Final Report GWRDC Project No DAS 11

Improving wine quality by regulated deficit irrigation

Michael G. McCarthy

South Australian Research & Development Institute
Nuriootpa Centre
Nuriootpa SA 5355

Grape and Wine Research and Development Corporation

Cooperative Research Centre for Viticulture

SOUTH AUSTRALIAN RESEARCH AND DEVELOPMENT INSTITUTE



Final Report

Project Title: **Improving wine quality by regulated deficit irrigation**

Project Number: **DAS11**

Organisation: **S.A. Research & Development Institute**

Location: **Waikerie, SA**

Supervisor: **M.G.McCarthy**

Time Span: **July 1990-June 1996**

Objectives:

To determine which fully specified controlled deficit irrigation schedule causes the greatest improvement in the quality of wine made from Shiraz grown in the semi-arid continuously irrigated winegrowing regions of S.E. Australia.

To develop functions describing the relationship with plant water status indicators and soil water availability and atmospheric evaporative demand.

TABLE OF CONTENTS

	Page
1. INTRODUCTION	1
2. MATERIALS AND METHODS	1
2.1 Site selection/soils/irrigation design	1
2.2 Experimental treatments	1
2.3 Soil moisture release curves	2
2.4 Statistical analysis	3
2.5 Small-lot winemaking	4
2.6 Sensory evaluation	4
3. RESULTS	6
3.1 Summary of weather 1991-1995	6
3.2 Timing and depth of irrigation	6
3.3 Soil water content	8
3.4 Monthly water use and crop coefficient	9
3.5 Soil water deficit index	9
3.6 Vine developmental phases	10
3.7 Vegetative growth	10
3.8 Berry Growth	11
3.9 Harvest	12
3.10 Components of yield	12
3.11 °Brix	14
3.12 °Brix versus berry weight	15
3.13 Solutes per berry, non-solutes per berry	16
3.14 G-G per g berry weight	17
3.15 Anthocyanin per g berry weight	17
3.16 Comparison of total G-G, anthocyanin-glucose and red-free G-G at harvest	20
3.17 Sensory evaluation of small-lot wines	23
4. DISCUSSION	25
4.1 Vine water use	25
4.2 Vine development phases	25
4.3 Berry growth and yield	26
4.4 Phenological correlates	27
4.5 Maximum berry weight	27
4.6 Glycosyl -glucose	28
4.7 Sensory evaluation of small-lot wines	29
5. RECOMMENDATIONS FOR THE AUSTRALIAN VITICULTURAL INDUSTRY	29
5.1 Irrigation design and monitoring	29
5.2 Control of vegetative growth and yield	30
5.3 Indices of wine quality	30
6. PUBLICATIONS AND TECHNOLOGY TRANSFER ARISING FROM THE STUDY	31
7. REFERENCES	33

1. Introduction

Regulated Deficit Irrigation (RDI), and Withholding Irrigation (WI) is used on pear or peach trees to enhance the yield of fruit above a specified size and reduced unwanted vegatative growth. There has been only relatively minor use of RDI or WI in winegrapes, primarily because the detailed applied experimental work has not been carried out. For winegrapes, not only is the interaction of irrigation management on yield important, but in addition, the effect on °Brix accumulation, pH and acid balance as well as colour (for red and black grapes), aroma and flavour is also important. These factors add another dimension to the role of RDI or WI in winegrape vineyards that prior to this experiment has not been investigated. Clear evidence of the value of RDI in improving winegrape quality would be welcomed by grapegrowers and winemakers as a means to increase the supply of red-wine grapes suitable for the expanding 750ml bottle export market.

2. Materials and methods

2.1 Site selection/soils/irrigation design

The experimental site was located at Sunlands (Lat. 34° 08'S, Long. 139° 52'E) near Waikerie, South Australia. The experimental site was within a 30 ha block of cv. Shiraz as part of a commercial vineyard of about 400 ha. The choice of the site was guided by information from a soil survey done in 1986, three years before establishing the experiment. This survey classified soil texture, some soil physical characters, potential rootzone depth, estimated soil water holding capacity and the presence of any water table. Some of these details are listed in Table 2.1. The criteria used in selecting the actual site were:

- no water table within 2 m of the soil surface
- uniform soil texture of at least 2m depth
- an elevated site to minimise frost incidence

Table 2.1 Selected soil physical and chemical properties for each depth layer of the Waikerie site

Depth interval (cm)	Texture	Colour	pH ($CaCl_2$)	Salinity ECe ($mS.cm^{-1}$)	Free lime	Root presence
0-65	loamy sand	5YR 5/6	7.6	0.67	nil	3/3
65-110	loamy sand	5YR 5/6	8.1	0.66	very high	2/3
110-180	loamy sand	5YR 5/6	8.0	1.13	very high	1/3

The vines in this block were 2 m apart in rows 4 m wide, planted on own-roots in an east-west direction in 1969 and trained to a horizontally divided canopy 1 m wide. The planting had been irrigated with over-canopy impact sprinklers since establishment. Irrigation, pest and disease control, soil management and fertiliser applications were done according to local accepted practice. A randomised block design of eight treatments (7 irrigated and an unirrigated), replicated nine times, was used. Each treatment plot was a rectangle comprising five vines in each of three adjacent rows. All data collection was from the middle three vines of the centre row of each plot. The other 12 vines were barriers. Irrigation water was supplied to each plot via polythene irrigation pipe laid on the surface on either side of the vine trunk line and connected to a buried pipe manifold at one end of the vine rows. Water meters measured the volume of water applied to all nine plots in each of the seven treatments that were irrigated.

2.2 Experimental treatments

Details of the experimental treatments are given Table 2.2 in and schematically presented in Figure 2.1. The treatments were begun in spring 1991 and continued over four growing seasons until harvest 1995. In some seasons the duration of treatments was influenced by rainfall, especially during the 1992-93 season. At the end of each stress period sufficient irrigation water was applied to refill the top 1.2 m soil to the pre-determined full point. A single irrigation was applied mid-way through the stress period of treatment seven in all but the final year when it was decided to allow maximum vine water stress to develop. Anthesis was defined as 50 percent cap fall and veraison the first appearance of red colour in berries.

Table 2.2 Description and timing of irrigation treatments.

Treatment no.	Treatment name	Description
1	Fully irrigated	Irrigated between bud-burst and harvest after 30 mm soil water depletion in 1.2 m soil depth
2	Post anthesis deficit	Same as 1 but no irrigation for approx. 1 month after anthesis
3	Pre-veraison deficit	Same as 1 but no irrigation for approx. 1 month before veraison
4	Post veraison deficit	Same as 1 but no irrigation for approx. 1 month after veraison
5	Pre-harvest deficit	Same as 1 but no irrigation for approx. 1 month before harvest
6	Anthesis-veraison deficit	Same as 1 but no irrigation between anthesis and veraison
7	Veraison-harvest deficit	Same as 1 but a single irrigation between veraison and harvest (no irrigation during this period in 1994-95)
8	Unirrigated	No irrigation

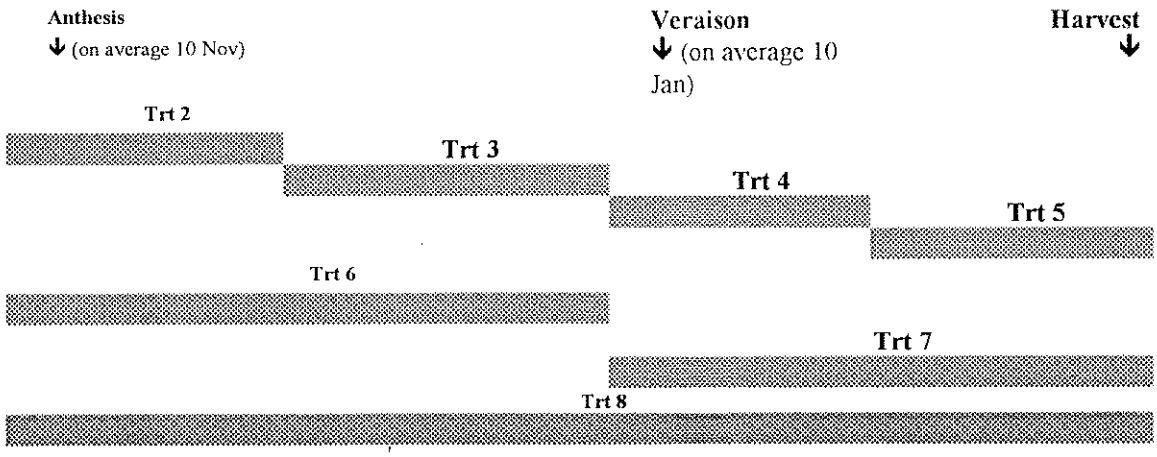


Figure 2.1 Schematic representation of the irrigation withholding periods (shaded) used in treatments 2 to 8. Treatment 1 was fully irrigated.

An automatic weather station was installed to record weather conditions at the experimental site. Reference crop evapotranspiration (Eto) was estimated on a daily basis using average data by the method of Priestley & Taylor (1972). Soil water content was measured by the neutron scatter technique using the methods detailed by Greacen (1981). Neutron probe access tubes were installed in each plot of four of the nine replicates. Neutron probe counts were measured at 10, 20, 30, 40, 50, 60, 80, 100 and 120 cm depth on every Monday, Wednesday and Friday between anthesis and harvest, twice weekly during other times of the growing season and monthly when the vines were dormant.

2.3 Soil moisture release curves

The water holding characteristics of the soil profile were determined on a set of intact soil cores. Duplicate samples were taken at 10, 30, 50, 80 and 100 cm and the soil water content at 0, 2, 4, 10, 13, 17.5, 43, 68 kpa and 1.5 MPa was determined. Wilting point was taken to be the soil water content at -1.5 MPa. The data presented in Table 2.3 are the average of values at all depths.

Table 2.3 The effect of change in soil matric potential on volumetric soil water content averaged from all depths that soil cores were collected.

Soil matric potential	0	-2 kpa	-4 kpa	-10 kpa	-13 kpa	-17.5 kpa	-43 kpa	-68 kpa	-1.5 MPa
Soil water content (%)	31.5	25.0	17.5	9.6	8.4	8.1	7.1	6.7	5.3

The daily crop coefficient for each treatment was calculated from the ratio of the daily change in soil water content in the top 120 cm soil depth to daily evapotranspiration derived from data recorded by the automatic weather station. The average daily soil water depletion between 1 and 10 days after an irrigation (one day discounted for drainage) of irrigated vines was calculated from the average daily depletion for the ten irrigation cycles between anthesis and harvest. A quadratic equation was fitted to the curve to describe the relationship between days after irrigation and soil water content. The average daily crop coefficient (k_c) of irrigated vines after an irrigation was

calculated in a similar manner to the average daily soil water depletion and a line fitted to the data. Weekly and monthly crop coefficient was calculated from the daily crop coefficient between budburst and harvest.

Vegetative growth was estimated by measuring weekly the length of four marked shoots on a single vine in each plot of the nine replicates. Measurements continued in each season until the shoot tip was damaged or shoot growth ceased. No shoot length measurements were taken in the 1994-95 growing season. After leaf fall in each year the number of mature shoots per vine was recorded. The weight of prunings removed from the three test vines in each plot was recorded each year. Only data from 4 treatments are presented.

In the 1992-93, 1993-94 and 1994-95 season, 20 berries per plot of selected treatments were collected weekly from anthesis until berry softening for the determination of berry weight. Commencing soon after berry softening in January of each year a minimum of 50 berries, using the same sampling procedure as previously described, were collected weekly from each plot until two-three weeks after each treatment was harvested. Berries were counted by placing them in a tared 50 hole counting plate, weighed and weight per berry calculated. Picking date was set by the small-lot winemaker who required fruit of at least 23.5 °Brix and all treatments of similar ripeness.

At harvest the number of bunches per vine were counted as they were picked and the total weight of fruit per vine recorded to the nearest 0.1 kg. Two of the three vines in each plot were harvested for yield estimation and to supply sufficient fruit for small-lot winemaking. In the weeks following harvest of fruit for winemaking berry sampling was continued on the remaining vine in each plot. Average bunch weight was calculated from the total fruit weight and number of bunches per vine and berries per bunch derived from the average bunch weight divided by average berry weight. The number of mature shoots per vine was counted after leaf drop in each season. Vines were then spur pruned. In 1991 and 1992, 120 buds per vine (predominantly as two-bud spurs) were retained. In 1993 and 1994, 100 buds were retained. Shoot weight was calculated from pruning weight and the number of shoots per vine.

After the appearance of red colour in berries in January of each year, samples of about one hundred berries were collected weekly from each plot. The berry samples were stored in plastic bags in a portable refrigerator until return to the laboratory. In 1994 and 1995 additional berries were collected from each plot and 50 berries were placed in a labelled screw-top plastic container and frozen for later analysis of glycosyl-glucose (see Chapter 5). The remaining berries were used to detemine °Brix, pH and titratable acid. The °Brix of the homogenate used for calculating glycosyl-glucose content and concentration per berry was determined in a similar manner and these data were used to calculate solutes per berry and non-solute weight per berry. The method of Williams et al. (1995) was used to determine G-G and the concentration of anthocyanins was measured spectrophotometrically at 520 nm (Somers and Evans, 1977). Both G-G per berry and per g berry weight were expressed as µmol glucose. Anthocyanin-glucose (as µmol glucose) was calculated using the method of Iland et al. (1996). Red-free G-G was calculated using the same method reported by Iland et al. (1996) ie. by subtraction of anthocyanin-glucose (as µmol glucose) from µmol G-G (per berry or per g berry weight).

2.4 Statistical analysis

Unless otherwise stated, the data were statistically analysed by normal analysis of variance using the computer program STATISTIX®. The test for the difference between means was based on the least significant difference method (the T method) if the F value was significant. Simple logistic models (Genstat 1987) of the generalised form given in Equation 1 were fitted to plots of total G-G and anthocyanin per berry and per g berry weight.

Equation 1 Generalised form of the simple logistic model fitted to plots of total G-G and anthocyanin-glucose per berry and per g berry weight against °Brix.

$$Y = A + \frac{C}{1 + e^{-B(X-M)}}$$

Where Y = G-G or anthocyanin-glucose per berry and per g berry weight
A = Intercept (of line on Y axis)
B = Slope (the slope of the curve around the inflection point)
C = Asymptote (the upper Y axis value)
M = Inflection point (the X axis value at which the fitted curve changes slope)
X = °Brix

Curves of the relationship between the total G-G and anthocyanin-glucose and °Brix were generated using the appropriate values of A, B, C and M from the logistic modelling and uniformly spaced °Brix values between, and including the minimum and maximum °Brix of berry samples from each treatment. The standard error and estimate

of the mean for each of the derived constants (A, B, C, M and the slope and intercepts of the linear regressions derived from the two-phase modelling) were used to test for the difference between seasons. The plots of red-free G-G against increasing °Brix exhibited an initial period of decreasing concentration followed by a period of increasing concentration after a minimum point. Various statistical models were compared to best describe the relationship between red-free G-G and °Brix. Ultimately a two-phase linear model (Genstat 1987) was selected; when fitted to the data this permitted a statistical comparison of the effect of irrigation treatment on the slope of each line. An example of a two-phase linear model derived for the rise in red-free G-G per berry with the increase in °Brix of fully irrigated vines during the 1993-94 season is shown in Figure 2.2b. Correlation matrices of the difference in slope of the two sets of lines and the x and y values at the interception point were derived.

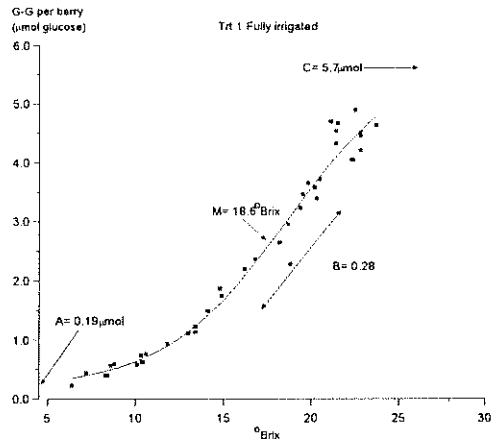


Figure 2.2 a Increase in G-G per berry with the rise in °Brix for fully irrigated vines during berry ripening in the 1993-94 season. Data points indicate G-G per berry and °Brix of each sample comprising 8 sampling times in 5 replicate plots. The fitted logistic model is described by the plotted curve. Constants A, B, C and M are indicated.

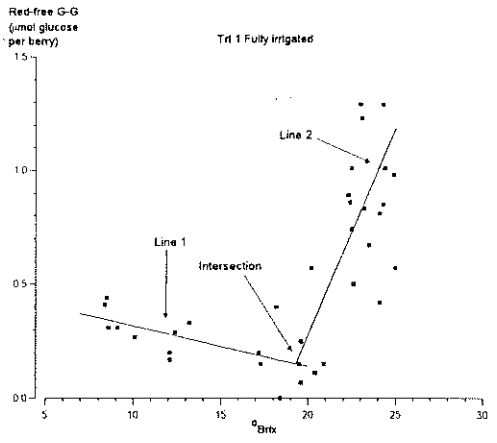


Figure 2.2 b Change in red-free G-G per berry with °Brix for fully irrigated vines during berry ripening in the 1994-95 season. Data points indicate red-free G-G per berry and °Brix of each sample as in Figure 2.2 a. Lines 1 and 2 of the two-phase linear model are described by the two fitted lines.

2.5 Small-lot winemaking

In each year that small-lot wines were made each treatment was harvested as grapes reached 23.5 °Brix. The harvested grapes were transported the Nurioopta Viticultural Centre where they were stored overnight at 2°°C. The following morning they were taken to the Grape and Wine Research Unit at Roseworthy for processing. All the grapes from each treatment were were processed via a 5 tonne/hr Zambelli roller-destemmer crusher into 3 x 20L fermentation vessels; thus there were three fermentation replicates for each irrigation treatment. Samples for analysis (pH, T.A., °Brix and potassium) were taken and sulphur dioxide (40mg/L) added. After allowing the vessel to warm to room temperature, the must was inoculated with 5%v/v of actively fermenting culture of Lalvin V1116 (Saccharomyces cerevisiae) yeast. Fermentation was conducted at 20°C and monitored by daily baume checks using a hydrometer. The wines were removed from skins at approx 1.5 Be and the skins lightly pressed (approx. 150 kPa) via a water bag press and allowed to complete fermentation at 20°C. At the completion of fermentation (as indicated by residual sugar 95 g/L clinitest) the wines were racked off lees into full 5L glass vessels to which had been added 0.2g/L bentonite and 40 mg/L SO2 and placed at 2°C for settling. Following cold stabilisation, samples were taken for analysis (pH, T.A. total SO2 and alcohol) and filtered through a 0.45um membrane into bottles.

2.6 Sensory evaluation

1993-94

Triangle tests were conducted on the fermentation replicates within treatments to determine whether there were any fermentation replicate differences. Thirty panelists were involved. The only differences found were between replicates 2 and 3 of the unirrigated treatment and replicates 1 and 2 of the post veraison deficit treatment. Where no significant differences were found, one of each of the replicates was selected based on similarity of °Brix. Where a perceptible difference was discovered the additional wine was also included for comparison at the next stage of sensory testing. Ten wines to be compared: one representing each treatment plus two additional fermentation replicates that were shown to be perceptibly different from the other fermentataion replicates. A incomplete block design was employed. Each panelist received four of the 10 wines and were asked to rank them on aroma intensity. They were then given another different subset of 4 of the 10 wines and were asked to rank them on flavour intensity. Thirty

panelists were involved. The testing was repeated the following week using the same panelists, giving in total 60 ranking exercises. As the design was an incomplete one, this represented a total of 24 replications.

1994-95

Unlike the 1994 trial, triangle tests were not conducted on the fermentation replicates within treatments. One group of the lowest °Brix wines were selected for comparison, and a second group of higher °Brix wines were compared. Unfortunately all the wines made from the unirrigated fruit were comparatively ripe so this wine could not included within the lower °Brix comparison. A second control wine was used instead. Preliminary benchtop testing revealed that the lower °Brix wines were very similar so a greater number of tasters (and hence reps) were used to enable a separation of the wines. A incomplete block design was employed. Each panelist received four of the eight wines and were asked to rank them on aroma intensity. They were then given another different subset of four of the eight wines and were asked to rank them on flavour intensity. The high brix and low brix comparisons involved, 56 and 84 tastings respectively (typically two tastings per panelist over two weeks). As the design was an incomplete one, this represented a total of 28 and 42 replications respectively. The rank data was analysed using the method of Skillings and Mack (1981).

3. Results

3.1 Summary of weather 1991-1995

Based on average temperature for the months September to March (Table 3.1) the 1994-95 growing season was the warmest of the four years and 1992-93 the coolest. Average monthly temperature for December 1994 to February 1995 was higher than previous years and this is reflected in data for monthly evaporation (Table 3.2) and solar radiation data (Table 3.3). The 1992-93 growing season was by far the wettest of the three seasons (Table 3.4) during which the automatic rainfall gauge operated, with more than twice the growing season rainfall of the other two years. A single rainfall event on 14 January 1995 accounted for nearly 40 percent of the total rainfall recorded during the drought conditions of 1994-95. Some data collected by the automatic weather station, i.e. wind-run, relative humidity, soil and canopy temperature are not presented.

Table 3.1 Growing season monthly mean temperature (°C) 1991-1995.

	1991-92	1992-93	1993-94	1994-95
September	13.2	11.2	13.0	12.5
October	17.3	16.1	15.4	16.7
November	18.8	16.2	18.9	18.1
December	20.2	19.9	19.5	22.6
January	19.5	22.1	20.7	22.6
February	21.9	21.5	21.3	22.2
March	22.1	19.1	18.6	20.1
Average	19.0	18.0	18.2	19.3

Table 3.2 Growing season monthly ETo (mm).

	1992-93	1993-94	1994-95
September		107.9	112.4
October		169.7	171.9
November		203.3	176.0
December		192.9	229.1
January		217.4	211.3
February	118.4	161.1	183.8
March	151.9	166.6	
Total		1218.9	1084.5

Table 3.3 Growing season monthly solar radiation (Mj/m^2) 1992-1995.

	1992-93	1993-94	1994-95
September	-	192.2	198.3
October	-	281.5	289.7
November	-	334.5	292.3
December	-	321.7	377.5
January	-	359.2	332.7
February	195.5	271.7	303.3
March	259.7	289.4	-

Table 3.4 Growing season monthly rainfall (mm) 1992-1995.

Month	1992-93	1993-94	1994-95
September	52.8	24	18.4
October	43.4	53.2	11.4
November	39.6	29.4	19.2
December	120.6	45.8	8.4
January	88.0	2.0	46.0
February	0.2	9.6	21.4
March	7.4	1.2	5.2
Total	352.0	165.2	130.0

3.2 Timing and depth of irrigation

The irrigation 'full line' or Field Capacity for 120cm soil depth was set at 130mm. This was determined from measurement of the soil water content after periods of significant winter rainfall. The irrigation 'refill line'was set at 100 mm, (30 mm soil water depletion). The total depth of all irrigations applied and rainfall between budburst and harvest for all treatments are summarised in Table 3.5 and the dates and depth of irrigation water applied for all treatments during 1994-95 are indicated in Figure 3.1.

Table 3.5 Total depth (mm) of irrigations applied to all treatments and growing season rainfall (mm) for years 1991 to 1995.

	Fully irrigated	Post anthesis deficit	Pre-veraison deficit	Post veraison deficit	Pre-harvest deficit	Anthesis-veraison deficit	Veraison-harvest deficit	Rainfall
1991-92	549.8	490.2	540.4	494.2	469.3	381.2	474.1	58.8
1992-93	345.4	324.4	274.8	305.0	248.6	206.8	246.4	352.0
1993-94	411.7	377.7	380.5	338.8	324.5	314.8	324.5	163.8
1994-95	602.3	553.2	566.3	521.2	438.6	363.0	446.3	130.0

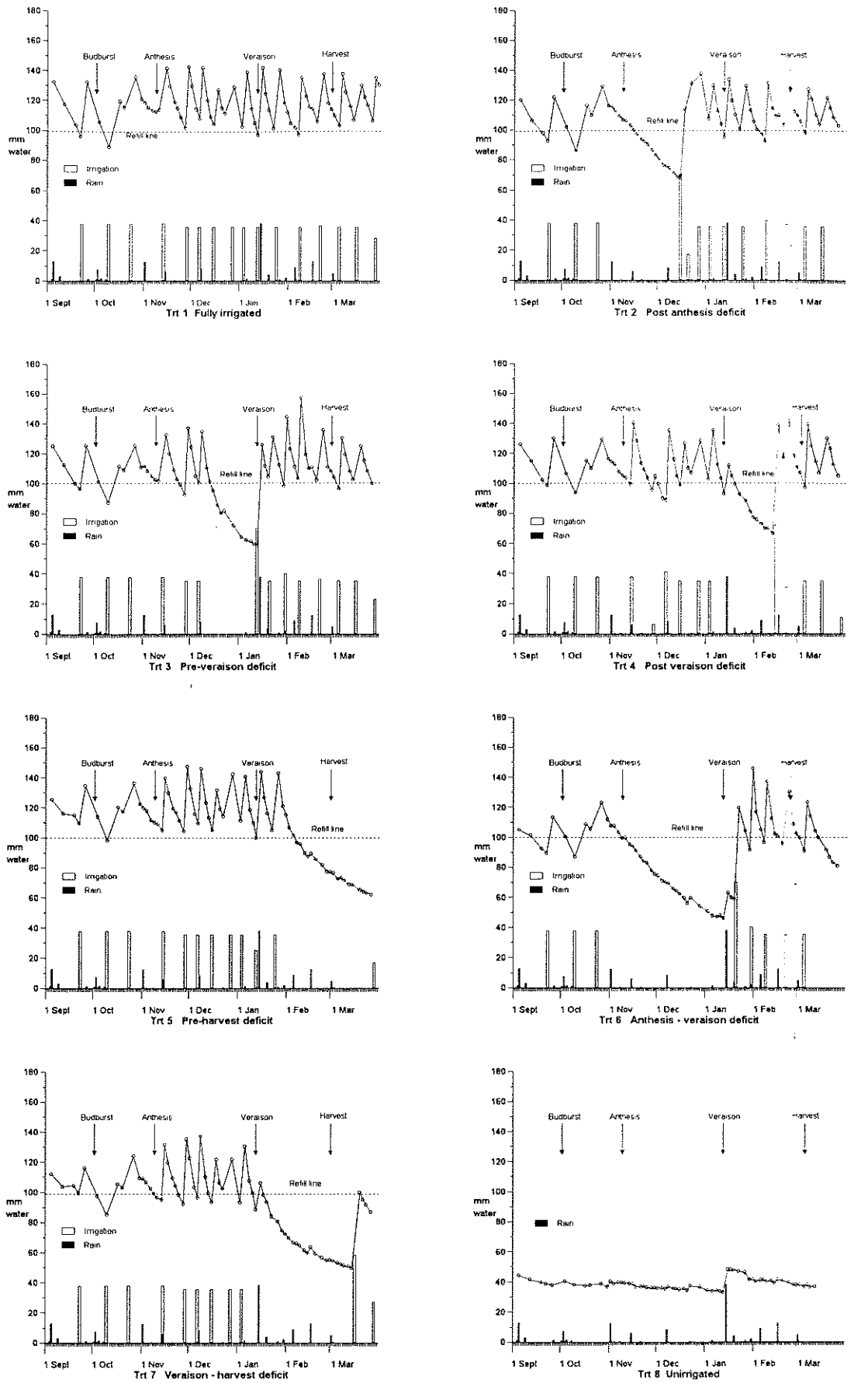


Figure 3.1 Depth of irrigation water applied, rainfall and soil water content of 120 cm soil depth against date for all treatments for the 1994-95 season. Depth of irrigation water applied □ (mm), rainfall ■ (mm) and soil water O (mm).

3.3 Soil water content

For the period from anthesis to harvest in 1994-95 the soil water content of fully irrigated plots declined by about 35 mm (i.e. the depth of water applied at each irrigation) in about 9 days (Figure 3.2). Immediately after an irrigation the daily change in soil water content was about 5.7 mm per day and about 2.7 mm per day the day before the next irrigation which, on average, was 10 days later. There was a similar decline in the soil water content of other treatments during periods they were irrigated the same as fully irrigated. Based on the fitted line the daily k_c was about 0.83 immediately after an irrigation and 0.41, or about half the initial value, the day before the next irrigation.

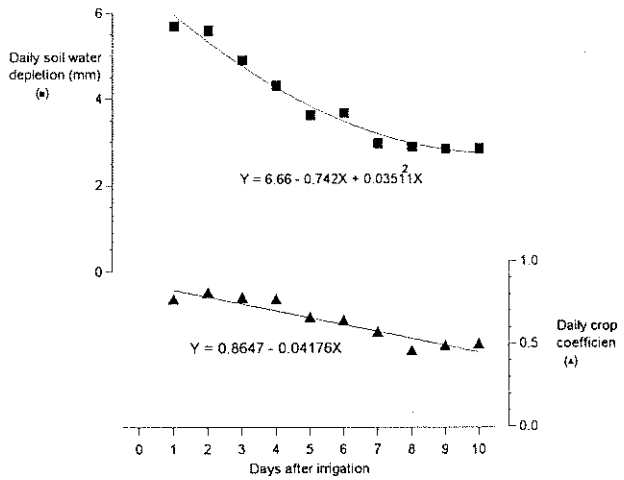


Figure 3.2 Average daily soil water content and daily crop coefficient of fully irrigated plots for the first ten days after irrigation between anthesis and harvest in 1994-95. One day discounted for drainage after each irrigation.

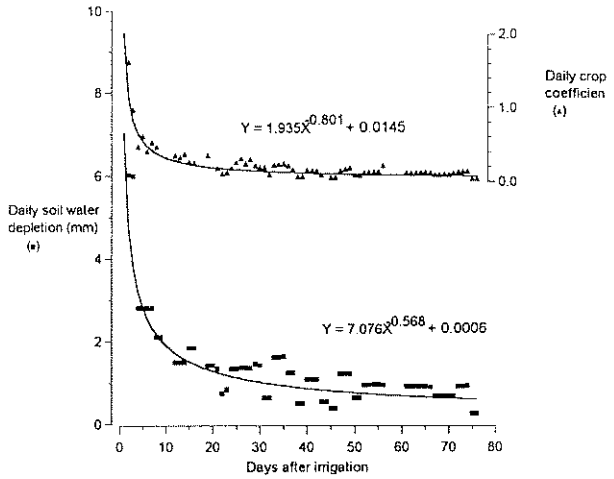


Figure 3.3 Daily soil water content and crop coefficient of anthesis-veraison deficit treatment (Trt 6) in 1994-95. Y = k_c or daily soil water depletion, X = days after irrigation

There was a similar rapid decline in the daily soil water content of anthesis-veraison deficit plots (Trt 6) at the start of the stress period (Figure 3.3). On day 1 the daily rate of soil water depletion was about 7.1 mm compared to 5.7 mm per day for fully irrigated vines and on day 9 was 2 mm compared to 2.7 mm. Although there was some day-to-day variation in both daily water use and the crop coefficient after day 10 there was a steady but lessening rate of daily change. Immediately before the end of this long stress period the daily rate of water use was less than 1 mm per day or a k_c of 0.1 or less.

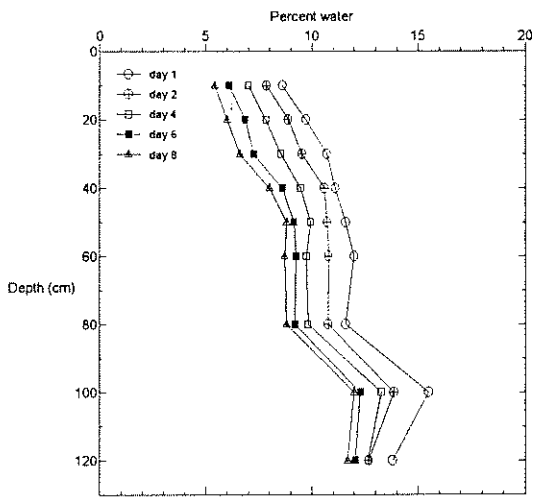


Figure 3.4 Percent soil water with soil depth on specified days after irrigation for fully irrigated treatment (Trt 1) between anthesis and maturity in 1994-95.

Fully irrigated vines extracted water nearly equally to 100 cm depth when averaged for all irrigation cycles between anthesis and maturity (Figure 3.4). Soil water extraction at 120 cm was only about 1 percent less compared with other depths which showed between a 3 and 4 percent change between irrigations. The line representing percent soil water on day 1 is assumed to be close to Field Capacity (Upper Drained Limit) for different positions down the soil profile. At Field Capacity there was between 2 and 3 percent more water at 100 and 120 cm depth and these zones remained wetter than all other depths between irrigations.

3.4 Monthly water use and crop coefficient

The average daily water 'use' of fully irrigated plots (Trt 1) calculated from neutron probe readings between October 1994 to March 1995 was 3.5 mm per day (Table 3.6). The crop coefficient for the corresponding period was 0.52. In comparison the crop coefficient for the same interval in 1993-94 season was 0.62 (data not presented). Daily water use increased between September 1994 and January 1995 to a maximum of 5.7 mm per day and then declined to 3.2 mm per day during March 1995. Between October and January there was a steady increase in crop coefficient to 0.72 in January 1995 and then a decline to 0.50 during March 1995. During November and December 1994 the average daily water use of the unirrigated anthesis-veraison deficit (Trt 6) plots was 1.4 and 0.9 mm per day with a crop coefficient of 0.28 and 0.15 respectively. There was however a continuum of change in daily water use and crop coefficient as the soil profile dried during the period when irrigation was withheld (Figure 3.3).

Table 3.6 Daily water use and crop coefficient per month and season average for fully irrigated plots from October 1994 to March 1995.

Month	Daily water use (mm)	Monthly crop coefficient
October	2.3	0.38
November	2.6	0.42
December	4.9	0.57
January	5.7	0.72
February	3.8	0.53
March	3.2	0.50
Season average	3.5	0.52

3.5 Soil water deficit index

A soil water deficit index (Figure 3.5) was derived from soil water content measured by the neutron probe. The index was defined as the cumulative sum of the daily difference (by interpolation) between the actual soil water content and the pre-defined irrigation refill line (which was set at 100 mm for all treatments). The index was not calculated for fully irrigated vines as theoretically these plots were always irrigated at this refill line (although in practice this was not always possible), nor was it calculated for unirrigated vines. If the soil water content was greater than the refill line at any stage during a stress period, for example, when the veraison-harvest treatment was given a single irrigation in late January-February 1992, 1993 and 1994, (or rainfall), the daily deficit index was set to zero for the number of days soil water content was above the refill line. The soil water deficit thus enabled a comparison of the soil water deficit that developed in each of the treatments in each year and between each of the four years.

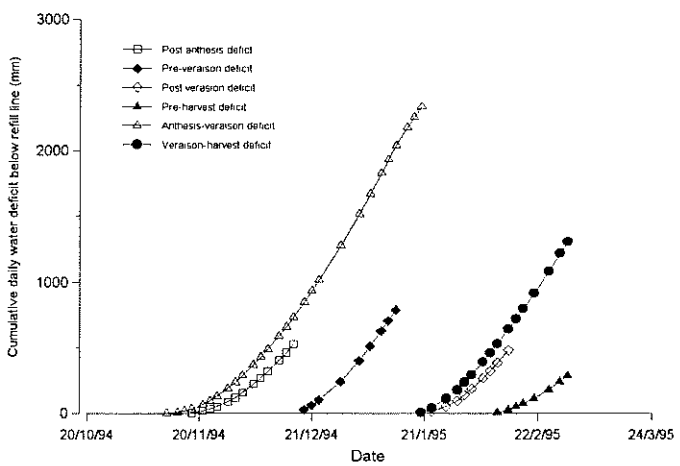


Figure 3.5 Cumulative daily deficit below irrigation refill line for 6 treatments for the 1994-95 season

3.6 Vine developmental phases

The modified E-L scale (Coombe, 1995) was used to define growth stages. The date of budburst varied by nine days (Table 3.7), anthesis by 17, and veraison by 16 days over the four years. Bud burst date appeared to be cyclical with 1991-92 and 1993-94 being on 22 September and the alternate years were eight or nine calendar days later. The number of days between budburst and anthesis varied from 40 days in 1991-92 to 49 days in 1992-93 and the number of days between anthesis and veraison ranged from 56 days in 1993/94 to 64 days in 1994-95. The interval between veraison and 20 °Brix for fully irrigated vines ranged from 29 days in 1995 to 50 days in 1994. There was a difference of about 20 days between budburst and 20 °Brix; in 1994-95 the interval was 134 days and in 1992-93 and 1993-94 was 154 days. There did not appear to be any consistent treatment effect on any of these intervals.

Table 3.7 Dates of key phenological events for fully irrigated vines (Trt 1) in the Waikerie experiment.

Stage	E-L stage	1991-92	1992-93	1993-94	1994-95
budburst	4	22/9/91	30/9/92	22/9/93	1/10/94
anthesis	19	1/11/91	18/11/92	9/11/93	11/11/94
veraison	34	2/1/92	18/1/93	4/1/94	14/1/95
10 °Brix	35	9/1/92	24/1/93	16/1/94	19/1/95
15 °Brix	36	21/1/92	8/2/93	30/1/94	29/1/95
20 °Brix	37-38	7/2/92	3/3/93	23/2/94	12/2/95

3.7 Vegetative growth

Shoot lengths are graphed against date during 1993-94 in Figure 3.6. Data for four treatments (3, 4, 5 and 7) were similar to Trt 1 and are excluded. Unirrigated shoots (Trt 8) were always the shortest and fully irrigated (Trt 1). Shoot elongation on unirrigated vines ceased earlier in each year resulting in shoots becoming progressively shorter over the three years of measurement; by 1994 elongation ceased at 70-80 cm length on about 20 November or about 7 weeks before veraison. In each of the three years shoots on vines that were not irrigated for the period between anthesis and veraison (anthesis-veraison deficit, Trt 6) were shorter than shoots on the post-anthesis deficit treatment (Trt 2), however, there was a large standard error for some of the measurements. Irrigation at the end of the post anthesis deficit period in early-mid December did not initiate any new shoot growth.

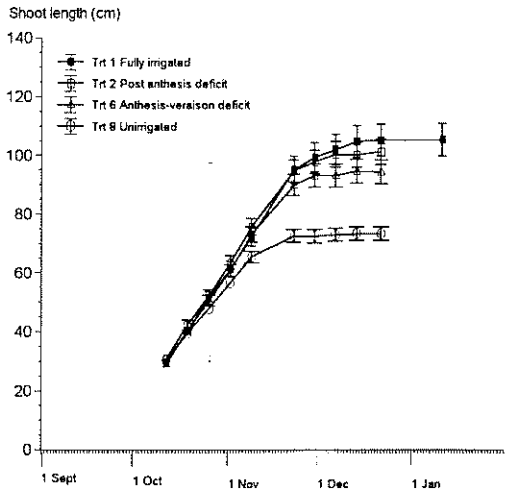


Figure 3.6 Shoot length (cm) of four treatments during the 1993-94 growing season. Total length of vertical bars indicate 2 x se at each date of measurement.

Shoots per vine (which reflect percent budburst since bud numbers per vine were comparable across treatments) are presented only for the 1994-95 season (Table 3.8) and are representative of previous season's data. There was no difference in the number of shoots per vine in treatments 1-7, (95 shoots per vine). The difference between fully irrigated (97 shoots) and unirrigated (86 shoots) was significant. The weight of prunings removed from unirrigated vines (Trt 8) was one-third of that removed from fully irrigated vines (Trt 1) in winter 1995 (Table 3.8) and was significantly less than all other treatments. Water deficit during the anthesis-veraison, pre- and post veraison period and veraison-harvest (Trts 6, 3, 4 and 7) resulted in a significantly lower pruning weight compared with fully

irrigated, but not significantly less than post-anthesis (Trt 2) or pre-harvest deficit (Trt 5) treatments. The effects of water deficit treatment on shoot weight (Table 3.8) were similar to those on the weight of prunings.

Table 3.8 Irrigation treatment effect on the number of shoots per vine, weight of prunings removed per vine (kg) and shoot weight per vine (g) for the 1994-95 season.
Numbers followed by the same letter are statistically similar ($p<0.05$).

Treatment	Shoots per vine	Pruning wt. (kg)	Shoot wt. (g)
Trt 1 Fully irrigated	97 a	1.3 ab	14.6 a
Trt 2 Post anthesis deficit	92 ab	1.2 bc	12.2 b
Trt 3 Pre-veraison deficit	95 ab	1.0 c	11.1 b
Trt 4 Post veraison deficit	94 ab	1.1 c	11.3 b
Trt 5 Pre-harvest deficit	95 ab	1.4 a	15.4 a
Trt 6 Anthesis-veraison deficit	95 ab	1.0 c	11.1 b
Trt 7 Veraison-harvest deficit	94 ab	1.0 c	10.7 b
Trt 8 Unirrigated	86 b	0.4 d	5.3 c

3.8 Berry Growth

In 1994-95 (Figure 3.7), the berries of unirrigated vines were lighter by about 30 days after anthesis than all other treatments and continued so for the remainder of the season. Post anthesis deficit (Trt 2) resulted in berries being significantly lighter than fully irrigated (Trt 1) at every sampling time during 1994-95 The pre- and post veraison deficit treatments were also similar at every sampling time in 1994-95. There was no effect of pre-harvest deficit (Trt 5) on berry weight compared to fully irrigated (Trt 1) except for one sampling in early March 1994. Water deficit during the anthesis-veraison period (Trt 6) resulted in berries which were significantly lighter than fully irrigated at every sampling time. Veraison-harvest deficit (Trt 7) resulted in berries that were significantly lighter than fully irrigated only in the final weeks of sampling in 1993-94.

In all four years the patterns of berry growth included a shrinkage after a peak weight was reached mid-way through ripening, even during the wet 1992-93 season. Although there were significant differences in berry weight between treatments there was only a small difference in percent loss of berry weight between treatments. On 6 March 1995 there was a range of 12 to 19 percent loss in weight or a difference of 7 percent compared to the maximum weight for each treatment and on 21 March 1995 the range was 9 to 15 percent, or a difference of 6 percent.

Although the weekly sampling procedure used in this experiment precludes determination of the actual day of maximum berry weight, the curves show that the maximum weight of berries on all the irrigated treatments (Trts 1-7) occurred within a narrow time span of 88 to 92 days after anthesis (5 days) or between about 2 February and 16 February (14 days). The maximum weight of unirrigated berries also occurred at the same time in the first three years but a week later in the final year (although there was little difference in weight over this 2 week period in February 1995 and similarly little change in weight over a 3 week period in February 1994).

The effects of the varying degree of water deficit on berry weight imposed on Trts 2, 3, 4 and 5 in each year are presented as a percentage of the weight of fully irrigated berries at 22.5 °Brix in Table 3.9. Treatment 6 (anthesis-veraison deficit) and Trt 7 (veraison-harvest deficit) were not included as they did not separate the effect of 'early' or 'late' water deficit on berry growth during the period between anthesis to veraison or veraison to harvest. In the absence of a soil water deficit berry weight of each treatment was assumed to be the same as fully irrigated and a linear regression was fitted to each treatment (Table 3.9). The slopes of the lines and the significance of the correlation between berry weight and cumulative soil water deficit decreased with time from anthesis; post anthesis deficit treatment had the steepest negative slope and the highest r^2 while the pre-harvest deficit treatment had the shallowest slope and the lowest r^2.

Table 3.9 Linear regression models to describe the relationship between berry weight as a percent of fully irrigated at 22.5 °Brix and cumulative daily soil water deficit for selected treatments. Y = berry weight as a percent of fully irrigated at 22.5 °Brix. X = cumulative daily soil water deficit (mm).

Treatment	Linear regression model	r^2
Trt 2 Post anthesis deficit	Y = -0.024*X +100	0.67
Trt 3 Pre-veraison deficit	Y = -0.0106*X +100	0.35
Trt 4 Post veraison deficit	Y = -0.0089*X +100	0.24
Trt 5 Pre-harvest deficit	Y = 0.0018*X +100	0.05

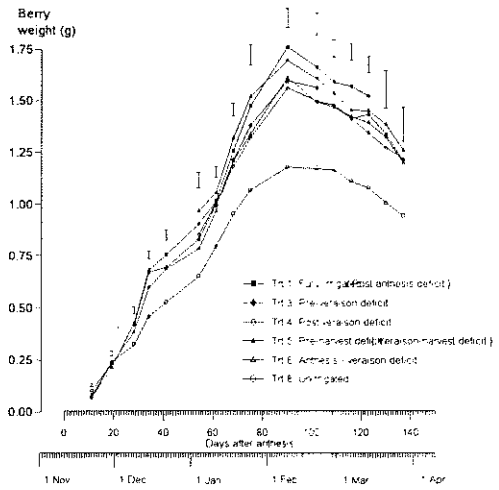


Figure 3.7 Berry weight plotted against time after anthesis for the 1994-95 season.
Vertical bars indicate l.s.d.($p<0.5$) for each sample date. Bracketed treatments indicate those which were similar to plotted treatment at every sample date

3.9 Harvest

There was nearly a four week difference (Table 3.10) in the date of harvest of fully irrigated vines between the four years with 1994-95 being the earliest and 1992-93 being the latest. These dates were chosen to give juice °Brix of 23.5; in the event °Brix values ranged from 23.1 to 25.0. In two of the years (1991-92 and 1993-94) unirrigated vines reached the required ripeness before other treatments. In 1992-93 both unirrigated and pre-harvest deficit (Trt 5) ripened early and were harvested on the same day. In 1995 the unirrigated and post veraison deficit (Trt 4) treatments were the last to be harvested. In the previousthree seasons post veraison deficit plots were harvested on the same day as fully irrigated plots. With the exception of the 1992-93 wet season both post anthesis deficit (Trt 2) and anthesis-veraison deficit (Trt 6) plots were harvested before fully irrigated (Trt 1) plots.

3.10 Components of yield

Bunches per vine. At harvest 1995 there was a difference of only 15 bunches per vine between the treatment with the greatest number of bunches (pre-veraison deficit - Trt 3) and unirrigated which had the least number of bunches per vine. This difference was not significant.

Berries per bunch. The number of berries per bunch on unirrigated vines (Table 3.11) declined throughout the duration of the experiment. By harvest 1995 there were about 40 percent fewer berries on unirrigated vines compared with fully irrigated. At harvest 1995, both post anthesis (Trt 2) and anthesis-veraison (Trt 6) vines had fewer berries per bunch than fully irrigated although not significantly less than pre- and post veraison and veraison-harvest deficit (Trts 3, 4 and 7 respectively). The number of berries per bunch also declined on treatments 1-7 during the experiment with the two treatments involving stress immediately after anthesis (Trt 2 and 6) declining by 18 to 24 berries per bunch and by between 8 and 14 berries per bunch for the other treatments.

Berry weight. Unirrigated vines had the lightest berries at harvest in each year (Table 3.10) although at harvest in 1992-93 season berries were only 0.12 g lighter than fully irrigated. At harvest 1995 the berries of unirrigated vines were nearly half the weight at harvest 1992-93. The 1994-95 growing season yielded the lightest berries at harvest and, surprisingly, the mean berry weight at harvest of all treatments in 1993-94 was the same as the previous rainy season.

Bunch weight. The bunches of unirrigated vines were always the lightest (Table 3.12) and by harvest 1995 were about one-third the weight at harvest 1992. Although not always significantly different from other treatments, fully irrigated vines (Trt 1) and pre-harvest deficit (Trt 5) produced the heaviest bunches. In 1993-94 there was no significant difference in bunch weight between treatments 1-7. The bunches of both pre-veraison deficit (Trt 3) and veraison-harvest deficit (Trt 7) vines were similar to fully irrigated for the other two years.

Table 3.10 Date of harvest, berry wt (g) and °Brix at harvest of fruit for small-lot winemaking for harvest years 1992 to 1995.
Berry weight and °Brix data are from the closest weekly sampling prior to indicated harvest dates.

Treatment	1991-1992	1992-1993	1993-1994	1994-1995
Trt 1 Fully irrigated	12/3/92	5/4/93	17/3/94	2/3/95
Berry wt (g)	1.35	1.39	1.52	1.20
°Brix	24.0	24.0	23.1	23.6
Trt 2 Post anthesis deficit	10/3/92	31/3/93	15/3/94	24/2/95
Berry wt (g)	1.29	1.40	1.48	1.10
°Brix	24.4	23.4	23.4	23.1
Trt 3 Pre-veraison deficit	10/3/92	5/4/93	22/3/94	2/3/95
Berry wt (g)	1.29	1.30	1.33	1.09
°Brix	24.5	23.3	24.7	24.2
Trt 4 Post veraison deficit	12/3/92	5/4/93	22/3/94	7/3/95
Berry wt (g)	1.32	1.29	1.27	1.11
°Brix	24.3	23.6	24.3	23.7
Trt 5 Pre-harvest deficit	10/3/92	24/3/93	15/3/94	2/3/95
Berry wt (g)	1.35	1.40	1.45	1.20
°Brix	24.9	23.5	23.2	24.5
Trt 6 Anthesis - veraison deficit	24/2/92	31/3/93	8/3/94	24/2/95
Berry wt (g)	1.25	1.38	1.42	0.99
°Brix	23.9	23.5	23.1	23.8
Trt 7 Veraison-harvest deficit	12/3/92	31/3/93	22/3/94	2/3/95
Berry wt (g)	1.31	1.39	1.32	1.17
°Brix	24.2	23.5	25.0	24.1
Trt 8 Unirrigated	18/2/92	24/3/93	1/3/94	7/3/95
Berry wt (g)	1.10	1.27	1.16	0.65
°Brix	25.0	23.8	23.3	24.1

Yield. Unirrigated vines yielded significantly less fruit than all other treatments for the three years for which data are presented. Low winter-spring-summer rainfall during 1994-95 (see Table 3.4) resulted in a 70 percent decline in yield of unirrigated vines between 1994 and 1995. The greatest difference in yield between treatments occurred in 1995 with nearly a 300 percent difference in yield between fully irrigated and unirrigated (Table 3.12) compared with 30 percent difference between the same two treatments at harvest 1992. At harvest 1995 the yield per vine of the three pre-veraison deficit treatments (Trt 2, 3 and 6) was significantly less than fully irrigated with post anthesis deficit and anthesis-veraison deficit vines yielding significantly less fruit than pre-veraison deficit. The anthesis-veraison deficit treated was the lowest yielding irrigated treatment although it was statistically similar to the post anthesis deficit treatment. Water stress during the post veraison period significantly reduced yield compared with irrigated vines but the pre-harvest deficit had no effect on yield, perhaps because of the short duration of this treatment.

Table 3.11 Irrigation treatment effect on the number of bunches per vine and berries per bunch for harvest years 1992, 1994 and 1995. Numbers followed by the same letter are statistically similar ($p<0.05$). n.s. = not significant.

	Bunches per vine	Berries per bunch
Trt 1 Fully irrigated	166	68 a
Trt 2 Post-anthesis deficit	156	57 b
Trt 3 Pre-veraison deficit	168	62 ab
Trt 4 Post-veraison deficit	160	63 ab
Trt 5 Pre-harvest deficit	154	67 a
Trt 6 Anthesis-veraison deficit	164	59 b
Trt 7 Veraison-harvest deficit	154	62 ab
Trt 8 Unirrigated	153	42 c

Table 3.12 Irrigation treatment effect on bunch weight (g) and yield per vine (kg) for harvest years 1992, 1994 and 1995. Numbers followed by the same letter are statistically similar ($p<0.05$). Tonnes per ha. = kg per vine x 1.25

Treatment	Bunch weight (g)	Yield kg/vine
Trt 1 Fully irrigated	80.7 a	13.4 a
Trt 2 Post-anthesis deficit	62.8 cd	9.8 cd
Trt 3 Pre-veraison deficit	67.8 bc	11.4 b
Trt 4 Post-veraison deficit	70.6 bc	11.2 bc
Trt 5 Pre-harvest deficit	80.5 a	12.4 ab
Trt 6 Anthesis-veraison deficit	58.1 d	9.6 d
Trt 7 Veraison-harvest deficit	72.7 ab	11.2 bc
Trt 8 Unirrigated	28.5 e	4.7 e

3.11 °Brix

The berries of unirrigated (Trt 8) and anthesis-veraison deficit (Trt 6) vines were significantly riper than fully irrigated (Trt 1) at all sampling times except the final four samplings in 1994-95. Post anthesis water deficit enhanced berry ripening compared with fully irrigated. This accorded with the response for the pre-veraison deficit treatment (Trt 3) with an enhancement in maturity in 1994-95.

Although the °Brix curves of six treatments are presented in Figure 3.8 there was only minor variation in °Brix prior to the final sampling in 1994-95. At sampling times five, six and seven, the °Brix of all treatments was similar, although the ranking did change (see inset - Figure 3.8). Pre-harvest (Trt 5), veraison-harvest (Trt 7) and unirrigated plots (Trt 8) increased more rapidly in °Brix than, for example, the berries from fully irrigated plots. The berries from pre-harvest deficit vines were the ripest at the final sampling, although not significantly higher than the other treatments. A similar pattern was observed in previous years.

There was a range of only 2 days in the number of days between anthesis and 10 °Brix but 13 days between the shortest and longest interval between anthesis and 20 °Brix. Due to a slowing in the rate of increase in °Brix during the latter stages of ripening in 1991-92 and 1994-95 seasons by day 120, the °Brix of fully irrigated vines was similar for the three years.

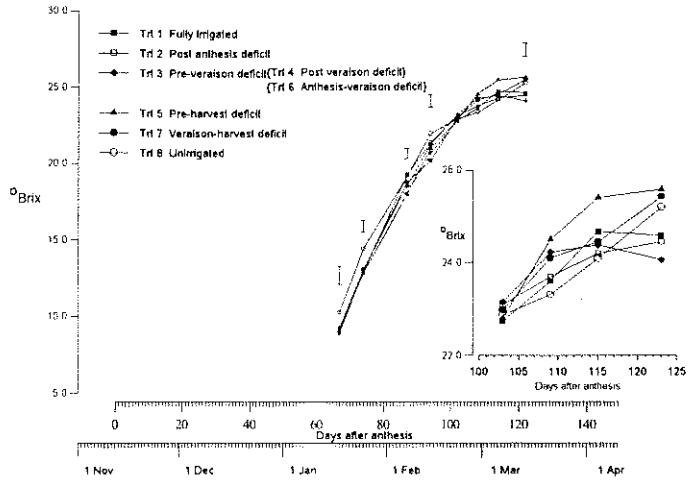


Figure 3.8 Increase in °Brix with time for the 1994-95 season.
Vertical bars indicate l.s.d.($p<0.05$) for each sample date. Bracketed treatments indicate those which were similar to plotted treatment at every sample date.

3.12 °Brix versus berry weight

In 1994-95 the average °Brix at maximum berry weight for Trts 1-7 was 18.5 and 22 for unirrigated (Figure 3.9). The berries from the fully irrigated (Trt 1) and the pre-harvest deficit (Trt 5) had the highest °Brix levels at maximum berry weight and unirrigated the lowest berry weight. A steady decline in berry weight between the °Brix at maximum weight and about 22 °Brix for treatments 1-7 was followed by a marked decline in berry weight as soluble solids concentration increased to 25 °Brix.

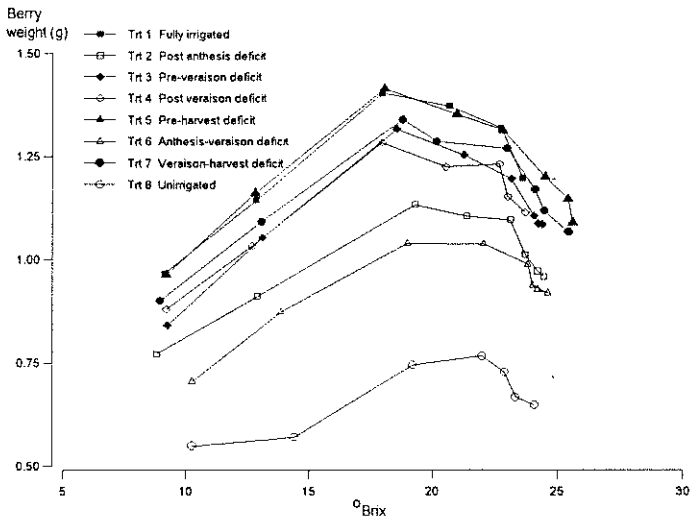


Figure 3.9 Relationship between berry weight and °Brix for all treatments during berry ripening during the 1994-95 season.

The average °Brix at maximum berry weight for treatments 1-7 in each of the four years are listed in Table 3.13 showing a range of about 17 to 19.

Table 3.13 Average °Brix at maximum berry weight for treatments 1-7 for the 1991-92 to 1994-95 season.

Season	°Brix
1991-92	19.1
1992-93	17.2
1993-94	16.8
1994-95	18.5

3.13 Solutes per berry, non-solutes per berry

Data on solutes per berry and non-solutes per berry against days after anthesis are presented only for selected treatments. The pattern of development of solutes per berry for other treatments was similar to fully irrigated. After an initial delay in 1993-94 (Figure 3.10) the berries of fully irrigated, pre-harvest deficit and veraison-harvest deficit treatments (Trts 1, 5 and 7) accumulated more solutes per berry than unirrigated vines; a difference was apparent at the third sampling time in 1994-95 (Figure 3.11). The solute content of Trt 5 continued to increase while fully irrigated, veraison-harvest deficit and unirrigated remained constant or decreased. During the latter stages of berry ripening in 1994-95 there was little difference in the solute concentration of Trts 1, 5 and 7; in all of these the rate of increase slowed after the sampling at 95 days after anthesis (Figure 3.11). The solute content of these treatments was nearly double that of unirrigated vines during berry ripening in 1995 reflecting the small size of unirrigated berries. The increase in solutes per berry of unirrigated vines at the final sampling time (Figure 3.11) was associated with a small increase in berry weight at this sampling time.

Non-solute weight per berry was the difference between berry weight and solutes and therefore is primarily water. Fully irrigated, pre-harvest deficit and veraison-harvest deficit treatment berries reached maximum non-solute weight by the fourth sampling time in 1994 (or about 95 days after veraison) (Figure 3.12), and by the third sampling time in 1995 (or about 88 days after veraison) (Figure 3.13). Non-solute weight was higher in 1993-94 than 1994-95 reflecting the larger berries in 1993-94, and in both years there was a significant loss in non-solute weight beginning after the fourth and third sampling respectively. The non-solute weight of veraison-harvest deficit berries (Trt 7) was less than fully irrigated and pre-harvest deficit treatments (Trt 5) by mid-January 1994, or about three weeks after the commencement of the irrigation deficit, and veraison-harvest deficit berries lost weight at a faster rate than fully irrigated. There was a rapid decline in the non-solute weight of pre-harvest deficit treatment berries between sampling times 5 and 6 in 1993-94. Berries of veraison-harvest deficit vines were lower in non-solute weight than fully irrigated in mid-January 1995 (Figure 3.13) but there was little difference between fully irrigated and pre-harvest deficit treatments. The non-solute weight of unirrigated berries increased by about 20 percent over the first five weeks of sampling in 1994 and then declined by more than 30 percent by the final sampling such that by the final sampling the non-solute weight was lower than immediately after veraison. Missing data for the first two samplings on unirrigated vines (Figure 3.13) during berry ripening in 1995 make interpretation difficult but there was a decline in non-solute weight with increasing °Brix.

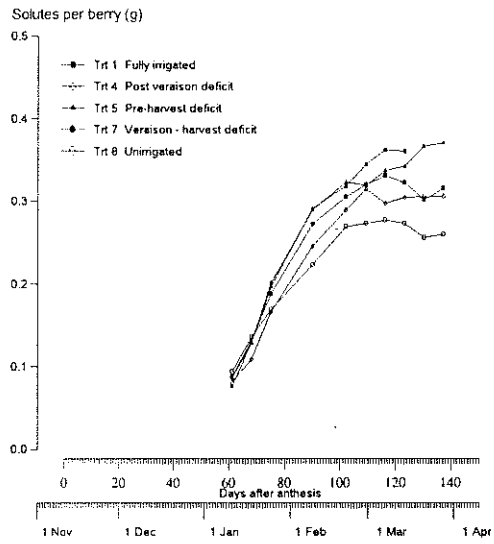


Figure 3.10 Solutes per berry for fully irrigated, post veraison deficit, pre-harvest deficit, veraison-harvest deficit and unirrigated treatments against days after anthesis during berry ripening in the 1993-94 season.

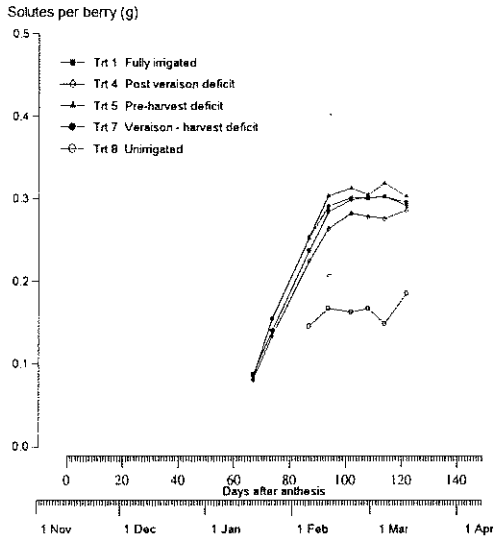


Figure 3.11 Solutes per berry for fully irrigated, post veraison deficit, pre-harvest deficit, veraison-harvest deficit and unirrigated treatments against days after anthesis during berry ripening in the 1994-95 season.

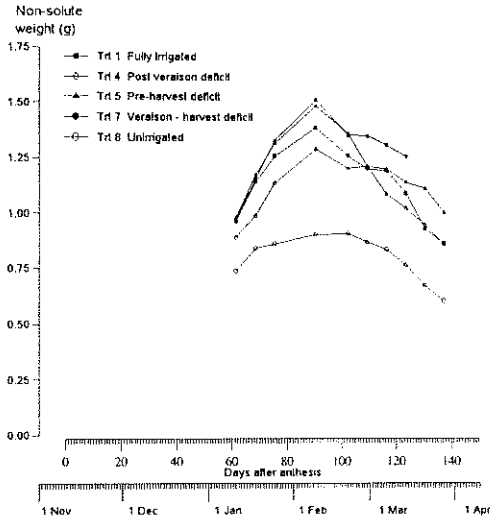


Figure 3.12 Weight of non-solutes per berry of fully irrigated (Trt 1), post veraison deficit (Trt 4), pre-harvest deficit (Trt 5), veraison-harvest deficit (Trt 7) and unirrigated (Trt 8) treatments against days after anthesis during berry ripening in the 1993-94 season

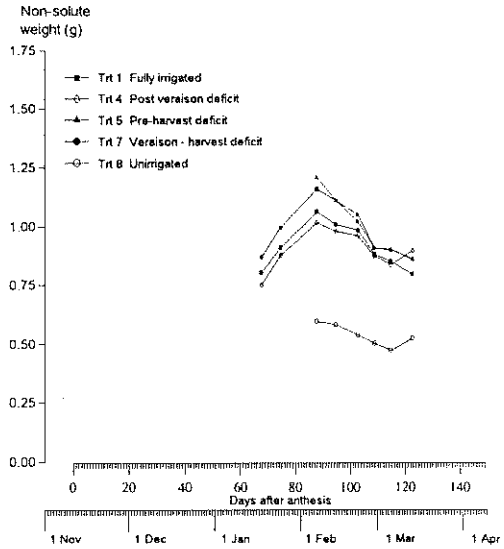


Figure 3.13 Weight of non-solutes per berry of fully irrigated (Trt 1), post veraison deficit (Trt 4), pre-harvest deficit (Trt 5), veraison-harvest deficit (Trt 7) and unirrigated (Trt 8) treatments against days after anthesis during berry ripening in the 1994-95 season

3.14 G-G per g berry weight

There were no differences between treatments in G-G per g berry weight in 1993-94 (Figure 3.14) except that the inflection point of the curve fitted to the post veraison deficit treatment (Trt 4) was lower than the anthesis-veraison deficit treatment (Trt 6) and unirrigated. In 1994-95 the shape of the curve representing the increase in G-G per g berry weight for the post veraison deficit treatment (Trt 4) was different to all other treatments (Figure 3.15), other treatments being similar to fully irrigated. With the exception of Trt 4, the estimate of the slope was significantly higher, and the asymptote lower in 1994-95 than 1993-94. The inflection point for Trts 1,5,6 and 7 was higher in 1994-95 compared with 1993-94 while Trts 2, 3 and 8 were lower. With the exception of fully irrigated (Trt 1) which had a higher intercept in 1994-95 than 1993-94, there was no difference in the intercept of other treatments between the two years.

3.15 Anthocyanin per g berry weight

There were only minor differences between treatments within each year. In 1993-94 the inflection point of the curve fitted to the post veraison deficit treatment (Trt 4) was lower than unirrigated (Trt 8) and in 1994-95 the slope of Trt 8 was greater than Trt 4 (Figure 3.16). The slope of the Trt 8 curve was lower than the post anthesis deficit treatment (Trt 2). There were no significant effects of treatment on anthocyanin per g berry weight in either year although there were differences between the two years in the pattern of development. The inflection point in 1993-94 was about 22 °Brix compared with about 18 °Brix in 1994-95 (Figure 3.17). This difference was significant for all treatments and there were higher levels of anthocyanin per g berry weight in 1993-94 compared with 1994-95 (as they were per berry); at 20 °Brix, berries contained about 1 mg anthocyanin per g berry weight in 1993-94 compared with about 0.75 mg in 1994-95

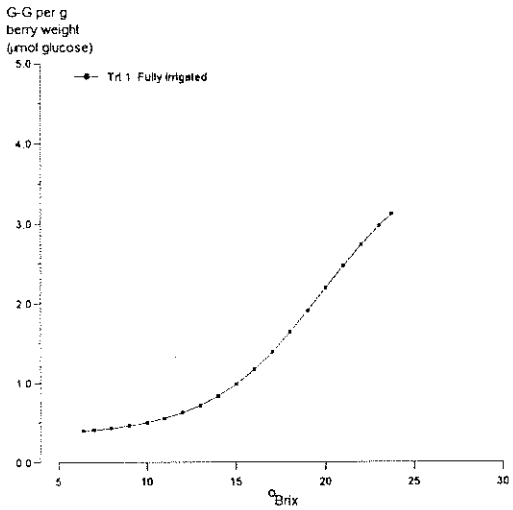


Figure 3.14 Fitted logistic model for G-G per g berry weight plotted against °Brix for the fully irrigated treatment during the 1993-94 season.
Other treatments were similar to fully irrigated. Actual minimum and maximum x-axis values are plotted but other points are placed at uniformly spaced x-axis values.

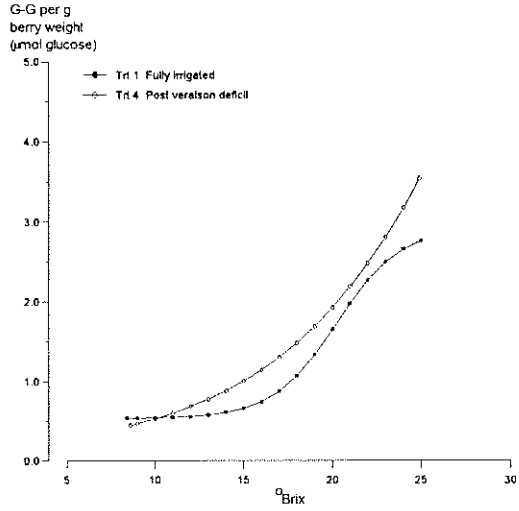


Figure 3.15 Fitted logistic models for G-G per g berry weight plotted against °Brix for the fully irrigated and post veraison deficit treatments during the 1994-95 season.
Actual minimum and maximum x-axis values are plotted but other points are placed at uniformly spaced x-axis values to distinguish treatments

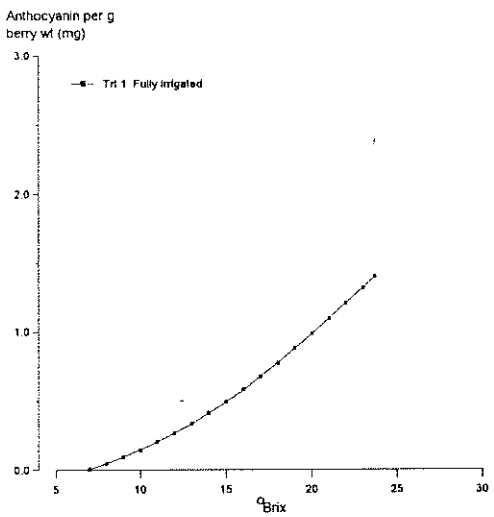


Figure 3.16 Anthocyanin per g berry weight for the fully irrigated treatment plotted against °Brix for the 1993-94 season. All other treatments were similar to fully irrigated. Actual minimum and maximum x-axis values are plotted but other points are placed at uniformly spaced x-axis values.

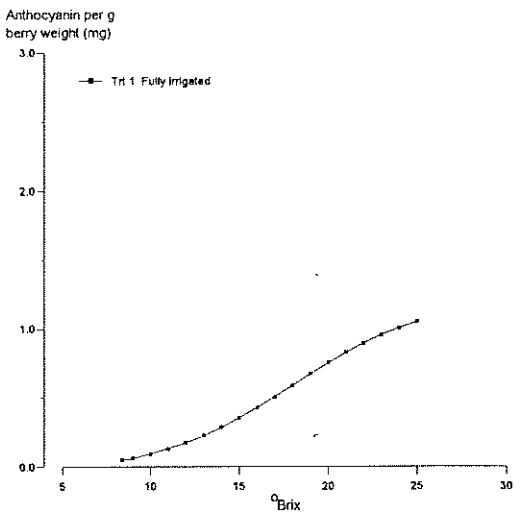


Figure 3.17 Anthocyanin per g berry weight plotted against °Brix for the fully irrigated treatment for the 1994-95 season. All other treatments were similar to fully irrigated. Actual minimum and maximum x-axis values are plotted but other points are placed at uniformly spaced x-axis values.

Red-free G-G per g berry weight

Red-free G-G was calculated from the subtraction of anthocyanin-glucose from the glucose in total G-G and expressed as µmol per berry (content) or per g berry weight (concentration). The pattern of development of red-free G-G per g berry weight was similar to red-free G-G per berry. There were no significant differences between treatments in red-free G-G concentration within either year however there were significant differences between years. The pooled data are presented in Figure 3.18 & Figure 3.19 and summarised statistics of the two phase modelling on the pooled data in Table 3.14. These data show the similarity in the intercept (0.42 and 0.46) and slope (-0.018 and -0.013) for the two years. The intersection in 1994-95 occurred at 3 °Brix higher (19.3 compared with 16.3) than in 1993-94 but this difference was not significant.

Table 3.14 Linear regression constants and intersection point for line 1 and 2 for two phase linear regression modelling of red-free G-G per g berry weight for all treatments against °Brix for the 1993-94 and 1994-95 seasons.

	1993-94		1994-95	
	Line 1	Line 2	Line 1	Line 2
intercept	0.42	-0.61	0.46	-2.27
slope	-0.018	0.046	-0.013	0.128
°Brix at intersection of lines 1 & 2	16.3		19.3	
Red-free G-G (µ mol glucose) per g berry weight at intersection of lines 1 & 2	0.14		0.20	

After the intersection, red-free G-G per g berry weight increased 2.8 times faster in 1994-95 than in 1993-94 (slope of 0.128 versus 0.046). Table 3.15 shows that, at 20 °Brix the red-free G-G per g berry weight was similar in both years (0.31 and 0.29 µmol) but, at 25 °Brix the concentration was 1.7 times higher in 1994-95 than in 1993-94. In both years the increase in red-free G-G per g berry weight between 20 and 25 °Brix was similar to the increase in red-free G-G per berry, however the amounts of these two increases were about three times greater in 1994-95 than in 1993-94.

Table 3.15 Red-free G-G content (µ mole glucose) per berry and concentration per g berry weight at 20 and 25 °Brix for 1993-94 and 1994-95 seasons.

	1993-94			1994-95		
Red-free G-G (µ mole glucose) :-	20 °Brix	25 °Brix	Δ	20 °Brix	25 °Brix	Δ
per berry	0.46	0.68	0.22	0.35	0.96	0.61
per g berry weight	0.31	0.54	0.23	0.29	0.93	0.64

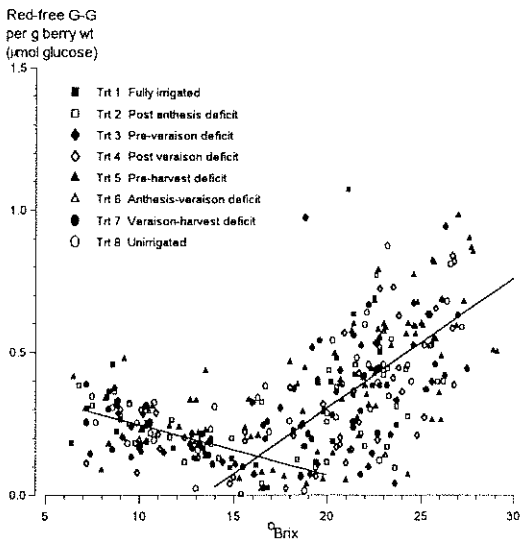


Figure 3.18 Two phase linear regression model of red-free G-G concentration per g berry weight plotted against °Brix for all treatments for the 1993-94 season

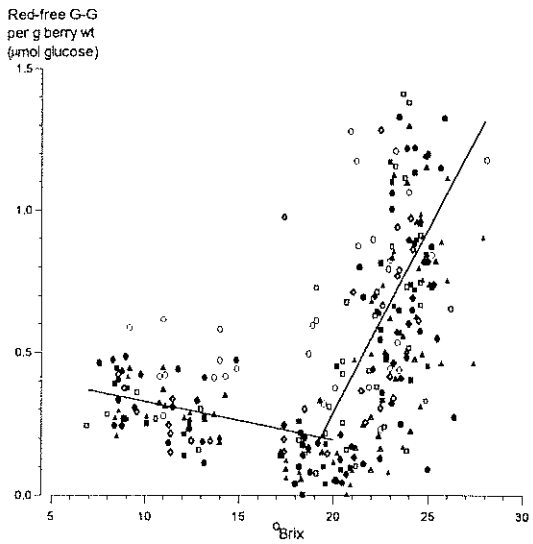


Figure 3.19 Two phase linear regression model of red-free G-G concentration per g berry weight for all treatments plotted against °Brix for the 1994-95 season. Data symbols are as described in previous figures.

3.16 Comparison of total G-G, anthocyanin-glucose and red-free G-G at harvest

Total G-G, anthocyanin-glucose and red-free G-G content and concentration at 23.5 °Brix were interpolated from the fitted curves for each treatment and are presented in Table 3.16.

Table 3.16 Total G-G, anthocyanin-glucose and red-free G-G of all treatments as content per berry and concentration per g berry weight at 23.5 °Brix for the 1993-94 and 1994-95 season derived from logistic and two phase linear modelling of red-free G-G against °Brix.Total G-G, anthocyanin-glucose and red-free G-G expressed as µmol glucose.

Treatment	1993-94					
	G-G		Anthocyanin-glucose		Red-free G-G	
	per berry	per g berry weight	per berry	per g berry weight	per berry	per g berry weight
Trt 1 Fully irrigated	4.74	3.08	3.89	2.59	0.85	0.56
Trt 2 Post anthesis deficit	4.35	2.96	3.82	2.59	0.54	0.38
Trt 3 Pre-veraison deficit	4.35	3.18	3.69	2.70	0.66	0.49
Trt 4 Post veraison deficit	4.18	3.30	3.59	2.86	0.63	0.47
Trt 5 Pre-harvest deficit	4.40	2.99	3.84	2.61	0.56	0.38
Trt 6 Anthesis-veraison deficit	4.08	2.94	3.48	2.51	0.58	0.43
Trt 7 Veraison-harvest deficit	4.37	3.20	3.76	2.74	0.65	0.48
Trt 8 Unirrigated	3.64	3.25	3.18	2.80	0.52	0.49
	1994-95					
	G-G		Anthocyanin-glucose		Red-free G-G	
	per berry	per g berry weight	per berry	per g berry weight	per berry	per g berry weight
Trt 1 Fully irrigated	3.09	2.58	2.23	1.85	0.91	0.77
Trt 2 Post anthesis deficit	2.78	2.78	2.08	2.00	0.66	0.68
Trt 3 Pre-veraison deficit	3.15	2.80	2.29	2.00	0.84	0.78
Trt 4 Post veraison deficit	3.46	2.98	2.57	2.21	0.91	0.79
Trt 5 Pre-harvest deficit	3.19	2.58	2.44	1.97	0.64	0.56
Trt 6 Anthesis-veraison deficit	2.42	2.48	1.89	1.95	0.67	0.61
Trt 7 Veraison-harvest deficit	3.46	2.93	2.59	2.19	0.81	0.68
Trt 8 Unirrigated	2.31	3.49	1.53	2.28	0.73	1.09

Statistical comparisons between treatments were not attempted. There was a similar ranking of treatments for G-G and anthocyanin-glucose concentration (Table 3.17). The unirrigated treatment (Trt 8) tended to have the lowest G-G and anthocyanin-glucose content but the highest concentration, illustrating the effect of berry weight on these measures. Both the content and concentration of G-G and anthocyanin-glucose of treatments 4 and 7 (post veraison and veraison-harvest deficit) were higher than other irrigation treatments (Trts 1-7) in both years. There were differences in the rankings of treatments based on red-free G-G concentration compared with those for G-G and anthocyanin G-G, especially in the 1993-94 values (Table 3.17).

Table 3.17 Ranking of concentration of treatments from highest to lowest based on total G-G, anthocyanin-glucose and red-free G-G per g berry weight at 23.5 °Brix.
Areas of similar shading intensity highlight similar treatment groupings for the two seasons, combined cells within a season were of similar rank.

	Highest							Lowest
	G-G per g berry weight							
1993-94	4	8	7	3	1	5	2	6
1994-95	8	4	7	3	2	5	1	6
	Anthocyanin-glucose per g berry weight							
1993-94	4	8	7	3	5	1	2	6
1994-95	8	4	7	3	2	5	6	1
	Red-free G-G per g berry weight							
1993-94	1	3	8	7	4	6	5	2
1994-95	8	4	3	1	2	7	6	5

Red-free G-G concentration of samples adjacent to specific °Brix levels

In Australia, Shiraz grapes used for premium quality red wines are often left to ripen beyond the 23.5 °Brix chosen as the designated maturity for small-lot winemaking in the Waikerie experiment. Such grapes reputedly have enhanced flavour compared with grapes at lower maturity and this offers an opportunity to test whether their red-free G-G concentration is higher than at lower °Brix levels. In each season berry sampling continued beyond 23.5 °Brix however, in 1993-94, the ripest sample from fully irrigated vines (Trt 1) was 23.7 °Brix; this was set as the minimum maturity level for selecting samples. As previously, a range of 23.7 to 24.7° was chosen to minimise the effect of °Brix on red-free G-G concentration, and, in selecting samples, replicates were disregarded, i.e. samples from the whole population that were closest to the selected °Brix level were chosen. In 1993-94 selected samples were in the range of 23.7 to 24.5 °Brix and the variation in red-free G-G per g berry weight was 0.24 to 0.65 μ mole per g berry weight or a difference of 2.7 times (Table 3.18). In 1994-95 samples were between 24.0 and 24.5 °Brix and the range in red-free G-G per g berry weight was from 0.65 to 1.06 μ mole per g berry weight. The average of all treatments within each year was 24.2 °Brix, the same for both years. The ranking of treatments based on red-free G-G per g berry weight in each year is shown in Figure 3.20.

Table 3.18 Red-free G-G (μ mole per g berry weight) of all treatments between 23.7 and 24.7 °Brix in 1993-94 and 1994-95.
Details on the number of samples in each treatment are given in Figures 5.17 and 5.18.

Treatment	1993-94		1994-95	
	°Brix	Red-free G-G per g berry wt.	°Brix	Red-free G-G per g berry wt.
Trt 1 Fully irrigated	23.7	0.24	24.2	0.78
Trt 2 Post anthesis deficit	24.1	0.34	24.1	0.85
Trt 3 Pre-veraison deficit	24.4	0.42	24.1	1.06
Trt 4 Post veraison deficit	24.2	0.50	24.4	1.02
Trt 5 Pre-harvest deficit	24.6	0.52	24.5	0.65
Trt 6 Anthesis-veraison deficit	23.9	0.49	24.2	0.71
Trt 7 Veraison-harvest deficit	24.4	0.65	24.4	0.70
Trt 8 Unirrigated	24.5	0.57	24.0	1.06
Average	24.2		24.2	

In 1993-94, as samples of higher °Brix were selected, the ranking of treatments on red-free G-G concentration per berry varied. For example at 23.5 °Brix the berries from fully irrigated vines (Trt 1) had the highest red-free G-G concentration while between 23.7 and 24.7 °Brix, the lowest (Figure 3.20). Only the post anthesis deficit treatment

(Trt 2) showed a consistent pattern being ranked seventh, sixth and seventh respectively in each of the °Brix ranges. However there was greater consistency in the ranking of treatments when compared for each °Brix range in 1994-95. Treatments 3 and 8 (pre-veraison deficit and unirrigated) were ranked first, second or third by each method, Trt 4 was ranked second, fourth and third, Trt 7 (veraison-harvest deficit) was ranked sixth or seventh and Trt 5 (pre-harvest deficit) was the lowest in each °Brix range.

Red-free G-G concentration per berry of each treatment between 23.7 and 24.7 was derived from a different number of samples per treatment and this may have contributed to inconsistencies in the ranking of treatments. The number of samples in each treatment varied from one to four in 1993-94 (Figure 3.21 Range of red-free G-G per g berry) and from one to ten in 1994-95 (Figure 3.22). The difference between the maximum and minimum red-free G-G concentration per berry within each treatment was influenced by the number of samples although for example, the range in the four values for Trt 4 in 1994-95 was the same as the ten samples selected from Trt 6. The difference between the maximum and minimum values for treatments where there was more than one sample was greater in 1994-95 than 1993-94. These data show clearly the greater variation in red-free G-G values in 1994-95 when levels were high and the difficulty that high variation conferred in searching for consistent differences between treatments.

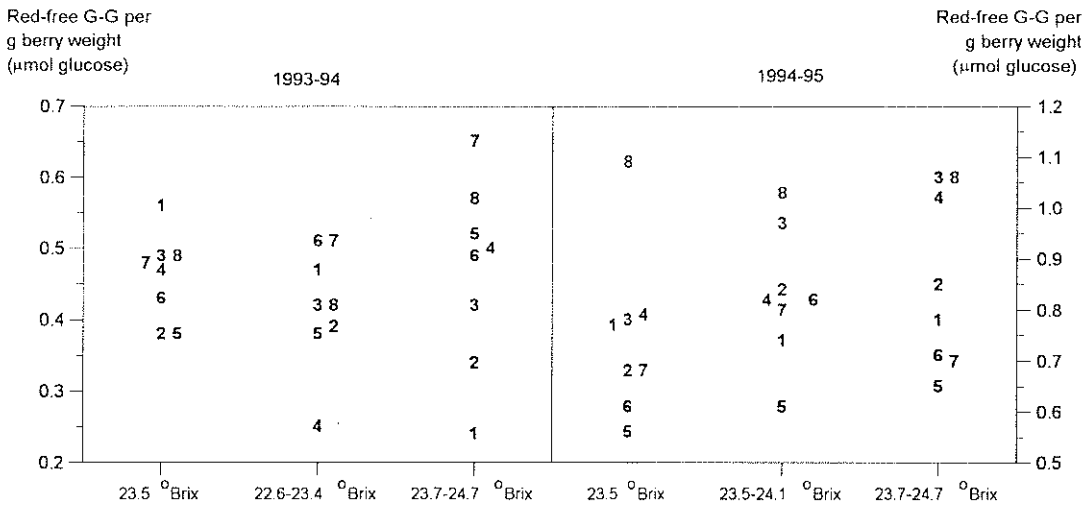


Figure 3.20 Ranking of red-free G-G per g berry weight for all treatments at 23.5 °Brix and two higher °Brix ranges within each year. Horizontal separation within each °Brix range is to distinguish treatment numbers. Treatment ranking at 23.5 °Brix is based on interpolated values. Note the different Y-axis scale for 1993-94 and 1994-95 seasons.

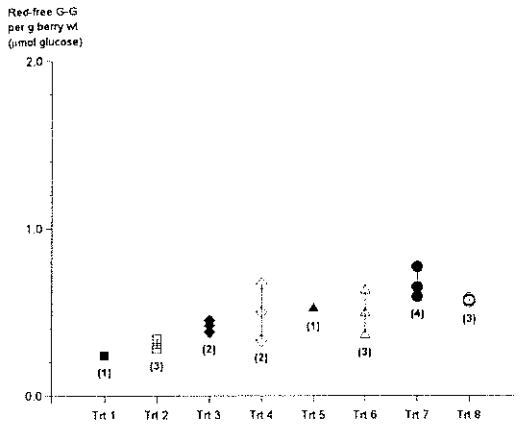


Figure 3.21 Range of red-free G-G per g berry weight between 23.7 and 24.7 °Brix for each treatment in the 1993-94 season.
Symbols indicate the minimum, mean and maximum value for each treatment. Numbers in brackets indicate the number of samples for each treatment.

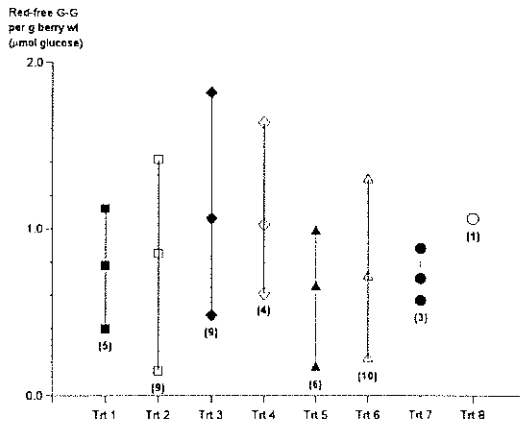


Figure 3.22 Range of red-free G-G per g berry weight between 23.7 and 24.7 °Brix for each treatment in the 1994-95 season.
Symbols indicate the minimum, mean and maximum value for each treatment. Numbers in brackets indicate the number of samples for each treatment
Note there was only one datum point for Trt 8 (unirrigated) within this °Brix range

3.17 Sensory evaluation of small-lot wines

The rank totals were as follows (note that the lower the rank the higher the intensity).

1993-94 wines

Aroma

T.= 17.4* LSD5% = 16

Rank Total	47	53	54	54	59	62	63	68	70	70
Treatment	Post anthesis deficit	Veraison-harvest deficit	Post veraison deficit	Post anthesis deficit	Anthesis -veraison deficit	Irrigated	Unirr	Unirr	Pre-harvest deficit	Pre-harvest deficit
oBrix	25.7	25.6	24.9	23.4	23.8	24	24.3	24.4	23.6	24.0

Flavour

Rank Total	46	47	50	54	60	63	67	369	69	75
Treatment	Post veraison deficit	Veraison-harvest deficit	Post anthesis deficit	Pre-veraison deficit	Irrigated	Unirr	Pre-harvest deficit	Anthesis-veraison deficit	Unirr	Pre-harvest deficit
oBrix	24.9	25.6	23.4	25.7	24.0	24.3	24.0	23.8	24.4	23.6

1994-95 wines

High brix wines
The rank totals were as follows (note that the lower the rank total the higher the intensity).

Aroma

T. = 23.9 (p=0.0012) LSD5% = 17

Rank Total	45	67	70	72	72	73	74	87
Treatment	Unirr	Pre-harvest deficit	Irrigated	Veraison-harvest deficit	Anthesis-veraison deficit	Post anthesis deficit	Post veraison deficit	Pre-verasion deficit
oBrix	26.1	25.1	25.5	25.1	25.3	24.9	25.4	25.3

Flavour

T. = 23.85 (p=0.0012) LSD5% = 17

Rank Total	46	65	66	71	72	76	80	84
Treatment	Unirr	Post veraison deficit	Irrigated	Pre-verasion deficit	Anthesis-veraison deficit	Veraison-harvest deficit	Pre-harvest deficit	Post anthesis deficit
oBrix	26.1	25.4	25.5	25.3	25.3	25.1	25.1	24.9

Low brix wines

Aroma

T. = 15.9 (p=0.026) LSD5% = 21

Rank Total	89	95	97	104	107	108	114	126
Treatment	Post anthesis deficit	Anthesis-veraison deficit	Post veraison deficit	Pre-harvest deficit	Veraison-harvest deficit	Irrigated	Pre-verasion deficit	Irrigated
oBrix	24.5	25.1	24.9	24.8	25.1	24..3	24.8	24.3

Flavour

T = 12.8 (p=0.077) ns: LSD5% = 21

Rank Total	97	98	98	99	102	109	109	128
Treatment	Post anthesis deficit	Veraison-harvest deficit	Anthesis-veraison deficit	Post veraison deficit	Pre-verasion deficit	Pre-harvest deficit	Irrigated	Irrigated
oBrix	24.5	25.1	25.1	24.9	24.8	24.8	24.3	24.3

4. Discussion

4.1 Vine water use

Over four years, ET_{crop} of fully irrigated vines ranged from 574 to 732 mm comprising 345 to 602 mm of irrigation and between 59 and 352 mm growing season rainfall. These data are however subject to some limitations as they assume no loss of rainfall or irrigation water below the zone available to plant roots which was defined as 120 cm deep or the depth of the neutron probe acess tubes. An assumption was also made that a single neutron probe tube placed in the vine row and mid-way between vines represented the pattern of soil water depletion for the whole of the rootzone. Irrigation applications to fully irrigated vines in the Waikerie experiment were similar to or slightly lower than those previously reported for vines growing in a similar climate. For example Sultana vines at Dareton, also in the Murray-Darling basin, had an irrigation requirement of 700 to 800 mm (Prior and Grieve, 1987) compared to a maximum of 600 mm applied here. The lower values from the Waikerie experiment may be attributable to lower vigour and yield, to the precise timing of water application, and to lower ET_o during the period of the experiment.

4.2 Vine development phases

The duration between key phenological events is schematically shown in Figure 4.1. The number of days between key phenological events for the vines used in this experiment are less than those reported by Coombe (1988) for Shiraz in a similar climate. The greatest variation in the number of days between growth stages in the Waikerie experiment was between veraison and 20 °Brix (14 days) compared with 8-9 days between budburst and anthesis or anthesis to veraison (Table 4.1).

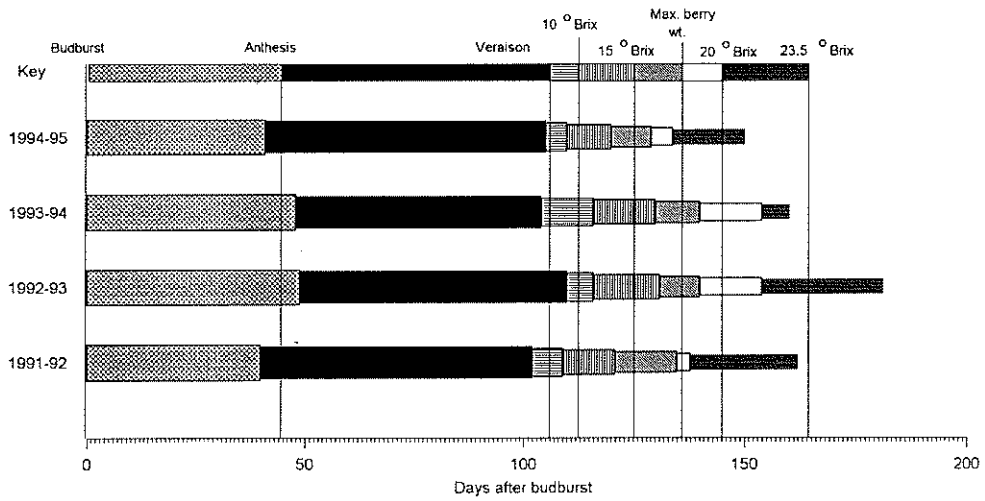


Figure 4.1 Schematic representation of the duration in days of phenological stages for fully irrigated Shiraz vines for four seasons.
Vertical lines indicate the average number of days after budburst for the indicated phenological stage.

Table 4.1 Duration in days between major phenological stages for fully irrigated vines for four seasons.

	Budburst to anthesis	Anthesis to veraison	Veraison to 20 °Brix	Total
1991-92	40	62	36	138
1992-93	49	61	44	154
1993-94	48	56	50	154
1994-95	41	64	29	134
Average	45	61	40	146

Shoot growth

Irrigation was applied to treatments 1-7 before budburst in each season to ensure uniform budburst and this is reflected in the absence of a treatment effect on the number of shoots per vine in the 1994-95 season. Unirrigated vines had fewer shoots than only fully irrigated vines in this season. Similar shoot number for Trts 1-7 also indicates no carryover treatment effect from the previous season. In all seasons shoot growth of fully irrigated vines (Trt 1) ceased by veraison and there was minimal lateral shoot development. The conclusion is that treatments involving water stress post-veraison (Trt 4, 5 and 7) had no effect on shoot growth. Shoot length of unirrigated vines was less than all other treatments by about a month after bud-burst.

The relative effect of irrigation treatment on pruning weight was determined by the water stress that developed during each period and this varied between seasons. Unirrigated vines always had the shortest shoots and the lowest pruning weight. Water deficit before veraison resulted in shorter shoots which correspondingly weighed less. As most shoot growth had stopped near veraison the effect of water stress on shoot length after this time was minimal, however, the shoots removed from the post veraison and veraison-harvest deficit vines in winter 1995 were lighter in weight than shoots on pre-harvest deficit vines. In winter 1996 the shoot diameter between the first and second dormant bud on veraison-harvest deficit vines was 0.42 mm smaller (7.16 vs 6.74 mm) than fully irrigated vines which indicated water stress after veraison had an adverse effect on shoot thickening. The effect of water stress on shoot thickening is seldom reported but data presented here suggests that there is a critical period after veraison during which shoot thickening is reduced; however, the importance of this response is yet to be determined.

4.3 Berry growth and yield

Berry growth

In each of the three years that berry weight was measured a normal double sigmoidal development was shown until a maximum was reached midway through ripening, followed by a marked loss in weight towards the end of the season in all treatments. There was a significant irrigation treatment effect on berry weight, all deficit treatments being smaller than fully irrigated at harvest. In addition there was a difference in berry weight between seasons, 1994-95 berries being smallest.

Loss in berry weight during the latter stages of ripening occurred in all treatments and in all years in the experiment reported here. The amount of water deficit did not appear to alter the rate of weight loss. Although weekly sampling precludes precise determination it is estimated that the maximum weight occurred at 91 ±3 days after anthesis. The constancy of this interval is unusual as there was about a three weeks variation in date of anthesis and a 16 day variation in the onset of veraison. The date on which berry weight decline started showed much greater variation than did days after anthesis; over the four years the dates were 31 Jan, and 17, 9 and 7 Feb., a spread of 18 days. There were also significant differences in berry weight between treatments and between year as well as differences in general growing conditions between the four seasons. The constancy of this phenomena has not been previously reported and it is not known whether it occurs in other cultivars.

Yield

Regardless of the timing of the soil water deficit, yield was significantly reduced compared with the fully irrigated control, for example in 1994-95 treatments 2-7 all yielded less fruit than fully irrigated (Figure 4.2). Although in previous years yield was not significantly reduced at low levels of soil water deficit these data indicate the use of regulated deficit irrigation in the vineyard will require careful application.

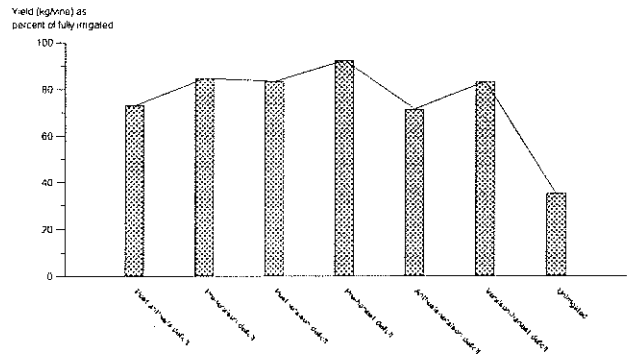


Figure 4.2 Yield, as a percent of fully irrigated, of treatments 2-8 at harvest in the 1994-95 season.

4.4 Phenological correlates

There was a range of only two days in the number of days between anthesis and 10 °Brix, a range of 3 days between anthesis and 15 °Brix weight but a difference of 23 days between the shortest and longest period between anthesis and 23.5 °Brix (Figure 4.3). Although harvest date (ie 23.5 °Brix) varied by 23 days between the four years, the difference of only two days between anthesis and 10 °Brix and three days between anthesis and 15 °Brix suggests a genotypic control of berry development to this stage rather than, for example, an external control subject to influence by the weather.

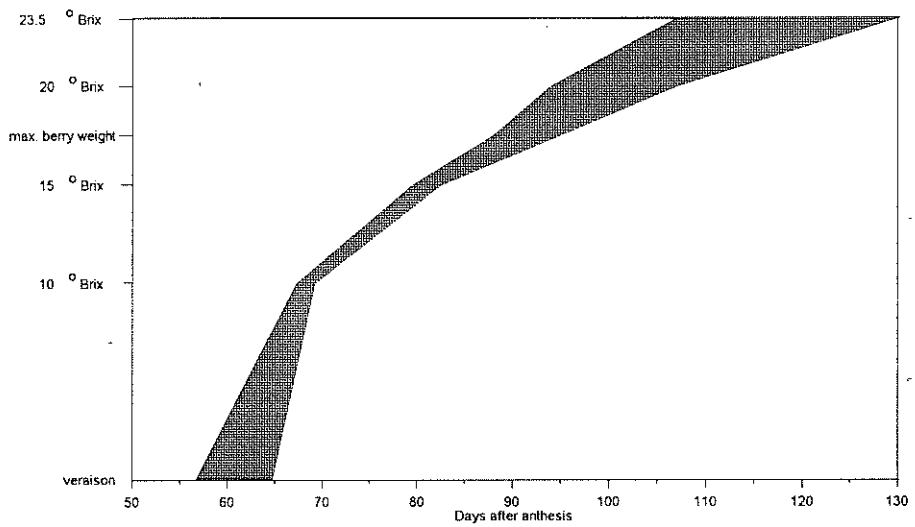


Figure 4.3 Variation in the number of days between anthesis and key phenological events of fully irrigated vines (Trt 1) over the years 1991-92 to 1994-95. Y axis not to scale.

4.5 Maximum berry weight

The onset of berry weight loss was unrelated to °Brix as there was a range in °Brix at maximum berry weight for the four seasons. For example, in 1993-94 there was a range of 16.5 to 18 °Brix for treatments 1-7 and 19 to 22 °Brix for unirrigated, in 1994-95 between 18 and 19.5 for Trts 1-7 and 19.5 to 22 for unirrigated (Figure 3.9). The similarity of the curves of berry weight and of non-solute weight per berry, coupled with the known predominance of water plus solutes in grape berries, support the contention that weight loss is due to water loss. It is indeed singular that maximum berry weight occurred at about 91 days after anthesis in all four years of the Waikerie experiment and in all treatments. For the remainder of this report, this stage will be identified as "weight-max". Weight-max. also signalled a change in solute accumulation. In both years, in the majority of treatments, there was no further increase in solute content per berry after weight-max.; two exceptions were the berries of fully irrigated (Trt 1) and pre-harvest deficit (Trt 5) which showed a small increase in solutes per berry after weight-max. in one season. However the major conclusion is that both water *and* solute accumulation stopped in Shiraz berries at weight-max. The sudden cessation of solute movement into Shiraz berries at weight-max. is surprising as the phenomenon has not been reported before.

4.6 Glycosyl -glucose

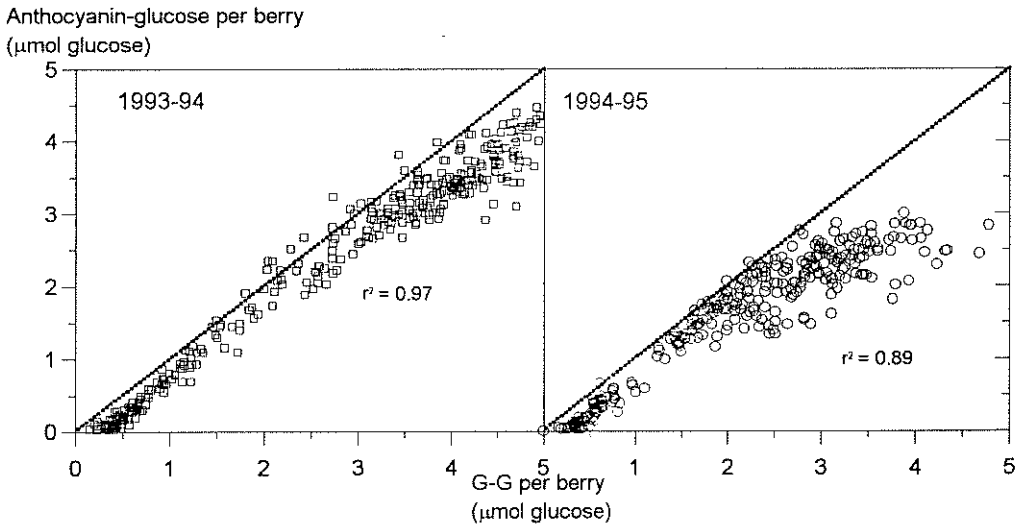
The Waikerie data show that water stress prior to veraison had no significant effect on G-G content or concentration at the first sampling soon after veraison compared with fully irrigated although there was up to a two-fold difference between treatments in G-G content per berry. For example, at 10 °Brix, the G-G content per berry of the fully irrigated treatment was 0.56 μmol glucose compared with 0.29 μmol glucose per berry of unirrigated vines. There was a sigmoidal development of G-G, and within the error associated with determining the occurrence of maximum berry weight, the inflexion point of the curves of G-G content per berry against °Brix occurred at °Brix levels similar to those at weight-max. of each treatment (Table 4.2).

Table 4.2 °Brix at weight-max. and inflexion point of logistic curves of G-G content per berry against °Brix for Trts 1-7 in 1993-94 and 1994-95.

	1993-94	1994-95
°Brix at maximum berry weight of Trts 1-7	16.8	18.5
°Brix at inflexion point of logistic curves of G-G content per berry against °Brix for treatments 1-7	17.1	19.3

The steady increase in G-G content and concentration per berry during berry ripening (albeit with a slowing during the latter stages) contrasts with the rise in °Brix and solutes per berry of fully irrigated vines during berry ripening in 1993-94 and 1994-95. In 1993-94, due to the combination of an increase in solute content per berry and then a loss in berry weight, °Brix continued to increase in a near-linear manner to the final sampling. In 1994-95 there was no increase in solute content of fully irrigated berries after weight-max., and although berries lost weight after this time, the rate of increase in °Brix slowed. These data indicate that solute and G-G accumulation in ripening berries are independent although the cessation of solute accumulation after weight-max. in 1994-95 may be correlated with the more rapid increase in red-free G-G in that year compared with 1993-94. Compared with 1993-94, a decreasing proportion of the total G-G per berry occurred as anthocyanin-glucose at higher G-G level in 1994-95 (Figure 4.4). In 1993-94, at 4.0 μ mol glucose G-G per berry, 86 percent was anthocyanin-glucose compared with 65 percent at the same G-G content per berry in 1994-95. This difference is explained by the larger proportion of red-free G-G that accumulated in berries during 1994-95 as ripening progressed beyond about 2 μ mol glucose G-G per berry.

Figure 4.4 Relationship between anthocyanin-glucose content per berry and G-G content per berry for all samples of

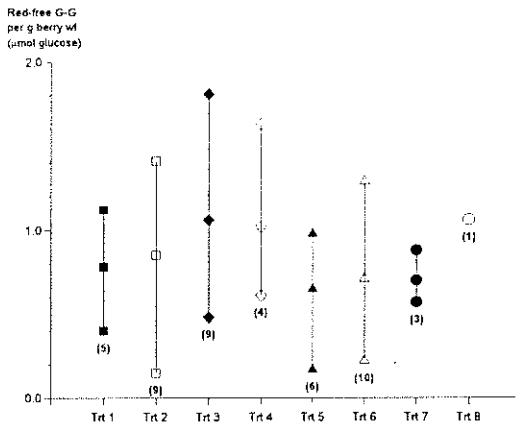


all treatments for the 1993-94 and 1994-95 seasons. Diagonal line represents the case of all G-G per berry being anthocyanin-glucose.

Data presented on the change in red-free G-G during ripening display, for the first time, the formerly unknown pattern of development of total non-pigmented glycosides in black grapes with a significant change coinciding with weight-max. Judicious interpretation of these data is advisable especially in the decline in red-free G-G content and concentration during the initial stages of berry ripening. These data however indicate that during the initial stages of berry ripening the apparent decline in red-free G-G content per berry was independent of °Brix accumulation. In contrast to the similar rate of decline before the minimum point in each season, red-free G-G content and concentration per berry increased at three times the rate in the latter stages of ripening in 1994-95 compared to 1993-94. Surprisingly however, there was no significant difference in the rate of increase between

treatments within each season. Red-free G-G per berry was 24 percent higher at 23.5 °Brix in 1994-95 than 1993-94 however red-free G-G concentration per berry was 60 percent higher (average for all treatments).

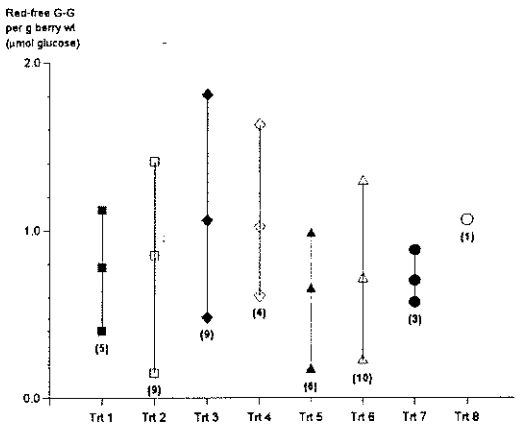
The number of samples for each treatment within the two chosen °Brix ranges in each season determined the ranking of treatments based on red-free G-G concentration, more so in 1993-94 than 1994-95. The fewer number of samples in the 23.7-24.7 °Brix range for each treatment compared with the 22.6-23.4 °Brix range (5 samples per treatment) in 1993-94 resulted in a large change in the average red-free G-G concentration. For example in the lower °Brix range, Trt 1 red-free G-G concentration was 0.47 μ mol glucose per g berry weight (mean of 5 samples) while at the higher °Brix range was 0.24 μ mol glucose per g berry weight. In 1994-95 although there were more samples in the 23.7-24.7 °Brix range (there was also some overlap in the two °Brix ranges) there was a large difference between the maximum and minimum concentration within each treatment



(

Figure 3.22 Range of red-free G-G per g berry weight between 23.7 and 24.7 ^{oBrix} for each treatment in the 1994-95 season.
Symbols indicate the minimum, mean and maximum value for each treatment. Numbers in brackets indicate the number of samples for each treatment Note there was only one datum point for Trt 8 (unirrigated) within this ^{oBrix} range

). The occurrence of high variability was not consistently associated with an individual treatment or replicate and the absence of a significant difference, especially for the slopes and intercepts from two-phase modelling, was contributed to by the high variance of the data. Vine-to-vine variability is an inherent problem in field experiments and this variability appears to be greater for secondary metabolites such as red-free G-G



(

Figure 3.22 Range of red-free G-G per g berry weight between 23.7 and 24.7 ^{oBrix} for each treatment in the 1994-95 season.
Symbols indicate the minimum, mean and maximum value for each treatment. Numbers in brackets indicate the number of samples for each treatment Note there was only one datum point for Trt 8 (unirrigated) within this ^{oBrix} range

). Analytical error associated with the assay itself did not contribute to the variability (Williams et al., 1995), nor is the high variance explained by ripeness differences, however the range in red-free G-G concentration of individual berries on a bunch, between bunches, and the effect of bunch location within the canopy is still to be determined as is the optimum sample size. The duration of the ripening phase appears to be unimportant as the shorter interval between weight-max. and harvest in 1994-95 compared with 1993-94 did not reduce the variability between samples

of the same treatment. No data is at hand on the variability in the °Brix of berries however, an examination of °Brix levels in berries at harvest appears warranted.

The anthocyanin concentration in black grapes has been used with advantage to indicate wine quality and some Australian wineries use grape colour at harvest as an index of quality in addition to °Brix and pay accordingly. When compared at similar °Brix there was a positive effect of post-veraison water deficit on anthocyanin-glucose in both years indicating water deficit during the first three to four weeks after veraison may improve wine quality. Logic however suggests that red-free G-G, which includes flavour compounds and, of course many others apart from flavour such as quercetin-glycoside (Price et al.,1995) may be a more appropriate measure for this purpose. It is the difference, yet equally, the similarities, in ranking of treatments based on anthocyanin-glucose compared with red-free G-G and wine quality that remain to be resolved. Data presented in this thesis show that anthocyanin accumulation (and sugar accumulation) is largely over by weight-max. and the increase in red-free G-G content per berry occurs after this event. This late increase in red-free G-G matches industry experience on flavour development in ripening grapes.

4.7 Sensory evaluation of small-lot wines

For both years there was a strong correlation between wine aroma and flavour score and must °Brix even within the narrow °Brix range that fruit was harvested. This correlation tended to mask any treatment differences and highlights the critical importance of harvesting fruit from experimantal plots as close as possible to the same °Brix. These data also perhaps put into question the results of previous experiments involving small-lot winemaking where treatments were harvested at different maturity levels. In both years however wines made from the post anthesis deficit treatments scored higher in aroma and flavour that their must °Brix would suggest indicating a postive effect on wine quality with this treatment. Further statistical analysis of these data is required to determine the realtionship beween score, °Brix and yield. Preliminary examination of the data does however indicate, that for this set of small-lot wines, there is no significant correlation between any of the analytical measures of wine quality and aroma or flavour score.

5. Recommendations for the Australian viticultural industry

The results from the Waikerie experiment indicate that a well designed and monitored vineyard irrigation system can substantially reduce irrigation application, offer the possibility of control of vegetative growth and yield, and perhaps an improvement in wine quality. For cv. Shiraz, a new phase of grape berry development has been identified. Investigation of the changes in berry metabolism that occur at this stage will undoubtedly follow and could ultimately add to the ability of viticulturists to manipulate grape quality.

5.1 Irrigation design and monitoring

The annual volumetric irrigation licence for vineyards in government irrigation districts in the Riverland area of South Australia is currently 10.7 Ml/ha. In the Waikerie experiment the total annual water application ranged from 3.45 to 6.02 Ml per ha or between 44 and 68 percent less than the licenced volume. This substantial reduction in irrigation application was due to the use of a competent micro-irrigation system permitting precise control of water application and in turn guided by the regular measurement of soil water content with a neutron probe.

Soil water content was measured three times per week to ensure timely irrigation in this experiment; frequent readings are necessary to monitor water movement through the soil profile. While thrice-weekly readings are not necessary in commercial vineyards it is recommended that soil water content be measured at least twice weekly to ensure that irrigation is applied when required. The accuracy and reliability of the capacitance sensors used in this experiment to continuously monitor soil water content will need to be improved to overcome their present limitations. Soil matric potential rather than soil water content should be measured to allow for differences in soil texture. Whichever system of continuous soil water monitoring is used, the large database that will eventuate will require specialist computer software to enable irrigators to optimise water application.

The successful commercial application of WI or RDI will be determined by the vineyard irrigation system as there will need to be sufficient flexibility to enable water to be withheld or heavier than normal irrigations applied at the end of a period of water deficit. There are large areas of irrigated vineyard where such flexibility is not possible without a major upgrading of the irrigation dispensing system or where there is no soil water monitoring. No 'leaching irrigations' were applied in the Waikerie experiment although this practice is still widely used. It is recommended that the need for a leaching component be re-examined where micro-irrigation systems that have a high distribution uniformity are used.

5.2 Control of vegetative growth and yield

Increased winery demand for grapes suitable for processing into wine for export has resulted in the introduction of minimum maturity levels which are higher than previously accepted for bulk wine production. Some grapegrowers are finding these higher maturity levels difficult to achieve. In vineyards in the Murray-Darling basin the widespread use of virus-free scion and rootstock planting material, micro-irrigation, fertigation and improvements in pre-and post planting soil management have resulted in high yields. Such fruit often fails to reach the minimum maturity level and, in the belief that water stress will enhance maturity, it is common practice for grape growers to withhold irrigation prior to harvest. Data from the Waikerie experiment indicates that any enhancement of juice °Brix from water stress prior to harvest may be due to berry shrivel and not to increased solute content per berry. In vigorous vineyards, pre-harvest water deficit is too late to be of practical use in reducing excessive vegetative growth and the negative effects that dense vine canopies can have on fruit and wine quality. The Waikerie experiment demonstrated that berry size is most sensitive to water deficit during the post anthesis period and the level of water deficit necessary to achieve this will also reduce shoot growth. In vineyards in which excessive vigour and yield negatively impact on fruit quality a water deficit after anthesis may sufficiently reduce yield and vigour to ensure rapid fruit ripening. Preliminary results from large scale trials of post anthesis irrigation deficit indicate a positive improvement on wine quality, especially in vineyards where very high yields were due to large berries. The rapid development of a soil water deficit during the post anthesis period may not be possible in vineyards with deep soils with high water holding capacity or in cooler and wetter than normal seasons. In these situations the soil profile may need to be dried by using cover crops with a high water requirement. Shallow soils will not present such problems although care would be needed to ensure that excessive water deficit during the post veraison period did not slow solute accumulation.

5.3 Indices of wine quality

No conclusions on the merit of the red-free G-G measure as an index of wine quality can be yet drawn. Subject to a correlation between red-free G-G and wine quality being established for wines made from ripe fruit, the late rapid rise in red-free G-G, especially in 1994-95, indicated a comprehensive vineyard sampling program is necessary if red-free G-G is to be used as an additional guide to harvest. Winemakers who regularly assess grape berry flavour in vineyards organoleptically often report the sudden and rapid development of flavour just prior to harvest; this may correlate with the late rise in red-free G-G reported here.

The effect of the timing of water deficit on glycosylated secondary metabolite accumulation in berries is unclear, due primarily to variability between samples within treatments. Surprisingly there were no significant differences in anthocyanin-glucose and red-free G-G between the extremes of the irrigation treatments applied in the Waikerie experiment when compared at the same °Brix level. The irrigation treatments used in the Waikerie experiment produced a wide range in yield and there were large differences in leaf canopies, yet despite this, there was no significant difference in secondary metabolite concentration within a season but a large difference between season. These data suggest the major influence on glycosylated secondary metabolite accumulation could be region and season with a lesser influence of yield and canopy configuration.

Although there were no significant differences in analytical measures of grape quality used in the Waikerie experiment there were significant differences between treatments when small-lot wines are ranked on wine aroma and flavour. G-G and red-free G-G represent the total pool of glycosylated compounds and glycosylated secondary metabolites and thus may be too general to correlate with wine quality. A simple analytical measure on grapes at harvest that equates with wine quality remains a crucial challenge.

6. Publications and technology transfer arising from the study

Publications:

Doctoral thesis - 'Timing of water deficit on fruit development and composition of Vitis vinifera cv. Shiraz". Awarded May 1997. (scientific papers in preparation)

Refereed Journals

"Identification and naming of the inception of aroma development in ripening grape berries." B.G. Coombe & M. G. McCarthy. Australian Journal of Grape and Wine Research 1997(3):18-20.

Industry Publications

Manipulation of the concentration of glycosyl-glucose in Shiraz grapes with irrigation management. M.G. McCarthy, P. G. Iland, B. G. Coombe and P. J. Williams. In:Proceedings of the Ninth Australian Wine Industry Technical Conference, ed(s). Stockley, C. S.:101-104. Adelaide. South Australia: Winetitles.

The glycosyl-glucose assay - its application to assessing grape composition. Iland, P.G., Gawel, R., McCarthy, M.G., Botting, D. G. et al. (1996). In: Proceedings of the Ninth Australian Wine Industry Technical Conference, ed(s). Stockley, C. S.:98-100. Adelaide. South Australia: Winetitles.

Irrigation influences on berry composition and shoot growth M. G. McCarthy (1996) In Proceedings of an ASVO seminar, Quality management in Viticulture. 2 August 1996, Mildura Victoria.

Regulated deficit irrigation of grapevines and its commercial applications. M. G. McCarthy. Aust. N. Z. Wine Ind. J. 7: 277-279 1992.

Exploiting the benefits of improved irrigation systems. M. G. McCarthy, In: Proceedings of a seminar Water for Viticulture, Optimising the Resource. 47-49. December 1995. Adelaide. South Australia. : Winetitles

Extension activity

Regulated Deficit Irrigation: Where to next. Vititec'96 " Managing water for optimum grape production. Coonawarra, October 1996.

Riverland Shiraz project. Orlando Wyndham seminar, Improve the quality of your Shiraz, Barmera, August 1996.

MIA Shiraz project. Orlando Wyndham seminar, Improve the quality of your Shiraz, Griffith, September 1996.

Irrigation management to improve wine quality. CCW seminar, Shiraz Quality, Barmera, October 1996

Irrigation management to improve wine quality. Australian Vintage grower information day, Loxton & Robinvale, November 1996.

Irrigation management to improve wine quality. SouthCorp grower information days, Waikerie, Loxton, Karadoc & Griffith, Spring 1996.

Irrigation management to improve wine quality. BRL/Hardy Technical staff presentation, Berri, SA October 1996

Irrigation management to improve wine quality. BRL/Hardy growers information day, McLaren Vale SA, December 1996.

Irrigation management for quality fruit production. BRL Hardy Group Technical Conference, Marysville, Victoria. June 1997.

Innovation in water management. South Australian Farmers Federation Wine Grapes Section Annual General Meeting, Blanchetown, July 1997.

Growing Shiraz for quality and profit. 1997 Southcorp benchmark tasting and Shiraz seminar. Great Western, July 1997.

Best Practice Vineyard Management - Irrigation. Seminar presented to Charles Sturt University students, Wagga Wagga, July 1997

Irrigation Management - Scheduling for performance. VineTech. Cowra, NSW. August 1997.

Graduate education/training

Two seminars to post graduate students, Department of Horticulture, Viticulture & Oenology, Waite Campus, 1996, 1997.

7. References

Coombe, B. G. (1988). Grape Phenology. In: Viticulture. Volume 1. Resources in Australia, eds. Coombe, B. G. and Dry, P. R.:139-53. Adelaide: Australian Industrial Publishers.

Coombe, B. G. (1995). Adoption of a system for identifying grapevine growth stages. Aust. J. Grape & Wine Res. 1: 104-10.

Dry, P. R. and Smart, R. E. (1988). The grapegrowing regions of Australia. In: Viticulture. Volume 1. Resources in Australia, eds. Coombe, B. G. and Dry, P. R.:37-60. Adelaide: Australian Industrial Publishers.

Genstat. (1987). Genstat 5 Committee, Statistics Department, Rothamsted Experimental Station, England: Oxford University Press.

Greacen, E. L., ed. (1981). Soil water assessment by the neutron method. Melbourne, Australia: CSIRO Division of Soils.

Iland, P. G., Cynkar, W., Francis, I. L., Williams, P. J., and Coombe, B. G. (1996). Optimisation of methods for the determination of total and red-free glycosyl glucose (G-G) in black grapes of *Vitis vinifera*. Aust. J. Grape & Wine Res. 2: 171-8.

McCarthy, M. G. (1986). Influence of irrigation, crop thinning and canopy manipulation on composition and aroma of Riesling grapes. M. Ag. Sc. Thesis, University of Adelaide, Waite Agricultural Research Institute.

Price, S. F., Breen, P. J., Valladao, M., and Watson, B. T. (1995). Cluster sun exposure and quercetin in Pinot Noir grapes and wine. Am. J. Enol. Vitic. 46: 187-94.

Priestley, C. H. B. and Taylor, R. J. (1972). On the assessment of surface heat flux and evaporation using large scale parameters. Monthly weather review 100: 81-92.

Prior, L. D. and Grieve, A. M. (1987). Water use and irrigation requirements of grapevines. In: Proceedings of the Sixth Australian Wine Industry Technical Conference, ed. Lee, T. H.:165-8. Adelaide, S.A. 14-17 July 1986: Australian Industrial Publishers.

Somers, C. T. and Evans, M. E. (1977). Spectral evaluation of young red wines: anthocyanin equilibria, total phenolics, free and molecular SO_2, "chemical age". J. Sci. Fd. Agric. 28: 279-87.

Williams, P. J., Cynkar, W. , Francis, I. L., Gray, J. D., Iland, P. G., and Coombe, B. G. (1995). Quantification of glycosides in grapes, juices and wines through a determination of glycosyl glucose (G-G). J. Agric. Food Chem. 43: 121-8.