Although raisins from all treatments showed some browning, raisins from grapevines subjected to water deficits during ripening (T6) tended to be affected more readily (Table 3). The incidence of this undesired browning varied from season to season and during the 1995/96 season raisins from grapevines subjected to water deficits from pea size until veraison (T5) showed significant browning. Analysis of raisins produced during the 1995/96 season showed that there were no significant differences in the P, Ca, Mg and K content of the flesh or skins of brown raisins compared to those raisins that retained their yellow colour (Table 4). However, the Na content of the flesh and skins of brown raisins was considerably higher than in the yellow raisins.

A possible role of Na in browning of dipped raisins may be as follows. Osmotic adjustment accompanied by reduced starch and increased fructose and glucose can occur in grapevines to avoid stress imposed by water deficits (Düring, 1984). Although it is generally accepted that mineral ions can accumulate in plants as a result of osmotic adjustment in reaction to water deficits (Kramer, 1983), evidence that this happens in grapevines could not be found in the literature. However, it has been shown that osmotic adjustment is due to accumulation of Na, K and Cl ions as well as reducing sugars when grapevines are exposed to salt stress (Williams *et al.*, 1994 and references therein). Functioning of xylem vessels, which constitute the only pathway for Ca to flow into grapevine berries, normally degenerates after véraison (Lang & Düring, 1991). Consequently, Ca content in berries generally remains constant during ripening compared to other mineral ions (Schrader *et al.*, 1976; Morrison & Iodi, 1990; Maxa *et al.*, 1995; Esteban *et al.*, 1999). Hence, Na uptake and translocation via the xylem to the berries, as a result of osmotic adjustment, could have increased Na:Ca ratios (Table 4).

According to Macheix *et al.* (1990 and references therein), ortho-diphenol oxidase (o-DPO), the enzyme responsible for polyphenol oxidation, is mainly located in the chloroplasts of grape cells and increased oxidation responsible for browning of fruit is associated with membrane degeneration. It is generally accepted that monovalent cations (Na and K) increase membrane permeability, whereas divalent cations (Ca and Mg) reduce permeability (Greulach, 1973). Increased Na:Ca is also believed to increase membrane permeability (Greenway & Munns, 1980). Hence, by increasing membrane permeability, the higher Na concentrations in the brown raisins presumably enhanced contact between o-DPO in chloroplasts and substrates in other cell parts. This could have increased polyphenol oxidation and browning, irrespective of rapid raisin drying. Dipped raisins produced from

TABLE 3

Effect of water deficits during various pre-harvest phenological phases on browning of Sultanina raisins.

Treatment number	Phases when water deficits were induced	Brown raisins (%)			
		1994/95	1995/96	1996/97	1997/98
T1	No water deficits	9.5	10.9	8.7	8.2
T2	At bud break	4.7	9.7	9.2	12.5
T3	Before flowering	7.7	9.1	8.3	13.3
T4	Flowering to pea size	2.0	5.5	7.4	7.0
T5	Pea size to veraison	6.7	20.0	7.3	7.5
T6	Veraison to harvest	20.0	9.1	11.8	18.3
LSD ($p \leq 0.05$)		11.6	13.7	NS*	NS

* NS = Not significant.

TABLE 4

Phosphorus and cation concentrations as well as Ca:Na ratios in flesh and skins of yellow and brown dipped Sultanina raisins as measured during the 1996/97 season.

Treatment number	Raisin colour	Flesh/ skins	P (%)	Ca (%)	Mg (%)	K (%)	Na (%)	Ca:Na
T1	Yellow	Flesh	0.49	0.52	0.16	0.83	0.014	37.1
		Skins	0.45	0.51	0.15	0.82	0.017	30.0
	Brown	Flesh	0.46	0.44	0.18	0.98	0.027	16.3
		Skins	0.36	0.53	0.14	1.39	0.034	15.6
T5	Yellow	Flesh	0.35	0.31	0.13	1.00	0.012	25.8
		Skins	0.44	0.54	0.14	0.98	0.015	36.0
	Brown	Flesh	0.40	0.31	0.15	1.13	0.032	9.7
		Skins	0.47	0.44	0.18	1.11	0.043	10.2
	LSD ($p \leq 0.05$)	NS*	NS	NS	NS	0.028	NS	

* NS = Not significant.

grapevines that were subjected to water deficits throughout the season did not turn brown during drying (Myburgh, 2003a). This suggests that sudden water deficits contributed to the browning of T5 and T6 raisins in the present study, which is in agreement with the findings of Nagarajah (1992). Since Na does not affect o-DPO activity (Macheix *et al.*, 1990 and references therein), high Na concentrations *per se* could not have been directly involved in the browning process. Hence, it is more likely that Na induced browning indirectly through increased membrane permeability.

Post-harvest water deficits

Soil water content

Data for the 1997/98 season are presented as an example of the effect of the stage at which irrigation was terminated during the post-harvest period on soil water content (Fig. 2). Since evapotranspiration was low after May (Myburgh, 2003a), soil water depletion was so slow that T10 was subjected to water deficits for a relatively short period in comparison to T7, T8 and T9. Since tensiometers stopped functioning at *ca* –0.07 MPa, it can be assumed that soil matric potential in the root zone was well below this value where irrigation was terminated early during the post-harvest period (T7 and T8). Measuring soil water content just before budbreak during 1996 showed that soil water matric potential in the 0-600 mm soil layer of these treatments was *ca* –1.70 MPa, which is slightly below permanent wilting point.

Vegetative growth

Although not quantified, visual observation revealed that the stage at which irrigation was terminated after harvest had no effect on budbreak during the 1995/96, 1996/97 and 1998/99 seasons. During the 1997/98 season typical delayed budbreak symptoms, *i.e.* uneven budding, stunted shoot growth and white canes, were observed where grapevines were subjected to post-harvest water deficits during 1997 (T7, T8, T9 and T10). Some shoots eventually developed as the growing season progressed. After harvest excessive shoot regrowth occurred to such an extent that cane mass of these treatments was significantly higher at pruning compared to T1 (Table 5). During the 1996/97 season cane water content of T7 to T10 determined just before budbreak was approximately 4% less compared to that of T1 canes (Table 6). At that stage mean gravimetric soil water content in the 0-600 mm layer of T7 to T10 varied around 3%, which was slightly less than the permanent wilting point water content of 3.5% (Myburgh, 2003a). Hence, extremely dry soil conditions during winter could have contributed to delayed budbreak that occurred during the 1997/98 season. Since these dry conditions did not cause total shoot desiccation and grapevine die back, water was probably extracted from deeper soil layers.

Water deficits during the post-harvest period had no significant effect on cane starch content at pruning (Table 7). Surprisingly, excessive post-harvest shoot growth during the 1997/98 season did not limit starch accumulation in canes of T7, T8, T9 and T10 in comparison to that of T1. Furthermore, budding and shoot growth were not affected during the following season, *i.e.* 1998/99. These results suggested that neither water deficits nor excessive post-harvest shoot growth limited reserve accumulation in the canes under the conditions that prevailed when this study was undertaken. This does not exclude the possibility that water deficits could have a meaningful effect on reserve accumulation in trunks and roots (J.J. Hunter, personal communication).

Yield

In comparison to the control (T1), the stage at which irrigation was terminated after harvest of the preceding season had no significant effect on mean yield of T7, T8, T9 and T10 during the 1995/96, 1996/97 and 1998/99 seasons (Table 8). During the 1997/98 season yields of all treatments were relatively low compared to the mean yield obtained during the other three seasons. Yields of most vineyards along the Lower Orange River were generally low during this particular season. In comparison to T1, water deficits significantly reduced yields of T7 to T10 during the 1997/98 season. Yields of T7 to T10 also tended to decrease with an increase in exposure to water deficits during the post-harvest period. The decrease in bud fertility from pruning until flowering in the case of T7 to T10 suggested that abortion of bunch primordia, which occurred at some stage during this period, had reduced the number of bunches per grapevine (Table 8). Since bud fertility of T7 to T10 was comparable to T1 at pruning, and all treatments were irrigated before budbreak, abortion caused by water deficits must have occurred between pruning and budbreak. In addition, water deficits between pruning and budbreak probably limited bunch differentiation, which also occurs during this period (Pratt, 1971 and references therein), to such an extent that bunch masses of

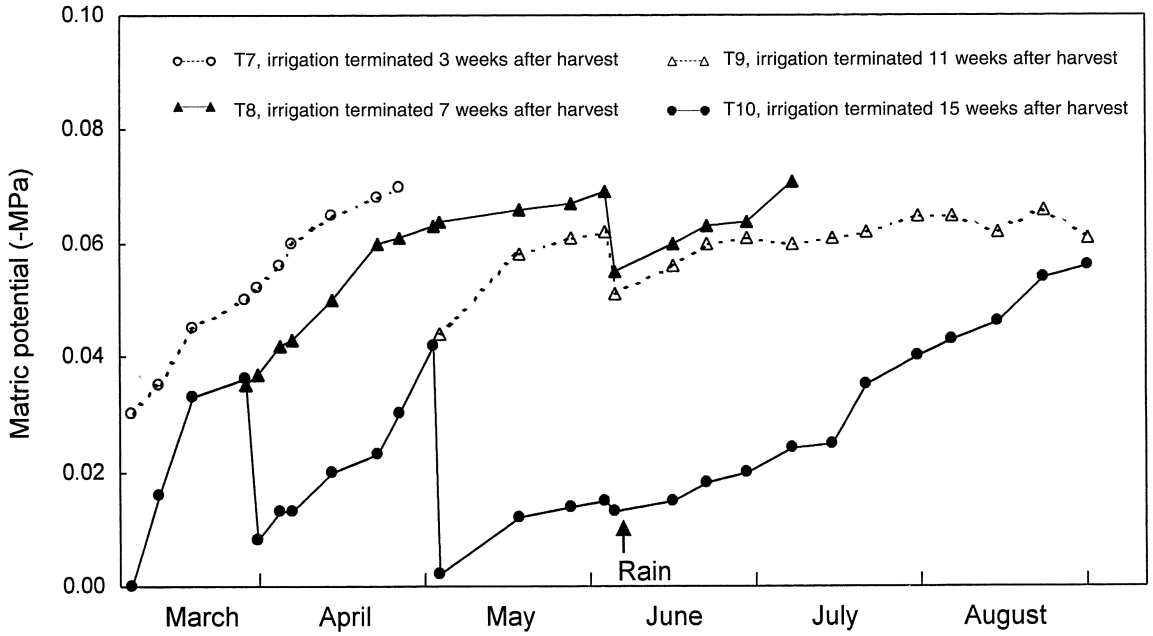

FIGURE 2

Soil water matric potential where irrigation was terminated at various stages during the post-harvest period as measured in 1998 at Upington.

TABLE 5

Effect of water deficits during the post-harvest period on cane mass of Sultanina grapevines determined at pruning over four seasons at Upington.

Treatment number	Stage at which irrigation was terminated	Cane mass (t/ha)			
		1995/96	1996/97	1997/98	1998/99
T1	Not terminated	2.0	1.8	2.0	1.3
T7	3 weeks after harvest	1.9	1.6	4.1	1.1
T8	7 weeks after harvest	1.7	1.5	4.1	1.0
T9	11 weeks after harvest	2.0	1.6	3.3	1.4
T10	15 weeks after harvest	2.2	1.9	4.4	1.6
	LSD ($p \leq 0.05$)	NS*	NS	2.4	NS

*Not significant.

TABLE 6

Effect of water deficits during the post-harvest period on soil water content (mass%) and cane water content of Sultanina grapevines determined just before bud break during 1996.

Treatment number	Stage at which irrigation was terminated	Soil water content (%)	Cane water content (%)
T1	Not terminated	8.2	47.1
T7	3 weeks after harvest	2.8	42.7
T8	7 weeks after harvest	2.7	42.5
T9	11 weeks after harvest	3.0	42.9
T10	15 weeks after harvest	3.3	43.6
	LSD ($p \leq 0.05$)	1.2	2.7

TABLE 7

Effect of water deficits during the post-harvest period on starch content of canes in Sultanina grapevines at pruning as determined over four seasons at Upington.

Treatment number	Stage at which irrigation was terminated	Cane starch content (mg/g dry mass)			
		1994/95	1995/96	1996/97	1997/98
T1	Not terminated	27.8	19.1	14.6	18.7
T7	3 weeks after harvest	20.4	21.7	16.9	18.5
T8	7 weeks after harvest	28.0	25.1	16.5	18.8
T9	11 weeks after harvest	27.2	25.8	14.1	18.2
T10	15 weeks after harvest	*	24.1	14.2	20.4
	LSD ($p \leq 0.05$)	NS**	NS	NS	NS

*Not determined.
**NS = Not significant.

TABLE 8

Effect of water deficits during the post-harvest period on yield, number of bunches per grapevine and bunch mass at harvest, as well as bud fertility of Sultanina as measured at two stages during the 1997/98 season at Upington.

Treatment number	Stage at which irrigation was terminated	Production (t/ha)		Bunches per grapevine		Bunch mass (g)		Bud fertility (%)	
		mean*	1997/98	mean	1997/98	mean	1997/98	at pruning	at flowering
T1	Not terminated	42.7	23.9	68	48	377	299	66.7	52.8
T7	3 weeks after harvest	41.7	3.9	79	14	317	150	55.6	30.6
T8	7 weeks after harvest	41.0	1.9	81	8	304	146	52.8	30.6
T9	11 weeks after harvest	43.1	6.5	85	20	294	181	69.4	41.7
T10	15 weeks after harvest	42.7	8.7	76	25	337	199	55.8	33.3
	LSD ($p \leq 0.05$)	NS**	14.2	NS	15	NS	76	NS	22.0

*Mean for 1995/96, 1996/97 and 1998/99 seasons.
**NS = Not significant.

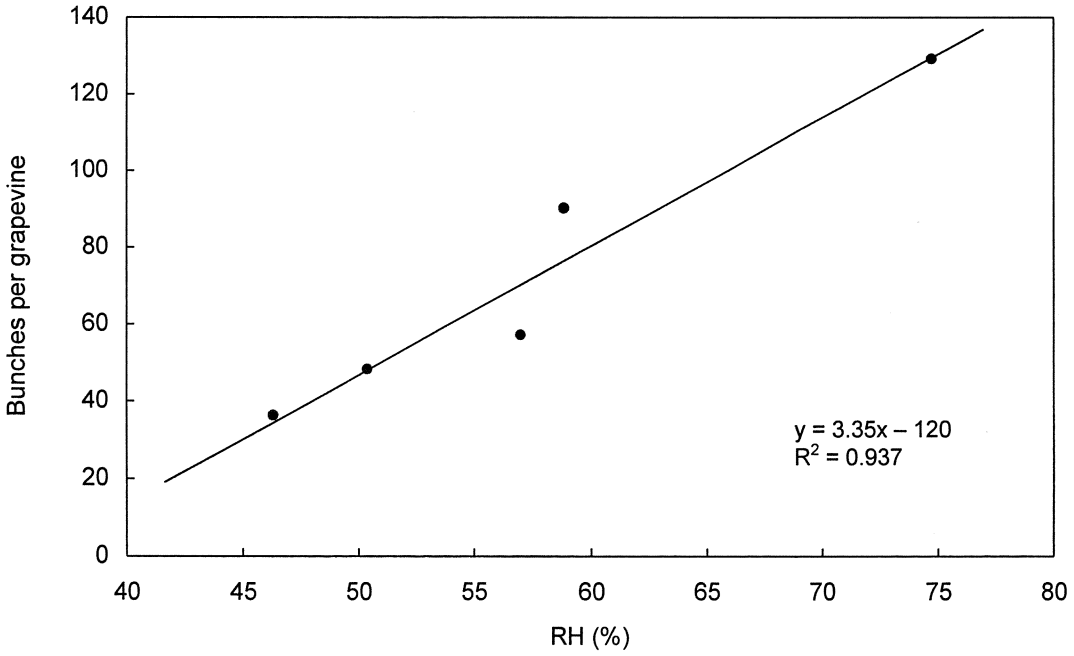

FIGURE 3

Relationship between bunches per grapevine and mean relative humidity (RH) during August and September as measured for Sultanina over five seasons at Upington.

grapevines subjected to water stress were significantly lower than those of T1 (Table 8). Hence, low yields of T7 to T10 during the 1997/98 season were most likely due to a combination of bunch abortion and reduced bunch mass as a result of water stress.

Since the low yields only occurred during one of the four seasons, factors other than soil water deficits must also have influenced yield. Examination of the meteorological and yield data revealed that the generally low yields during the 1997/98 season coincided with abnormally low August and September relative humidity values. Furthermore, where grapevines were irrigated at 60% PAW depletion throughout the season, a significant linear relationship existed between number of bunches per grapevine and mean relative humidity from August to September (Fig. 3). A similar relationship was found for flood-irrigated Sultanina on alluvial soil in the Lower Orange River region (Myburgh, 2003b). Low relative humidity (50%) not only delayed budbreak under controlled conditions in growth cabinets, but also reduced the number of buds in comparison to 95% relative humidity (Düring, 1979). This suggested that dry air probably played a role in bunch abortion and poor bunch differentiation. Extremely dry soil conditions, as discussed above, could also have contributed to poor grapevine fertility via bud desiccation as well as insufficient solute production and/or translocation from roots to buds. A combination of dry meteorological conditions and water deficits during the post-harvest period and winter could also have contributed to the delayed budbreak mentioned earlier. The foregoing indicates that the effects of post-harvest conditions on seasonal variation of Sultanina yield may be of similar significance as are pre-harvest conditions as discussed by May (1961). These aspects need to be investigated by continued research.

CONCLUSIONS

Under the conditions that prevailed during this trial, water stress over short periods during the various pre-harvest phenological phases had no effect on growth and yield. However, this does not rule out the possibility that prolonged water deficits could result in yield losses. Since water deficits during ripening did not have a consistent, positive effect on TSS accumulation, but reduced raisin quality, irrigation should not be held back during this particular period. Severe water deficits between pruning and budbreak, in combination with low relative humidity, reduce yield significantly compared to continued irrigation at 60% PAW depletion throughout the post-harvest period. This combination of adverse soil and meteorological conditions also delays budbreak and induces excessive shoot growth after harvest. Water deficits during the post-harvest period have no significant effect on cane starch content at pruning, suggesting that withholding irrigation at this stage to reduce vegetative growth does not increase reserve accumulation in shoots.

LITERATURE CITED

Buttrose, M.S., 1974. Fruitfulness in grapevines: Effects of water stress. Vitis 12, 299-305.

Christensen, P., 1975. Response of "Thompson Seedless" grapevines to the timing of preharvest irrigation cut-off. Am. J. Enol. Vitic. 26, 188-194.

Düring, H., 1979. Wirkungen der Luft- und Bodenfeuchtigkeit auf das vegetative Wachstum und den Wasserhaushalt bei Reben. Vitis 18, 211-220.

Düring, H., 1984. Evidence for osmotic adjustment to drought in grapevines (*Vitis vinifera* L.). Vitis 23, 1-10.

Esteban, M., Villanueva, J. & Lissarrague, J.R., 1999. Effect of changes in berry composition of Tempranillo during maturation. Sugars, organic acids, and mineral elements. Am. J. Enol. Vitic. 50, 418-434.

Goosen, R.J., 1956. Irrigation of Sultanas along the Lower Orange River. Farming in S. Afr. 32, 45-48.

Greenway, H. & Munns, R., 1980. Mechanisms of salt tolerance in nonhalophytes. Ann. Rev. Plant Physiol. 31, 149-190.

Greulach, V.A., 1973. Plant function and structure. Collier Macmillan Publishers, London.

Grncarevic, M. & Radler, F., 1971. A review of the surface lipids of grapes and their importance in the drying process. Am. J. Enol. Vitic. 22, 80-86.

Hardie, W.J. & Considine, J.A., 1976. Response of grapes to water-deficit stress in particular stages of development. Am. J. Enol. Vitic. 27, 55-61.

Hunter, J.J., Ruffner, H.P. & Volschenk, C.G., 1995. Starch concentrations in grapevine leaves, berries and roots and the effect of canopy management. S. Afr. J. Enol. Vitic. 16, 35-40.

Kramer, P.J., 1983. Water relations of plants. Academic Press, London.

Lang, A. & Düring, H., 1991. Partitioning control by water potential gradient: Evidence for compartmentation breakdown in grape berries. J. Exp. Bot. 42, 1117-1122.

Macheix, J.J., Fleuriet, A. & Billot, J., 1990. Fruit phenolics. CRC Press, Florida.

Matthews, M.A., Anderson, M.M. & Schultz, H.R., 1987. Phenologic and growth responses to early and late season water deficits in Cabernet franc. Vitis 26, 147-160.

Matthews, M.A. & Anderson, M.M., 1989. Reproductive development in grape (*Vitis vinifera* L.): responses to seasonal water deficits, Am. J. Enol. Vitic. 40, 52-60.

Maxa, E., Brandes, W. & Schmuckenschlager, J., 1995. Untersuchungen zum Verlauf der Zucker-, Säure- und Mineralstoffgehalte während der Traubenreife bei den Sorten *Grüner Veltliner* und *Rheinreisling*. Mitt. Klosterneuburg 45, 42-48.

May, P., 1961. The value of an estimate of fruiting potential in the Sultana. Vitis 3, 15-26.

McBean, D. McG., Joslyn, M.A. & Nury, F.S., 1971. Dehydrated fruit. In: Hulme, A.C. (ed.). The biochemistry of fruits and their products. Academic Press, London. pp. 635-662.

McCarthy, M.G., 1997. The effect of transient water deficit on berry development of cv. Shiraz (*Vitis vinifera* L.). Aust. J. Grape Wine Res. 3, 102-108.

Morrison, J.C. & Iodi, M., 1990. The influence of waterberry on the development and composition of Thomson Seedless grapes. Am. J. Enol. Vitic. 41, 301-305.

Myburgh, P.A., 1998. Water consumption of South African vineyards: A modelling approach based on the quantified combined effects of selected viticultural, soil and meteorological parameters. PhD dissertation, Stellenbosch University, Private bag X1, 7602 Matieland (Stellenbosch), South Africa.

Myburgh, P.A., 2003a. Responses of *Vitis vinifera* L cv Sultanina to level of soil water depletion under semi-arid conditions. S. Afr. J. Enol. Vitic. 24, 16-24.

Myburgh, P.A., 2003b. Possible flood irrigation technologies to reduce water use of Sultanina grapevines in a hot, arid climate. S. Afr. J. Plant Soil. 20 (In press).

Nagarajah, S., 1992. Water stress and the colour of dried Sultanas. Dried Fruits News, December, 10-12.

Pratt, C., 1971. Reproductive anatomy in cultivated grapes – A review. Am. J. Enol. Vitic. 22, 92-109.

Saayman, D. & Albertse, G.J.J., 1984. Drying of grapes. Farming in S. Afr., Viticulture and Oenology series, E.16/1984, Viticultural and Oenological Research Institute, Stellenbosch.

Schrader, U., Lemperle, E., Becker, N.J. & Bergner, K.G., 1976. Der Aminosäure-, Zucker-, Säure- und Mineralstoffgehalt von Weinbeeren in Abhängigkeit vom Kleinklima des Standortes der Rebe. 3. Mitteilung: Säure- und Mineralstoffgehalt. Wein Wiss. 31, 160-175.

Schultz, H.R. & Matthews, M.A., 1988. Vegetative growth distribution during water deficits in *Vitis vinefera* L.. Aust. J. Plant Physiol. 15, 641-656.

Smart, R.E. & Coombe, B.G., 1983. Water relations of grapevines. In: Kozlowski T.T. (ed.). Water deficits and plant growth VII. Academic press, New York. pp. 137-196.

Soil Classification Work Group, 1991. Soil classification – A taxonomic system for South Africa. Memoirs on natural resources of South Africa no. 15. Dept. Agric. Developm., Pretoria.

Van Zyl, J.L., 1984a. Interrelationships among soil water regime, irrigation and water stress in the grapevine (*Vitis vinifera* L.). PhD dissertation, Stellenbosch University, Private bag X1, 7602 Matieland (Stellenbosch), South Africa.

Van Zyl, J.L., 1984b. Response of Colombar grapevines to irrigation as regards quality aspects and growth. S. Afr. J. Enol. Vitic. 5, 19-28.

Van Zyl, J.L., 1987. Diurnal variation in grapevine water stress as a function of changing soil water status and meteorological conditions. S. Afr. J. Enol. Vitic. 8, 45-52.

Williams, L.E., Neja, R.A., Meyer, J.L., Yates, L.A. & Walker, E.L., 1991. Postharvest irrigation influences bud break of 'Perlette' grapevines. Hortscience 26, 1081.

Williams, L.E., Dokoozlian, N.K. & Wample, R., 1994. Grape. In: Schaffer, B. & Anderson, P.C. (eds). Handbook of environmental physiology of fruit crops, Vol I, Temperate crops. CRC Press, Boca Raton. pp. 85-133.

Winkler, A.J., 1962. General viticulture. University of California Press, Los Angeles.

Zeeman, A.S., 1981. Oplei. In: Burger, J.D. & Deist, J. (eds). Wingerdbou in Suid-Afrika. ARC Infruitec-Nietvoorbij, Stellenbosch. pp. 185-201.