EFFECT OF TIMING OF WATER DEFICIT ON FRUIT DEVELOPMENT AND COMPOSITION OF VITIS VINIFERA cv. SHIRAZ

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List of Abbreviations

μ	micro
CS	susceptibility factor
CST	central summer daylight saving time
$dScm^{-1}$	deciseimens per centimetre
E	evaporation
E-L	Eichhorn and Lorenz
EC_e	electrical conductivity of the soil saturation extract
$EC_{irrigation\ water}$	electrical conductivity of irrigation water
EP_s	evapotranspiration of the planting square
ET_{crop}	crop evapotranspiration
ET_o	potential evapotranspiration
FVT	free volatile terpenes
g	gram
G-G	glycosyl-glucose
GDD	growing degree days
hr	hour
K^+	potassium ion
k_c	crop coefficient
kg	kilogram
kpa	kilopascal
L	litre
l.s.d.	least significiant difference
Lat.	latitude
Long.	longitude
LWP	leaf water potential
mg	milligram
$Mj.m^{-2}$	megajoules per square metre
$mol.m.^{-2}.s^{-1}$	moles per square metre per second
MPa	megapascal
NCR	neutron count ratio
nm	nanometres
$p<0.05$	probability less than 5 percent
PVT	potential volatile terpenes
RDI	regulated deficit irrigation
SD	stress day factor
T	transpiration
Trt	treatment
VSW	volumetric soil water content
weight-max.	maximum berry weight
WI	withholding irrigation

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SUMMARY

An irrigation experiment was established on Vitis vinifera cv. Shiraz in a mature vineyard in the Australian Murray-Darling basin, a region characterized by dry, warm to hot summers. The randomized block experiment comprised nine replicates of eight treatments, including an unirrigated treatment (rainfall only), a treatment so that no water stress occurred (fully irrigated), and six other treatments irrigated as in the fully irrigated treatment apart from specific periods without irrigation. Four of the six stress periods were each about 4 weeks in duration either after anthesis, before veraison, after veraison or before harvest. One treatment was water stressed for the entire period between anthesis and veraison and another for the period between veraison and harvest. Each of the 72 plots comprised 15 vines with measurements made on the middle three vines in each of four consecutive growing seasons. Soil water content at nine depths to 1.2 m was determined with a neutron probe three times a week in four replicates and a soil water release curve was used to convert soil water content to soil water tension. Soil water content was used to determine the timing and depth of irrigation for each treatment. An automatic weather station was installed in the middle of the experimental area. Irrigation water was applied by full-cover microjets installed during the growing season before the start of the experiment (prior to this the vines were irrigated using over-canopy sprinklers). The effect of water stress on vegetative growth, plant water stress, grape berry development, yield and its components, and crop water use were measured, in most cases weekly. In addition, components of berry composition were measured as berries ripened as was glycosyl-glucose (G-G) and anthocyanin concentration in the last two seasons. Red-free G-G was calculated from the difference in G-G and anthocyanin-glucose for each sample.

Significant findings were:

(a) Depending on the timing of the water deficit, the depth of irrigation applied ranged from approximately the same as fully irrigated to 240 mm less in one of the four seasons. The depth of water applied to fully irrigated vines during the growing season ranged from 550 to 602 mm. Growing season rainfall which ranged from 59 to 352 mm had a large influence on total water application and the water stress that resulted in each treatment. The daily change in soil water content varied from about 6 mm per day immediately after an irrigation to less than 1 mm per day when vines were water stressed. The average rootzone soil matric potential of fully irrigated vines was less negative than -30kpa while

withholding irrigation for extended periods resulted in soil matric potential more negative than -1.0 MPa and midday leaf water potential to -1.4 MPa. There were also significant effects on the diurnal pattern of leaf water potential and stomatal conductance. Water stress between anthesis and veraison restricted shoot growth; shoots were between 15 and 30 cm shorter than those of fully irrigated vines. The shoots of unirrigated vines were 30 to 40 cm shorter than those on fully irrigated vines and in the final year the weight of prunings removed from unirrigated vines was about 30 percent of the weight of fully irrigated vines. Surprisingly there was no effect of water deficit treatment on the date of budburst, percent budburst, fruitfulness, anthesis date or veraison.

(b) The normal double sigmoidal growth of berries was observed in all treatments in the three seasons that berry weight was determined from anthesis, however, there were significant treatment effects on berry weight. In the last year of the experiment water stress between anthesis and veraison reduced berry weight relative to fully irrigated by about 17 percent by the end of the stress period compared to about a 5 percent reduction in berry weight when irrigation was withheld between veraison and maturity. Withholding irrigation for about three weeks after anthesis in November 1994 resulted in a 30 percent reduction in berry weight by the end of the stress period compared to fully irrigated while withholding irrigation before veraison resulted in only about a 10 percent reduction in weight compared to fully irrigated. There was no compensatory increase in berry weight when normal irrigation was resumed in either of these treatments and berries were still lighter than fully irrigated at harvest. Withholding irrigation after veraison slowed the rate of berry weight increase and, in this case, re-application of water resulted in a compensatory increase in weight in some seasons. Water stress during the period before harvest had no effect on berry weight. The difference in berry weight between treatments was reflected in yield per vine. The reduction in berry size was correlated with average rootzone soil matric potential and a soil water stress index.

(c) Over the four years of the experiment maximum berry weight was attained between 88 and 94 days after anthesis after which berry weight declined steadily. Except for the severely water stressed vines the timing of the onset of the loss in weight was not affected by treatment. For all treatments for all seasons maximum berry weight occurred midway during ripening when total soluble solids were between 15 and 18 °Brix. The onset of the berry weight loss was more closely correlated to the number of days after anthesis than to

°Brix. Between maximum and final berry weight in each season there was about a 20 percent loss in berry weight; this was the same for all treatments. There was only a small increase in solutes per berry after maximum berry weight was reached. The results suggest that the loss in berry weight was due to the cessation of phloem water movement into berries which occurred in all treatments.

(d) The berries of water stressed vines ripened faster than fully irrigated vines with water stress before veraison having a greater hastening effect than stress after veraison. In three seasons the fruit of unirrigated vines ripened earlier than all other treatments. Growing degree days after anthesis were closely correlated to °Brix for fully irrigated vines and the polynomial equation that best described the relation between growing degree days and °Brix was similar to previous studies. The berries of fully irrigated vines reached 23.5 °Brix at 1280 GDD after anthesis in three of the four years. Between years there was a notable constancy of the interval from anthesis to 10 °Brix and from anthesis to 15 °Brix, for example, on fully irrigated vines the range was only 2 days while at 23.5 °Brix the range was 23 days. In contrast to other irrigation experiments, when compared at the same °Brix there was no effect of water stress on pH or titratable acid. The chloride concentration of homogenized berries increased between 0.02 and 0.04 mg per g fresh weight per week between veraison and harvest and the berries of unirrigated vines accumulated two to three times more chloride than fully irrigated. On average the berry chloride concentration during 1994-95 was about double that of the previous season.

(e) Although there were seasonal effects, there were only minor treatment effects on the pattern of development of G-G and colour when plotted against °Brix, either as a concentration per berry or an amount per berry. Curves were fitted using a logistic model and a sigmoidal curve best described the pattern of development of both G-G and colour with the rise in °Brix. There were some significant differences in the intercept, slope, asymptote or inflection point of fitted curves but a large standard error within each treatment masked many significant differences between treatments. When plotted for all treatments G-G and colour per berry were closely correlated in each year although in 1993-94 colour increased more rapidly with the increase in G-G per berry than in 1994-95. A two phase linear model was used to describe the change in red-free G-G with berry ripening. There was an initial period when red-free G-G decreased; thereafter it increased sharply. There were few significant differences between treatments in each year, again, due to a high standard error between treatments. Although the negative slope

representing the initial decline in red-free G-G was similar between seasons there was nearly a three-fold difference in the rate of accumulation of red-free G-G (per berry or per g berry weight) after the intersection of the two linear regression lines between seasons. At harvest in 1994-95, compared with 1993-94, berries had lower G-G and anthocyanin G-G but higher red-free G-G. The minimum point or intersection point appeared coincident with the number of days after anthesis and maximum berry weight.

STATEMENT

This thesis contains no material which has been accepted for an award of any degree or diploma in any University and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference is made in the text.

I give my consent to this copy of my thesis, when deposited in the University library, being available for loan and photocopying.

M. G. McCarthy

7 January, 1997

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Chapter One - General Introduction

1.1 Introduction

Most of the world's supply of the grapes used for winemaking comes from areas characterised by Mediterranean climates. In some of these areas grape yields are low, for example, Spain, with the largest planted area of grapes (*ca.* 1.4 m ha) is only the world's fourth largest in terms of tonnes produced (Tinlot and Rousseau, 1994) with an average yield of 3.3 t/ha. In contrast the average yield per hectare in the United States of America (California) is 16.8 t/ha and Australia, 15.0 t/bearing ha. This large difference from the yield in Spain is due for the most part to irrigation.

In unirrigated vineyards in Mediterranean climates, where winter rainfall predominates, vine growth is dependent upon stored soil water and, depending on the volume stored, vines may or may not suffer a water shortage at some stage of the growing season. Both Smart and Coombe (1983) and Williams and Matthews (1990) summarised the effects of water shortage on vine development and yield as well as physiological responses. Briefly, these responses are:

- severe water stress can affect vine phenology with earlier budburst and veraison but often maturity is delayed.
- pre-budburst water deficit can reduce budburst. Stress early in the annual growth cycle usually reduces the rate and duration of shoot elongation (with an accompanying earlier periderm development), reduces leaf size and decreases the number and length of laterals.
- rachis length, berry size, berry set, and yield are reduced. Depending on the timing of the deficit, bud fruitfulness may be affected although Williams and Matthews (1990) cited examples of positive and negative effects on fruitfulness.
- water stressed vines develop more negative midday leaf water potentials and stomatal conductance is reduced.
- although not well documented, soil water deficit influences root distribution.

High soil water status (but not sufficient to cause waterlogging), has the opposite effect on grapevine growth and yield. Consequently well irrigated vineyards characteristically have long thick shoots with many laterals, large bunch frameworks, more berries per bunch and larger berries. Midday leaf water potential will be more negative than pre-dawn levels (but less negative than water stressed plants) and recover faster in the late

afternoon. Although stomatal closure may still occur on days with high vapour pressure deficit, it will occur later in the afternoon.

Over-irrigation causes major long term damage to the environment such as pollution of underground basins, besides reducing yield. Extensive earthworks are often necessary to dispose of drainage water (Webber and Jones, 1992). As an example vineyards in the San Joaquin Valley of California may be receiving between 1.6 and 3.0 times more water than is necessary (Williams and Matthews, 1990). In some horticultural areas of the Murray-Darling Basin of Australia up to 50 percent, or about 450 mm per year of applied irrigation water, is lost below the plant rootzone (A.P. Meissner - pers. comm.). This drainage water not only results in the flow of saline water into the river system, thus increasing the salinity of irrigation water to downstream users, but also contributes to a rising water table which may eventually ascend into the rootzone. Irrigation efficiency (irrigation applied/irrigation requirement) is currently as low as 25 percent for some sections of irrigated agriculture (Wolff and Hübener, 1996). Improved irrigation efficiency will significantly reduce the detrimental effects of irrigation on the environment.

In irrigated viticulture, improvements in irrigation efficiency have resulted from the conversion of flood and furrow systems to drip and sprinkler systems. Excessive irrigation has been checked by the increased use of soil water monitoring devices such as the tensiometer, gypsum block and neutron probe to define soil water content and more closely match irrigation application to crop water use. Many of these developments in precision irrigation scheduling have been applied in countries such as Australia, Israel and South Africa, where irrigation water is of limited availability or of high salinity.

In the Murray-Darling basin irrigation area water has been applied throughout the vine growing season using a calendar based schedule and more recently by measurement of soil water content. Micro-irrigation systems and soil water monitoring devices are now widely used in vineyards. The ability to precisely control the timing and depth of irrigation water has led to the questioning of the accepted practice of applying water sufficient to meet plant requirement at every irrigation. It has been demonstrated for some other perennial horticultural crops that water can be withheld during growth stages that are less sensitive to water stress and this may also be the case for the vine.

Stone and pome fruit growers are now able to use irrigation to manipulate plant growth to improve yield and at the same time reduce irrigation application. Such

manipulation of fruit and shoot growth is possible because of the pattern of development of fruit and shoots (Figure 1.1). Flowering occurs before the emergence of leaves and shoots, and the cumulative fruit growth follows a double-sigmoidal curve. The rate of dry weight growth increases during the first phase, lessens during the second, and again increases in the third (last) phase. Chalmers et al. (1981) reported phase I, II and III to be 72, 28 and 59 days respectively however the duration of each phase was determined by locality and variety. Late season fruit had a longer phase II than early season fruit as depicted in Figure 1.1. More than 50 percent of the increase in fruit dry weight occurred during phase III and, for the variety 'Golden Queen', two-thirds of the increase in dry weight occurred during this last phase (Mitchell and Chalmers, 1982). The absence of competition between vegetative and fruit growth during the second phase, especially for late season fruit, was associated with a period of rapid shoot growth. They suggested therefore that careful irrigation management during this period should reduce vegetative growth with little effect on final fruit yield.

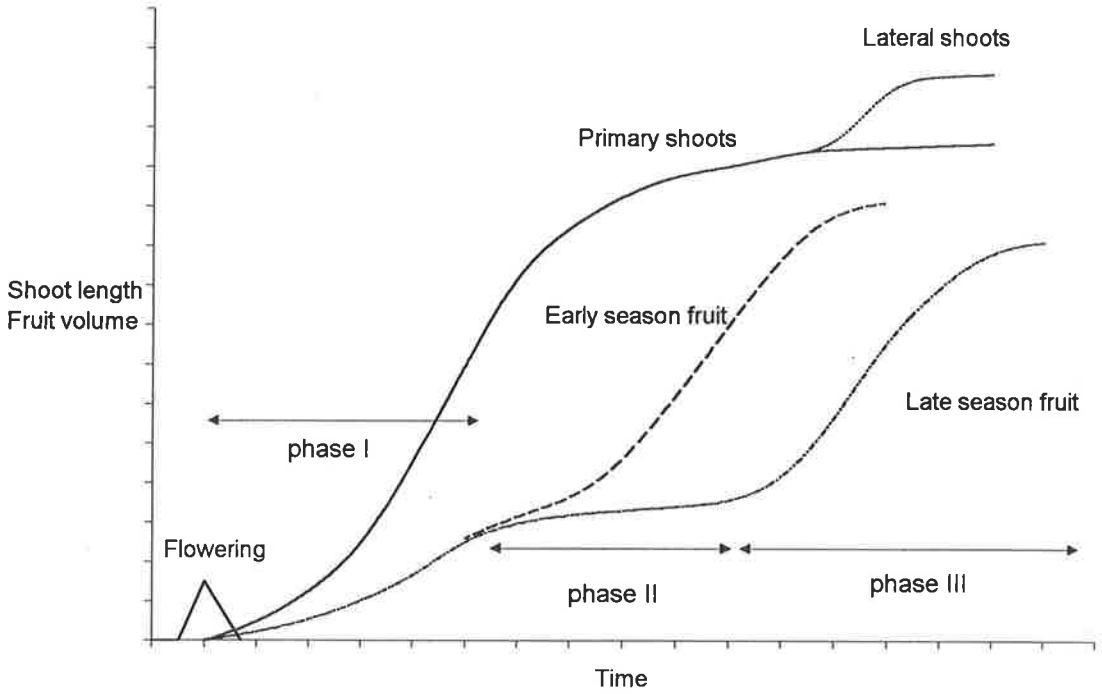

Figure 1.1 Schematic representation of shoot and fruit growth of stone fruit.

The application of less water during phase I or phase I and II (68 percent less than control in phase I, 52 percent less in phase II) did not reduce fruit weight, gross yield or canning yield per tree (Chalmers et al., 1981) in the first year of an irrigation experiment which also included different planting density of 'Golden Queen' peach. In the second year deficit irrigated trees had more fruit, although not significantly more than the well irrigated control, and this treatment resulted in higher yield per tree or per cm^2 trunk cross sectional area. Although reduced irrigation did not significantly restrict vegetative growth in each year, there was a significant cumulative effect over the three years of the experiment. Reduced irrigation coupled with high tree density amplified the effect on shoot growth and yield. The reduced irrigation regimes used by Chalmers et al. (1981) were based on withholding every second irrigation compared to fully irrigated which received daily applications of water. As no data were presented on changes in soil water content either at the start of each irrigation treatment or during the course of each deficit treatment it is unclear how rapidly soil water became limiting. In subsequent work (Mitchell and Chalmers, 1982) the irrigation regimes were defined as fraction of class A pan evaporation calculated for the area of the planting square (Ep_s) although, again little data were presented on soil water content. Reducing irrigation to 12.5 percent of the fully irrigated control during phase I and II, followed by replacement of 130 percent of Ep_s during phase III, led to significantly higher yield per tree as a result of higher fruit number per tree. The weight of summer prunings removed was significantly reduced.

The terms Regulated Deficit Irrigation (RDI), and Withholding Irrigation (WI) were adopted by Chalmers et al. (1981) and Mitchell and Chalmers (1982) to describe replacement of less than the full irrigation requirement of trees. Mitchell et al. (1986) and Mitchell at al.(1989) demonstrated that WI and RDI saved water, increased fruit yield and decreased the need for summer pruning of pear trees growing in the Goulburn Valley of Victoria. The term RDI in particular, is now widely used in perennial tree fruit horticulture, albeit sometimes incorrectly. In many reports on the use of RDI the degree of water stress imposed either as a fraction of ET_{crop} or as a soil matric potential is not defined. A clearer definition of RDI seems warranted as it could equally apply to any situation where less than the full irrigation requirement was applied.

Most of the RDI and WI experimental work cited above was on pear or peach trees grown primarily for processing (canning) and, as such, yield per tree of fruit above a specified size was the major consideration. For winegrapes, however, 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 to date has not been investigated.

In the grapevine, commencement of shoot growth precedes flowering and fruit development by about 8 weeks (Figure 1.2). Shoot development continues at a rapid rate during flowering and phase I of the double sigmoid pattern of berry growth and, except in high vigour sites, slows by the end of the lag phase (phase II).

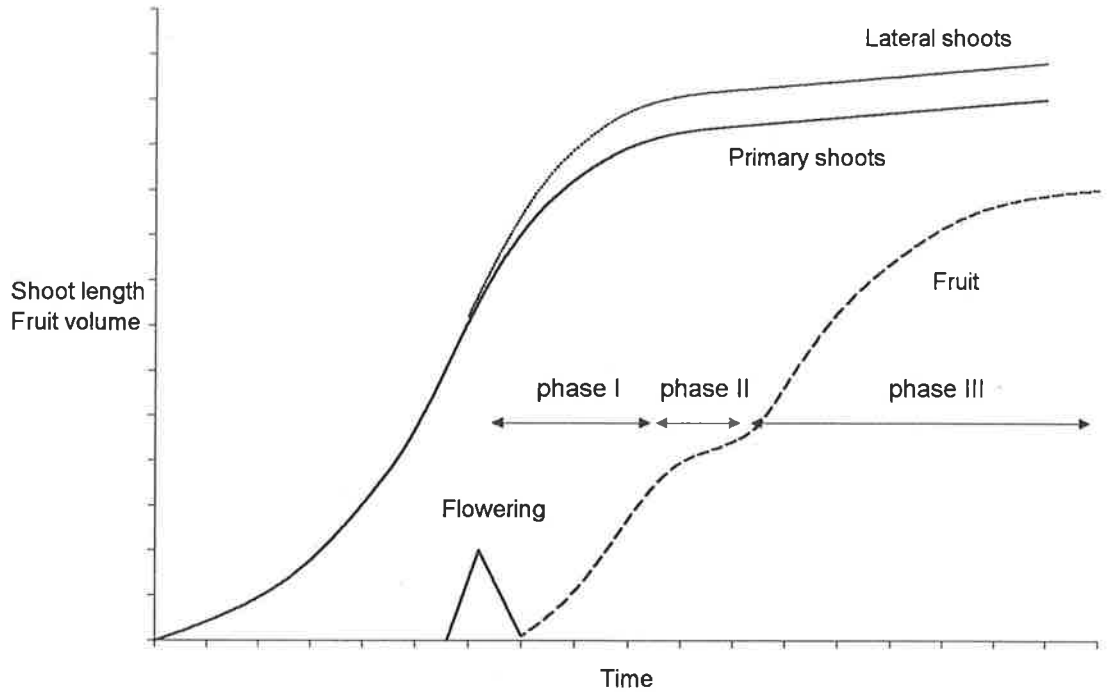

Figure 1.2 Schematic representation of shoot and fruit growth of the grapevine.

During the first 3 to 4 weeks after anthesis there is rapid cell division in the berry and some cell expansion (Coombe 1960, Harris et al., 1968). Thereafter cell enlargement accelerates and there is a rapid increase in the size of the berries. The berries remain firm and green. Water stress during the early stages of phase I can result in berry drop (Alexander 1965). There is a slowing in the rate of berry expansion in phase II. In Cabernet Franc approximately 75 percent of the final fruit size is established in phase I

(Matthews and Anderson, 1989), the remaining 25 percent being in the ripening phase (phase III). Phase II ends and phase III begins as the berries soften and expand and sugar accumulation commences.

During phase III of berry growth sugar accumulates, acidity decreases, the berry softens, skin colour develops and berries enlarge. The increase in berry size is the result of cell enlargement only. The rate of shoot elongation slows on vines that have high shoot vigour.

The duration of each phase of berry development in Vitis vinifera is determined by variety and locality. Phase I and III were of similar duration (40 and 36 days respectively) and phase II was 24 days for Concord (Nitsch et al., 1960). For a range of seeded and seedless varieties phase II spanned from imperceptible to about 30 days (Coombe, 1960) and for Cabernet Franc growing in drainage lysimeters in the hot climate of Mildura in the Australian Murray-Darling basin the duration was 14 days (Hardie and Considine, 1976). Coombe (1980) reported that for Muscat Gordo Blanco phase I spanned between 40 and 50 days, phase II, 20 to 30 days and between the first 40 and 55 days of phase III there was a linear increase in °Brix. Hardie and Considine (1976) suggested that as berries are relatively insensitive to water stress during phase II it may be possible to control vegetative growth during this period without reducing berry size. Coombe (1976) however commented on the difficulty in defining the boundaries between phase I and II and similarly between II and III and it may be for this reason that the effect of water stress during phase II has not been closely examined. However for varieties with a well defined or extended phase II water savings may be possible during this period without affecting yield. Control of vegetative growth to improve fruit exposure and reduce disease incidence in vigorous winegrape varieties is required before phase II as canopy development is nearly complete by this time. Water stress before flowering is seldom feasible except in hot dry environments or sites with shallow soil and, although vegetative growth can be controlled during this period by water deficit, such is not recommended as elongation of the bunch framework may be adversely affected. The use of water stress to control vegetative growth is consequently limited to the period after flowering but this conflicts with the need to minimise water stress on the developing berries.

A reduction in berry size may however improve wine quality. Smaller berries would result in a less compact bunch which would confer some additional disease resistance by

allowing more rapid drying by air movement around berries. A more open bunch framework would expose a higher percentage of each berry to sunlight and greater sunlight levels within and around the bunch would improve the colour concentration of red and black grapes (Smart, 1982). The higher skin to pulp ratio of small compared with large berries may also add to wine colour and possibly flavour although such wine may be higher in K^+ and chloride. Earlier ripening may be possible if a reduction in yield could be achieved without reducing the effective leaf area.

It was demonstrated more than 30 years ago that periods of water stress as short as four weeks can significantly reduce berry growth (Alexander, 1965). With the exception of the earlier work of Hardie and Considine (1976) with vines in small drainage lysimeters, there has been no attempt to examine the effects of shorter stress periods on vine growth and phenology in Australia. There are several recent reports of the use of early- or late-season, or pre- versus post-veraison water deficit on growth and ripening (Poni et al. 1993, 1994, Matthews et al. 1987, Matthews and Anderson 1989, Naor et al. 1993) but all of these investigations involved extended periods of water stress such as the entire period between veraison and harvest.

As pre-veraison berry growth involves both cell division and cell enlargement, both processes being sensitive to water stress (Alexander, 1965), a more detailed study of the effects of water stress during this period is warranted. Similarly, water stress at different times during the post veraison period has not been fully explored. There may also be times of differing susceptibility especially of sugar, colour, and secondary metabolite accumulation during berry ripening. This feature may be able to be used to improve wine quality.

The hypothesis to be tested in this experiment was therefore :

"That water deficit applied to fruiting grapevines influences fruit development and that the amount of the effect depends upon the timing of the deficit."

1.2 General experimental methods

1.2.1 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 environment is described as warm, with mean January temperature in the range 23 to 24.9 °C, growing season evaporation of about 1300 mm and an aridity index of about 510 mm (Dry and Smart 1988).

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 1.1. 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 1.1 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 source of cuttings to establish the vineyard is unknown. 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. During the winter before laying out the experiment the position of all vines within the area was mapped to ensure there were no missing vines in each plot. Vines were reasonably uniform.

1.2.2 Experimental design

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. The complete experimental area was 210 metres long and 60 metres wide. A plan of the experiment is included in the Appendix. The irrigation system was designed by Mr. D. Sparrow (irrigation engineer) who aimed to maximise the distribution uniformity of irrigation water in all plots. Each plot was irrigated with Plastro Tornado® Ray-jet full circle under-canopy sprinklers (68 L per hour) placed mid-way between adjacent vines. Irrigation water was supplied to each plot via polythene irrigation pipe (19, 25 or 32 mm diameter depending on plot location) laid on the surface on either side of the vine trunk line and connected to a buried pipe manifold (each 50 mm diameter) 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. Water application was controlled by a solar-powered irrigation controller and water supply pressure by a single pressure regulator.

1.2.3 Experimental treatments

Details of the experimental treatments are given in Table 1.1 and schematically presented in Figure 1.3. 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 1.2 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

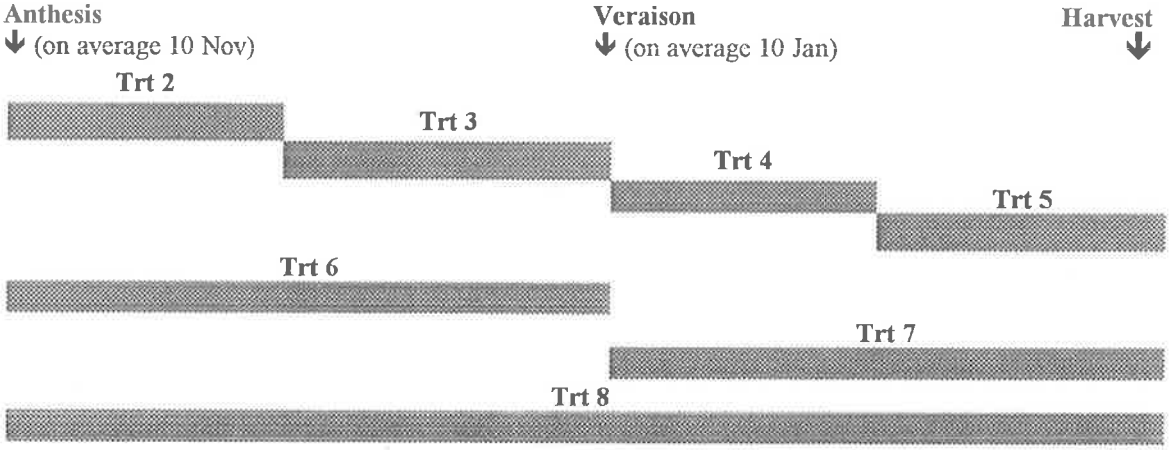

Figure 1.3 Schematic representation of the irrigation withholding periods (shaded) used in treatments 2 to 8. Treatment 1 was fully irrigated.

1.2.4 Pruning

It was decided to convert the "machine pruned" vines to hand spur pruned vines at the start of the experiment. The number of shoots per "machine pruned " vine in each plot was recorded before pruning in winter 1991 to indicate vine capacity. There were between 100 and 120 shoots per vine and it was decided therefore to use 120 buds as the upper limit to avoid masking any yield differences. Prior to adjusting the final spur number in 1992 all dead spurs and poorly positioned and weak spurs were removed. In winter 1992 and 1993 all vines were pruned to 60 two-bud spurs; this was reduced to 50 two-bud spurs in 1994 and 1995. The vine canopy of all treatments was allowed to grow naturally in each season and no shoot removal or trimming was carried out

1.2.5 Automatic weather station

An automatic weather station was installed to record weather conditions at the experimental site. Rainfall data was needed for the calculation of crop water use, and temperature and wind-run to calculate evaporation. Temperature and relative humidity sensors were placed in a standard weather shelter approximately 1m above the canopy (R. Smart - pers comm.) in the middle of the experimental block in November 1992. Output from the sensors was monitored every 15 minutes by a datalogger. A tipping bucket rainguage was later added in winter 1992 and global solar radiation (400-900 nm), wind speed, soil and canopy temperature sensors were added in January 1993. Prior to the installation of the weather station at the experimental site, data from an automatic weather station which is located in a vineyard 2 km to the north-east was used. Reference crop evapotranspiration (Eto) was estimated on a daily basis using average data by the method of Priestley & Taylor (1972) representing "the rate of evapotranspiration from an extensive surface of 8 to 15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water" (Doorenbos 1977). The evapotranspiration for every 15 minute period was calculated them summed for each 24 hour period.

1.2.6 Growing degree days

Growing degree days were calculated using the method of Williams et al. (1985 b). A database was used to subtract 10 °C (the minimum temperature threshold) from each 15 minute logger reading; if the result was positive this number was divided by 96 (15 minutes = 1/96 of a day), and then all 96 values were summed at the end of each twenty four hour period.

1.2.7 Statistical analyses

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. Time series data were analysed separately for each sampling time. The same computer program was used to fit linear regression models. Polynomial curves were fitted using the computer program PlotIt®. Additional details of the two-phase linear and logistic modelling techniques used for the analysis of data presented in Chapter Five are presented in 5.2.

1.3 Summary of weather 1991-1995

Based on average temperature for the months September to March (Table 1.3) 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 1.4) and solar radiation data (Table 1.5). The warmer conditions experienced during 1994-95 are also reflected in growing degree days (GDD) (Figure 1.4) which accumulated more rapidly from about 50 days after bud-burst. There was a near-linear increase in GDD after this time in 1991-92, 1992-93 and 1993-94. By 150 days after bud-burst about 240 more GDD had accumulated compared with the previous three seasons.

Table 1.3 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 1.4 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

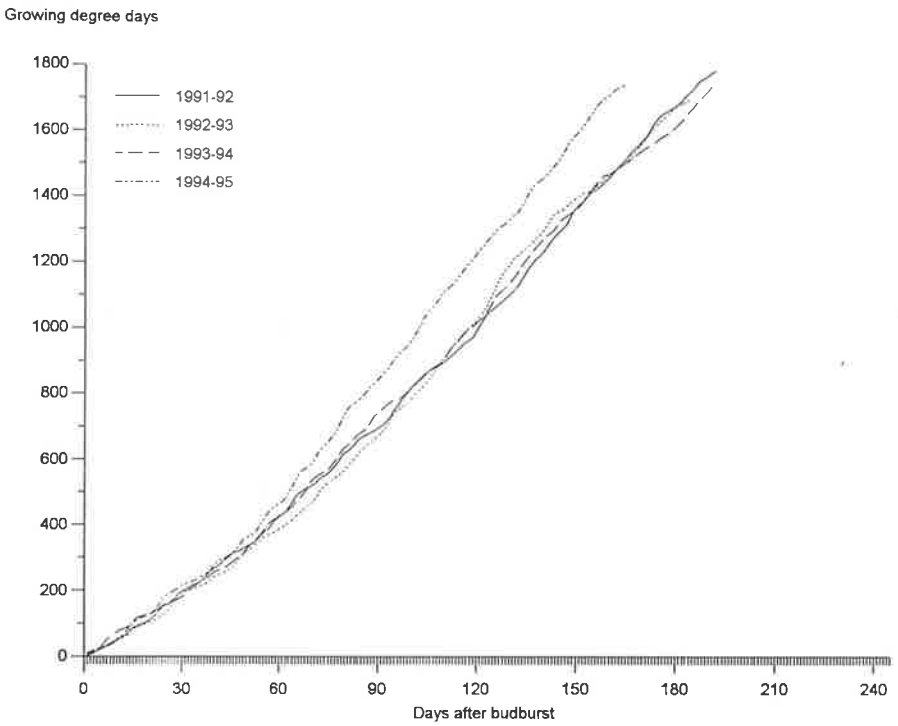

Figure 1.4 Cumulative growing degree days after budburst for four growing seasons.

Table 1.5 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	-

The 1992-93 growing season was by far the wettest of the three seasons (Table 1.6) 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 1.6 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

Chapter Two - Effect of timing of water deficit on soil water content and plant water use

2.1 Introduction

The rate of water use of deciduous crops ranges from low in spring after budburst, increases as the canopy develops to a period of high daily use until it falls again in autumn after the crop is removed and leaf fall begins. Efficient irrigation aims to match the volume of water applied to the daily or weekly vineyard water use. Vineyard water use or evapotranspiration (ET_{crop}) comprises evaporation from the soil surface (E) and plant water use (T) and consequently varies greatly between site, season and management practices. In semi-arid areas such as the Murray-Darling basin of Australia, Prior and Grieve (1987) estimated ET_{crop} to be between 700 and 800 mm and Williams and Grimes (1987) reported ET_{crop} to be about 800 mm for the San Joaquin Valley of California. Both of these areas are characterised by a potential evapotranspiration (ET_o) in excess of 1000 mm. Stevens and Cole (1987) applied on average 1342 mm irrigation water to a vineyard irrigated with micro-jets in the Murray-Darling basin although this included an amount for leaching with each irrigation. Application of 700-800 mm in semi-arid environments represents the quantity necessary to ensure maximum productivity. If ET_{crop} is restricted by reducing the quantity of water applied, yield will also decline. Grimes and Williams (1990) reported that yield was linearly related to ET_{crop} between replacement of 40 to 100 percent of ET_{crop}.

The most widely used method of determining vineyard irrigation requirement has been by ET_o, either measured or calculated by mathematical models from factors such as temperature, wind, humidity, solar radiation and others. ET_o is multiplied by the crop coefficient (k_c) to give an estimate of the daily, weekly or, most frequently, the monthly water requirement. K_c values have been derived for most agricultural crops in a range of environments, those most widely in use being those by Doorenbos & Pruitt (1977) although others have been derived. For example the crop coefficient of well irrigated Thompson Seedless grapevines grown in a lysimeter in the San Joaquin Valley of California varied from 0.15 shortly after budburst to 1.1 during mid-summer (Williams et al., 1993). Applying water at less than 0.6 of the rate of application to vines in the lysimeter (0.6 k_c) resulted in lower berry weight on non-lysimeter vines in the same plot. The k_c values derived by Williams et al. (1993) ensure there is no water stress at any time during the growing season resulting in maximum productivity. This may not be suitable for use in

vineyards where yield is to be restricted, for example, to ensure rapid sugar accumulation or to control vegetative growth for disease suppression. Because of the manner in which k_c is derived it is also site and crop specific although it serves as a general indication of the likely irrigation requirement in regions where no previous information is available. Van Zyl and Weber (1981) suggested that not only is the crop coefficient determined by soil, climate and crop but also the irrigation schedule. High frequency irrigation results in high surface evaporation when the soil is wet, especially in warm-hot climates, and hence a high crop coefficient. In this situation the use of k_c to schedule irrigation can result in unacceptably low water use efficiency. The use of k_c to schedule irrigations in regions with large fluctuations in weather conditions during the growing season will similarly result in low efficiency. The weather during spring and summer in southern Australia is dominated by the irregular passage of large anticyclonic high pressure systems that move from west to east. These high pressure systems can take between 7 and 10 days to move across the continent bringing hot to very hot conditions as winds turn northerly with the passage of the system. When it passes there follows a sudden and rapid drop in temperature as winds turn southerly with colder air from lower latitudes. In such climates unless k_c is calculated over short intervals, under- or over-irrigation will result and consequently measurement of soil water content to determine irrigation requirement is preferred. This method still results in over-application of water if significant rainfall occurs shortly after irrigation.

Vine water requirement is indirectly determined by measuring soil water content. A range of methods are used to measure or estimate soil water either as volumetric content or soil matric potential. Both measures are seldom reported together and some irrigation experiments report neither. Volumetric content is most widely used to quantify the effects of irrigation. The neutron scattering technique using what is often called the neutron probe has proved to be a reliable method as shown, for example, by the extensive irrigation experiments of Bravdo and co-workers in Israel (Bravdo et al. 1985, Hepner et al. 1985, Naor et al., 1993). An assumption made in the use of volumetric soil water content to quantify the degree of water stress is that water is equally available between Field Capacity and Wilting Point (Veihmeyer and Hendrickson 1927, 1955). The concept of equal availability of water at all levels between Field capacity and Wilting point has been questioned by many workers and there is increasing evidence that crop yield will be increased if irrigation is applied before the wilting point is reached. In coarse-textured soils most of the available water is held at low matric potential and the assumption of equal

availability may be valid, but in soils containing silt and clay fractions significant quantities of water are held at high matric potential and consequently may not be equally available. Soil matric potential can be measured with a tensiometer and an electrical resistance block (gypsum block) and these devices have been used in some irrigation experiments to quantify the effect of, or to schedule, irrigations (Goodwin and Macrae 1990, Klein 1983, and Stevens et al. 1995). Although the relationship between soil volumetric water content and soil matric potential for an individual soil can be described, specialist laboratory equipment such as a pressure membrane apparatus is needed and also an understanding of the hysteresis effect of soil wetting and drying (Haines, 1930).

Direct measurement of plant water status to determine irrigation requirement is not widely used either because of technical difficulties or of practical problems. Advances in monitoring xylem flow (sap flow) offer promise (Lascano et al., 1992) although this method is still to be widely adopted. Stem and leaf water potential measured with a Scholander pressure bomb is used experimentally, and although routine measurement of plant water status is not a practical method, especially pre-dawn when leaf water potential is the least negative, it permits extrapolation from one site to another (Matthews et al., 1987). As there is a correlation between pre-dawn leaf water potential and soil water content and soil water potential (Natali et al., 1985; Van Zyl, 1987) either of the latter may offer a practical alternative. The increased availability of equipment to continuously monitor soil water content and soil matric potential may offer a means of estimating pre-dawn leaf water potential by using soil water data automatically recorded before sunrise every day.

In fully irrigated vineyards water is applied in a regular sequence throughout the growing season in an attempt to minimise the effects of water stress at all stages. The actual timing and quantity of water applied is determined by guesswork and experience and/or soil water monitoring. The increased flexibility possible with micro-irrigation systems in both the quantity and timing of irrigations and the use of soil water monitoring devices has led to a questioning of the accepted practice of meeting the total crop water requirement at every irrigation. This may not be necessary and water savings, yet with the maintenance of yield, might be achieved with an appropriate strategy. Such a strategy was provided by the discovery of the effects of imposing water deficits at specific stages during the development of pome and stone fruit (Chalmers et al., 1981; Mitchell et al., 1989). These authors found that 'regulated deficit' and 'withholding irrigation' in peach and pear

orchards resulted in water savings of 26 and 27 percent respectively with no loss in yield per hectare, and often an increase. Stone and pome fruit growers use irrigation to manipulate plant growth, improve yield and save water using the concepts of regulated deficit irrigation (RDI) and withholding irrigation (WI) described in Chapter 1.1. In experiments with these techniques on the grapevine Matthews et al. (1987) on cv. Cabernet Franc achieved a 46 percent saving in water or 1.4 ML/ha (calculated from Matthews and Anderson, 1989) when water was withheld after veraison and a reduction in yield of 0.9 t/ha or an eight percent loss. While 'withholding irrigation' before veraison, achieved a water saving of 1.7 ML/ha, there was a 16 percent loss in yield of about 1.7 t/ha. The sensitivity of yield to water stress before veraison is evident from the 0.98 t/ha reduction in yield for each ML water saved compared with a reduction of 0.66 t/ha for each ML saved after veraison. In contrast, Goodwin and Jerie (1989) found that reducing the fraction of ET_o applied to drip irrigated Chardonnay vines between budburst and early berry growth resulted in a saving of 0.6 ML/ha with no adverse effect on growth and yield. This suggests that the timing of the RDI or WI period may be critical for the grapevine. To date this matter has not been fully investigated.

Given the increasing demand for available water, the rising cost of additional water, and the growing concern over the detrimental environmental effects of irrigated agriculture (Wolff and Hübener, 1996) it seems likely that strategies such as regulated deficit and withholding irrigation which result in similar or increased yield with less water would be rapidly adopted. With the exception of the previously quoted experimental results there has been no thorough field investigation of grapevine response to brief, phenologically-based periods of water stress at intervals during berry development. Acceptance of a new approach to vineyard irrigation will depend on the following factors: accurate definition of the timing of water stress, quantification of the likely water savings, and an indication that such a strategy will enhance wine quality without any undue reduction in yield.

In this Chapter data are presented on the fate of soil water and plant water use effects of an array of timed deficit treatments on field grapevines, in particular the timing and quantity of water applied in each irrigation treatment, the effect of each treatment on soil water content and soil matric potential and, the change in soil water content with evaporation and plant water use during the growing season. These data are integral to the

interpretation of the responses in vegetative and reproductive growth presented in subsequent Chapters.

2.2 Materials & Methods

2.2.1 Measurement of soil water content

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. Tubes were located in line with vine trunks, 1 m to one side or other of the middle vine in each plot. Adjacent micro-sprinklers were positioned to ensure no interference to water distribution around the access tube by either the vine trunk or trellis posts. Tubes were installed by boring a slightly undersized hole and knocking the tube in with a "dead-blow" mallet and a tightly fitting removable machined top-cap to prevent distortion of the top of the tube as it was knocked into the ground. Excess soil from inside the tube was removed with an under-size auger and then the inside of the tube cleaned with a cylindrical brush. Tubes were capped with a tight-fitting plastic cap to prevent water and other objects from falling into the tube between neutron probe readings. Additional access tubes were installed for later calibration of the neutron probe count and soil water content determined gravimetrically. A Campbell-Pacific DR 503 HydroProbe was used. It was calibrated prior to each day's readings in a 250L drum of water, the soil tube count being divided by the water drum count to give a count ratio. The water drum standard count for each day was calculated from 32 individual counts. To check for stability of the neutron source this count was statistically compared (Chi-squared) with the previous standard count. 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. A 16 second count (Greacen, 1981) was used. All data were processed using the Department of Agriculture computer program "IBIS" which calculated percent water at each measured depth from the count ratio, and estimated the total amount of water in the soil profile. These data were then processed by a standard computer graphing program.

The neutron probe was calibrated on several occasions during the 1991-92 growing season with the aim of assessing a wide range of soil water content. Neutron probe counts were taken in the standard manner (Greacen, 1981) and the average of three counts was used. Duplicate soil cores (250 cm^3) contained in brass rings 7.6 cm outside diameter were then collected at 10 cm intervals down the side of the tube to a depth of 120 cm. These were immediately sealed and weighed. Soil cores were oven-dried overnight (105 °C) and

weighed after cooling to room temperature. A linear regression of volumetric soil water content (VSW) against neutron probe count ratio (NCR) was derived using the Department of Agriculture computer program "Calstat". This program derives a separate regression equation for each depth interval and is able to combine regressions that are statistically similar. However, to ensure the greatest accuracy for this experiment separate regressions were used for each depth interval i.e. data of adjacent depths were not combined. The regression equation to relate NCR to VSW was:

$$NCR = a(VSW) + b$$

Where: NCR = neutron count ratio

VSW = volumetric soil water content (mm per cm)

a = slope of fitted line from linear regression

b = intercept (y axis) of fitted line

Table 2.1 details the regression constants used during the experiment

Table 2.1 Slope and intercept constants used to relate neutron probe count ratio to volumetric soil water (mm per cm).

Depth (cm)	Slope (a)		Intercept (b)		r^2
	estimate	standard error	estimate	standard error	
10	0.01975	0.00161	0.00672	0.0128	96.7
20	0.01816	0.00176	0.05219	0.0149	99.9
30	0.01595	0.00221	0.08955	0.0196	93.9
40	0.01683	0.00311	0.08115	0.0291	99.9
50	0.01851	0.00400	0.07329	0.0367	95.7
60	0.01609	0.00284	0.10073	0.0265	93.4
80	0.01599	0.00180	0.11768	0.0164	94.9
100	0.01599	0.00180	0.11768	0.0164	94.9
120	0.01599	0.00180	0.11768	0.0164	94.9

The volumetric water content at depths not measured with the neutron probe was estimated from the average of the two adjacent readings. The total volume of water in the 120 cm of soil profile was calculated by summing the actual and estimated water content at each 10 cm interval.

2.2.2 Capacitance soil water sensors

A set of capacitance soil water sensors was installed in a single plot of each treatment in November 1991 to provide additional data on soil water content both within the 120 cm depth assessed by the neutron probe and also at further depths down to 250 cm. Sensors were installed in accordance with the manufacturer's recommendations and were placed at 10, 30, 50, 80, 120, 150, 200 and 250 cm depths in a PVC access tube. Readings were taken at 15 minute intervals during each growing season and hourly during the rest of the year, however in the 1994/95 growing season hourly readings were taken. Sensors were calibrated in the same manner as the neutron probe. A single capacitance sensor connected to a logger was lowered in a pre-installed "wet" and "dry" tube and triplicate readings taken. Triplicate soil cores were collected at 10, 30, 50, 80 and 120 cm depths. The three brass rings (250 cm^3) were pushed into the soil around the outside of the tube such that the vertical centre of the 6 cm high ring was at the correct depth. The samples were immediately sealed and weighed. Soil cores were oven-dried overnight (105 °C), and reweighed after cooling to room temperature. A polynomial curve was derived using the computer program "PlotiT" to describe the relationship between capacitance sensor count and soil water content. The average daily soil water content at each sensor depth was calculated. Total soil water in the profile was calculated in a manner similar to that used for the neutron probe.

2.2.3 Soil moisture release curves

The water holding characteristics of the soil profile were determined on a set of 250 cm^3 intact soil cores collected in May 1993. 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 using a standard suction plate. Wilting point was taken to be the soil water content at -1.5 MPa. The data presented in Table 2.2 are the average of values at all depths. As no satisfactory mathematical function could be derived to describe the relationship between soil water content and soil matric potential between 0 and -1.5 MPa estimates of soil matric potential at one percent (0.1 percent at the inflection point) intervals were derived by interpolation from hand-drawn curves for each depth. Soil water content measured by the neutron probe at each depth was converted to soil matric potential using the values derived from the most appropriate soil moisture release curve and the soil matric potential at other depths estimated by interpolation. The average soil matric potential for

the total 120 cm depth was calculated.

Table 2.2 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

2.2.4 Daily soil water content and crop coefficient

In the 1994-95 season, the daily total soil water content to 120 cm depth for each treatment was calculated. To allow for soil water drainage after irrigation, neutron probe readings taken less than twenty four hours after an irrigation or a significant rainfall event were not included. A standard 'full-point' soil water content was used when neutron probe readings were not taken after this one-day period, e.g. an irrigation on a Friday of a three-day 'weekend' and no readings taken until the following Tuesday or during the Christmas-New Year holidays when readings were less frequent. As neutron probe readings were taken at about the same time every second or third day for the majority of the growing season the soil water content for in-between days was estimated by linear interpolation.

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. Because daily evapotranspiration was calculated as the sum to midnight and daily change in soil water content calculated as the sum to midday, there is some error associated with the daily crop coefficient, especially when there was significant change in weather conditions overnight. The automatic weather station measured rainfall as it occurred and calculated evapotranspiration for each preceding 15 minute interval. Consequently there was not the complication that arises with manual recordings at 0900 hr for rainfall and evaporation which represents the previous 24 hours from a normal 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.

2.3 Results

2.3.1 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) or an average rootzone soil matric potential of about -50kpa.

By year two of the experiment neutron probe data were processed on the same afternoon that readings were taken. If any treatment required irrigation the volume of water to apply was programmed into the irrigation controller the following morning, and the irrigation started. In each year an irrigation was applied to all irrigated treatments prior to budburst and irrigations continued after harvest until leaf fall. The total depth of all irrigations applied and rainfall between budburst and harvest for all treatments are summarised in Table 2.3 and the dates and depth of irrigation water applied for all treatments are indicated in Figures 2.1 to 2.4.

The total amount (depth) of irrigation water applied was always highest on fully irrigated vines but there was a difference of nearly 200 mm between the 1993-94 and 1994-95 season (Table 2.3); total growing season crop water use (irrigation + rainfall) for irrigated vines ranged from 574 mm in 1993-94 to 732 mm in 1994-95. Of the irrigated treatments (Trts 1-7) the largest difference in the volume of water applied was 239 mm between fully irrigated (Trt 1) and anthesis-veraison deficit vines (Trt 6) in 1994-95. The smallest difference was 9 mm between the fully irrigated and pre-veraison deficit treatment in 1991-92.

Table 2.3 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

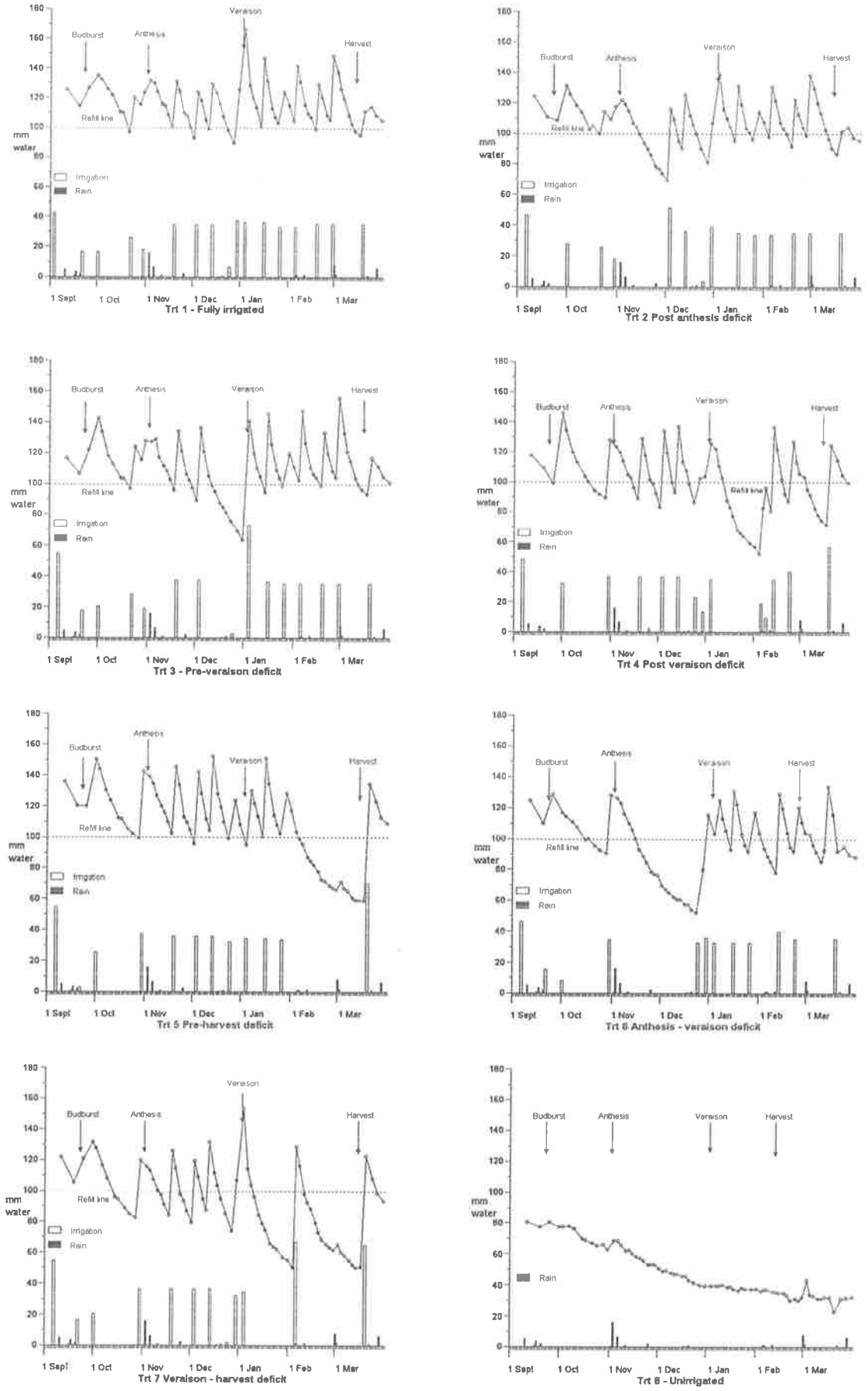

Figure 2.1 Depth of irrigation water applied, rainfall and soil water content of 120 cm soil depth against date for all treatments for the 1991-92 season.
Depth of irrigation water applied □ (mm), rainfall ■ (mm) and soil water O (mm).

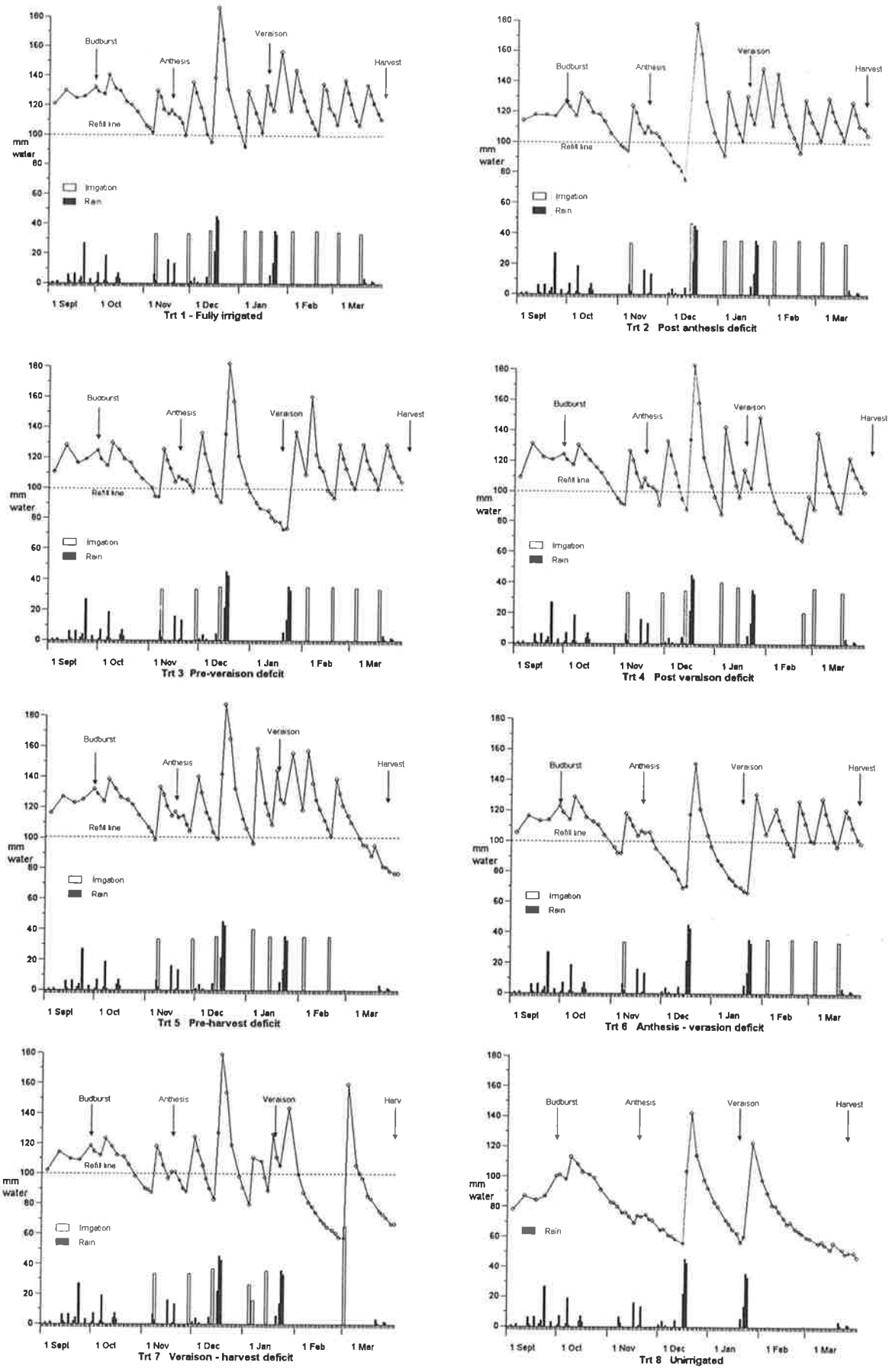

Figure 2.2 Depth of irrigation water applied, rainfall and soil water content of 120 cm soil depth against date for all treatments for the 1992-93 season.
Depth of irrigation water applied □ (mm), rainfall ■ (mm) and soil water O (mm).

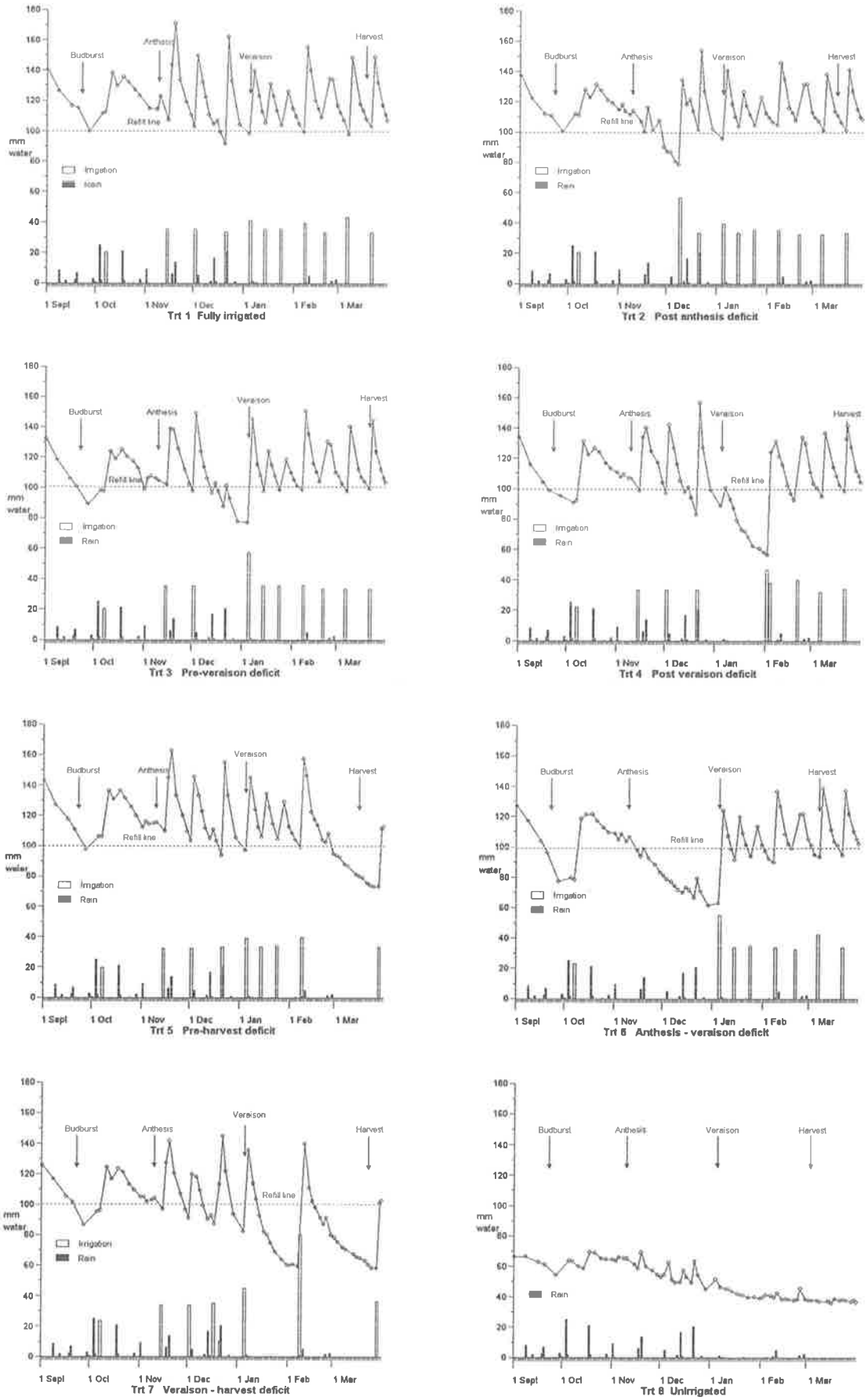

Figure 2.3 Depth of irrigation water applied, rainfall and soil water content of 120 cm soil depth against date for all treatments for the 1993-94 season.
Depth of irrigation water applied □ (mm), rainfall ■ (mm) and soil water O (mm).

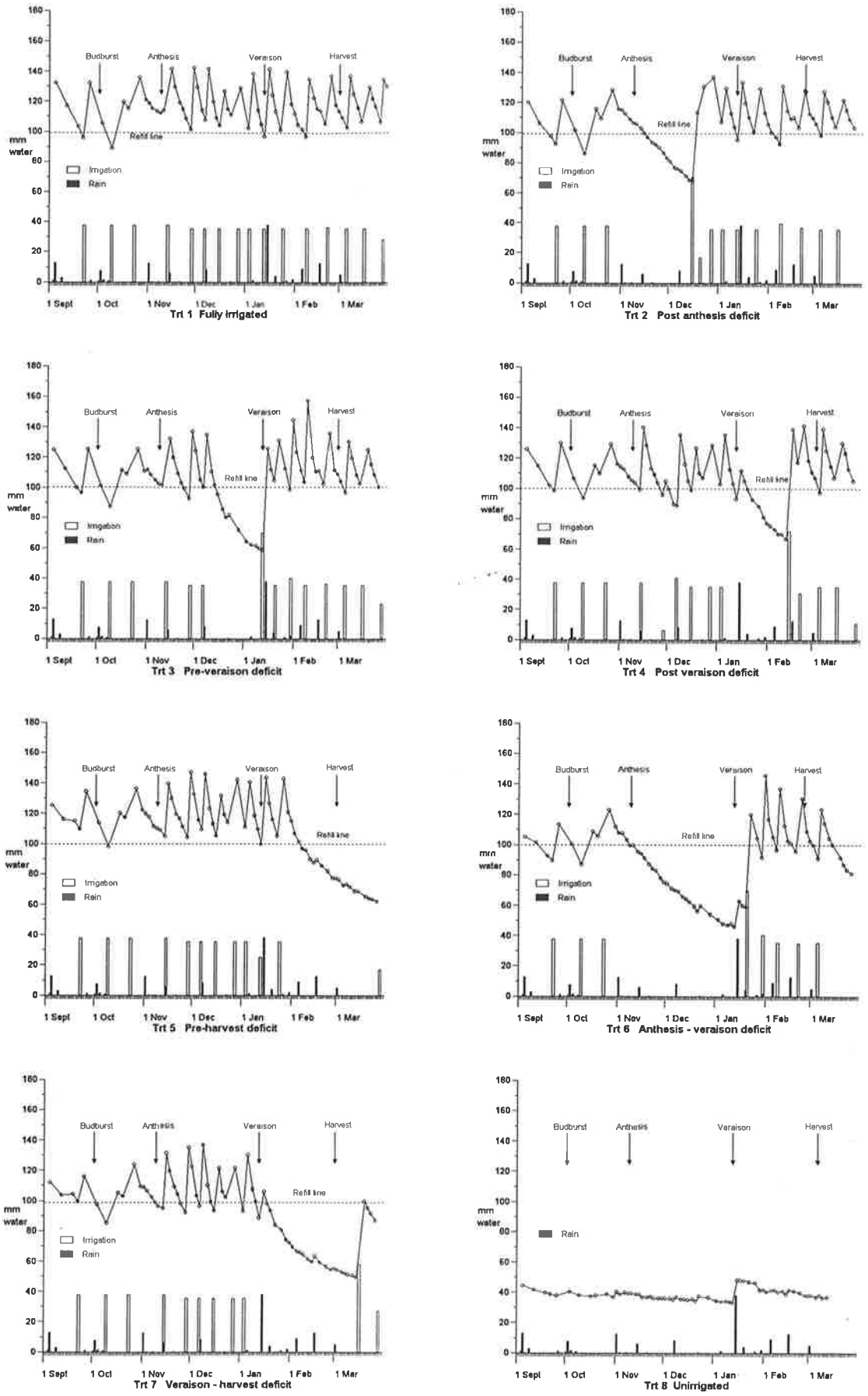

Figure 2.4 Depth of irrigation water applied, rainfall and soil water content of 120 cm soil depth against date for all treatments for the 1994-95 season.
Depth of irrigation water applied □ (mm), rainfall ■ (mm) and soil water O (mm).

2.3.2 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 2.5). 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. From the linear regression equation fitted (r^2 =0.88) there was a daily decline in the crop coefficient (k_c) of about 0.04 per day. 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.

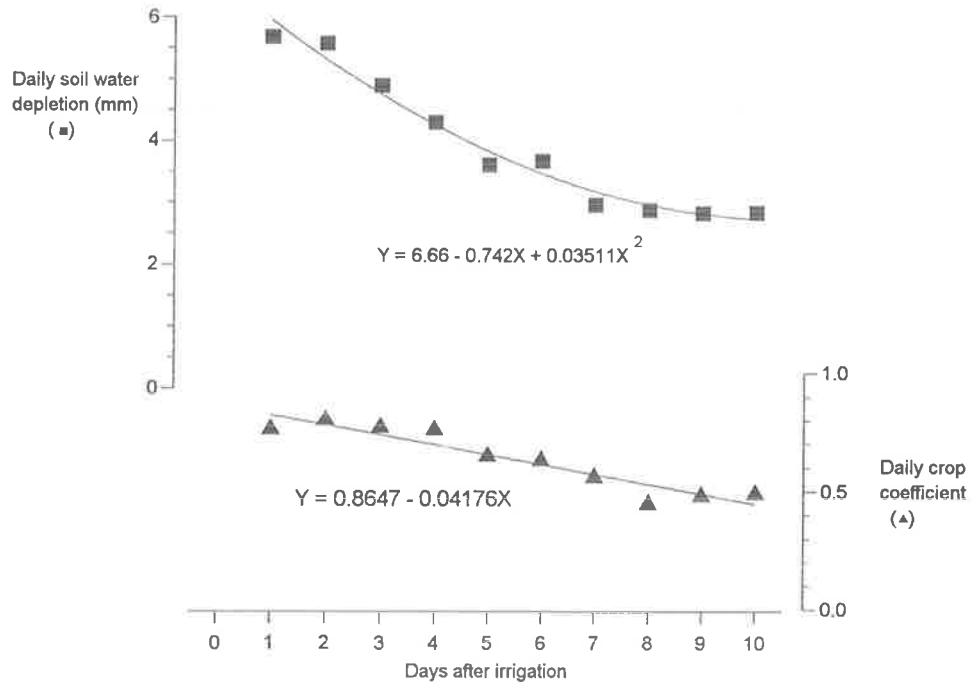

Figure 2.5 Average daily soil water content and daily crop coefficient of fully irrigated plots for the first ten days after irrigation between anthesis and harvest in 1994-95. One day discounted for drainage after each irrigation.

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 2.6). 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. The day-to-day variation in water use appeared to be the result of weather conditions with lower daily rates occurring during cooler days and then increasing as periods of hot weather were encountered. This pattern was repeated from about 10 days after irrigation to the end of the stress period. A similar, but less marked pattern was observed for daily k_c .

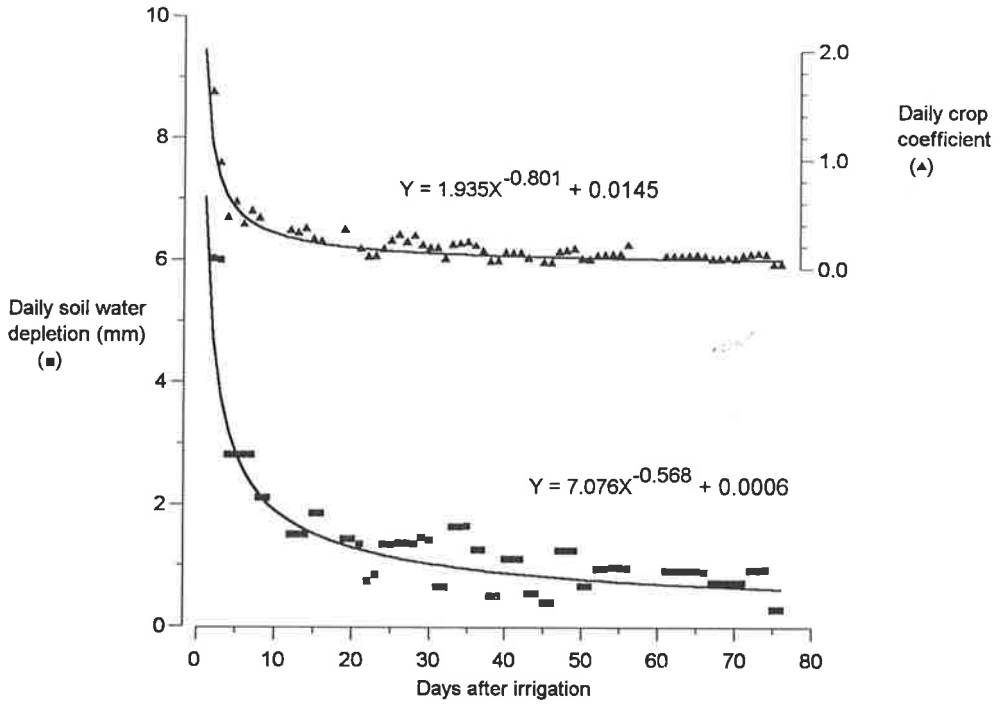

Figure 2.6 Daily soil water content and crop coefficient of anthesis-veraison deficit treatment (Trt 6) in 1994-95.
Data points represent actual and calculated daily values and the fitted curve (between day 1 and 76 days after irrigation) is from the appropriate exponential equation.
Y = k_c or daily soil water depletion, X = days after irrigation.

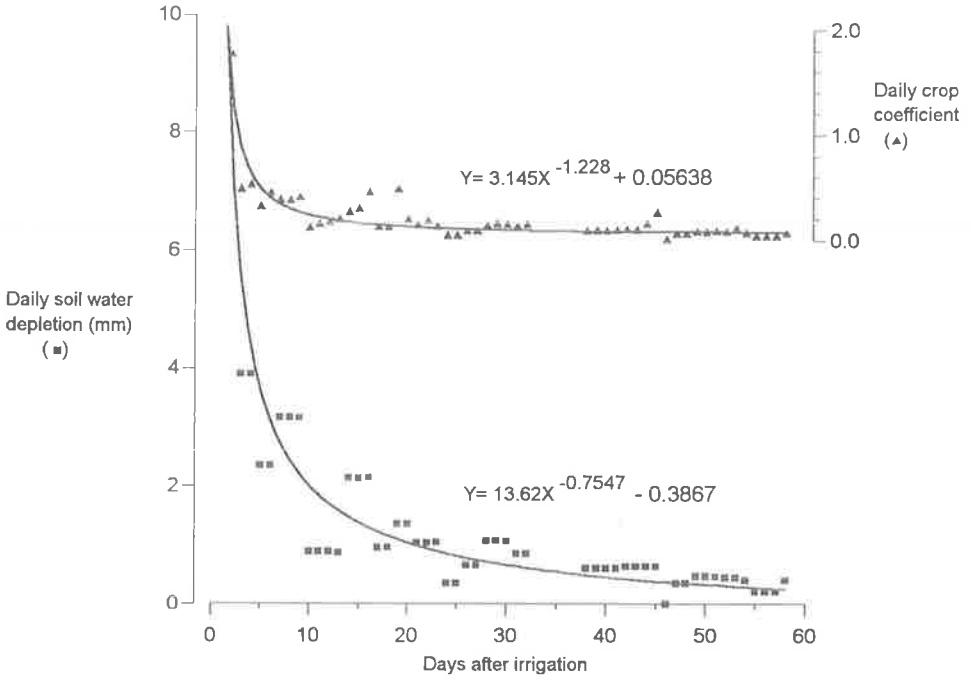

Figure 2.7 Daily soil water content and crop coefficient of veraison-harvest deficit treatment (Trt 7) in 1994-95.
Data points represent actual and calculated daily values and the fitted curve (between day 1 and 58 days after irrigation) is from the appropriate exponential equation.
Y = k_c or daily soil water depletion, X = days after irrigation.

There was about a sixty-day period between irrigations for the veraison-harvest deficit treatment (Trt 7) in 1994-95 (Figure 2.7). Although the pattern of change in soil water content was similar to that for anthesis-veraison deficit plots (Trt 6), the daily rate of water use for veraison-harvest deficit plots (Trt 7) was greater than the anthesis-veraison plots by about day 10. At the end of the stress period the daily rate of water use of veraison-harvest deficit plots was about half that of anthesis-veraison plots after a similar number of days. There were only minor differences in the daily k_c values of these two treatments.

Fully irrigated vines extracted water nearly equally to 100 cm depth when averaged for all irrigation cycles between anthesis and maturity (Figure 2.8). 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.

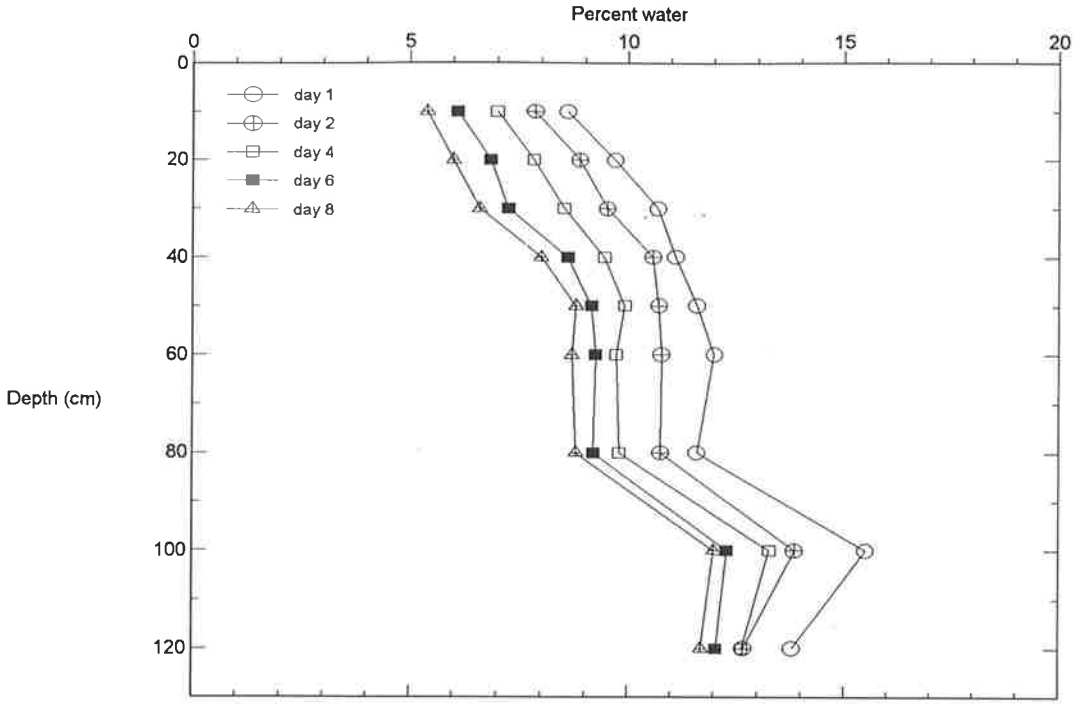

Figure 2.8 Percent soil water with soil depth on specified days after irrigation for fully irrigated treatment (Trt 1) between anthesis and maturity in 1994-95.

There was a much larger change in percent soil water between irrigations when water was withheld for more than 80 days during the anthesis-veraison period (Trt 6) in November-December 1994 (Figure 2.9) compared with the 10 days between Trt 1 irrigations . There was a large volume of soil water extracted at all depths between days 2 and 9 and during the last 30 days of the deficit period. Between days 2 and 81 the soil water content decreased by between 4.5 and 7 percent with a greater decline in soil water content in the deeper zones than closer to the soil surface. Inaccuracy of the neutron probe at very low water content probably accounts for the small increase in soil water content at 10 cm depth between day 51 and 81 as no rain was recorded during this period. The water content of the whole of the 120 cm soil profile was much lower after 81 days of withholding irrigation than after only eight days in the fully irrigated plots with most of the profile probably at or near to wilting point. Comparison of data in Table 2.2 and Figure 2.9 indicates that the 10 cm depth may have been below wilting point by day 30, the 20 and 30 cm depth by day 39 and the 40, 50, 60 and 80 cm depths by day 81.

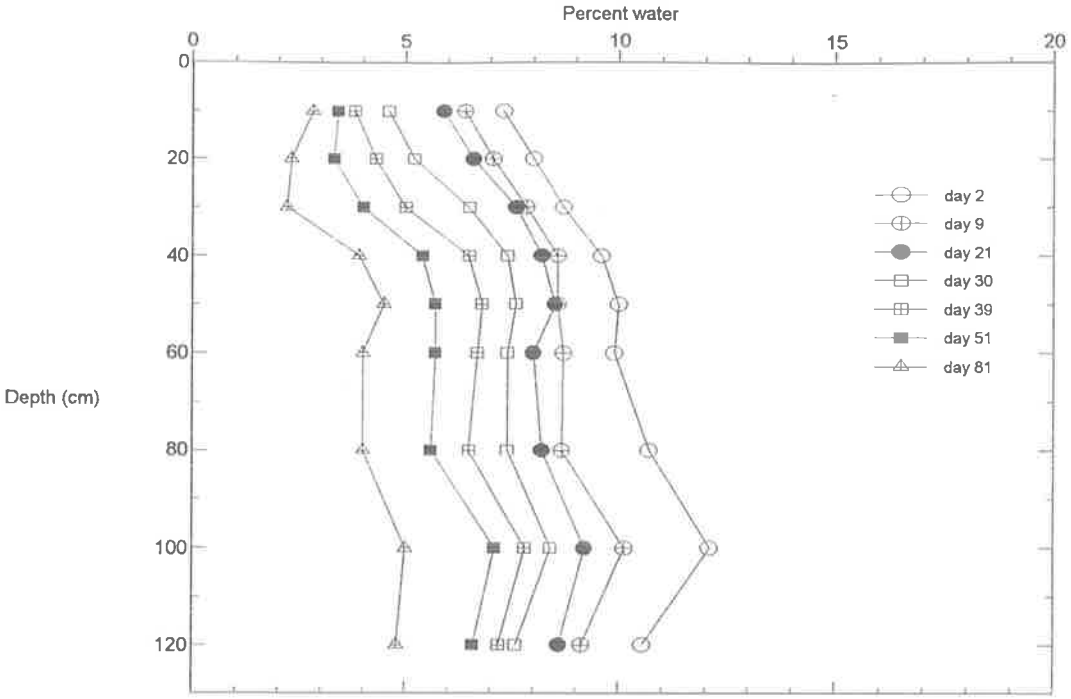

Figure 2.9 Percent soil water with soil depth on specified days after irrigation for anthesis-veraison deficit treatment (Trt 6) during November-December 1994.

2.3.3 Soil matric potential

Data on the change in soil matric potential are presented only for the 1993-94 and 1994-95 seasons as these best highlight the differences in soil matric potential during the anthesis-veraison period.

The sandy soil of the experimental site was free draining with most of the plant available water held at soil matric potential less negative than -50 kpa with only a small change in soil water content between -0.1 and -1.5 MPa. This resulted in the soil matric potential rapidly becoming more negative as the soil profile dried during each deficit period and consequently the development of highly negative soil matric potential towards the end of each stress period, in particular in 1994-95 (Figures 2.10 and 2.11). With the exception of two occurrences before anthesis in the 1994-95 growing season the average rootzone soil matric potential of fully irrigated plots for both seasons was less negative than -30 kpa. There were brief occurrences of soil matric potential as negative as about -0.2 MPa but these were primarily due to the rapid drying of the upper 10 cm layer. During the 1993-94 season average soil matric potential of the post anthesis (Trt 2) and pre-veraison deficit (Trt 3) treatments were less negative than about -0.45 and -0.55 MPa respectively and for the combined anthesis-veraison deficit treatment (Trt 6) soil matric potential between -1.3 and -1.4 MPa was reached. Irrigation resulted in average soil matric potential becoming rapidly less negative to about -10 kpa. The effect of a single irrigation applied to the veraison-harvest deficit treatment (Trt 7) in early February 1994 was transient (Figure 2.11) with average soil matric potential becoming more negative during the following weeks.

Although there were some fluctuations in 1994-95, soil matric potential became more negative by about 40 kpa per day during the approximate 30 day stress period for the post anthesis deficit treatment (Trt 2). Depending on the duration of the deficit there were periods of soil matric potential which indicated severe water stress, for example, towards the end of the anthesis-veraison (Trt 6) and veraison-harvest (Trt 7) stress periods. For both treatments there was a steady, near-linear change in soil matric potential from -1.1 to -1.2 MPa and then a slowing in the rate of change to -1.5 MPa. Data presented in Figures 2.10 and 2.11 indicate more negative average soil matric potential was achieved in 1994-95 than 1993-94 and there were also longer periods of severe water stress in 1994-95.

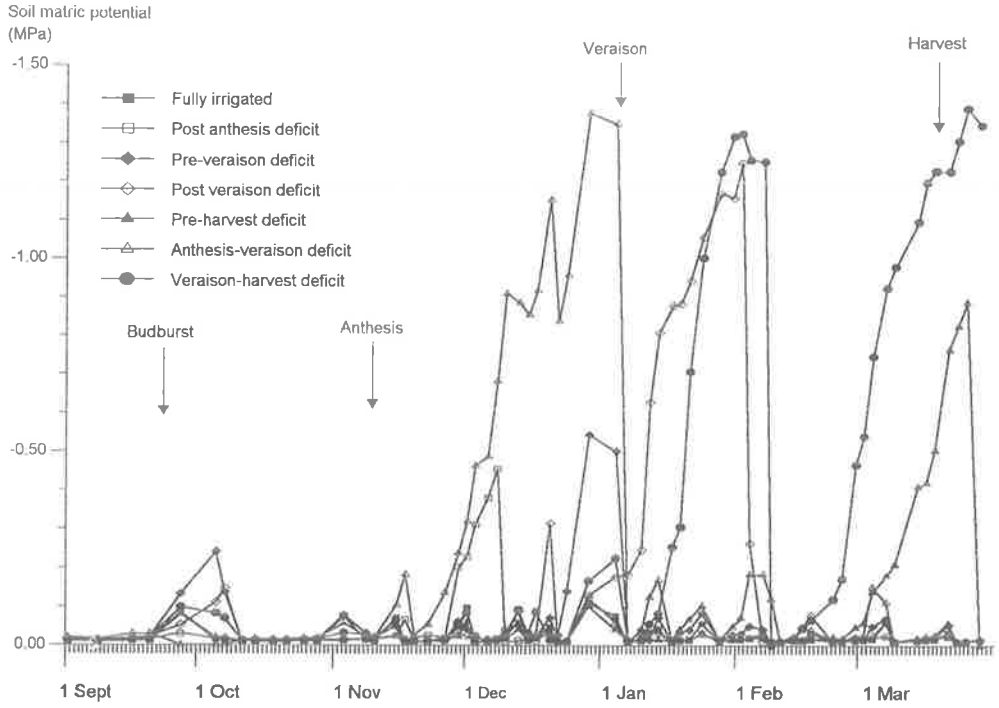

Figure 2.10 Calculated average soil matric potential (MPa) for 120 cm soil depth for treatments 1-7 for the 1993-94 growing season.
Note inverted scale on y axis. Values derived from neutron probe readings (Figure 2.3) and soil water release data (Table 2.2).

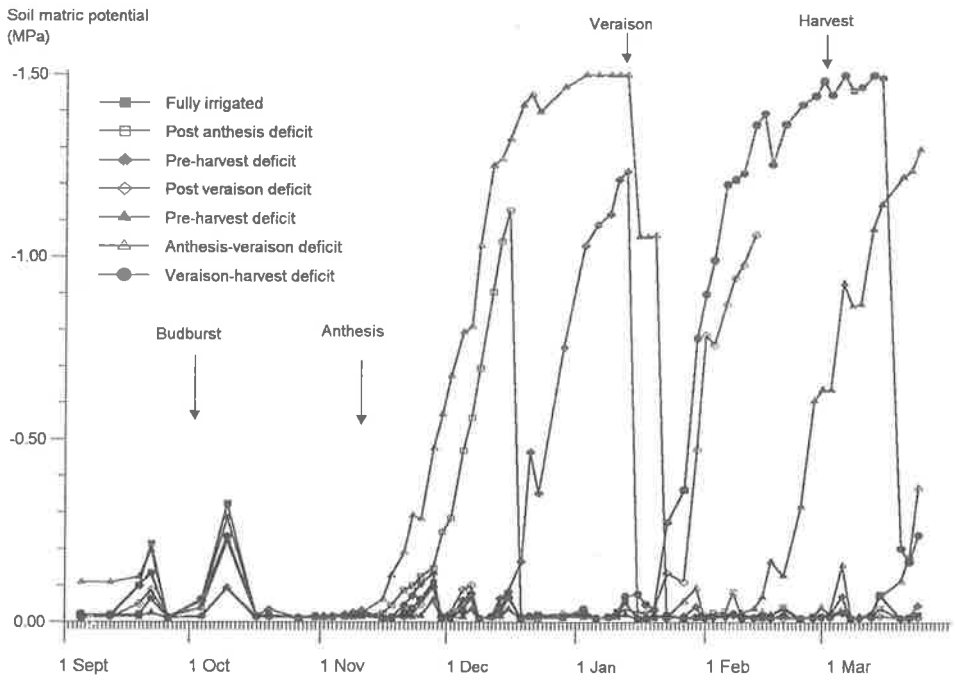

Figure 2.11 Calculated average soil matric potential (MPa) for 120 cm soil depth for treatments 1-7 for the 1994-95 growing season.
Note inverted scale on y axis. Values derived from neutron probe readings (Figure 2.4) and soil water release data (Table 2.2).

2.3.4 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 2.4). 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 2.6).

Table 2.4 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

2.3.5 Soil water deficit index

A soil water deficit index (Figures 2.12 to 2.15) 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. The pattern of water extraction through the profile suggested uniform root distribution and no attempt was made to weight the index based on root distribution as reported by Stevens et al. (1995). These authors also used soil matric potential rather than soil water content as reported here. 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.

The effect of the unseasonal rainfall during the 1992-93 season is clearly evident with both low cumulative deficits (Figure 2.13) and periods of minimal deficit such as for the anthesis-veraison deficit treatment (< 500 mm). In comparison the same treatment in 1994-95 (Figure 2.15) developed the highest deficit index of about 2,300 mm over the four years, 1,270 mm in 1991-92 (Figure 2.12) and about 1,160 mm in November-December 1993 (Figure 2.14). With the exception of the 1994-95 season only low to moderate deficit was achieved in the post anthesis treatment and although higher deficit indices were developed on the pre-veraison treatment in years one to three they were less than half that achieved during December 1994 with nearly 800 mm. A moderate deficit index was attained with post veraison deficit vines in all years with the greatest deficit in January-February 1992. The total deficit attained in the pre-harvest deficit treatment was determined by harvest date, for example, 1995 fruit ripened rapidly and the deficit period only lasted for about 20 days during which 290 mm accumulated. In 1992, approximately 820 mm deficit accumulated over about 33 days for the same treatment. Irrigation or rain resulted in a two-stage development of deficit for veraison-harvest deficit vines for years one to three; in January-February 1995, when no irrigation was applied, about 1300 mm accumulated. The cumulative soil water deficit index enabled a comparison of the effectiveness of all the treatments over the four years and highlighted those periods when high cumulative soil water deficit developed (Table 2.5).

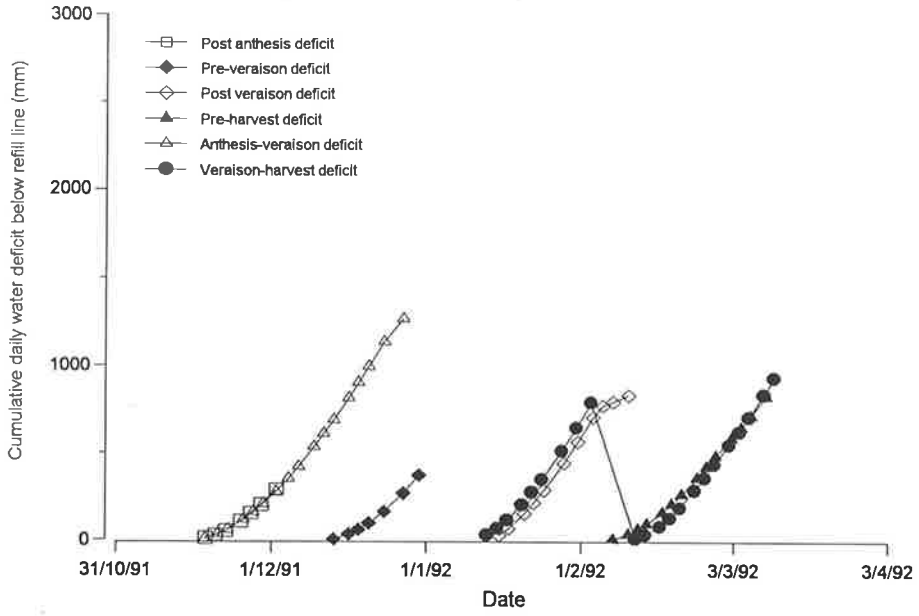

Figure 2.12 Cumulative daily deficit below irrigation refill line for 6 treatments for the 1991-92 season.

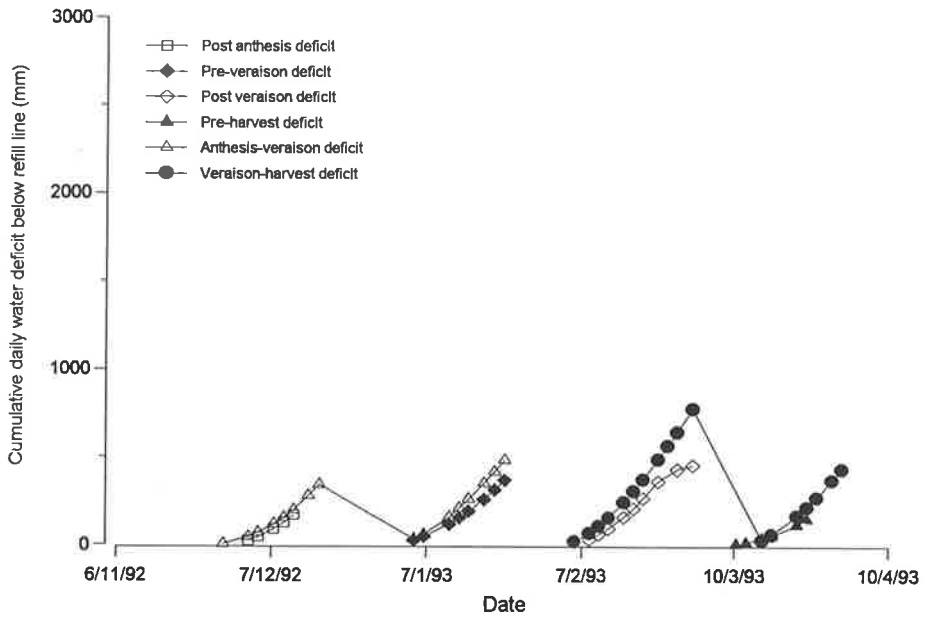

Figure 2.13 Cumulative daily deficit below irrigation refill line for 6 treatments for the 1992-93 season.

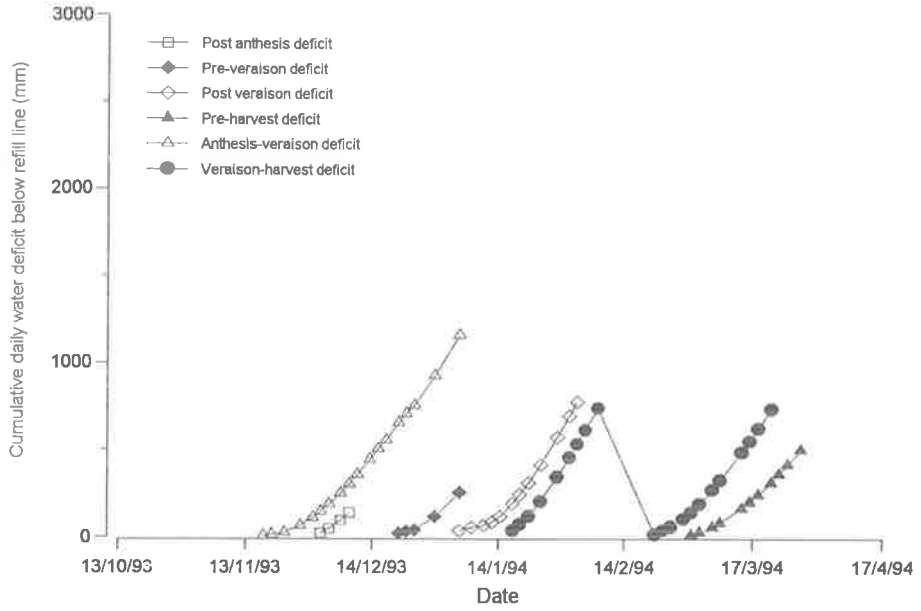

Figure 2.14 Cumulative daily deficit below irrigation refill line for 6 treatments for the 1993-94 season.

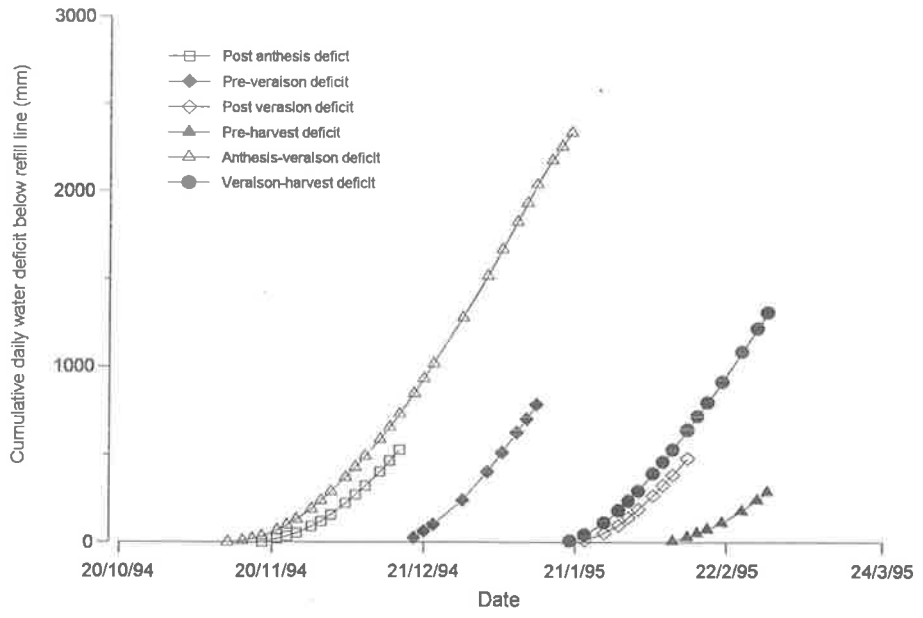

Figure 2.15 Cumulative daily deficit below irrigation refill line for 6 treatments for the 1994-95 season.

Table 2.5 Period of maximum cumulative water deficit development selected from four years.

Treatment	Period of maximum cumulative water deficit accumulation
Post anthesis deficit	November-December 1994
Pre-veraison deficit	December 1994-January 1995
Post veraison deficit	January-February 1992
Pre-harvest deficit	February-March 1992
Anthesis-veraison deficit	November-December 1994
Veraison-harvest deficit	January-February 1995

2.3.6 Capacitance soil water sensors

The accuracy of capacitance soil water sensors has been questioned by Evett et al. (1995) and thus the results presented in this section are subject to some uncertainty. There appeared to be differences in the sensitivity of individual sensors used in the experiment reported here to changes in soil water content and this difference was not always consistent. The sensors installed in the anthesis-veraison deficit treatment (Trt 6) were the most reliable and it was possible to monitor changes in soil water content during periods that irrigations were regularly applied or withheld during the anthesis-veraison period.

The sensors detected changes in soil water content after each irrigation applied to Trt 6 plots prior to the start of the stress period in November 1994 (Figure 2.16). There appeared to be a small increase in percent soil water at the deeper layers during this time i.e. at 150, 200 and 250 cm. The percent water readings at each depth immediately after an irrigation were not comparable with water content at other depths, for example, soil water content at 120 cm depth peaked at about 14 percent compared with a maximum of nine percent at 150 cm depth and 11 percent at 200 cm depth. During the approximately 80 days that irrigation was withheld there was a decrease in soil water content at each measured depth except at 250 cm where there was a small increase. The greatest change in percent water content was about a six percent decrease at 120 cm while the decrease at 150 cm was only about two percent and at 200 cm, three percent. Only the sensor at 10 cm depth recorded a change in water content after 38 mm rain on 14 January 1995 (see Fig. 2.4, Trt 6) and it was not until a 70 mm irrigation was applied on 21 January that there was

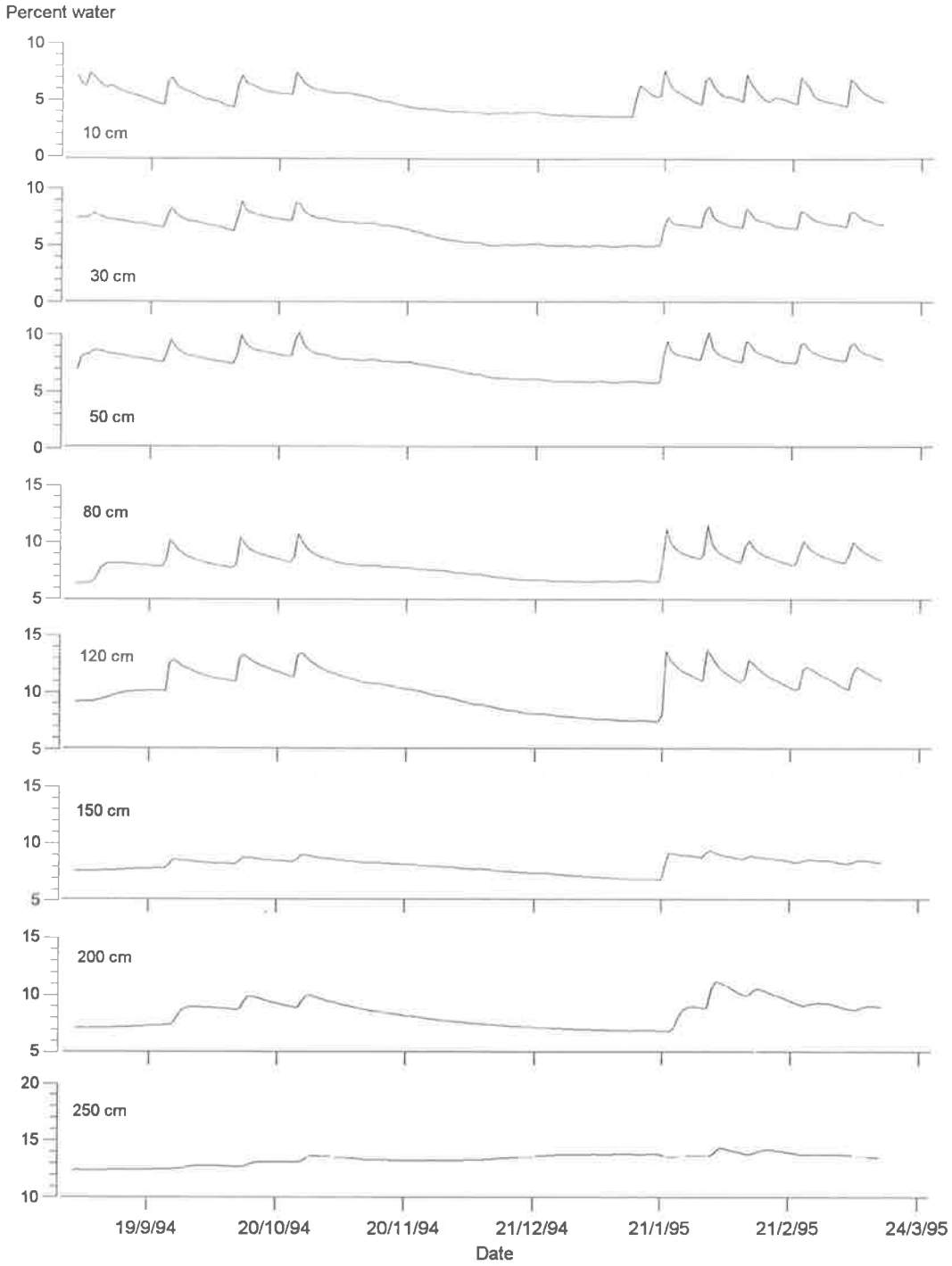

Figure 2.16 Percent soil water calculated from capacitance sensors from 1 September 1994 to 15 March 1995 for anthesis-veraison deficit treatment (Trt 6).
Note the different percent water scale for the 80, 120, 150 cm, 200 and 250 cm depths.

an increase in soil water content at 30 cm and deeper. Prior to this rain the upper soil layers were near wilting point and it is possible the rain was held in the upper 30 cm of the soil profile. The capacitance sensors would have also been sheltered from some of the rainfall by the vine canopy and a large percentage of the rainfall would have been lost as evaporation directly from the soil surface.

The capacitance readings permitted monitoring of the "wetting front" during the irrigation at the end of the anthesis-veraison stress period in January 1994. The 15 minute readings during 1993-94 permitted greater accuracy in determining the rate of water movement compared with hourly readings during 1994-95. Irrigation commenced at 1100 hours, 5 minutes before soil water content was automatically measured by the sensors. By the next set of readings (i.e. 20 minutes after the start of the irrigation), the soil water content at 10 cm had increased (Figure 2.17). The time taken for the wetting front to reach each sensor was calculated from the difference in time between the start of the irrigation and the time at which there was a 0.2 percent increase in soil water content between consecutive 15 minute readings. The increase in water content measured by each sensor as the wetting front moved below each depth ranged from less than 0.5 to about 7 percent. There was uniform downward movement of the wetting front at about 14 cm per hour to 120 cm then a slowing to 3.3 cm per hour during the following 40 hour period. The calculated depth of water to refill 120 cm soil depth took 6.5 hours to apply by which time the wetting front had reached 90 cm deep. During the period between veraison and harvest when the same depth of irrigation was applied to Trt 6 as to the fully irrigated plots there was no change in soil water content below 150 cm (Figure 2.18). The increase in soil water content at 120 cm between 14 and 20 February 1994 without irrigation or rain highlighted some of the inconsistent results obtained with the capacitance sensors.

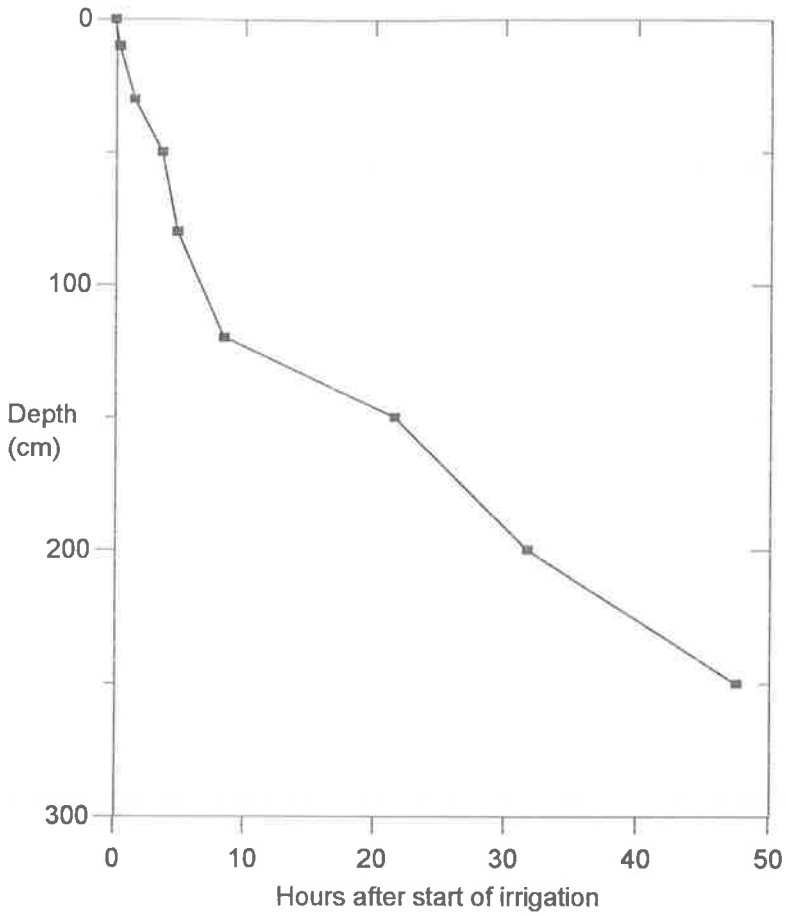

Figure 2.17 Time (hours) after the start of an irrigation for capacitance soil water sensors to detect an increase in soil water at each depth.

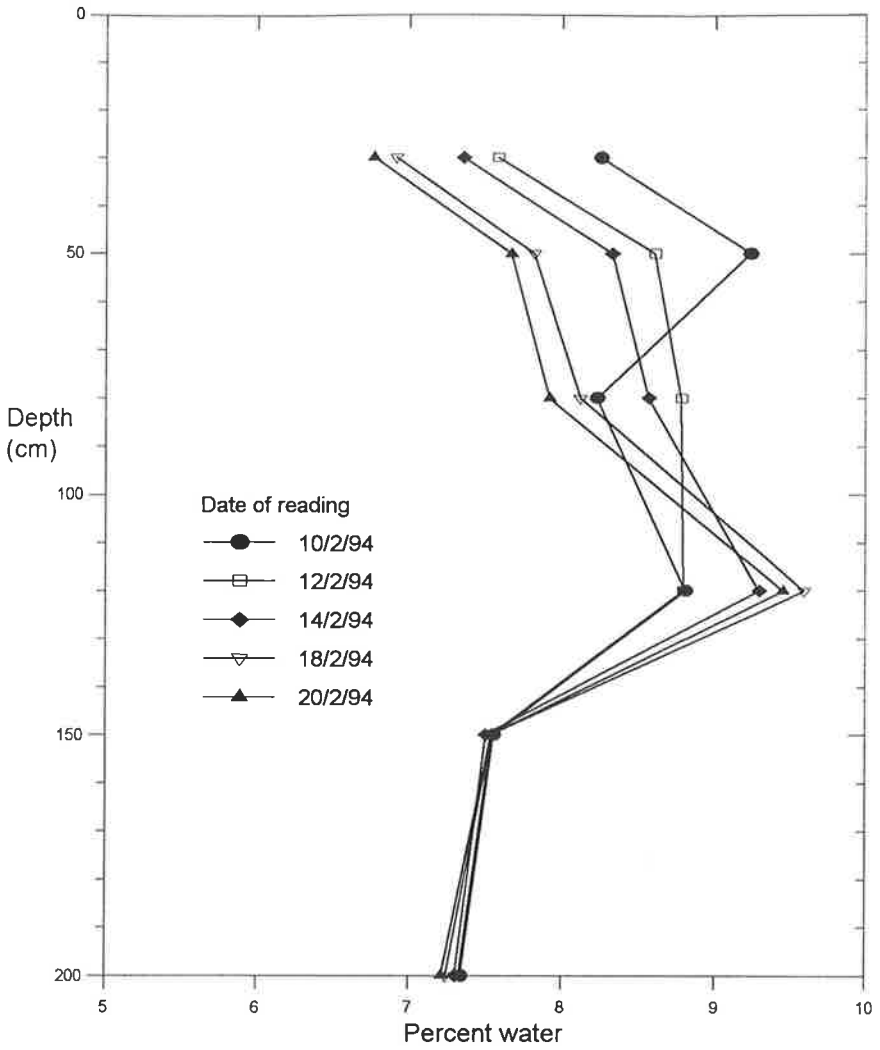

Figure 2.18 Change with soil depth in percent water measured with capacitance soil water sensors on specified days after irrigation during February 1994.
Percent soil water at 10 cm depth not shown.

The contribution of soil water in the 120-250 cm zone to vine water requirement cannot be quantified because of discrepancies between the total soil water content measured with the neutron probe and the capacitance sensors. The sensors were not as accurate as the probe in the estimation of the total soil water content; this was indicated by the agreement between the soil water content measured by the probe after an irrigation and the depth of water applied (Figures 2.1 to 2.4). This finding is similar to that of Evett et al. (1995). During the stress period between anthesis and veraison total soil water extraction in the 0-120 cm zone measured by the neutron probe was 76 mm compared with 53 mm by the capacitance sensors (Figure 2.19) or about 30 percent less. Furthermore, the change in soil water content determined by the capacitance sensors in the 0-120 cm zone during the

period before harvest was up to 50 percent less than the amount determined by the neutron probe, the accuracy of which was supported by the agreement between depth of irrigation applied and the increase in soil water content. The change in soil water content in the 120-250 cm zone, measured by the capacitance sensors, during the deficit period was estimated to be about 20 mm. If the relationship between probe and capacitance readings for the 0-120 cm zone was similar to that for the 120-250 cm zone, the actual change in soil water content in this zone during the stress period could range from 30 to 40 mm or nearly half the total water extraction in the 0-120 cm zone.

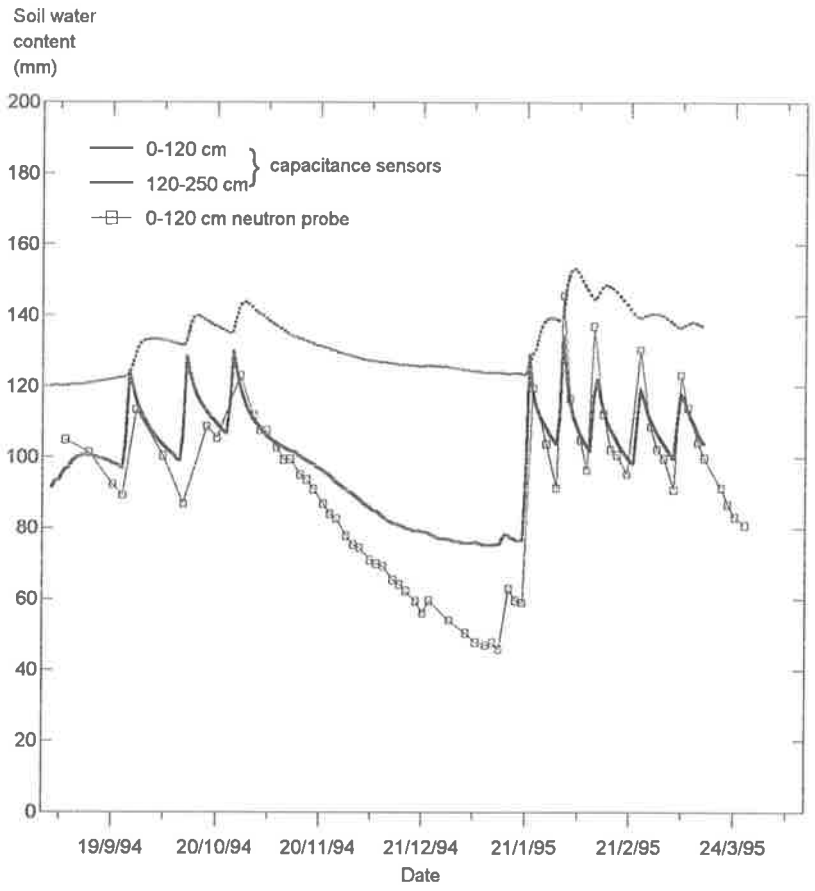

Figure 2.19 Change in soil water content for the 0-120 cm depth zone of anthesis-veraison deficit treatment (Trt 6) during 1994-95 measured with either a neutron probe or capacitance sensors and the 120-250 cm depth zone measured with capacitance sensors.

2.4 Discussion

2.4.1 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. In the absence of an accurate assessment of the amount of rainfall that drained below the rootzone during the rainy 1992-93 season, ET_{crop} cannot be accurately estimated for that season; however it appears to be neither the lowest nor highest. 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. Readings from capacitance sensors indicated that although, when fully irrigated there was only a small volume of soil water extracted below 120 cm, during periods of water deficit a significant quantity of water may have been extracted below 120 cm. 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. A grid of neutron probe tubes, perhaps also to greater depth may have more accurately quantified vine water use.

The high drought tolerance of the species Vitis vinifera was demonstrated here by the ability of unirrigated vines to survive solely on the low rainfall although the adjacent irrigated vines would have moderated temperature and relative humidity conditions more than would be the case in an unirrigated vineyard. The vegetative growth and yield of the unirrigated vines was severely restricted (see next Chapter). Van Zyl and Weber (1981) suggested that unirrigated vines may survive by several mechanisms such as extracting small amounts of water from soil at matric potentials more negative than -1.5 MPa, from dew on leaves, from condensation on roothairs and on soil particles near the surface due to vapour pressure gradients. As the contribution of these mechanisms in supplying limited amounts of water to unirrigated vines was not determined in the experiment reported here the relative importance of each cannot be assessed. Van Zyl and Webber (1981) also suggested there may be upward movement of water from deeper layers in the soil although this would be determined by depth, soil texture and salinity. Test wells located in a vine block to one side of the experimental area indicated the presence of a water table between 300 and 350 cm depth but the water was of high salinity as indicated by piezometer readings of 3.6 to 7 dS/m when taken from a location in the same vineyard. The elevated chloride concentration

in berries of unirrigated vines (data presented in Chapter Four) suggests that some water was extracted from the zone above the saline water table. Van Zyl and Webber (1981) highlighted the important contribution of sub-rootzone water and the need to measure it. Although this was attempted by the use of capacitance sensors the measures are unreliable and consequently the contribution of soil water below 120 cm to the total water requirement of vines in this experiment remains unresolved.

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. The crop coefficients for the 1994-95 growing season are also lower than those of Prior and Grieve (1987) although at Waikerie there was a steadier rise and fall in k_c through the growing season. Williams et al. (1993) reported a rapid rise in k_c from about 0.2 up to 1.0 or more prior to harvest then a rapid decline. The rapid increase in k_c was associated with rapidly developed large canopies that form in the hot San Joaquin Valley of California. The k_c values reported by Williams et al. (1993) were for vines growing in a large weighing lysimeter and thus may not be representative of vines in a commercial vineyard. From personal observation it is my judgement that their Thompson Seedless vines were more vigorous than the Shiraz vines used in the Waikerie experiment; this would, in part, account for the higher k_c values. The recommended k_c values given by Doorenbos and Pruitt (1977) are also higher than those derived here with only a 0.1 unit change between November and April (data adjusted for Southern Hemisphere) and a k_c of 0.45 for October compared with 0.38 reported here. Prior and Grieve reported a range in k_c for October between about 0.2 and greater than 0.6 depending on whether neutron probe readings or lysimeter measurements were used to determine k_c. Hence the values derived for the Waikerie experiment are similar to previous reports but highlight the influence on k_c of other factors such as locality, soil type, variety, rootstock and other cultural practices.

Evapotranspiration calculated from the change in soil water content, as done here, cannot be apportioned to the two components of crop water use and evaporation from the soil surface. Immediately after an irrigation, evaporative loss would have been high while

the soil surface was wet. Van Zyl and Weber (1981) found that the ratio of evapotranspiration to Class A pan readings declined as the soil matric potential became more negative following an irrigation which wet nearly the entire soil surface as did the microsprinklers used in this experiment. Stevens et al. (1995) reported a seasonal water loss of 320 mm or 1.5 mm per day due to evaporation from the soil. For an average irrigation cycle of about ten days for fully irrigated vines in 1994-95 this was 13-14 mm water lost by evaporation or 40 percent of the total application. This is similar to the 38 percent water loss due to evaporation after a single irrigation to a bare soil surface reported by Gardner and Gardner (1969). The decline in soil water content and consequently k_c by day 5 after irrigation (Figure 2.5) indicated that evaporative loss was high during this time. Subsequent loss of water by evaporation was determined by the ability to move water to the upper soil layers of the profile where it could evaporate (Hillel, 1971) and in the coarse sandy-loam of the experimental site the rate of water movement to upper layers was probably low. When the surface soil dried the change in soil water content declined to about 3 mm per day less or a k_c of between 0.4 and 0.5. During this period daily crop water use would have been greater than evaporation although relative contribution cannot be quantified.

During extended periods of water stress there was insufficient available water to meet vine requirement as evident by the reduced yield, more negative leaf water potential and higher stomatal resistance (Chapter Three). In the final stages of these extended stress periods the daily loss in soil water content was less than 1 mm per day (Figure 2.6 and 2.7) and may be ascribed solely to crop water use. During these extended stress periods vine roots extracted water from at least 200 cm soil depth and the relative contribution of water below 120 cm to total water use increased as the upper layers dried. It is assumed that this water was sufficient to ensure vine survival, however, as previously described, the percent contribution cannot be quantified from the capacitance sensors.

Withholding irrigation during the anthesis-veraison period (Trt 6) reduced vegetative growth (Chapter Three) compared with the veraison-harvest deficit (Trt 7) and fully irrigated vines (Trt 1); however, there were only minor differences in the pattern of water extraction. There was little difference in the pattern of water use between fully irrigated plots and anthesis-veraison deficit plots between mid-January and harvest 1995 (data not shown) when both treatments received the same level of irrigation and, although plotted for

different periods of the growing season comparison of Figures 2.6 and 2.7 indicate only minor differences in the rate of water use between Trt 6 and 7. Sixty days after irrigation the veraison-harvest deficit and anthesis-veraison deficit vines had each extracted about 80 mm water from 120 cm soil depth. Reynolds and Naylor (1994) suggested that if vines develop a large leaf area during the pre-veraison period, the post veraison water requirement would be higher than the post veraison need of vines which develop lower leaf area during the pre-veraison period. Notwithstanding regular monitoring of soil water content, this was not apparent in this experiment, and may be attributed to the relatively small difference in canopy size between Trt 6 and Trt 7.

2.4.2 Indices of soil water availability

Soil water content was converted to soil matric potential to enable a comparison of the soil water stress achieved in the Waikerie experiment with that recorded in other investigations. The validity of this conversion is dependent on a series of experimental techniques all of which have some error, for example:

- Stability of probe radioactive count.
- Statistical fit of the linear regression of neutron probe count and gravimetric soil water content, especially at low soil water content.
- Random field variability in soil cores used for neutron probe calibration and soil water release curve.
- Accuracy of soil water release curve.
- Interpolation of soil matric potential from the water release curve, in particular in the range where a small change in percent water translates to a large change in soil matric potential.
- Interpolation of soil matric potential water at depths not measured with the probe.

Additional problems arise in the presentation of soil matric potential data. In this experiment average soil matric potential for the whole rootzone was used without any weighting for root distribution (Stevens et al., 1995). During the first year of the experiment it was evident there was uniform water extraction to at least 120 cm depth in plots of fully irrigated vines and in vine plots subjected to extended deficit periods there was uniform extraction in the final year (Figures 2.8 and 2.9). Data from the capacitance sensors also indicated uniform extraction below 120 cm when water was withheld for

extended periods. Soil matric potential at each depth could also be used however, selecting the most suitable depth for deeply rooted grapevines would pose some difficulty.

The average soil matric potential of fully irrigated plots in the experiment reported here, with the exception of two occasions, was less negative than -30 kpa. When compared with previous experiments this indicates that fully irrigated vines were not water stressed. Shoot growth of Thompson Seedless vines slowed when soil matric potential at 30 cm depth was more negative than -50 kpa and ceased when it was more negative than -65 kpa (Christensen, 1975). The application of a large volume of water based on a calendar schedule (Wildman et al., 1976) resulted in soil matric potential always being less negative than -30 kpa at 135 cm depth compared with about -80 kpa in plots that were irrigated according to tensiometer readings. Heavily irrigated plots did not yield as much fruit as plots where irrigation timing was determined from tensiometer readings although more prunings (weight) were removed from the former. Van Zyl (1987) reported the onset of water stress when the soil matric potential of the entire vine rootzone was at -64 kpa which is more negative than the rootzone average soil matric potential for this experiment. Hardie and Martin (1989) recommended less negative rootzone soil matric potential during the flowering-fruit set period. Although soil matric potential in the Waikerie experiment may have been more negative than the -10 kpa recommended by Hardie and Martin (1989) during flowering-fruit set, the fully irrigated vines in the experiment reported here were seldom water stressed.

During extended periods of withholding irrigation, rootzone soil matric potential was more negative than previous studies although the highly negative potential in the upper soil layers would have skewed the average. The rootzone average soil matric potential of cv. Chardonnay vines was -0.31 MPa at the end of a withholding irrigation treatment that spanned budburst to after flowering (Goodwin and Jerie, 1989). Neja et al. (1977) reported soil matric potential that may have been as negative as -1.0 MPa prior to harvest of an irrigation experiment. By disregarding soil matric potential in the dry 10 and 20 cm layer soil matric potential would be up to 0.3 MPa less negative although Figures 2.10 and 2.11 indicate that even with this adjustment, with the exception of the fully irrigated treatment, all treatments were subjected to significant stress. The effect of water stress on vegetative and reproductive growth is discussed in the next Chapter.

During the last 10 days of the withholding period of the anthesis-veraison deficit treatment in the 1994-95 season, the soil matric potential of the 0-120 cm zone was -1.5

MPa. Although there were visible signs of wilting during the day, often before midday, plants recovered turgor by each morning. This suggests that either the calculated soil matric potentials are more negative than actual, or vines were extracting sufficient water from below 120 cm to meet the daily water requirement. Although, as previously stated in Chapter 2.3.6, there were problems associated with the capacitance sensors, they did however indicate that vine roots extracted significant quantities of water from depth when subjected to extended periods of stress.

While soil matric potential as presented in Figures 2.10 and 2.11 may give a better indication of the level of plant stress than soil water content it does not account for the level of stress and its duration. In an attempt to integrate the level of stress and its duration Hiler and Clark (1971) developed a daily soil water stress index (SDI) to quantify the effect of irrigation treatments. This was derived from a stress day factor (SD) and a crop susceptibility factor (CS). In its simplest form SD was calculated from the daily evaporative demand and the pre-dawn rootzone soil matric potential and CS is an index of the sensitivity of yield to water stress at different phases of the growth cycle of the crop. Subsequent investigations have modified the SDI to include a weighting for root distribution, for example, Du Plessis (1985). At the start of an irrigation experiment Stevens et al. (1995) reported 73 percent of the total root length density in 120 cm soil was in the upper 60 cm of the soil profile and these data were used to describe the relationship between root-weighted soil matric potential and vegetative and reproductive growth. Stevens et al. (1995) used a root-weighting factor because Cock (1984) found that soil water potential became less negative with depth indicating less water extraction in deeper soil layers. A weighting for roots assumes no change in distribution caused by either the irrigation treatment or time. However in the experiment reported by Stevens et al. (1995) root distribution may have been changed by the irrigation treatment, and the change from cultivation to zero tillage during year one of the experiment probably resulted in root growth in shallow soil layers.

Stevens et al. (1995) began to accumulate deficit after the soil had drained to field capacity after which the daily deficit was calculated from reference crop evapotranspiration (ET_o) and modified monthly crop factors taken from Dorrenbos and Pruitt (1977). The method developed for the present experiment was less empirical as it was based on soil water content and a fixed refill line (although the full-line could have equally been used as the start of stress accumulation). A stress day factor based on soil matric potential could

have been derived for this experiment however, as previously stated, the method used to derive soil matric potential results in some inaccuracy which was not quantified.

More extensive use of a water stress index would overcome the problems that arise when comparing results of irrigation experiments and, although additional measurements are required, equipment is now available to automatically record soil water content. Veihmeyer and Hendrickson (1950) stated that the occurrence or absence of periods of dry soil was more important than tabulation of the amounts of water applied in irrigation experiments, however, more than forty years later, many irrigation experiments still only report the volume of irrigation applied during the growing season and perhaps the change in percent soil water; some of this work is cited in the introduction. This paucity of information may explain the varied response to irrigation reported by Smart and Coombe (1983) although they suggested the previous history of vines used for irrigation experiments may have significant effects on responses. The number of years that the Waikerie experiment spanned hopefully moderated the effects of previous vine irrigation management. To address the criticism made by Veihmeyer and Hendrickson (1950) the timing, depth of irrigation and soil water content were prescribed and accurately measured during the four years of the experiment; these data are presented in Figures 2.1- 2.4 and Table 2.3. As previously described the volume of irrigation water applied varied between seasons and treatment. Withholding irrigation resulted in soil water content lower than the refill line however the rate of this decline and the length of time the soil profile was below the refill line varied between treatments and especially between years. The soil deficit index developed in 2.3.5 is a method which integrates these effects. In the next Chapter the index is used to quantify the effect of water deficit on berry growth.

2.5 Conclusions

a. *Neutron probe readings proved a reliable method of monitoring soil water content. On average, fully irrigated vines were irrigated every 10 days during the growing season with a total of between 550 and 602 mm of irrigation applied during the four growing seasons to fully irrigated vines over the four years of the experiment. Daily evapotranspiration of fully irrigated vines was 5.7 mm per day immediately after irrigation and about 2.7 mm the day before irrigation. The daily evapotranspiration of anthesis-veraison and veraison-harvest treatment vines declined to less than 1 mm per day towards the end of the period of water deficit.*

b. *The crop coefficient of fully irrigated vines, which varied between 0.83 and 0.41 between irrigations, was within the range of previously reported experiments.*

c. *Fully irrigated vines extracted water uniformly from the upper 120 cm of the soil profile. The spatial extraction of soil water could not be quantified from the single neutron probe access tube located mid-way between vines. During periods of water deficit soil water extraction occurred to at least 200 cm but could not be quantified due to inaccuracies in capacitance sensors.*

d. *The average rootzone soil matric potential of fully irrigated vines was less negative than -30 kpa. During extended periods of soil water deficit, eg anthesis-veraison and veraison-harvest deficit treatments, the average rootzone soil matric potential declined to -1.5MPa.*

e. *A cumulative soil water deficit index was used to integrate the duration and amount the soil water content was below the irrigation refill line. High levels of cumulative soil water deficit were established before veraison in 1994-95 (year 4) and after veraison in 1991-92 (year 1).*

Chapter Three - Effect of timing of water deficit on growth, plant water stress, yield and its components

3.1 Introduction

A simple manipulation of vegetative growth that maintained or enhanced wine grape quality without adversely affecting yield would be a technique welcomed by many viticulturists. The need for manipulation of vegetative growth in the vineyard has increased with the wider use of planting material free of harmful viruses, vigour inducing rootstocks and other vineyard management practices such as micro-irrigation, fertigation and pre-plant soil preparation. Shoot crowding in the canopy causes higher humidity which is conducive to disease; also the shading of fruit causes less fruit colour and higher malic acid contents which may impair wine quality. Canopy manipulation by trellising alone is not altogether viable as multi-wire trellis systems can be difficult to mechanically prune and harvest. The use of rootstocks to reduce vigour has not been widely accepted in Australia, and there is a dearth of experimental work on the subject (May, 1994). Of other possible methods of manipulating vigour without adversely affecting yield is the control of soil water availability during the phases of berry development described in Chapter One.

There have been numerous studies on the effects of water stress on berry growth relative to shoot growth, however the optimum timing of water stress and the critical soil water status have not been clearly defined. Hardie and Considine (1976) demonstrated that the timing of water stress determined the yield loss on vines growing in small drainage lysimeters. There was more than 50 percent loss in yield when stress was applied immediately after anthesis compared with a 24 percent loss when stress was applied during the 32 days prior to harvest. All water stress treatments delayed berry ripening, stress during the lag phase causing the greatest delay. No data were presented on the effect of the timing of water stress on vegetative growth.

Neja et al. (1977) demonstrated that reducing irrigation from about mid-way between flowering and veraison up to harvest ('early cut-back' irrigation), sufficiently induced water stress which reduced vegetative growth when compared to fully irrigated vines. In comparison to fully irrigated vines, those irrigated by 'early cut-back' had more and heavier bunches per vine, however berry weights were similar suggesting there must have been more berries per bunch on 'early cut-back' vines. Yield per vine was higher than on fully irrigated as bunch rot in this treatment reduced yield. Fruit from the 'early cut-back'

treatment was riper when harvested on the same day than unirrigated and fully irrigated. Over the three years of the experiment about 120 mm water was saved annually and yield was increased by about 1.4 T/ha in each year. Neja et al. (1977) suggested the soil matric potential required to achieve the result in the 'early cut-back' treatment was more negative than previously reported in the literature for warm climates. When no irrigation was applied between flowering and veraison to harvest ('early cut-off' irrigation), although nearly double the quantity of water was saved compared with fully irrigated, excessive soil water stress developed, leaf drop occurred, grapes were not as ripe at harvest and yield was reduced.

In another experiment of this type on Thompson Seedless by Christensen (1975), ceasing irrigation at about veraison (P. Christensen, pers. comm. 1996) reduced shoot growth, however, berry weight at harvest was less than on vines that received an extra two irrigations prior to harvest. Shoot growth slowed when the soil matric potential at 30 cm depth was more negative than -50 kpa and stopped at -65 kpa. There was no effect of early cessation of irrigation on the increase in berry volume or weight during the first 2 years, however in year three, berries were lighter and smaller in volume compared with the treatment that received an extra two irrigations. Although berries were lighter and smaller when mature, the rate of increase in berry weight and volume after anthesis was about the same for both treatments. Christensen (1975) attributed this berry size effect to possible carry over effects of the earlier cessation of new leaf development in each season which may have affected photosynthesis. Hardie and Martin (1989) interpreted the work of Neja et al. (1977) and Christensen (1975) as suggesting that vegetative growth is more sensitive than berry growth to water stress and that vigour control could be achieved by careful manipulation of soil water content without reducing yield. As Hardie and Considine (1976) demonstrated that periods of berry growth differ in sensitivity to water stress, the timing of such stress would need to be carefully controlled.

Goodwin and Jerie (1989) showed that withholding irrigation from budburst until after flowering had no significant affect on vegetative growth and there was also no effect on the number of fertile berries per bunch. Pre-veraison water stress affected mainly berry size with no effect on the number of berries per cluster or clusters per vine in a drip irrigation experiment on Cabernet Franc vines in California (Matthews et al., 1987). The berries in all irrigation treatments of this experiment exhibited double-sigmoid growth

curves and about 85 percent of the increase in berry diameter occurred in phase I. The rate of fruit growth was more inhibited by pre-veraison water stress than post veraison stress. There were fewer berries per bunch when irrigation was withheld before veraison which Matthews and Anderson (1989) suggested may have been the result of reduced branching of the anlagen. Data presented by Matthews and Anderson (1989) indicated pre-veraison deficit significantly improved set compared with post veraison deficit however a discrepancy between their data (Table 4) and the text confuses the interpretation. There was no effect of the timing of water stress on the dates of bloom, veraison and harvest. Pre-veraison stress caused the cessation of shoot growth about 40 days earlier than on vines receiving continuous irrigation where shoot growth continued until soon after veraison. There were no effects of post veraison stress on shoot growth. Poni et al. (1984) also reported that shoot growth in well irrigated plots ceased by veraison and there was no effect of post veraison stress on shoot growth. Van Rooyen et al. (1980) showed little difference in the soil matric potential required for optimum reproductive and vegetative growth during phase I of berry development of cv. Waltham Cross grafted on Jacquez rootstock grown in drainage lysimeters. The predicted percent soil water content for optimum yield and vegetative growth ('optimum' was not defined) during phase I was 84 and 85 percent respectively while, during phase II, the values were 15 and 53 percent respectively. These data indicate that during phase I both berry and vegetative growth may be equally sensitive to water stress. This finding contradicts the suggestion of Hardie and Martin (1989) who suggested that vegetative growth is more sensitive. The slowing in the rate of shoot growth probably accounts for the lower sensitivity of vegetative growth to water availability during phase II and the lower soil water content required for optimum berry growth supports the findings of Hardie and Considine (1976) that berries have increased resistance to water stress during phase II.

There is a need for a well controlled experiment to investigate the effect of water stress during each of the stages of berry and shoot development. This is the aim of the present experiment and, in particular to determine if irrigation can be used to reduce vegetative growth without adversely affecting yield.

3.2 Materials & Methods

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. Five berries, two from near the top of the cluster, two from near the middle, and one from near the bottom were removed from a sufficient number of bunches to give the required number of berries. The samplings reduced crop load of each vine by less than five percent. Approximately equal numbers of berries were collected from each of the three vines in each plot. The berry samples from each plot were stored in plastic bags in a portable refrigerator until weighed. The berries collected from each plot were always weighed on the same day they were sampled. The 20 berries were counted and then weighed and from this weight per berry was calculated. 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.

Leaf water potential was measured by Scholander pressure bomb (Scholander et al., 1965) on three leaves excised from the middle vine in the selected plot. Mature leaves that were fully exposed to the sun at the time of removal were selected. The leaf petiole was re-cut with a scalpel before insertion into the bomb chamber. To allow rapid placement of the leaf in the pressure bomb the equipment was transported to each field plot. A binocular microscope was used to view the end of the petiole. Four of the nine treatment replicates were sampled. Measurement of pre-dawn leaf water potential commenced about one hour before sunrise and was always completed by sunrise. Post solar noon measures commenced at approximately 13:15 hr Central Summer Daylight Saving Time (CST), solar noon at the experimental site in January being about 13:20 hr CST.

Stomatal conductance was estimated using a Delta-T Devices® Mk3 automatic porometer. On each occasion measures were taken of the rate of change in relative humidity in the cup when placed on a fully exposed leaf. This was repeated on four to six mature leaves on the middle vine of selected treatments in four replicates and four treatments were usually measured in each replicate. A calibration was established for each set of measurements using the factory-supplied diffusive resistance calibration plate and a third order polynomial curve fitted to the data. A set of calibration equations for a range of air temperatures and relative humidity was developed to allow a cross-check of both equipment performance and the calibration equation on each occasion. Readings were taken in accordance with the equipment manual and, although the difference in leaf/cup temperature was always kept to a minimum (< 2 °C), a temperature correction was applied to readings using data supplied with the instrument. The 50 percent relativity range switch was most usually used, leaf count varied between 50 and 400 counts and leaf temperature ranged from about 10 °C to 40 °C. The conversion from individual count to stomatal conductance with the appropriate temperature correction was done with a computer 'spreadsheet' and data summarised using a computer database.

3.3 Results

3.3.1 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 3.1), 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 3.1 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

3.3.2 Vegetative growth

Shoot lengths are graphed against date during three years in Figures 3.1-3.3. 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) the longest although in 1991-92 there was no difference in length until a month after bud-burst when the slower shoot growth rate of unirrigated vines became apparent (Figure 3.1). Shoot lengthening ceased during the last few days of November and there was no increase in length during December. In the wetter season of 1992-93 shoot growth on fully irrigated vines continued to the end of December (Figure 3.2) while, in 1993-94 shoot elongation ceased in mid-

December (Figure 3.3). 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.

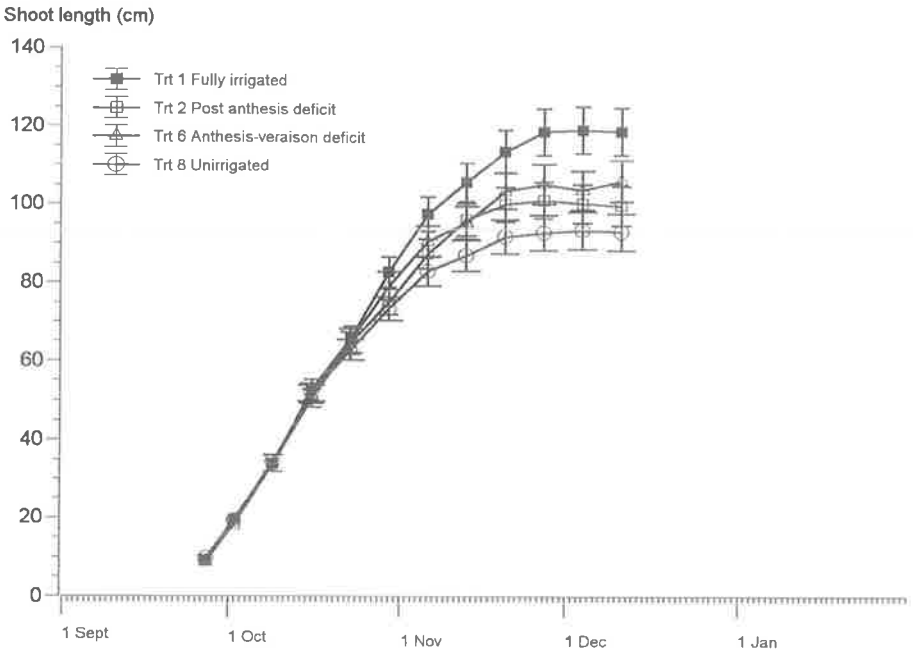

Figure 3.1 Shoot length (cm) of four treatments during the 1991-92 growing season. Total length of vertical bars indicate 2 x se at each date of measurement.

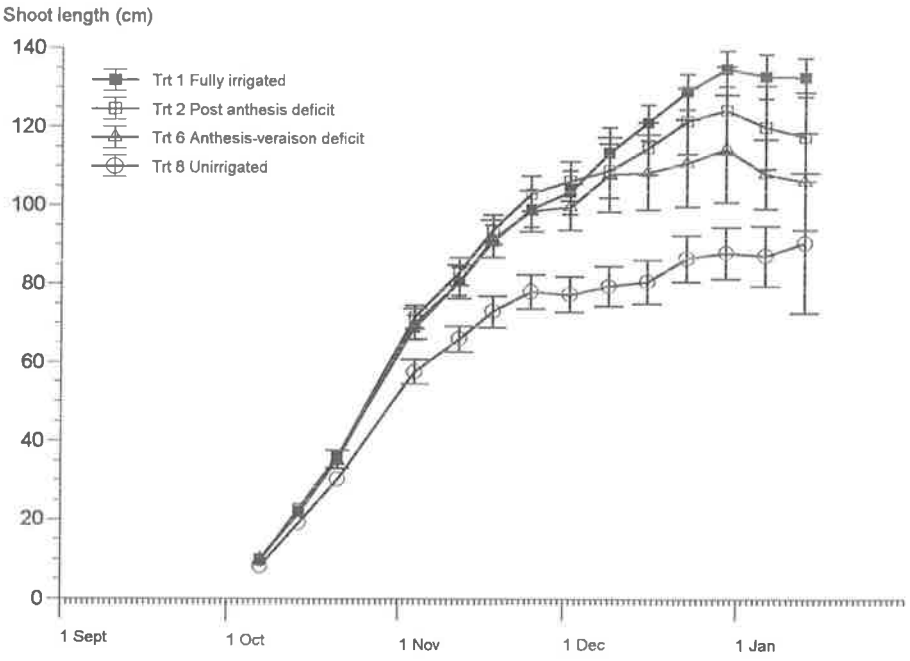

Figure 3.2 Shoot length (cm) of four treatments during the 1992-93 growing season. Total length of vertical bars indicate 2 x se at each date of measurement.

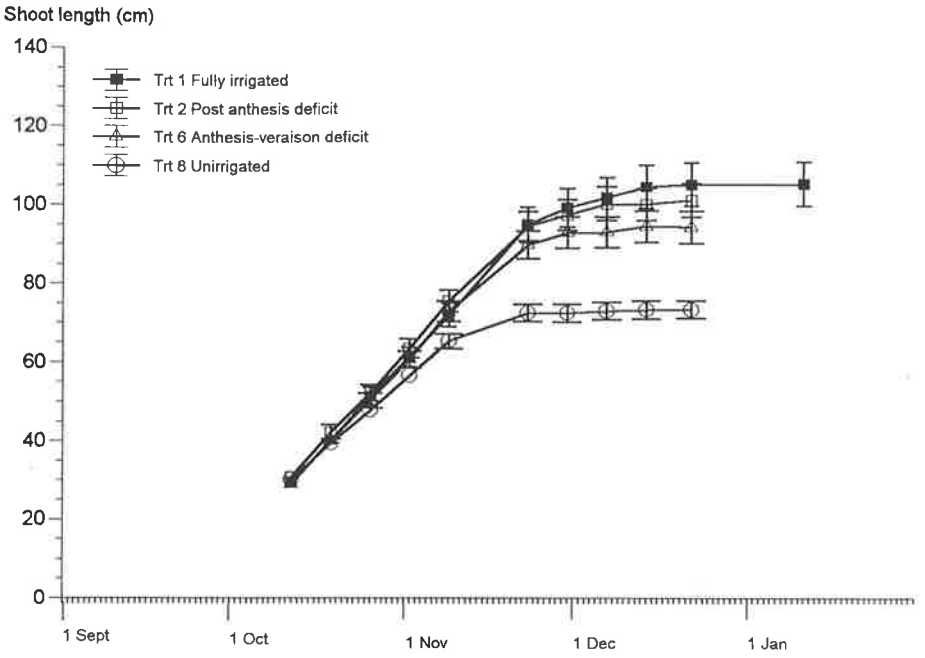

Figure 3.3 Shoot length (cm) of four treatments during the 1993-94 growing season. Total length of vertical bars indicate 2 x se at each date of measurement.

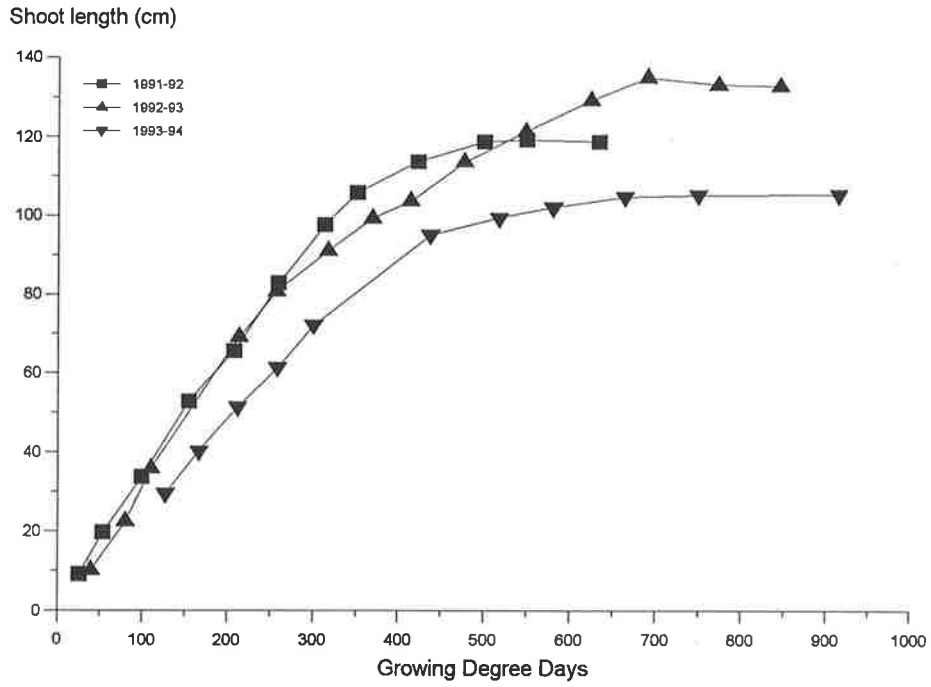

Figure 3.4 Shoot length of fully irrigated vines (Trt 1) with growing degree days (base 10 °C) after budburst for three seasons.

A graph of shoot length against growing degree days (Figure 3.4) showed a near-linear increase in shoot length of fully irrigated vines starting from budburst to about 300 growing degree days. Shoots ceased elongating at about 500, 700 and 650 GDD respectively in the three seasons.

The daily rate of shoot growth was subject to treatment and seasonal effects (Table 3.2). The rate was always greatest on fully irrigated vines (Trt 1) and least on unirrigated vines (Trt 8). In 1991-92 the rate of shoot growth exceeded that in the other two years, for example, during 1991-92, fully irrigated shoots increased in length by over 1.6 cm per day compared with 1 cm per day during the period of active shoot growth in 1993-94. The most rapid rate of shoot growth was 2.7 cm per day for shoots on fully irrigated vines during a one week period in mid-October 1991 (data not presented).

Table 3.2 Daily rate of shoot elongation (cm/day) for three treatments for years 1991 to 1994. Daily rate is calculated for the period between budburst and cessation of shoot elongation.

Year	Fully irrigated (Trt 1)	Post-anthesis deficit (Trt 2)	Anthesis-veraison deficit (Trt 6)	Unirrigated (Trt 8)
1991/92	1.63	1.52	1.26	1.24
1992/93	1.41	1.26	1.14	0.90
1993/94	0.98	1.06	1.02	0.80

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 3.3) 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 3.3) 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 3.3) were similar to those on the weight of prunings.

Table 3.3 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

3.3.3 Leaf Water Potential

1991-92

The diurnal pattern of leaf water potential (LWP) was observed in mid and late February 1992. On 14 February (Figure 3.5) there was little difference in post dawn LWP of the four selected treatments however by noon unirrigated vines had developed a more negative LWP which remained lower for the remainder of the day. By sunset both the post-veraison deficit (Trt 4) and the pre-harvest deficit (Trt 5) treatment vines recovered to a less negative LWP than did fully irrigated (Trt 1) and unirrigated vines (Trt 8) which were similar. By the 27 February (
Figure 3.6) the post dawn LWP (within an hour after sunrise) of leaves of the same vines of three of the same treatments previously measured was more negative and fell to a lower LWP during the day. Fully irrigated vines received a normal irrigation between the post dawn readings and those taken at about midday. No other treatments were irrigated. There was a near linear decline in LWP from post dawn to mid-afternoon for both the post veraison deficit and veraison-harvest deficit treatments. There was rapid recovery of LWP of two treatments (fully irrigated & post veraison deficit) measured after sunset to values similar to post dawn. Fully irrigated vines completely recovered LWP but, on post veraison deficit vines (Trt 4), the recovery was incomplete.

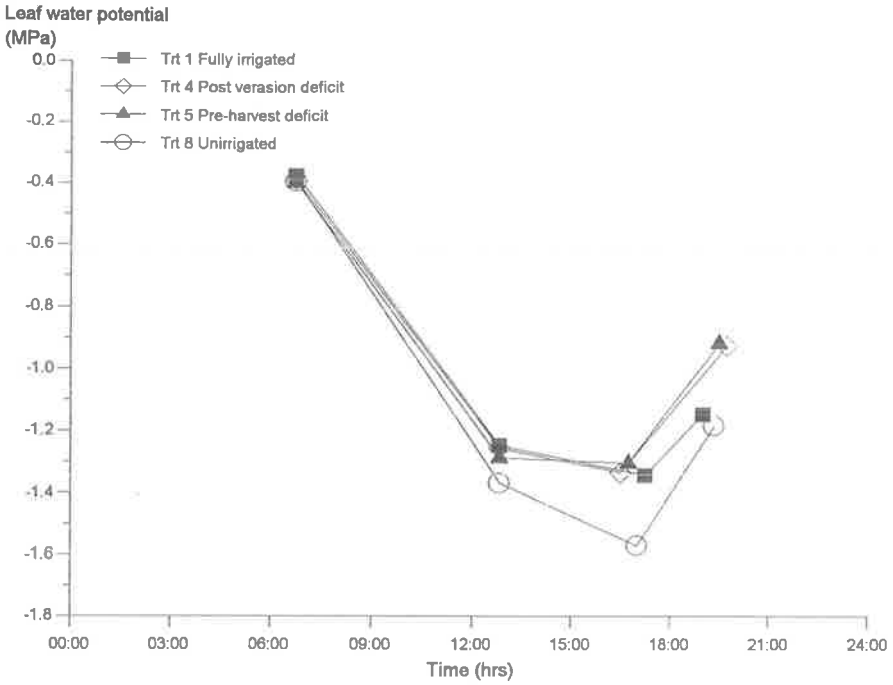

Figure 3.5 Diurnal pattern of leaf water potential from post dawn to pre-sunset on 14 Feb. 1992.

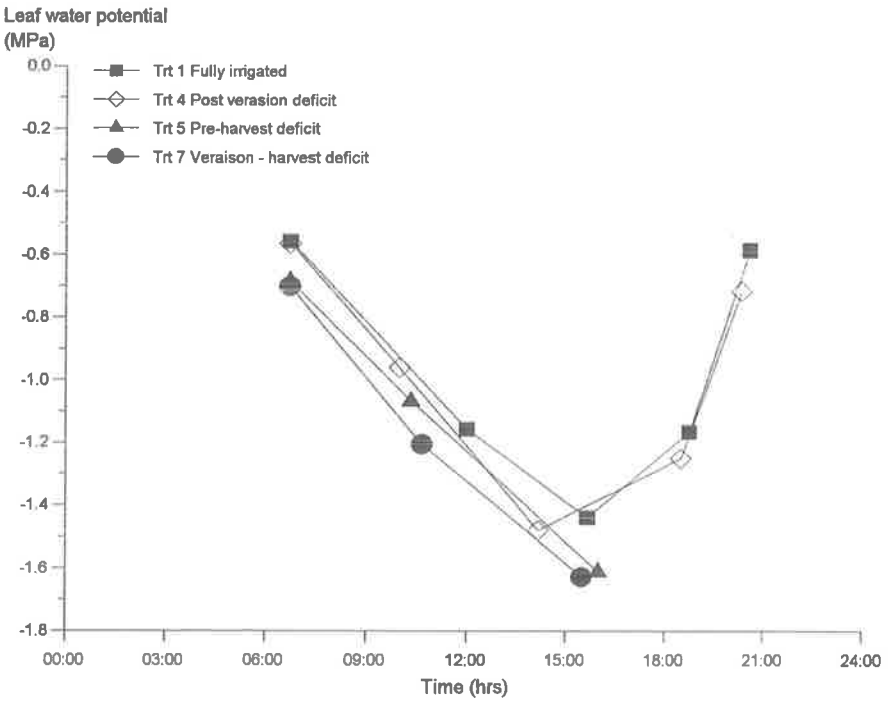

Figure 3.6 Diurnal pattern of leaf water potential from post dawn to post sunset on 27 Feb. 1992.

1993-94

During January to March 1994, pre-dawn LWP was measured on six occasions, two of which were on consecutive mornings (Figure 3.7). Post solar noon LWP was assessed on three days including the afternoon between the consecutive pre-dawn readings. Pre-dawn LWP of fully irrigated and veraison-harvest deficit vines became more negative while there was little change in the pre-dawn LWP of unirrigated vines. On one of the days LWP was measured (25 January 1994), the maximum temperature was 41 °C which was the third hottest day recorded during the four years of the experiment. Although the solar-noon LWP were the most negative recorded in 1994 they were about the same as the most negative values recorded in 1992 during which season the highest maximum temperature was 41.7 °C on 17 Feb. 1992 (the highest temperature recorded was 42.1 °C on 30 Nov. 1993). Post solar noon LWP readings were similar to those recorded in 1992 with unirrigated vines being most negative (-1.0 to -1.55 MPa) and irrigated vines -1.0 to -1.33 MPa.

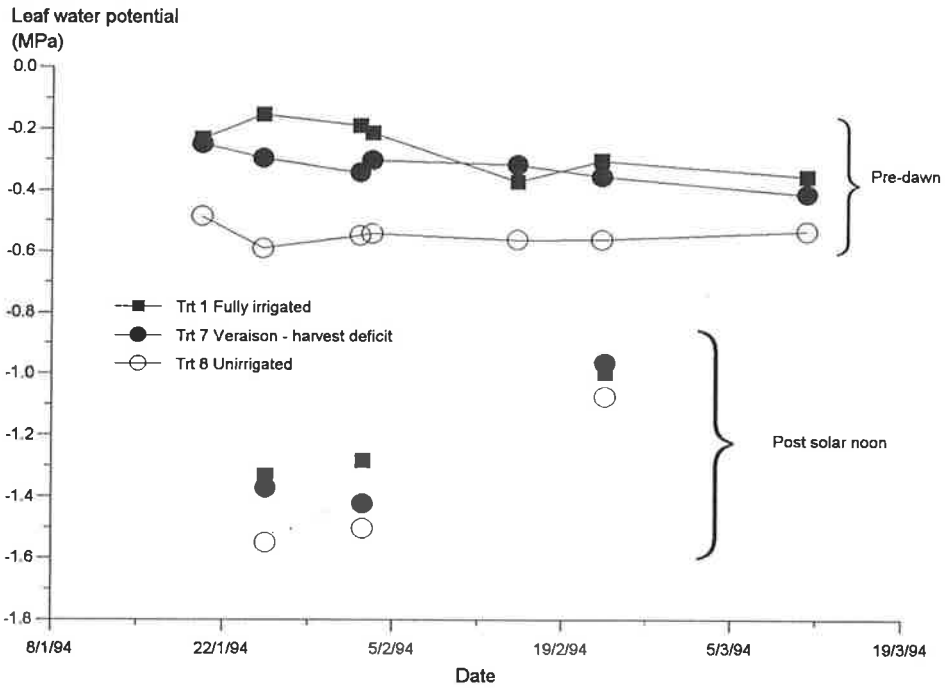

Figure 3.7 Leaf water potential of selected treatments during the 1993-94 growing season. Symbols with connecting lines represent pre-dawn leaf water potential (LWP). Symbol points represent LWP post solar noon.

3.3.4 Stomatal conductance

There was significant variation in diurnal stomatal conductance between treatments on most occasions but the measurements during February 1994 proved the most consistent. On both 2 and 22 February 1994 (Figure 3.8 and 3.9) fully irrigated vines had the highest stomatal conductance and unirrigated the lowest. On both days there was an increase in stomatal conductance during the morning and a decline around midday. On 2 February there was a mid-afternoon increase in conductance of leaves on fully irrigated and veraison-harvest deficit (Trt 7) vines and at 15:00 hr the conductance of fully irrigated vines was nearly four times that of unirrigated vines (0.73 vs 0.19 mol. $m^{-2}.s^{-1}$).

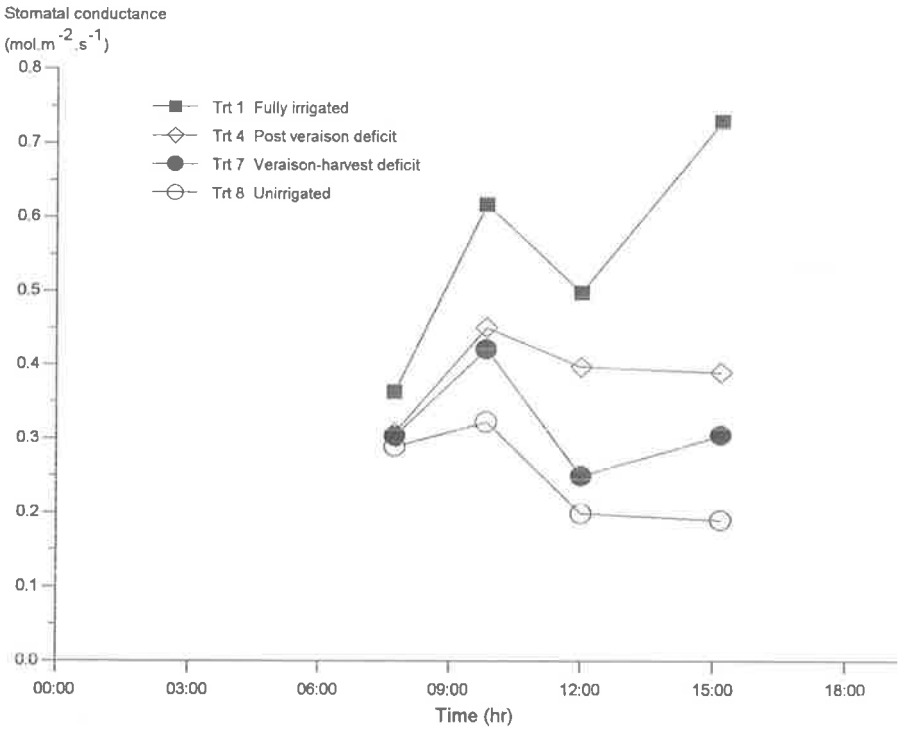

Figure 3.8 Diurnal pattern of stomatal conductance of four treatments on 2 Feb. 1994.

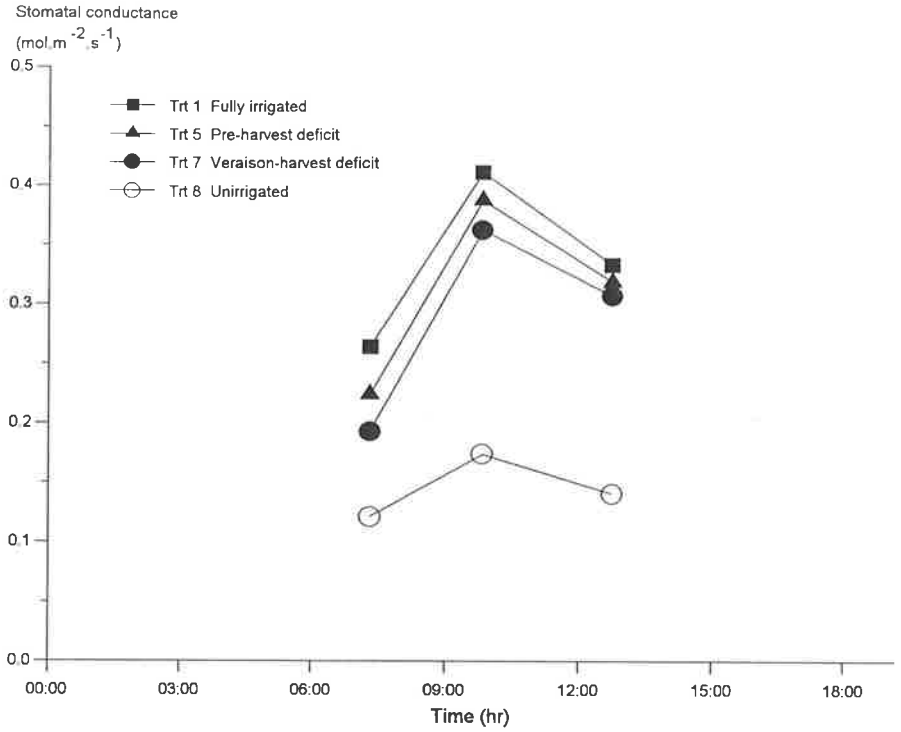

Figure 3.9 Diurnal pattern of stomatal conductance of four treatments on 22 Feb. 1994.

3.3.5 Berry Growth

Graphs of berry weight against date are shown in Figures 3.10 to 3.13. Because of statistical similarity some treatments are grouped in some years and are illustrated by a single treatment. The groupings differed between years because seasonal conditions influenced the effectiveness of each water deficit treatment.

The berries of unirrigated vines weighed significantly less than all other treatments throughout the 1991-92 season (Figure 3.10). During the 1992-93 season all treatments had berry weights not significantly different from each other until maximum weight was attained (Figure 3.11) whereafter, on six occasions, berry weight on unirrigated vines (Trt 8) was significantly lighter than all other treatments (which continued to be similar). This result was no doubt attributable to heavy rain during that summer.

In 1993-94 and 1994-95 (Figures 3.12 and 3.13 respectively), 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, but of similar weight at most samplings in 1993-94 and lighter than fully irrigated at 5 of the 10 sampling times in 1991-92. There was no difference in berry weight between post anthesis deficit (Trt 2) and pre- and post veraison deficit (Trts 3 and 4 respectively) treatments in 1991-92. The pre- and post veraison deficit treatments were also similar at every sampling time in 1994-95 and similar at 9 of the 11 sampling times that both treatments were sampled in 1993-94.

In each year 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 in 1991-92, 1994-95 and 1993-94, except during the first fortnight after anthesis and immediately after veraison.

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.

There was a decline in the weight of berries of unirrigated vines (Trt 8) in the years after the wet 1992-93 summer. In 1991-92 the maximum berry weight of unirrigated

berries was about 1.2 g, in 1992-93 about 1.6 g, in 1993-94 about 1.2 g, and in the final year the maximum berry weight of unirrigated vines was about 0.75 g, less than half that in February 1993. There was a recovery in berry weight of unirrigated vines during 1995-96 in response to winter-spring rain in 1995 (data not presented). In comparison to unirrigated the maximum weight of berries from fully irrigated vines (Trt 1) increased between 1991-92 and 1993-94 to a maximum weight of 1.76 g but in 1994-95 the maximum berry weight was about 1.37 g or about 25 percent lighter. This decline in berry weight of the fully irrigated treatment in 1994-95 was reflected in other treatments, for example, the pre-harvest deficit treatment (Trt 5), which was similar to fully irrigated in each year, also had lighter berries in that year.

Rain (46 mm) on 14 January 1995 (Figure 3.13) which was about 60 days after anthesis had a significant effect on berry weight of unirrigated and other treatments that were water stressed at that time. For treatments that were not subject to stress at the time (Trts 1, 2 and 3) the increase in berry weight between the two sampling times immediately before the rain was about 15 percent. The increase in berry weight for the corresponding period for the anthesis-veraison deficit treatment (Trt 6) and unirrigated (Trt 8) was 11 and 15 percent respectively. Over the week following the rain (and an irrigation on Trts 1, 2 and 3 the day before the rain) the average increase for the pre-rain non-stressed Trts 1, 2 and 3 was about 22 percent while the corresponding increase for the pre-rain stressed Trt 6 and Trt 8 was 34 and 32 percent respectively. The greater rate of increase in berry weight for unirrigated (Trt 8) was transient since, by the following week, the increase in weight was only minor.

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. During the period of weight gain for the 1993-94 and 1994-95 seasons the daily rate of increase ranged from about 40 mg per day for fully irrigated vines in early December 1993 to less than 5 mg per day for unirrigated. In mid-January 1995 there was a ten-fold difference in the daily rate of berry growth between fully irrigated and unirrigated (30 mg per day vs 3 mg per day respectively). During the period of loss in berry weight the daily rate ranged from minimal to about 20 mg loss per day. 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).

In Chapter Two, data on soil water depletion indicated the period between anthesis and veraison in the 1994-95 season and veraison to harvest in the 1991-92 season were the intervals during which maximum soil water deficit developed. The effects of water deficit during these two periods are shown in greater detail in Figure 3.14 and 3.15 (taken from Figures 3.13 and 3.10 respectively). The berries of the anthesis-veraison deficit treatment (Trt 6) weighed significantly less than fully irrigated (Figure 3.14) by 37 days after anthesis, or about the time when irrigation was applied to the post anthesis deficit treatment to end the stress period. It is likely that berry weight of the post anthesis deficit treatment (Trt 2) was similar to the anthesis-veraison deficit treatment (Trt 6) at this time as the berries of these two treatments were similar at the third sampling time or 12 days later. Re-application of water to the post anthesis deficit treatment resulted in an increase in weight relative to anthesis-veraison treatment berries although berries were still lighter than fully irrigated. Although the soil water content of the pre-veraison treatment fell below the refill line about 33 days after veraison it was not until the sampling 58 days after anthesis that the berries were significantly lighter than fully irrigated. Berries of the pre-veraison deficit treatment (Trt 3) remained lighter than fully irrigated to the end of the stress treatment period at which time they were the same weight as the post anthesis deficit treatment berries.

At the first sampling after veraison in 1991-92 (Figure 3.15) there was no significant difference in berry weight between fully irrigated (Trt 1), post veraison deficit (Trt 4) and pre-harvest deficit (Trt 5). A week later Trt 4 berries were lighter than Trts 1 and 5 which were similar and remained so for the rest of the sampling period (i.e. there was no effect of

pre-harvest deficit on berry weight). The berries of the post veraison deficit treatment remained significantly lighter than Trts 1 and 5 for five consecutive weeks although during the final 3 weeks (after the re-application of water), berries were of similar weight to Trts 1 and 5. During the last 3 weeks of sampling there was little loss in berry weight of Trt 4 compared with an overall continued loss in weight of berries of fully irrigated or pre-harvest deficit treatment vines.

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 Figure 3.16. 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 3.4). 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. The post anthesis period was the most sensitive to water deficit with a slope more than double that of the pre-veraison period. The slope of the lines representing the effect of water deficit during the pre- and post veraison periods were similar indicating a similar sensitivity to water stress. The low r^2 and near zero slope of the regression for the pre-harvest period indicated low sensitivity to stress during this period.

Table 3.4 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 post anthesis, pre-veraison, post veraison and pre-harvest deficit 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

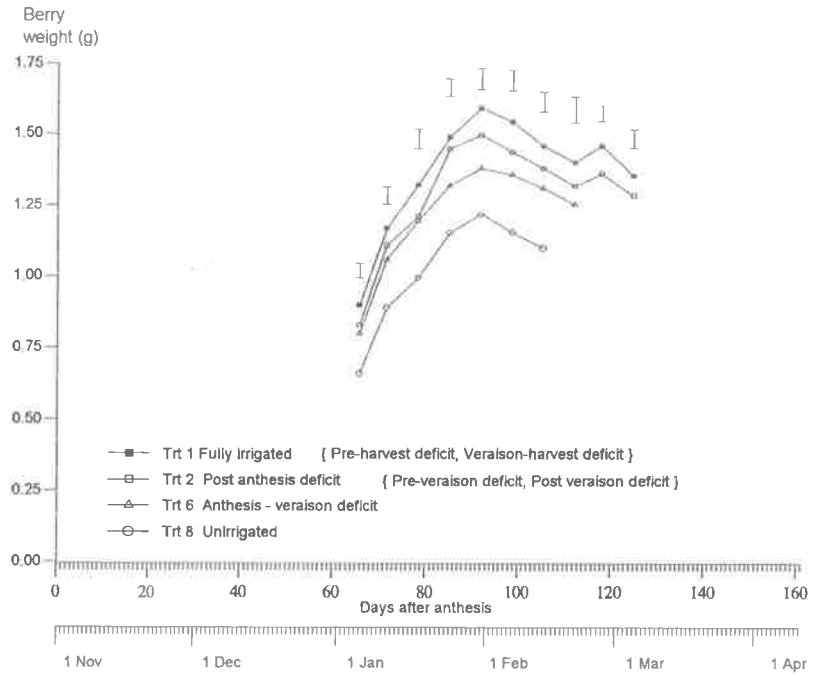

Figure 3.10 Berry weight plotted against time after anthesis for the 1991-92 season. Vertical bars indicate l.s.d.($p<0.5$) for each sample date.
Bracketed treatments indicate those which were similar to plotted treatment at every sample date.

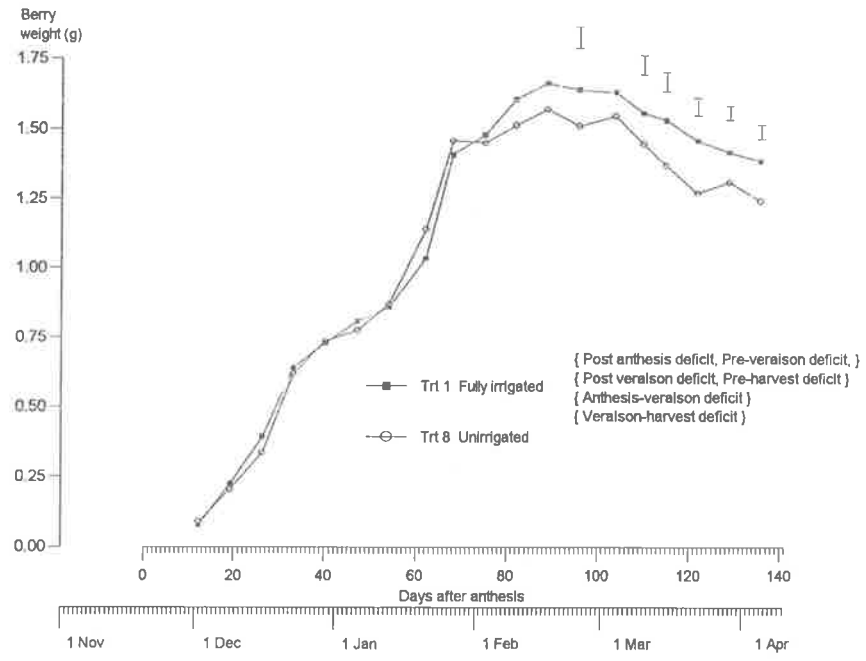

Figure 3.11 Berry weight plotted against time after anthesis for the 1992-93 season. Vertical bars indicate l.s.d.($p<0.5$) for each sample date. Bracketed treatments indicate those which were similar to plotted treatment at every sample date.

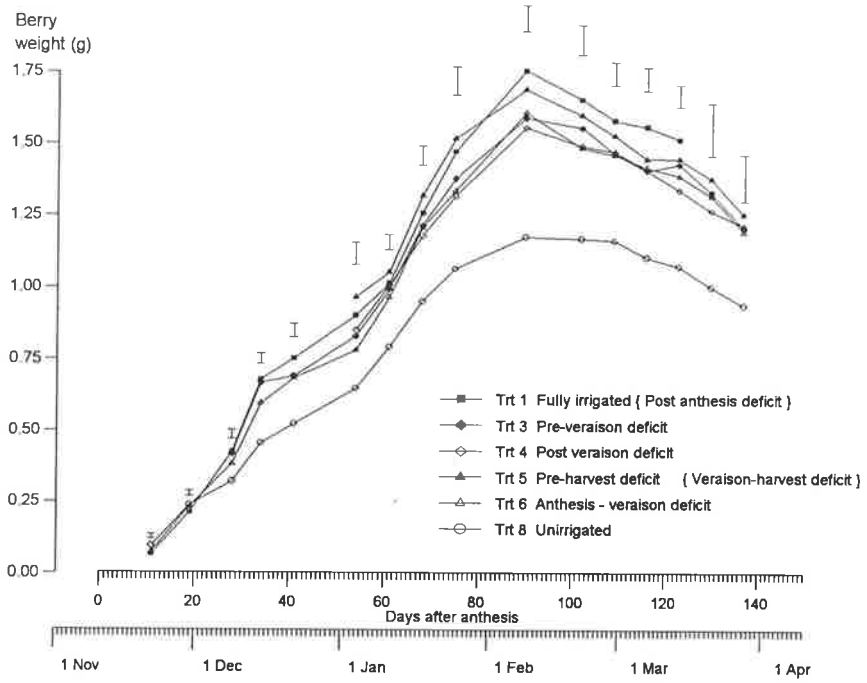

Figure 3.12 Berry weight plotted against time after anthesis for the 1993-94 season. Vertical bars indicate l.s.d.($p<0.5$) for each sample date. Bracketed treatments indicate those which were similar to plotted treatment at every sample date.

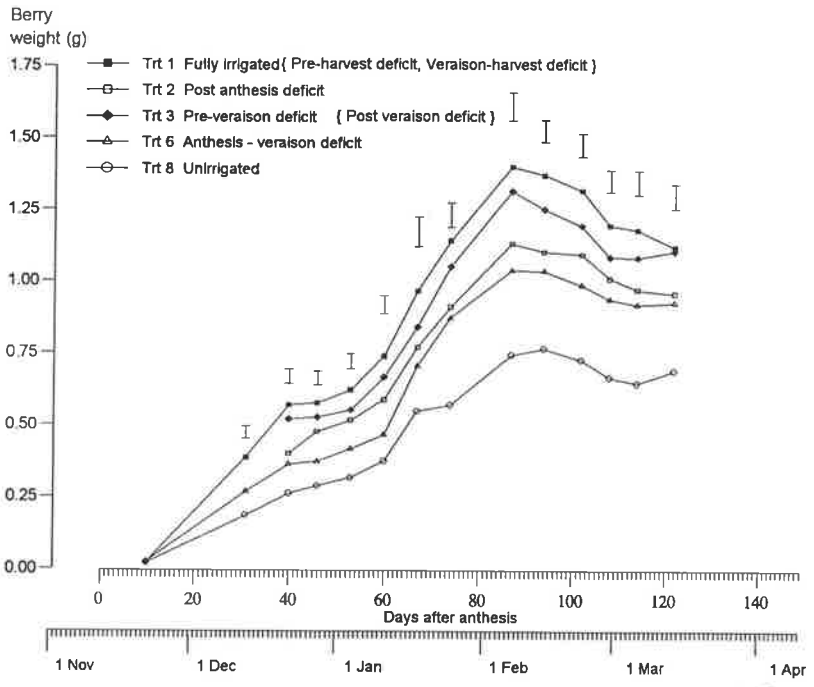

Figure 3.13 Berry weight plotted against time after anthesis for the 1994-95 season. Vertical bars indicate l.s.d.($p<0.5$) for each sample date. Bracketed treatments indicate those which were similar to plotted treatment at every sample date.

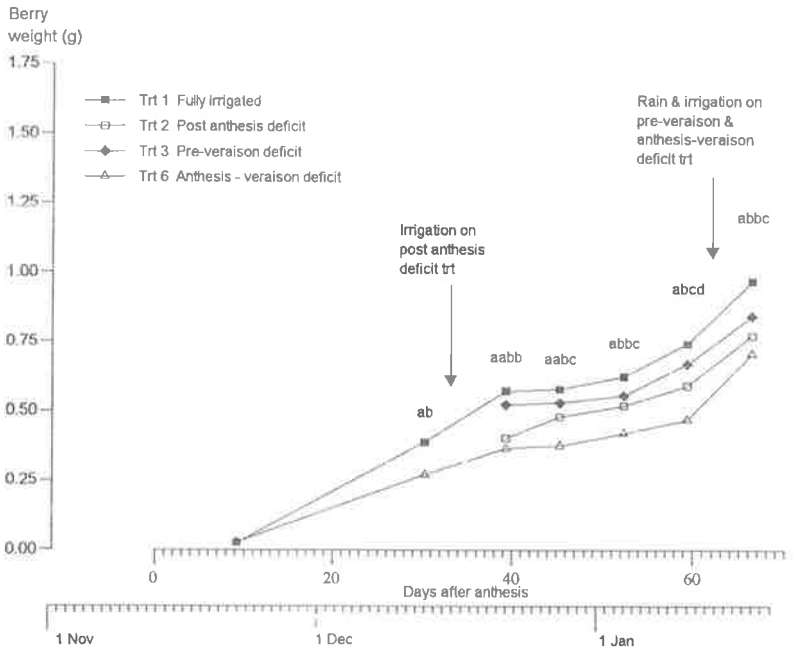

Figure 3.14 Berry weight plotted against time for fully irrigated, post anthesis, pre-veraison and anthesis-veraison deficit treatments between anthesis and veraison during the 1994-95 season.
Letters above data points represent, in descending order, significant difference between treatments with similar letters representing non-significance.

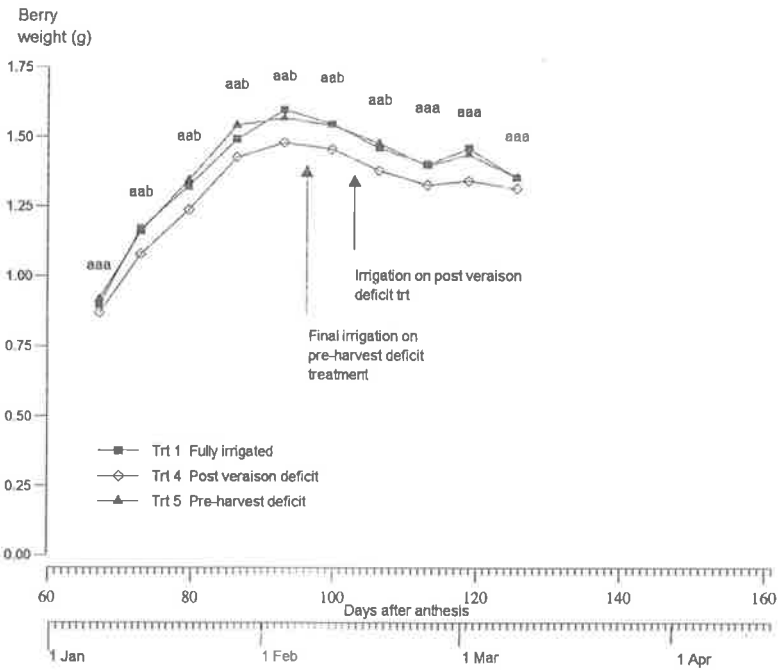

Figure 3.15 Berry weight plotted against time for fully irrigated, post veraison and pre-harvest deficit treatments between veraison and harvest during the 1991-92 season.
Letters above data points represent, in descending order, significant difference between treatments with similar letters representing non-significance.

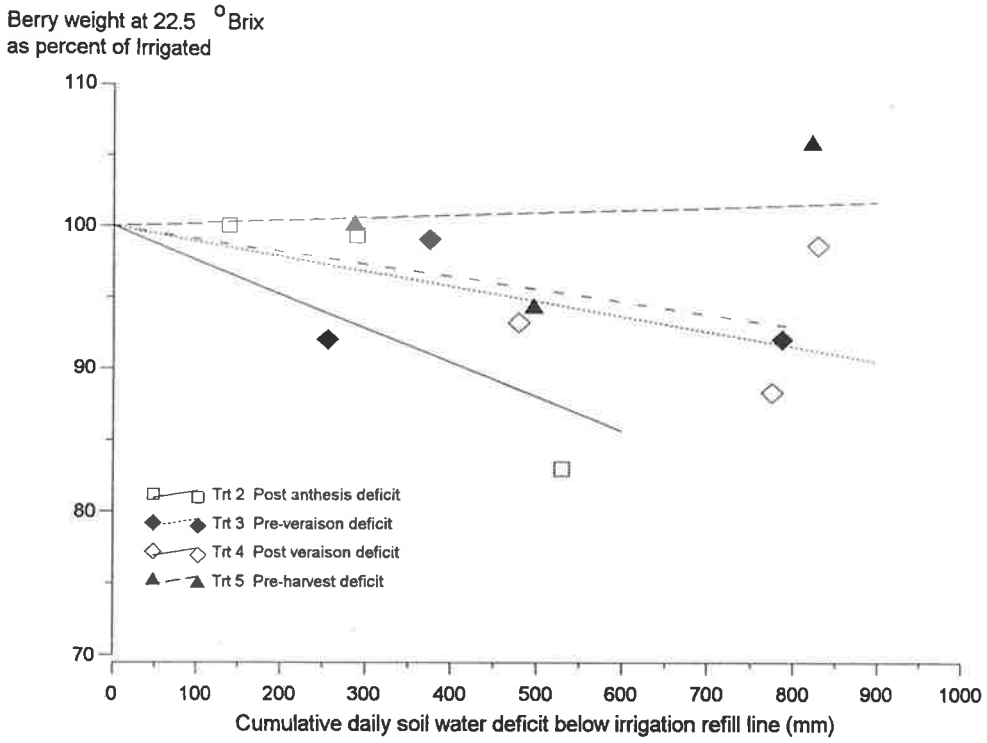

Figure 3.16 Relationship between cumulative daily soil water deficit (mm) below refill line and berry weight at 22.5 °Brix as percent of fully irrigated for post anthesis, pre- and post veraison and pre-harvest deficit treatments.
Data points for each treatment are the calculated soil water deficit and berry weight for the 1991-92, 93-94 and 94-95 seasons. In the absence of any deficit berry weight of all treatments was assumed to be equal to fully irrigated.

3.3.6 Harvest

There was nearly a four week difference (Table 3.5) 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 previous

Table 3.5 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

three 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.

3.3.7 Components of yield

Bunches per vine. At harvest 1992 there was a significant difference in the number of bunches per vine (Table 3.6) with only the pre-veraison deficit treatment (Trt 3) being significantly greater than fully irrigated with about 25 more bunches per vine. Pre-harvest deficit vines (Trt 5) had about 20 fewer bunches per vine than fully irrigated. Yield data and the components of yield for the 1992-93 season are not presented since above average rainfall during this growing season resulted in only low levels of soil water deficit (Figure 2.11) for all treatments. This, combined with a downy mildew outbreak in January 1993, masked any yield differences between treatments including unirrigated which yielded nearly as much fruit as the fully irrigated treatment. There was no treatment effect on the number of bunches per vine at harvest 1994 and on average there were about 30 more bunches per vine than in 1994-95. 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 3.6) declined throughout the duration of the experiment. At harvest 1992, unirrigated vines had a number of berries per bunch not dissimilar to fully irrigated vines, but by harvest 1995 there were about 40 percent fewer berries on unirrigated vines compared with fully irrigated. In 1994 there was no significant difference in berry number per bunch between treatments 1-7. 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 3.5) 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. As previously described the berry weight of all other treatments were similar at harvest 1992-93. In other years the berries of fully irrigated (Trt 1) and pre-harvest deficit (Trt 5) tended to be the heaviest although in 1993-94 the berries of the post anthesis deficit treatment (Trt 2) were only slightly lighter in weight than fully irrigated. 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 3.7) 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 3.6 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.

Treatment	Bunches per vine			Berries per bunch		
	1992	1994	1995	1992	1994	1995
Trt 1 Fully irrigated	182 bcd	194	166	81	67 ab	68 a
Trt 2 Post-anthesis deficit	176 bcd	190	156	81	67 ab	57 b
Trt 3 Pre-veraison deficit	207 a	210	168	75	73 a	62 ab
Trt 4 Post-veraison deficit	187 abc	193	160	71	77 a	63 ab
Trt 5 Pre-harvest deficit	164 d	197	154	78	72 ab	67 a
Trt 6 Anthesis-veraison deficit	187 ab	204	164	77	68 ab	59 b
Trt 7 Veraison-harvest deficit	176 bcd	177	154	76	75 a	62 ab
Trt 8 Unirrigated	166 cd	200	153	73	60 b	42 c
		n.s.	n.s.	n.s.		

Table 3.7 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		
	1992	1994	1995	1992	1994	1995
Trt 1 Fully irrigated	108.2 a	100.9 a	80.7 a	19.5 a	19.2 ab	13.4 a
Trt 2 Post-anthesis deficit	104.4 abc	98.7 a	62.8 cd	18.3 ab	18.6 ab	9.8 cd
Trt 3 Pre-veraison deficit	96.3 bc	96.9 a	67.8 bc	19.7 a	20.1 a	11.4 b
Trt 4 Post-veraison deficit	93.3c	97.5 a	70.6 bc	17.2 b	18.2 ab	11.2 bc
Trt 5 Pre-harvest deficit	106.0 ab	104.8 a	80.5 a	17.2 b	20.1 a	12.4 ab
Trt 6 Anthesis-veraison deficit	98.9 bc	97.2 a	58.1 d	18.0 ab	19.9 ab	9.6 d
Trt 7 Veraison-harvest deficit	99.1 abc	98.5 a	72.7 ab	17.2 b	17.3 b	11.2 bc
Trt 8 Unirrigated	80.3 d	70.5 b	28.5 e	13.3 c	13.8 c	4.7 e

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 1.5) resulted in a 70 percent decline in yield of unirrigated vines between 1994 and 1995. In 1992 the three post veraison deficit treatments (Trt 4, 5 and 7) all yielded significantly less than the fully irrigated in response to the higher soil water deficit developed during this period. There was no irrigation treatment effect on yield at harvest 1994 with treatments 2-7 being statistically similar to fully irrigated. Pre-harvest deficit vines were the highest yielding and, of the irrigated treatments, veraison-harvest the lowest with about 2.9 kg per vine less fruit. The yield of unirrigated vines was similar to 1992 harvest. The greatest difference in yield between treatments occurred in 1995 with nearly a 300 percent difference in yield between fully irrigated and unirrigated (Table 3.7) 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.

Irrigation treatment had only a minor effect on fruit weight/pruning weight ratio for either of the two years for which data are reported (Table 3.8). There was no effect on the ratio in 1993-94 while, at harvest 1995, only unirrigated was significantly different with about 5.4 kg more fruit per kg pruning weight than irrigated. Excluding the 1994-95 unirrigated treatment, fruit weight/pruning weight ratio was nearly five units higher at harvest 1994 than 1995.

Table 3.8 Irrigation treatment effect on the ratio fruit weight/pruning weight (kg/kg) for the 1994 and 1995 harvest.
Numbers followed by the same letter are statistically similar ($p<0.05$). n.s. = not significant.

Treatment	1994 harvest	1995 harvest
Trt 1 Fully irrigated	16.4	12.5 a
Trt 2 Post anthesis deficit	16.2	10.7 a
Trt 3 Pre-veraison deficit	18.2	12.2 a
Trt 4 Post veraison deficit	15.9	12.1 a
Trt 5 Pre-harvest deficit	16.5	10.5 a
Trt 6 Anthesis-veraison deficit	16.5	11.8 a
Trt 7 Veraison-harvest deficit	15.0	12.4 a
Trt 8 Unirrigated	16.0	17.9 b
	n.s.	

3.4 Discussion

3.4.1 Vine development phases

The duration between key phenological events is schematically shown in Figure 3.17. 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 average number of days between budburst and flowering for Shiraz grown in the Sunraysia district of the Murray-Darling Basin for the 1966 to 1970 seasons was 54 days and 118 days between flowering and harvest date, although the °Brix of the latter was not defined; the number of days between bud-burst and harvest was 172 days. The corresponding periods for the 1991 to 1994 seasons were 45, 101 and 146 days (Table 3.9) although the latter two intervals were determined to about 20 °Brix. In Chapter 4 data is presented suggesting harvest for winemaking was up to 20 days later (Figure 4.5), increasing the number of days between budburst and harvest to 166 days which is closer to the data summarised by Coombe (1988). 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. Anthesis was earlier than average

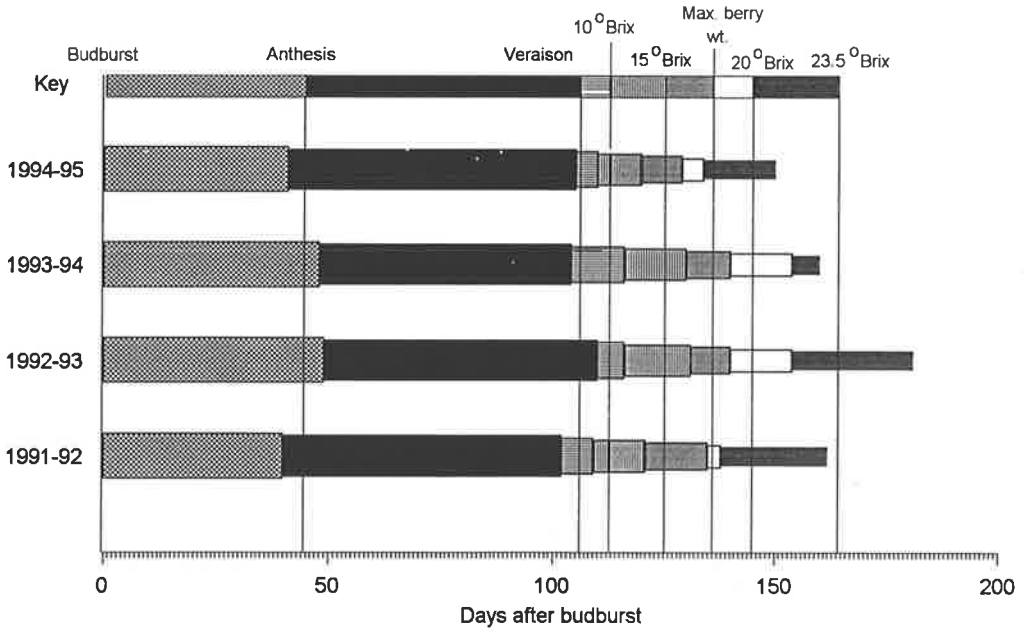

Figure 3.17 Schematic representation of the duration in days of phenological stages for fully irrigated Shiraz vines for four seasons.
Vertical lines indicate the average number of days after budburst for the indicated phenological stage.

in 1991-92 and 1994-95 and later than average for the intervening years. Although the number of days between anthesis and veraison was more in 1994-95 than the previous three years the number of days between budburst and veraison was average, however the number of days between veraison and 23.5 °Brix was below average due primarily to fewer days between veraison and 20 °Brix. The significance of these data are discussed further in Chapter Four. The data presented by Coombe (1988) are acknowledged to be subject to inaccuracies due to the manner in which they were collected suggesting that the data presented here are a more accurate estimate of the periods and the variation between key phenological events for Shiraz in the south-eastern region of the Australian Murray-Darling basin grapegrowing region.

Thompson Seedless grown in a wide range of climatic conditions in California varied in the time between budburst and anthesis from 375 to 450 growing degree days (GDD) (Williams et al., 1985a). This is significantly higher than the range of 273-326 reported here (Table 3.9) but more than the 200 GDD reported by Matthews et al. (1987) for Cabernet Franc in a cooler and more northerly site than any of those used by Williams et al. (1985a). The number of degree days from budbreak to maturity (20 °Brix) for the four years reported here ranged from 1244 to 1467 (average 1390) although there was a difference of less than 60 units between the last three years. This range is mid-way between the region 3 and 4

Table 3.9 Duration in days and cumulative growing degree 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	Days	40	62	36	138
	GDD	273	591	380	1244
1992-93	Days	49	61	44	154
	GDD	326	623	518	1467
1993-94	Days	48	56	50	154
	GDD	309	564	567	1440
1994-95	Days	41	64	29	134
	GDD	293	776	342	1411
Average	Days	45	61	40	146
	GDD	224	639	454	1390

data reported by McIntrye et al. (1987). The number of degree days from bloom to maturity are also similar to that reported by McIntyre et al. (1987) for a region between III

and IV (Winkler et al., 1974). There was however considerable variation around the mean which these authors suggested was an indication of one of the limitations of the day-degree system. Several authors have proposed an upper threshold level above which heat accumulation should be ignored, for example, McIntyre et al. (1987) suggested discounting any heat accumulation above an upper threshold in the range of 32 to 40 °C and Gladstones (1992) recommended an upper temperature threshold of 19 °C. Use of an upper threshold with temperature data from the Waikerie experiment did not reduce the error in predicting phenological events (data not shown).

3.4.2 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. Naor et al. (1993) similarly reported no effect of post-veraison irrigation treatment on shoot length.

Shoot length of unirrigated vines was less than all other treatments by about a month after bud-burst which is earlier than the 40 days reported by Kliewer et al. (1983) but later than Vaadia and Kasimatis (1961) who measured shorter shoots about a week after bud-burst. The shoot lengths measured in the study reported here are shorter than those reported by Naor et al. (1993), Kliewer et al. (1983) and Vaadia and Kasimatis (1961).

The maximum rate of shoot growth of about 2.7 cm per day occurred before anthesis and then declined. Van Zyl (1984) reported the highest daily rate of shoot growth (between 3 and 3.5 cm per day) between budburst and anthesis after which time the daily rate declined for all irrigation treatments. Smart and Coombe (1983) suggested the decline in the rate of shoot growth after anthesis was because of an interaction with developing fruits. Matthews et al. (1987) reported a daily maximum rate about 2 weeks after anthesis of 4.4 cm per day and a significant slowing in the rate of extension after about 500 degree days. The near linear increase in shoot length between budburst and about 300 GDD in each year in the Waikerie experiment also indicated the critical role of the rise in daily temperature in

shoot elongation. In 1991-92 and 1993-94 there was a gradual slowing in the rate of increase after 300-350 GDD while in 1992-93 shoots continued to increase in length to about 700 GDD which is greater than the 600 GDD after budburst on non-stressed vines reported by Williams et al. (1992).

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.

3.4.3 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. Comparison of Figures 3.12 and 3.13 indicate that as early as about 20 to 30 days after anthesis in 1994-95 the weight of berries on fully irrigated vines was lower than in 1993-94 and, by about forty days after anthesis, there was 0.18 g difference in berry weight which increased to about 0.34 g per berry at 90 days after anthesis and was maintained to day 120. A similar trend was observed for all other treatments. While water stress may account for some of this difference, higher daytime temperatures during the period after anthesis in 1994-95 may also have been a contributing factor. From about 10 days after anthesis the daily maximum temperature during Spring

1994 was significantly higher on many days compared with the previous year. From about day 11 to 16, 21 to 26, 29 to 40 and day 41 to 50 the daily maximum temperature was significantly higher with some days up to 17 °C hotter. Thirty one of the first 50 days after anthesis were, on average, 8 °C hotter in 1994 than the corresponding period in 1993. Kliewer (1977) reported a significant reduction in the berry weight of Carignane vines when day-time temperature was held at 35 or 40 °C instead of 25 °C between noon and 8 p.m. Cabernet Sauvignon berries sampled from vines growing in controlled temperatures greater than 32.5 °C were significantly lighter about 30 days after anthesis than berries on vines grown at 25 °C (Kliewer, 1977) further the berries of Tokay vines grown at 40 °C had fewer cells and, between about 30 and 50 days after anthesis, cells were also smaller (although this difference was not significant after veraison). Kliewer (1977) demonstrated that returning vines to normal temperature conditions between 9 and 18 days after anthesis did not result in any compensatory increase in weight when measured 90 days later. The day temperature above which berry size is reduced appears to be about 30 °C as the berries of Cabernet Sauvignon vines grown at 30 °C day/15 °C night were no different in final berry size to a 20 °C day/15 °C night regime treatment (Buttrose et al., 1971). Although the vines used in the Waikerie experiment were not subjected to constant temperature greater than 32.5 °C it is possible the lower berry weights recorded during 1994-95 were induced by higher temperature after anthesis.

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. The 20 percent loss in berry weight of fully irrigated vines between the maximum and final sampling is nearly twice that reported by Smart et al. (1974) for well irrigated vines of the same variety in a climatically similar environment. Withholding irrigation between veraison and leaf fall resulted in about a 26 percent loss in berry weight (Smart et al., 1974) which is similar to the 23 percent loss for the veraison-harvest deficit treatment (Trt 7) reported here even though the latter were about 20 percent lighter at the commencement of the period during which berries lost weight. Kliewer and Weaver (1971) did not report any loss in berry weight of Tokay grapes with increasing °Brix but this may have been because sampling stopped at about 20 °Brix. Freeman and Kliewer (1983) reported that maximum weight of Carignane berries occurred about 100 days after anthesis and in some cases there was a subsequent loss in weight, which they suggested was a result of water loss during the latter stages of ripening. It is not possible to

determine if the loss in berry weight occurred in other seasons as only data from one season were reported. Loss in berry weight occurred in each of the four years of the Waikerie experiment and began earlier than the 100 days reported by Freeman and Kliewer (1983). 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.

Berry weight at about day 90, combined with data on percent berry weight loss and previous knowledge of bunch number and berry number per bunch could be used as an indicator of potential yield. This method may be an improvement on current yield estimation procedures which are often inaccurate if carried out prior to the occurrence of maximum berry weight or, if done later in the season, are often too close to harvest to be of benefit.

The synchrony of the loss in weight after day 91 and the rise in °Brix, and the changes in solute accumulation and secondary metabolite concentration are highlighted in Chapters Four and Five.

Timing of water deficit on berry growth

Berry weight was most sensitive to water deficit during the period after anthesis (Trt 2) with up to a 15 percent decrease in berry weight despite only moderate water deficit. Water deficit during the pre-veraison period (Trt 3) reduced berry size but not to the same degree as Trt 2. The combination of Trt 2 and 3, i.e. anthesis-veraison deficit (Trt 6), resulted in an additive effect of Trt 2 and 3 on berry weight in 1994-95. At maximum berry weight in early February 1994, Trt 2 berries were 0.27 g lighter than fully irrigated, Trt 3 berries 0.08 g lighter and Trt 6 berries, 0.36 g lighter than fully irrigated. The return to the same irrigation regime as fully irrigated (Trt 1) at the end of each of these deficit periods did not result in a compensatory increase in berry weight. Similarly, Van Zyl (1984) showed that re-application of water after stressing field-grown vines between flowering and the

beginning of lag phase did not result in a compensatory increase in berry weight at harvest. Shiraz berries were responsive to irrigation immediately after the lag phase as is evident by the rapid rate of berry weight increase when water was reapplied about 60 days after anthesis in 1994-95 (Figure 3.13). Re-application of water to Shiraz vines that were stressed between bud-break and veraison (Smart et al., 1974) did not result in a compensatory increase in berry weight and the alleviation of drought conditions during stage III of berry growth did not result in an increase in the weight of Müller-Thurgau berries and only a slight increase in the weight of Bacchus berries (Eibach and Alleweldt, 1985).

The responses reported here on the effects of water deficit after anthesis concur with those of Alexander (1965) who suggested that, for approximately four weeks after flowering, grape berries were extremely susceptible to water stress and that this was then followed by a resistant period. Stressing field-grown vines between flowering and the beginning of the lag phase by reducing plant available moisture to about one-third of the control significantly reduced berry weight (Van Zyl, 1984) and withholding irrigation water between budburst and veraison (Smart et al., 1974) resulted in a 60 percent reduction in the maximum berry weight compared with berries from non-stressed vines. The imposition of severe water stress on container grown Cabernet Franc vines (Hardie and Considine, 1976) significantly reduced yield regardless of the timing of the stress. They showed that stress during anthesis decreased yield by reducing fruit set while stress either before or after the lag phase decreased yield by reducing berry weight, water stress during the lag phase had only a minor effect on yield. The stress levels imposed by Hardie and Considine (1976) were however probably much higher than those endured by the field-grown vines used in this experiment and may not be comparable. In a similar pot experiment, Reynolds and Naylor (1994) reported a significant reduction in berry weight with early irrigation deficits and that decreasing soil water holding capacity by changing the proportion of sand in the potting mixture increased berry weight. It was suggested these berry weight increases were due to an increased carbohydrate supply to the berries as there were fewer competing lateral shoots (Reynolds and Naylor, 1994). Shielding rain from field grown Concord vines in New York State between bloom and harvest (Poni et al., 1994) had no effect on berry diameter although this may be accounted for by the minor difference in soil water content between the unshielded/irrigated plots and the shielded plots before veraison.

Harris et al. (1968) calculated that Sultana berry pericarp growth is the product of cell division and cell expansion for about 25 days after anthesis, and thereafter is due to cell expansion. Matthews et al. (1987) suggested the smaller size of berries from early season water deficit plots was due to a reduced number of cells per berry. The results of the present experiment are consistent with a reduction in berry weight by post anthesis stress (especially evident in 1994-95) caused by reduced cell division while the reduction in weight caused by pre-veraison stress, again most evident in 1994-95, was probably the result of reduced cell expansion. Although cell number per berry may have been reduced by post anthesis water stress, subsequent cell enlargement was not impeded by water deficit as vines were fully irrigated up to harvest. As the volume of mesocarp cells can increase by 300-fold or more during berry enlargement (Coombe, 1976) it seems more likely that the capability of the exocarp to expand may have limited a compensatory increase in berry size rather than the ability of each cell to expand.

Water stress during the ripening stage of Colombar grapes influenced berry weight in only one of the three years of an experiment reported by Van Zyl (1984) who suggested careful scheduling of irrigations was necessary to ensure berry shrinkage did not occur during this final stage of berry development. Ceasing irrigation four weeks before harvest had no effect on the weight of Anab-e-Shahi grapes (Chittiraichelvan et al., 1987) although no details of soil water content were presented. The effect of post veraison water deficit (Trt 4) on Shiraz berries in the Waikerie experiment was temporary as re-application of water during 1991-92 resulted in berries being similar in weight to fully irrigated during the final three weeks; however there was an initial slowing in the rate of increase in berry weight after the water deficit was applied. When irrigation water was withheld from about veraison to harvest on Thompson seedless grapevines growing in the hot Central Valley of California there was a significant decrease in berry weight compared with 'late pre-harvest cut-off' (Christensen, 1975, P. Christensen - pers. comm, 1996). Berries of the 'early season cut-off' treatment were significantly lighter about 25 days after the last irrigation which suggests they may have been lighter prior to this. The reduction in berry size was not significant until the third season and the effect was greater on sandy soil with a low water holding capacity than on a deep sand loam with a large water holding capacity (Christensen, 1975). The 'early cut-off' treatment used by Christensen (1975) was similar to the veraison-harvest deficit treatment (Trt 7) for only the 1994-95 season of the experiment reported here as, in previous years, a single irrigation was applied mid-way between

veraison and harvest. At harvest in the 1994-95 season the berries of the veraison-harvest deficit treatment were 14 percent lower than fully irrigated. Christensen (1975) suggested that reduced photosynthetic capacity due to the predominance of old leaves or to stomatal closure may have been the cause of smaller berries, however this may also have been associated with the effect of high water deficit on bunch primordia.

The treatments used in the experiment reported here permitted further discrimination of the pre- or post veraison treatments used by Matthews et al. (1987). These authors found that fruit growth was inhibited by early and late season water deficits that developed when irrigation water was completely withheld either before or after veraison on vines growing in a shallow, gravelly loam-sand near St. Helena in the Napa Valley, California; berries exhibited a double-sigmoidal growth curve irrespective of the timing of the water deficit and there was a greater yield decrease associated with early deficits than with late deficits. In the experiment reported here the susceptibility of berry growth to water stress in four periods as well as the soil matric potential required to effect these responses have both been quantified. A crop susceptibility factor (CS), based on yield susceptibility to water deficit during different stages of development was developed by Hiler and Clark (1971) to quantify the effect of water stress at different stages on plant growth of grain sorghum and peanuts. They derived CS values of between 0.7 and 3.7 for peanuts between anthesis and late nut development. The period from anthesis to early pegging was 5 times more sensitive to water stress than during late nut development. There was a similar range in the CS value for different stages of development of grain sorghum. Although derived in a different manner to that of Hiler and Clark (1971), the slopes of the fitted lines in Figure 3.16 and Table 3.4 can be taken to represent the CS factors for Shiraz berries under the conditions of this experiment and are summarised in Table 3.10.

Table 3.10 Berry weight susceptibility to water deficit during four different growth stages as a percentage of fully irrigated.

Growth stage	Berry susceptibility factor (percent change in mg berry wt /mm soil water deficit)
Post anthesis	24
Pre-veraison	11
Post veraison	9
Pre-harvest	-2

Berry weight was most sensitive to water stress during the post anthesis period and least sensitive during the pre-harvest period. Water stress either before or after veraison had intermediate effects on berry weight. While these CS values are specific to this experiment they may be applicable to other sites. The low CS factor for the pre-harvest period was associated with a period of loss in berry weight irrespective of irrigation treatment. This may only apply to cv. Shiraz but warrants further investigation with other varieties.

The relative susceptibility of shoots and berries to water stress during each of the four stages used in this experiment could not be adequately determined, due in part to different methods for quantifying the responses. The effect of water stress on berries was assessed by the reduction in berry weight whereas, with shoots, length was measured. In addition shoot length was not measured in the final year of the experiment when the highest post anthesis and pre-veraison soil water deficits accumulated. As previously reported, shoot growth normally slowed towards veraison at this site, consequently the effect of water stress on shoots after veraison could not be determined. Van Rooyen et al. (1980) reported that during phase I the percent available moisture required for 'optimum' shoot growth was similar to that required for 'optimum' yield. During phase II higher water availability was required for shoot growth than berry growth. Data presented here indicate nearly a two-fold difference in berry sensitivity to water stress within phase I and a similar phenomenon may exist for shoot growth. An experiment to test this would be difficult involving non-destructive and possibly destructive measurement of both berries and shoots on test vines under a range of soil water deficit over defined periods.

Soil water tension and berry growth.

Calculation of soil water tension permitted a wide comparison with the results of other published experimental work. For example in the Waikerie experiment soil matric potential between about -0.45 and -0.8 MPa was necessary to reduce berry weight during the post anthesis period compared with fully irrigated. These values are similar to Godoy Avila (1985) who suggested that irrigation should be applied during berry development when soil matric potential was less negative than -0.5 MPa. During the pre-veraison period a soil matric potential of about -0.55 MPa was necessary to reduce berry weight which is more negative than the -0.31 MPa for drip irrigated Cabernet Sauvignon vines of Goodwin and Macrae (1990). The period immediately after veraison was more sensitive than the

period before harvest (Goodwin and Macrae, 1990) which accords with the data presented here that showed a rootzone soil water tension of -1.2 MPa before harvest had no effect on berry weight. Peacock et al.(1987) reported no effect on berry weight when soil matrix potential at 120 cm was -60 kpa during the growing season. An average soil matric potential of -0.31 MPa within the rootzone of drip irrigated Chardonnay vines had no effect on berry fresh weight (Goodwin and Jerie, 1989), this being less negative than the critical values presented here. Hardie and Martin (1989) recommended that rootzone soil matric potential be kept less negative than -80 kpa between fruit set and veraison and then, if water was limiting, be allowed to become more negative to -0.2 MPa between veraison and harvest. The objective of less negative critical points recommended by Hardie and Martin (1989) was to reduce vegetative growth, not berry growth, however, Neja et al. (1977) suggested that a soil matric potential more negative than -80 kpa was necessary for canopy control.

Data presented here indicate that berry weight is insensitive to variation in average rootzone soil matric potential of less than -0.5 MPa before veraison, and that soil matric potential more negative than -1.0 MPa may be necessary to reduce berry size after veraison. Shoot growth is reduced at less negative soil matric potential. These critical values may serve as an indicative guide to the soil matric potential necessary to reduce berry size, if that is the desired goal, but they need to be tested against direct measurement of soil matric potential, with other varieties and other climates and soil types. The deep soil profile in the Waikerie experiment resulted in the gradual development of soil water deficit; this may have permitted vines to adjust to increasing water stress as opposed to vines grown in a container or a shallow soil profile in which acute water stress can develop rapidly.

Yield

Yield per vine can be expressed in terms of its components, viz.:

Yield (kg) per vine = nodes retained x shoots per node x bunches per shoot x bunch weight (g) x 0.001.

Further,

Bunch weight (g) = {berries per cluster x berry weight (g)} + bunchstem weight (g)

Bunchstem weight is seldom reported and often the number of berries per cluster is calculated from cluster weight divided by berry weight.

In this experiment there was no difference in the number of nodes retained between treatments which was the same for the 1993-94 and 1994-95 season and in the latter year the number of shoots per vine was similar for Trts 1-7, i.e. the number of shoots per node were similar for these treatments. Although the difference in the number of bunches between treatments ranged about 30 per vine in 1993-94 to about 15 in 1994-95 (Table 3.6), it was not significant. There were about 30 more bunches per vine at harvest in 1993-94 than the following year when averaged for all 9 treatments. When expressed in the form of the above equation there was no difference in the number of bunches per shoot for Trts 1-7. The difference in bunch weight was due to differences in the number of berries per bunch and berry weight. With the exception of fewer berries per bunch for the two treatments that were stressed after anthesis in 1994-95 (Trts 2 and 6), there were no consistent treatment effects on the number of berries per bunch, bunch weight nor bunches per vine, ie the difference in yield for each year was primarily due to differences in berry weight. This however does not account for the significantly lower yield of veraison-harvest deficit vines (Trt 7) compared with fully irrigated in 1991-92 and 1994-95 (Table 3.7). The multiplicative effects of non-significant treatment effects on the components of bunch weight, bunch number and shoot number appear to account for the reported yield differences between Trts 1 and 7.

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 3.18). 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.

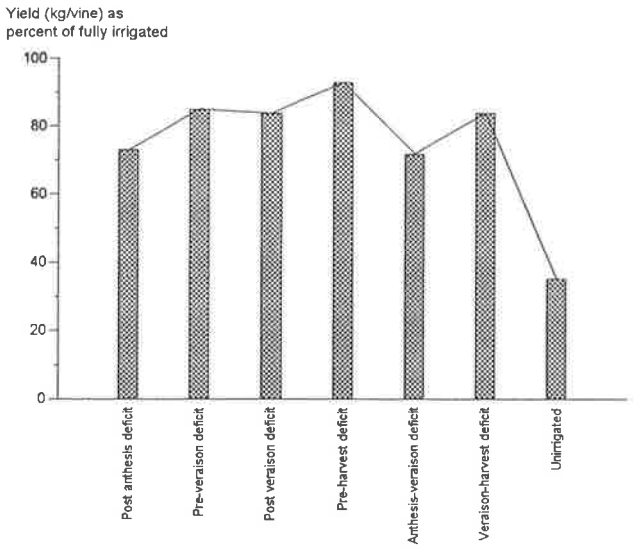

Figure 3.18 Yield, as a percent of fully irrigated, of treatments 2-8 at harvest in the 1994-95 season.

The absence of a treatment effect on bud fruitfulness corresponds to the findings of Matthews et al. (1987) who reported that all of the variation in yield between pre- and post veraison deficit vines were due to berry weight as there were no differences in the number of berries per cluster or clusters per vine. In a review of the effects of water stress on fruitfulness Smart and Coombe (1983) described inconsistent effects with both an increase and decrease in fruitfulness. Carbonneau and Casteran (1979) reported decreased floral initiation in Cabernet Sauvignon as a result of irrigation, albeit with the soil profile near to field capacity during the flower initiation period which probably resulted in vigorous shoot growth. Iland et al. (1995) demonstrated that the reduction in vegetative growth as a result of reduced irrigation in the experiment reported here resulted in higher levels of solar radiation in the fruit renewal zone. There was however no improvement in fruitfulness of basal buds suggesting that there may have been sufficient light within the canopy for optimum bud differentiation. Freeman et al. (1980) reported no consistent trend in bud fruitfulness on irrigated or unirrigated vines. Williams and Matthews (1990) suggested the absence of consistent effects of water deficit on fruitfulness may be due to the timing of the deficit in relation to the initiation of reproductive primordia and cited the data of Matthews and Anderson (1989) which showed a lowering of bud fruitfulness with pre-veraison deficit. The data presented here suggest the difference in soil water deficit around anthesis between fully irrigated and deficit irrigated vines was insufficient to result in a reduction in bud-fruitfulness in the following year.

The effect of water deficit on the number of berries per cluster and its effect on yield was apparent during 1994-95 and these data are consistent with data of Matthews and Anderson (1989) showing significantly fewer berries per cluster in the second year of an experiment on Cabernet Franc when vines were water stressed prior to veraison. Deficit irrigation of Chardonnay vines from budburst to after berry set did not reduce the number of berries per bunch (Goodwin and Jerie, 1989) although data for only one year were presented. As the number of berries per cluster is a function of both inflorescence number and the number of inflorescences that develop into berries, neither of which were measured in this experiment, the relative contribution of each cannot be separated. In the 1994-95 season soil water content of the anthesis-veraison and post anthesis deficit treatments fell below the refill line two and six days respectively after anthesis compared with, for example the 1991-92 season when soil water content was above the refill line for about 14 days after anthesis. This more rapid onset of water stress after anthesis may have reduced berry set, but in addition, there may have been some carry-over effects on the number of inflorescences per bunch from previous seasons

Bravdo et al. (1984) investigated the effects of irrigation and other treatments on the performance of Carignane vines, in particular, the relationship between wine quality and the ratio of vine yield to pruning weight (for which they coined the term 'crop load'). They proposed that wine quality declined, ie vines were overcropped, when the crop load exceeded 10-12. In further experiments with Cabernet Sauvignon Hepner et al. (1985) showed a positive correlation between crop load and quality of wines when the ratio was between 4 and 10. The ratio of crop load reported in Table 3.8 ranged from 10 to 18; in the 1993-94 season at Waikerie the ratio of all treatments was 15 and higher, and in 1994-95 the crop load of unirrigated vines was nearly 18 compared to 10.5 for the pre-harvest deficit vines. The weight of prunings removed was between 0.4 and 1.4 kg per vine in 1994-95 compared with 1.5 to 2.6 kg per vine reported by Bravdo et al. (1984) and Hepner et al. (1985). It seems unlikely that vines used in the Waikerie experiment were overcropped even though crop load values were high; the higher values were more likely the result of lower vine vigour as a consequence of lower fertiliser use. About 40 kg N/ha was applied annually in the vineyard used for the experiment reported here compared with 120kg N/ha reported by Bravdo et al. (1984).

3.4.4 Indices of plant water stress

Leaf water potential and stomatal conductance are regularly used in plant sciences to quantify water stress. Matthews et al. (1987) made the valid comment that many irrigation experiments on grapevines lack information on vine water status. They asserted that without quantifying plant water status it is difficult to extrapolate results from one climate to another or from one soil texture to another. These authors themselves failed to report data on soil water content. It is agreed that for the interpretation of the results from irrigation experiments, information on soil water content (mm/m) and soil matric potential are as important as plant water status and climatic conditions.

Leaf water potential

The diurnal pattern of leaf water potential (LWP) on fully irrigated vines during February 1992 was similar to that reported by Dundon and Smart (1984) for Shiraz vines in the same vineyard between veraison and harvest in 1978. The LWP of control vines measured by Dundon and Smart (1984) declined from about -0.4 MPa pre-dawn to about -1.5 Mpa between 15:00 and 18:00 hr then rapidly recovered towards sunset. In the present study LWP of fully irrigated vines immediately after dawn was in the range -0.45 MPa to -0.6 MPa and declined to about -1.4 MPa between 15:00 and 18:00 hr. In contrast to Dundon and Smart (1984) the LWP had fully recovered to post dawn levels by about 21:00 hr. LWP measurements on the 14 February 1992 were on vines that were due to be re-irrigated, and this accounts for the similar post dawn LWP of unirrigated and fully irrigated vines, the former being more severely stressed as shown by the more negative LWP during early afternoon. By the 1993-94 season, the pre-dawn LWP of unirrigated vines was always more negative than the other treatments measured. On 27 February 1992 irrigation was applied to Trt 1 (fully irrigated) vines after the post dawn readings however LWP decreased markedly during the morning and early afternoon when the maximum temperature was about 30 °C. Towards evening, fully irrigated vines recovered LWP more rapidly than stressed vines. Smart (1974) reported a similar response for irrigated Shiraz vines on a hot, cloudless day with LWP of both irrigated and stressed vines declining to about -1.6 MPa in the early afternoon.

The failure of high soil water content to minimise the diurnal pattern of LWP indicates that the transpiration rate exceeded the vine capacity to supply water to the leaves. A diurnal pattern was evident even on days when the vine root system was well supplied

with water, such as when irrigation was applied after pre-dawn readings. Data shown in Figure 2.17 indicated the soil water content of the majority of the vine root system rapidly increased after the start of an irrigation. Liu et al. (1978) reported vine roots to be the major resistance to water movement from the soil to stomates and Freeman (1983) suggested this was due to the low root density of grapevines. As root distribution and density was not determined in the Waikerie experiment the importance of root density in the diurnal pattern of LWP was not determined.

The LWPs of fully irrigated vines in the Waikerie experiment during berry ripening in the 1993-94 season are similar to the pre-dawn LWPs of irrigated Carignane vines in the experiment reported by Kliewer et al. (1983) although in the latter study leaves were wrapped in damp cheesecloth as they were excised from the shoot. The pre-dawn LWP of irrigated Carignane vines were -0.24 MPa and -0.12 MPa at harvest in two consecutive years and, although in the present study the least negative pre-dawn LWP of fully irrigated vines was recorded in late January-early February (-0.15 and -0.19 MPa), the values are similar.

The decreasing soil water content of Trt 7 (veraison-harvest deficit) during late January and early February resulted in more negative pre-dawn and post solar noon LWP. The single irrigation applied on 8 February 1994 resulted in pre-dawn LWP being similar to fully irrigated on 15 and 22 February, and 11 March with similar post solar noon readings on 22 February. There was however no significant correlation between soil water content or soil water tension and pre-dawn LWP. This may have been the result of an insufficient number of pre-dawn readings or the soil water content based on a single probe did not represent the true plant water availability. In contrast however, post solar noon LWP was linearly correlated, (r^2 = -0.56) with percent soil water content averaged over 120 cm soil depth but there was no significant correlation with the calculated soil matric potential. Smart and Barrs (1973) reported that, for grapes, up to 96 percent of the variation in the decline in LWP before midday could be attributed to solar radiation; soil water content resulted in only minor differences in midday LWP. Temperature and vapour pressure deficit had a significant effect on LWP when soil was either wet or dry while vapour pressure deficit had a significant effect on LWP only after an irrigation. Although all measurements were made on clear, sunny days the post solar noon temperature (13:00 hr) ranged from 23 to 40 °C, relative humidity from 50 to 20 percent and cumulative solar radiation from sunrise to 13:00 hr between 13.7 and 17.6 $Kw.m^{-2}$. It is suggested that these differences

may account for the lack of significant correlations between LWP and soil water status hence it is questionable whether LWP has merit as an irrigation scheduling tool in a region with large day-to-day changes in environmental conditions. Under such conditions, until a physiological measure that is better than LWP can be devised the routine measurement of soil water content will remain the most reliable method of irrigation scheduling.

Stomatal conductance

The effects of irrigation deficit on stomatal conductance was confounded by the high variability between readings on leaves on the same vine within a plot. No correlations were found between stomatal conductance and yield as were reported by Grimes and Williams (1990) nor between stomatal conductance and leaf water potential. Variability in stomatal conductance data collected on days that leaf water potential was also measured was too large to be of use and only data from 2 days during 1994 indicated treatment differences. In view of the high variability associated with measurement of conductance on leaf areas of less than 1 cm^2, Düring and Loveys (1996) recommended that five to ten readings at different locations on the same leaf be made. In this experiment a single reading was taken on each of four to six leaves on a single vine in each plot using a porometer cup with a contact area of 0.56 cm^2. On the two days that there was a pattern in the change of stomatal conductance during the course of a day, conductance rose during the morning and declined during the afternoon with stressed vines showing a more rapid decline in conductance than non-stressed. The rate of stomatal conductance was within the range previously reported for field grown vines, for example, Naor et al. (1994). Although inconclusive, the stomatal conductance data indicate that during periods when irrigation was withheld significant plant water stress developed; further that unirrigated vines were probably subjected to continuous water stress.

3.5 Conclusions

a. *The date of budburst, anthesis and veraison was not influenced by irrigation deficit.*

b. *The shoots of fully irrigated vines stopped growing by veraison in each year. Irrigation deficit during the post anthesis period reduced shoot length in three of the four seasons. Shoots on unirrigated vines were short and in the last year of the experiment stopped elongating soon after anthesis.*

c. *Leaf water potential was more negative and stomatal conductance of leaves on deficit irrigated vines was lower than fully irrigated vines when compared over the course of a day or season.*

d. *The growth of Shiraz berries exhibited a normal double sigmoidal development until a maximum weight was reached midway through ripening, followed by a marked loss in weight towards the end of the season. The onset of loss in berry weight occurred 91±3 days after anthesis in all treatments and years and, by harvest, about a 20 percent loss in weight had occurred.*

e. *The berries of unirrigated vines were always the smallest, especially in year 4 when they were about half the weight of fully irrigated at harvest.*

f. *An index of berry susceptibility to water stress was developed which showed that Shiraz berries were sensitive to water deficit during three of the four stages of development examined. Post anthesis water deficit (the pericarp division stage) reduced berry weight throughout their growth. Water deficit during the post veraison period reduced berry weight but the effect was sometimes transient. Berries were insensitive to water deficit during the pre-harvest period.*

g. *Water deficit during any of the four stages of berry development reduced yield, however there was no effect of irrigation deficit on the number of shoots per vine or bunches per shoot.*

h. *Harvest date (23.5 °Brix) of fully irrigated vines varied by four weeks over the four years. There was a difference of up to three weeks in the harvest date of treatments within a year, unirrigated plots were the first to be harvested in three seasons and fully irrigated were the last in two seasons.*

Chapter Four - Effect of timing of water deficit on grape berry ripening

4.1 Introduction

The effects of water deficit on grapevines and berry composition were reviewed by Smart and Coombe (1983), Williams and Matthews (1990) and Jackson and Lombard (1993). In this review emphasis is given to the irrigation responses most relevant to the Waikerie experiment.

The sugar content of winegrapes at harvest is important as it determines the alcohol content of the wine when fermented to dryness and hence affects aspects of wine quality. In their review, Smart and Coombe (1983) concluded that irrigation can increase or decrease the sugar concentration of grapes although the differences are less than 10%. The most widely recorded effect of irrigation on grape berry ripening is a delay in the rise in sugar concentration, although, the total sugar production per hectare is often much enhanced. In districts where there is adequate solar radiation and low disease risk during autumn a delay in maturity caused by irrigation is of little consequence as the grapes can be left longer to ripen. In contrast, in regions of low solar radiation, such as in high latitudes, a delay in harvest date caused by irrigation is a disadvantage because of the risk of adverse weather predisposing the vine to disease and leaf abscission.

Irrigation invariably increases berry size which reduces berry sugar concentration, but increases the sugar content per berry. On the other hand water stress may reduce berry size and sugar concentration may increase with no change in sugar content per berry. With judicious irrigation it is possible to increase yield with no effect on sugar concentration; for example, the application of 33 percent more water than the ET_{vine} over the full growing season resulted in heavier berries at harvest (albeit not significantly heavier than the control) in two seasons but reduced the °Brix of Thompson Seedless berries in only one of two seasons (Peacock et al., 1987). Excessive water stress may result in defoliation which delays maturity and weakens the vine. For example, Williams and Grimes (1987) reported the lowest soluble solids concentration in Thompson Seedless berries from vines that received the least amount of water and Hardie and Considine (1976) reported fruit from stressed vines growing in lysimeters took longer to reach the same ripeness as well irrigated vines. The yield of unirrigated Cabernet Sauvignon vines growing in a summer drought region in Spain was about 20 percent lower than those given 25 L water each fortnight and

the rate of °Brix accumulation in unirrigated berries was lower (Nadal and Arola, 1995). Irrigated berries were lower in tannin and anthocyanin concentration compared with unirrigated vines.

The timing of water stress determines the effect on °Brix. Water stress during phase II resulted in the greatest delay in maturity (Hardie and Considine, 1976). Water deficit applied either before or after veraison had no effect on sugar concentration when compared to well irrigated Cabernet Franc berries although the berries of the latter always had the highest sugar content (Matthews and Anderson, 1988). Water deficit during ripening significantly enhanced the sugar concentration of Colombar grapes which Van Zyl (1984) attributed to berry shrinkage as photosynthetic activity was only reduced by soil water deficit towards the end of the ripening period. Reducing the volume of irrigation applied to Sauvignon Blanc vines after veraison, brought a significant reduction in °Brix at maturity (Naor et al., 1993) however, plant water stress measures indicated that these vines were subjected to severe soil water deficit. In a New York vineyard planted to Concord the combined effects of heavy crop and late season water deficit significantly reduced the rate of increase in °Brix of grapes compared with either non-water stressed vines or water-stressed vines that were crop thinned (Poni et al., 1994). These authors (Poni et al., 1993) had previously reported that short periods of water stress (9 or 10 days) either before or after veraison had no effect on the °Brix or total soluble solids content per berry of potted Pinot Noir vines. It was suggested the lack of a significant difference between treatments was due to the short duration of each water deficit period, the high leaf to fruit ratio, and the complete recovery of photosynthetic activity following re-watering.

"Early season cut-off" of irrigation (no further irrigations after about veraison) had no effect on either °Brix or soluble solids content per berry in four of the five years of an irrigation experiment on Thompson Seedless grapes in the Central Valley of California (Christensen, 1975). In the final year of the experiment the berries from the "early season cut-off" were lower in °Brix and soluble solids per berry which the author attributed to the carry-over effects of reduced photosynthesis during berry ripening in each year. In a similar experiment in which irrigation was either reduced or ceased after veraison, Neja et al., (1977) reported that vines that continued to receive some irrigation ripened faster than unirrigated vines and they suggested the delayed ripening of unirrigated vines was the result of excessive defoliation. In summary, excessive soil water deficit during berry ripening will

slow the rise in sugar content per berry , however the effects of the timing and level of water deficit are still to be determined.

Irrigation often results in the development of a large leaf canopy causing fruit shading, which may in turn result in higher K^+ concentration, pH and malic acid in the berries. Wine with a high pH is more susceptible to bacterial spoilage and wine colour will be less stable. Fruit of irrigated Carignane vines had a higher K^+ concentration than unirrigated (Freeman and Kliewer, 1983) however there was no difference in the K^+ concentration of fruit from vines that were water stressed either before or after veraison (Matthews and Anderson, 1988). The K^+ concentration of wines made from Cabernet Sauvignon vines irrigated with either 220 or 400 mm water was similar (Hepner et al., 1985). In well irrigated Cabernet Franc vines at harvest malic acid concentration was higher than in fruit from vines which were water stressed before veraison (Matthews and Anderson, 1988). High malic acid, usually associated with higher titratable acidity in juice, increases the possibility of a malo-lactic fermentation which may, or may not, be desirable. Manipulation of vegetative growth with timing of irrigation may offer a method of minimising some of the undesirable effects on pH, K^+ and malic acid concentration.

Grapevines are sensitive to the salinity of the irrigation water and irrigation with medium or highly saline water requires efficient irrigation management and a leaching fraction to maintain soil salinity within acceptable limits. Prior et al. (1992) demonstrated that for grapevines, even when an adequate leaching fraction was applied, yield began to decline when $EC_{\text{irrigation water}}$ exceeded 0.4 dSm^{-1}. During periods of withholding irrigation (WI), when no irrigation water is applied, EC_e (soil water extract) rises as the soil profile dries. During periods of RDI, although some irrigation is applied, it is normally insufficient to cause any leaching of the rootzone and consequently EC_e would again be expected to increase. RDI, in conjunction with the use of irrigation water which ranged from 0.25 to 1.0 dSm^{-1} resulted in a significant increase in the chloride concentration of the petioles and fruit of peach trees (Boland et al., 1993). Fruit yield per tree was significantly reduced in year two when RDI and 1.0 dSm^{-1} irrigation water was applied. In irrigated vineyards of the Murray-Darling basin of Australia irrigation water is generally less than 0.5 dSm^{-1}, although it can rise to 1.0 dSm^{-1} during times of low river flow. By comparison, in grapegrowing regions in Australia where underground water is used for irrigation, water salinity can be as high as 3.4 dSm^{-1} (Cass et al., 1996), consequently any interaction between RDI and water salinity will be critical. This applies particularly to the uptake of

sodium and chloride into fruit and wine. The uptake of chloride by grapevines into the berries is significantly higher before veraison than between veraison and harvest. For example, Stevens (1995) reported a 4.5 times greater chloride uptake rate between flowering and veraison than between veraison and harvest. The uptake rate for the period between bud-burst and flowering was similar to that during the flowering-veraison period. To reduce vegetative growth, RDI should be applied to grapevines prior to veraison, or during the period when uptake of sodium and chloride is high. The Waikerie experiment provided the opportunity to investigate the interaction between water deficit and chloride uptake by monitoring chloride content in ripening berries.

4.2 Materials & Methods

4.2.1 Berry sampling, grape juice preparation & analysis

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. From scattered bunches five berries were randomly plucked, two from near the top, two from near the middle, and one from near the bottom. A similar number of berries were collected from each of the three vines in each plot. Deformed and diseased berries were excluded and care was taken to ensure the berries were not excessively deformed during sampling. The berry samples were stored in plastic bags in a portable refrigerator until return to the laboratory. After harvesting the crop for yield determination and small-lot winemaking, berry samples were collected from a single unpicked vine in each plot.

The weight of fifty berries was recorded as described in Chapter 3.2 (page 58). In 1994 and 1995 these 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 squeezed in a small bench-top press and the extracted juice collected. Approximately 50 ml of juice from each plot was centrifuged at 3000 r.p.m. for 5 minutes. Ten ml of supernatant was pipetted off to determine pH and titratable acid. Juice pH was measured using a glass electrode and titratable acidity (g/L tartaric acid) by automatic end-point titration to pH 8.2 using 1.33 N sodium hydroxide. The pH metre was calibrated daily against pH 4.01 and 7.00 buffer standard solutions and the laboratory was maintained at about 20 °C air temperature. Total soluble solids concentration of the juice was measured using a constant temperature Atago(TM) Abbe refractometer standardised using 20 °C distilled water. Soluble solids concentration was expressed as °Brix at 20 °C. The °Brix of the homogenate used for calculating glycosyl-glucose content and concentration per berry (Chapter Five) was determined in a similar manner and these data were used to calculate solutes per berry and non-solute weight per berry (primarily water plus small amounts of non-soluble polymers).

Solutes per berry (Coombe 1980) were estimated by the formula:

(homogenate °Brix/100) x berry weight (g)

and Non-solute weight per berry (g) was estimated by the formula:

Berry wt – solutes per berry

The supernatant of a small sample of grape berry homogenate was used to determine chloride concentration by specific ion electrode.

4.3 Results

4.3.1 °Brix

Due to above average rainfall and disease during 1992-93, as detailed in Chapter Two, data on berry ripening for that year are only presented in summary. °Brix was the same for treatments 1-7 at all sampling times and was the same as unirrigated on four occasions (Figure 4.2). At other sampling times the berries of unirrigated vines were riper than treatments 1-7.

In other years 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. For example, in early February 1992 (Figure 4.1) berries from unirrigated vines were about 3 °Brix riper than fully irrigated, and anthesis-veraison deficit berries about 1.7 °Brix riper than fully irrigated. In the 1991-92 and 1994-95 seasons, post anthesis water deficit enhanced berry ripening compared with fully irrigated, however, there was no effect in 1993-94. This accorded with the response for the pre-veraison deficit treatment (Trt 3) with an enhancement in maturity in 1991-92 and 1994-95 but not in 1993-94. In 1991-92 the berries of the post veraison deficit treatment (Trt 4) were always similar to fully irrigated (Trt 1) and, although plotted in Figure 4.3, Trt 4 was only significantly riper than fully irrigated on one occasion in each of 1993-94 and 1994-95.

Although the °Brix curves of six treatments are presented in Figure 4.4 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 4.4). 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.

During 1991-92 and 1994-95 berries on fully irrigated vines were riper on the same number of days after anthesis than berries from the same plots in 1993-94 (Figure 4.5) 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. A line was fitted to the combined data (Figure 4.5); the fitted line was more similar to the 1991-92 data than the other two years, 1993-94 being slower and 1994-95 faster.

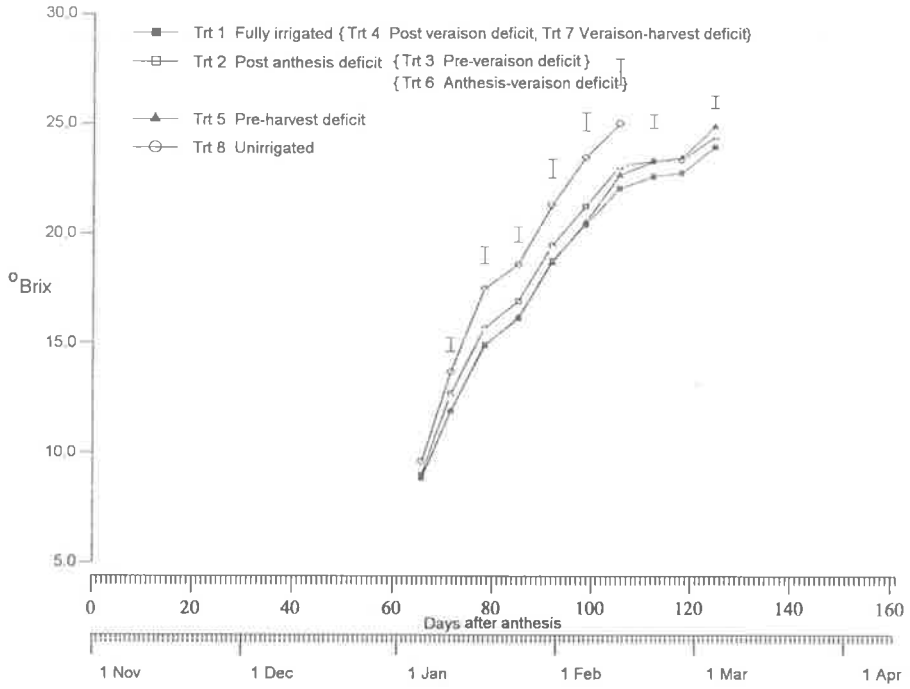

Figure 4.1 Increase in °Brix with time for the 1991-92 season.
Vertical bars indicate l.s.d.($p<0.05$) for each sample date. Bracketed treatments indicate those which were similar to plotted treatment at every sample date.

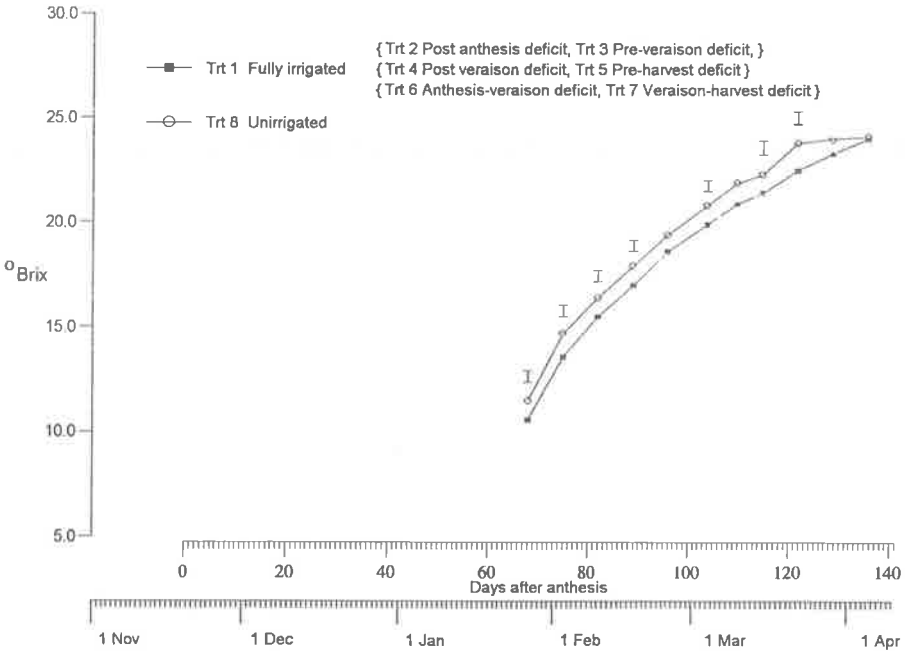

Figure 4.2 Increase in °Brix with time for the 1992-93 season.
Vertical bars indicate l.s.d.($p<0.05$) for each sample date. Bracketed treatments indicate those which were similar to plotted treatment at every sample date.

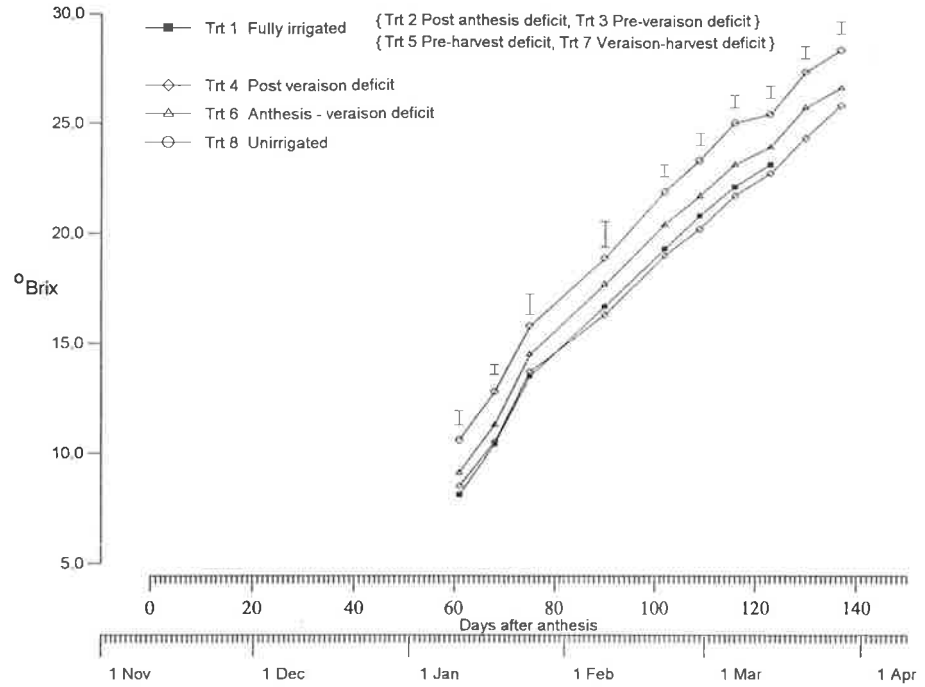

Figure 4.3 Increase in °Brix with time for the 1993-94 season.
Vertical bars indicate l.s.d.($p<0.05$) for each sample date. Bracketed treatments indicate those which were similar to plotted treatment at every sample date.

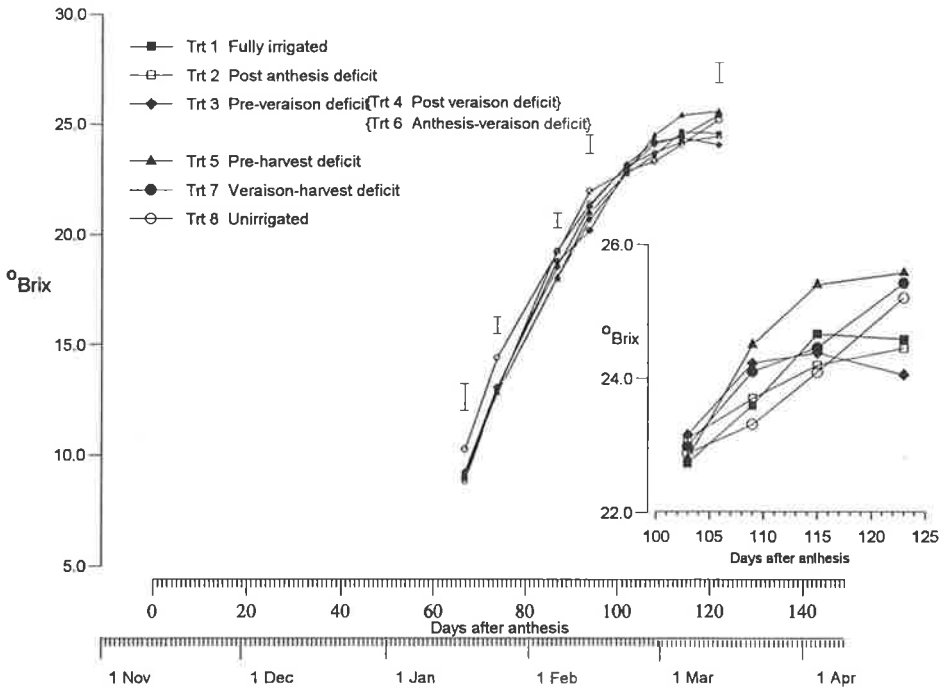

Figure 4.4 Increase in °Brix with time for the 1994-95 season.
Vertical bars indicate l.s.d.($p<0.05$) for each sample date. Bracketed treatments indicate those which were similar to plotted treatment at every sample date.

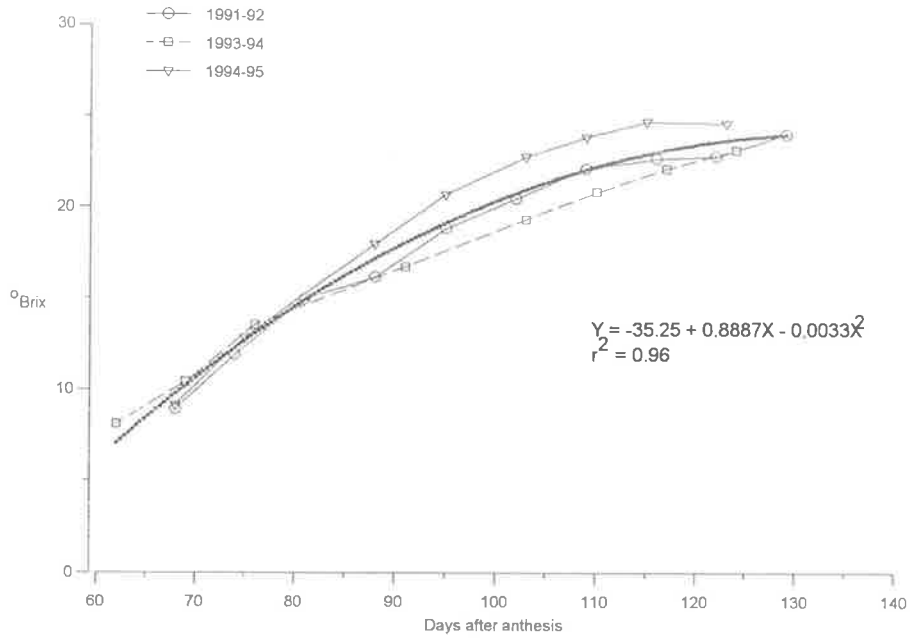

Figure 4.5 Relationship between °Brix of fully irrigated treatment vines and days after anthesis. The darkened line with no symbols represents the fitted non-linear function from the given equation for combined data for three years.

°Brix plotted against growing degree days (GDD) showed a similar trend to °Brix plotted against days after anthesis although treatments were not in the same order (Figure 4.6). In 1991-92 berries reached about 10 °Brix after about 650 GDD, in 1993-94 after about 700 GDD and in 1994-95 more than 800 GDD accumulated before berries of fully irrigated vines reached the same ripeness. There was a slowing in the rate of increase in °Brix with increasing GDD in 1991-92 and 1994-95 but no apparent slowing in 1993-94. Quadratic functions to describe the change in °Brix with GDD after anthesis were derived for each season (data not presented) and these showed a convergence of curves for two years at about 1100 GDD and a second convergence for all three years at 1280 GDD after anthesis when the berries were 23.5 °Brix. A quadratic function with a high coefficient of determination ($r^2 = 0.96$) was fitted to the combined data and the curve more closely followed the 1993-94 data than the other two years (Figure 4.6).

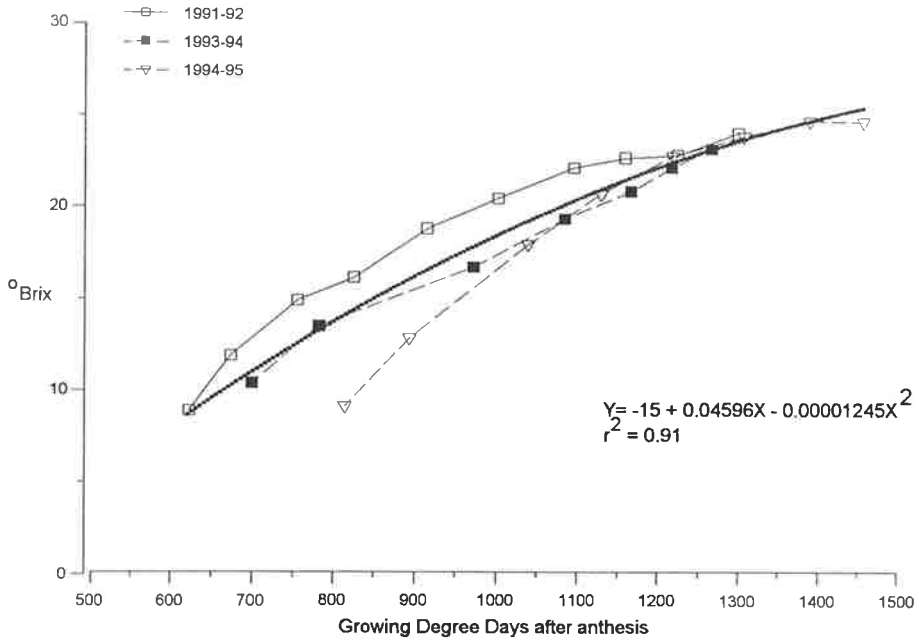

Figure 4.6 °Brix plotted against growing degree days after anthesis for fully irrigated vines. The darkened line represents fitted non-linear function described by the given equation.

4.3.2 °Brix versus berry weight

In Figures 3.10-3.13 berry weight was plotted against days after anthesis and in Figures 4.1-4.4, °Brix was also plotted against days after anthesis. In Figures 4.7 and 4.8, berry weight of all treatments for the 1993-94 and 1994-95 seasons are plotted against °Brix. In 1993-94 the average °Brix at maximum berry weight for Trts 1-7 was 16.8, ranging from 16.3 for the post veraison deficit treatment to 17.7 °Brix for the anthesis-veraison deficit treatment (Figure 4.7). Berry weight then declined steadily with increasing °Brix up to the final sampling with the most rapid decline in the post anthesis deficit treatment. The weight of unirrigated berries remained constant between about 19 and 23 °Brix then declined steadily to the final sampling time.

In 1994-95 the average °Brix at maximum berry weight for Trts 1-7 was 18.5 and 22 for unirrigated (Figure 4.8). 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.

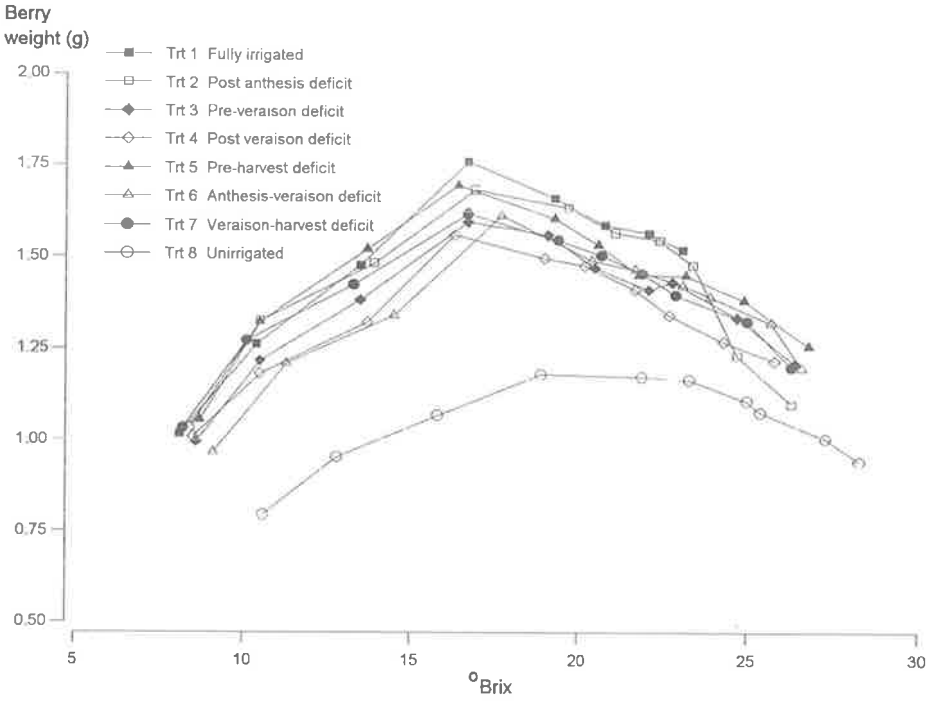

Figure 4.7 Relationship between berry weight and °Brix for all treatments during berry ripening during the 1993-94 season.

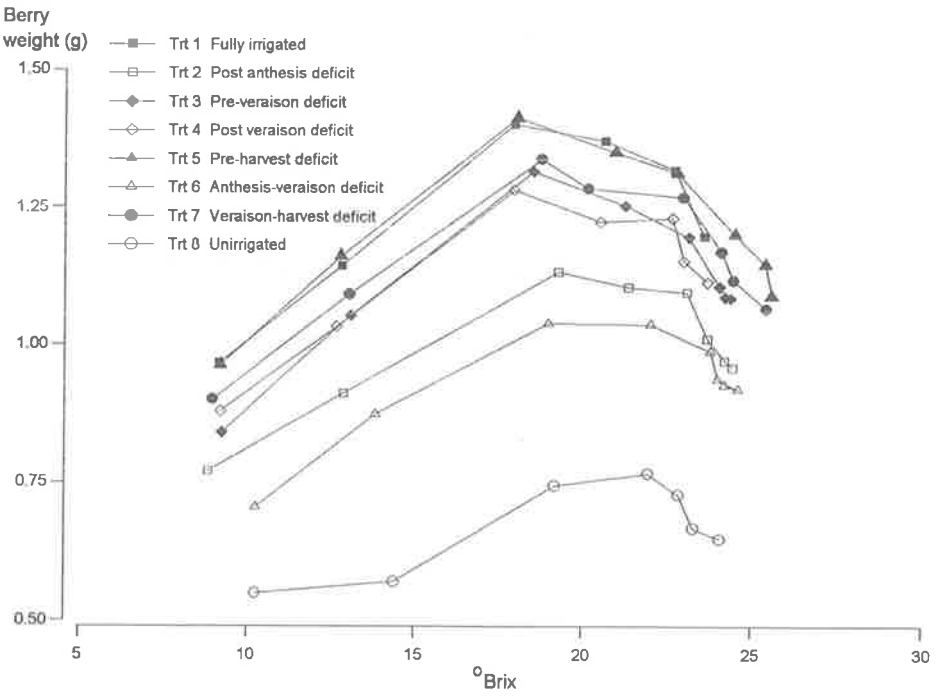

Figure 4.8 Relationship between berry weight and °Brix for all treatments during berry ripening during the 1994-95 season.

The average °Brix at maximum berry weight for treatments 1-7 in each of the four years are listed in Table 4.1 showing a range of about 17 to 19.

Table 4.1 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

4.3.3 Homogenate °Brix, solutes per berry, non-solutes per berry

There was a linear relationship between the two methods used to determine °Brix in 1993-94 and 1994-95 and the slope and intercept of the fitted lines were similar (Figure 4.9 and Figure 4.10). In 1993-94 the °Brix of homogenised samples was higher than that of the hand-expressed juice when the former was greater than about 16 °Brix. In 1994-95 homogenate °Brix was commonly greater than hand expressed juice and there was slightly more spread in the data than 1993-94, particularly at °Brix levels greater than 20 °.

Data on solutes per berry and non-solutes per berry against days after anthesis are presented only for selected treatments in Figures 4.11 to 4.14. The pattern of development of solutes per berry for other treatments was similar to fully irrigated. No statistical analysis of the data was attempted because of the varying number of samples per treatment available for the determination of homogenate °Brix. After an initial delay in 1993-94 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 (Figure 4.11); a difference was apparent at the third sampling time in 1994-95. 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 4.12). 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 4.12) was associated with a small increase in berry weight at this sampling time (Figure 3.13). Solutes per berry were calculated for the 1991-92 and

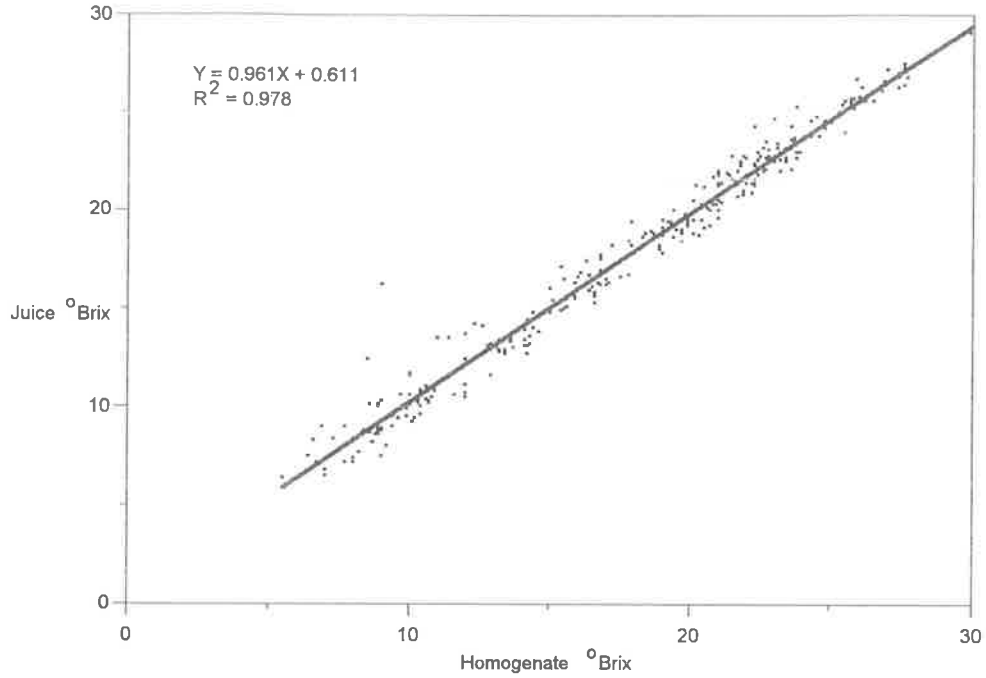

Figure 4.9 Relationship between °Brix of grape berry homogenate and expressed grape juice for selected samples from the 1994 season.
Line of best fit is described by the linear regression equation shown.

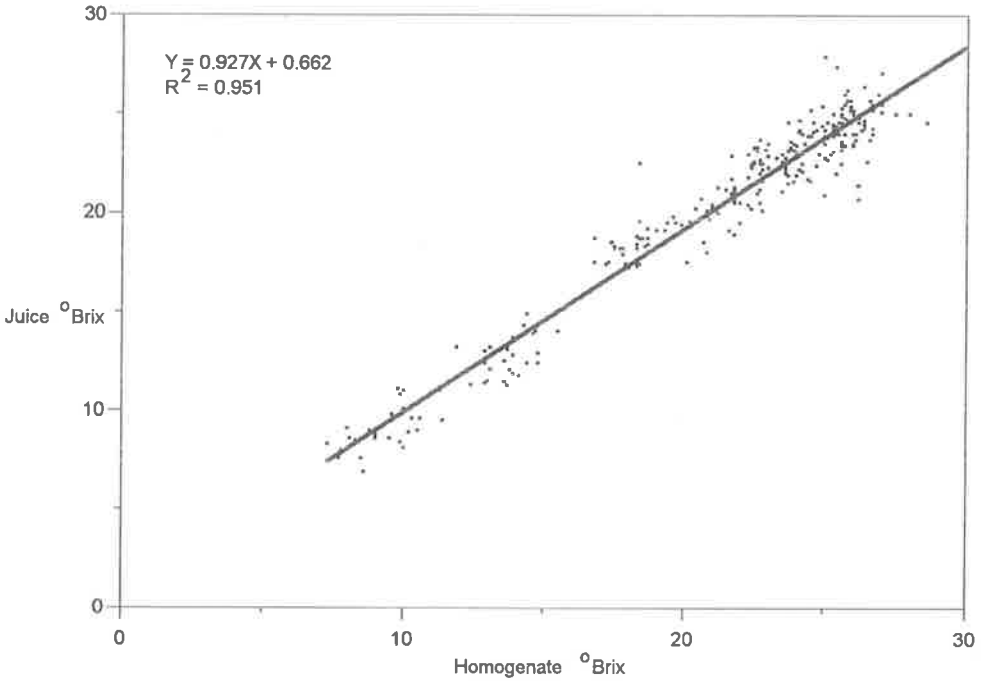

Figure 4.10 Relationship between °Brix of grape berry homogenate and expressed grape juice for selected samples from the 1995 season.
Line of best fit is described by the linear regression equation shown.

1992-93 season using °Brix of the hand-pressed sample as no homogenate samples were available. In both years (data not presented) solutes per berry of Trts 1-7 steadily increased to between 0.32 and 0.33 g per berry then remained constant for the final five weeks of sampling.

Non-solute weight per berry was the difference between berry weight and solutes and therefore is primarily water plus small amounts of non-solute polymers. Given the general plateau shape of the solutes development curves in Figures 4.11 and 4.12 it was unsurprising that the curves of non-solute weight (Figures 4.13 and 4.14) bear resemblances to those of berry weight shown in Figures 4.7 and 4.8. 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 4.13), and by the third sampling time in 1995 (or about 88 days after veraison) (Figure 4.14). 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 4.14) 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 (insufficient sample to determine homogenate °Brix) for the first two samplings on unirrigated vines (Figure 4.14) during berry ripening in 1995 make interpretation difficult but there was a decline in non-solute weight with increasing °Brix.

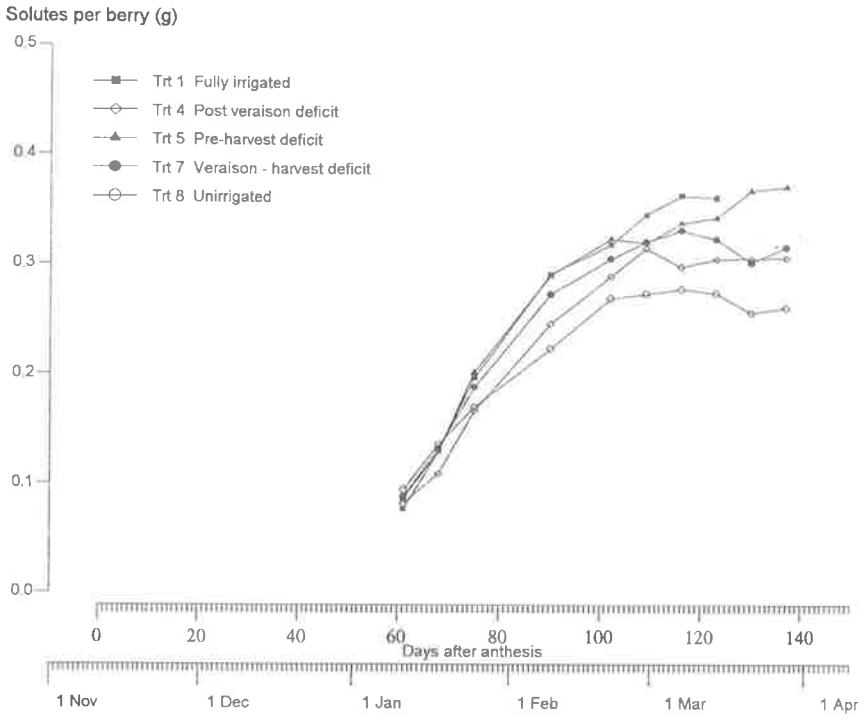

Figure 4.11 Solutes per berry for fully irrigated (Trt 1), post veraison deficit (Trt 4) pre-harvest deficit (Trt 5), veraison-harvest deficit (Trt 7) and unirrigated (Trt 8) treatments against days after anthesis during berry ripening in the 1993-94 season.

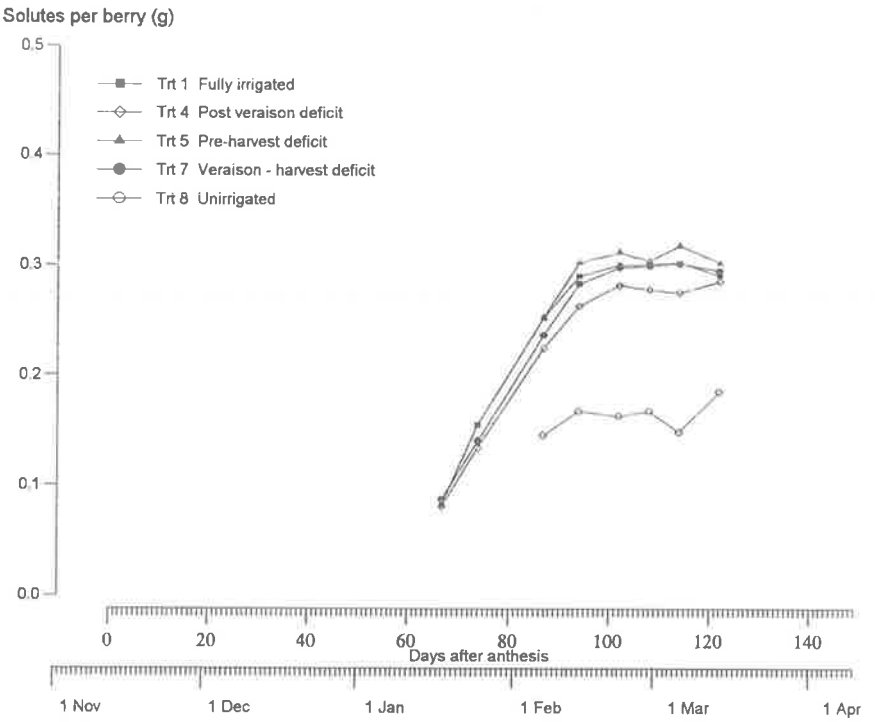

Figure 4.12 Solutes per berry for fully irrigated (Trt 1), post veraison deficit (Trt 4), pre-harvest deficit (Trt 5), veraison-harvest deficit (Trt 7) and unirrigated (Trt 8) treatments against days after anthesis during berry ripening in the 1994-95 season.

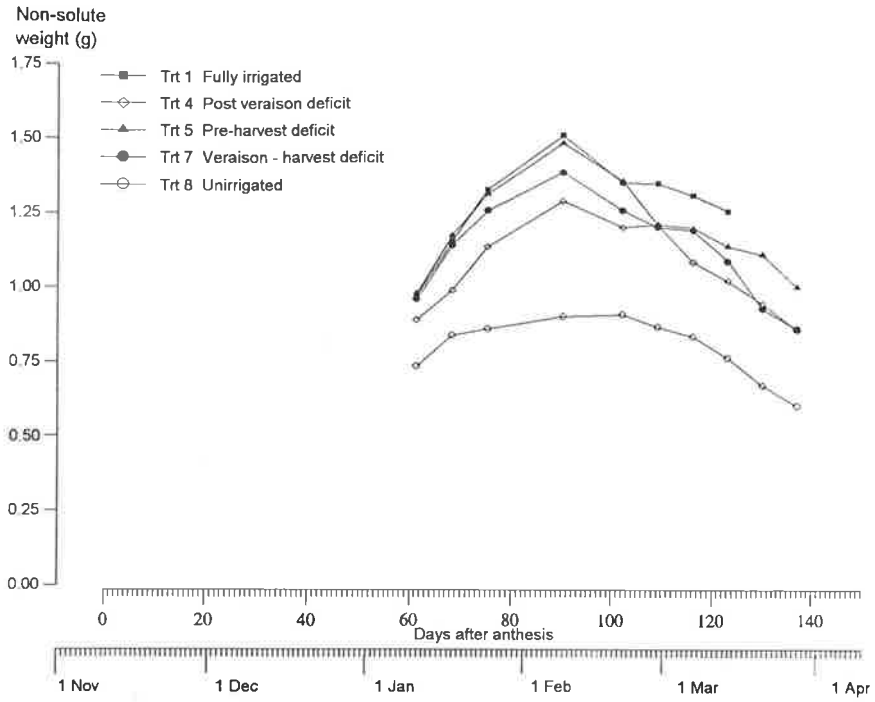

Figure 4.13 Weight of non-solutes per berry of fully irrigated (Trt 1), post veraison deficit (Trt 4), pre-harvest deficit (Trt 5), veraison-harvest deficit (Trt 7) and unirrigated (Trt 8) treatments against days after anthesis during berry ripening in the 1993-94 season.

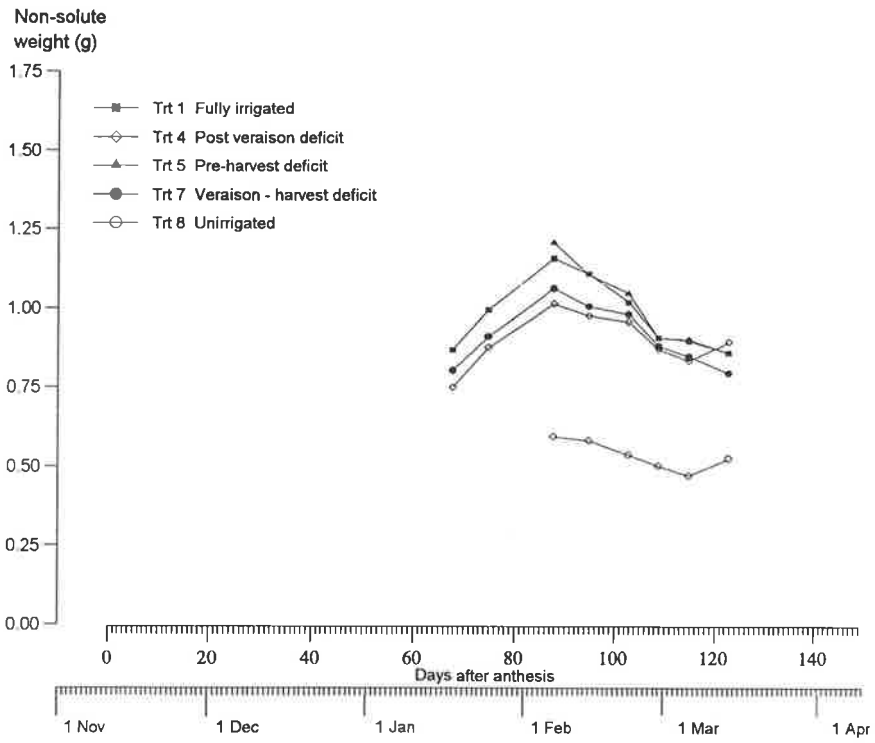

Figure 4.14 Weight of non-solutes per berry of fully irrigated (Trt 1), post veraison deficit (Trt 4), pre-harvest deficit (Trt 5), veraison-harvest deficit (Trt 7) and unirrigated (Trt 8) treatments against days after anthesis during berry ripening in the 1994-95 season.

4.3.4 Juice titratable acid

Data from the 1993-94 season are reported as they are typical of the response to irrigation deficit in the other three years. Titratable acid concentration declined rapidly from about 25 g/L to about 7 g/L between the first and fourth sampling time (Figure 4.15). Over the ensuing six weeks titratable acid only declined by about another 2-3 units. At all sampling times there were significant differences between treatments although the post veraison deficit (Trt 4), pre-harvest deficit (Trt 5) and veraison-harvest deficit (Trt 7) treatments were always similar to the post anthesis deficit treatment (Trt 2). More often that not, the berries of fully irrigated vines had the highest acid, although not always significantly higher, and unirrigated were always significantly lower than all other treatments.

To allow for differentiation between maturity and treatment effects, titratable acid was plotted against °Brix (Figure 4.16). Although the pattern of decline in titratable acid was similar to that in Figure 4.15, there was now no apparent treatment effect on titratable acid. Between the first sampling at about 8 °Brix and about 16 °Brix there were inconsistencies, however, once riper than 16 °Brix, the differences in titratable acid at a common °Brix were negligible and there was only a minor change in titratable acid between about 16 and 26 °Brix. Normal analysis of variance of titratable acid plotted against °Brix was not possible and, as there appeared to be only minor differences between treatments, no curve modelling was attempted. Analysis of covariance with °Brix as a covariate did not separate any consistent treatment effects (data not presented).

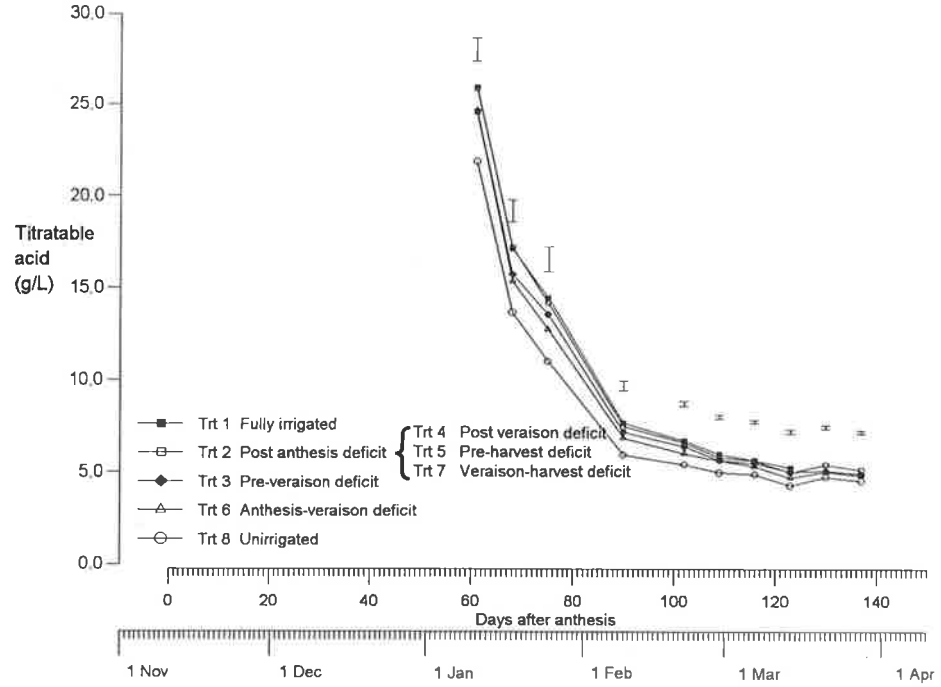

Figure 4.15 Titratable acid (g/L as tartaric acid) against days after anthesis during berry ripening in the 1993-94 season.
Vertical bars indicate l.s.d.($p<0.05$) for each sample date. Bracketed treatments indicate those which were similar to plotted treatments at every sample date.

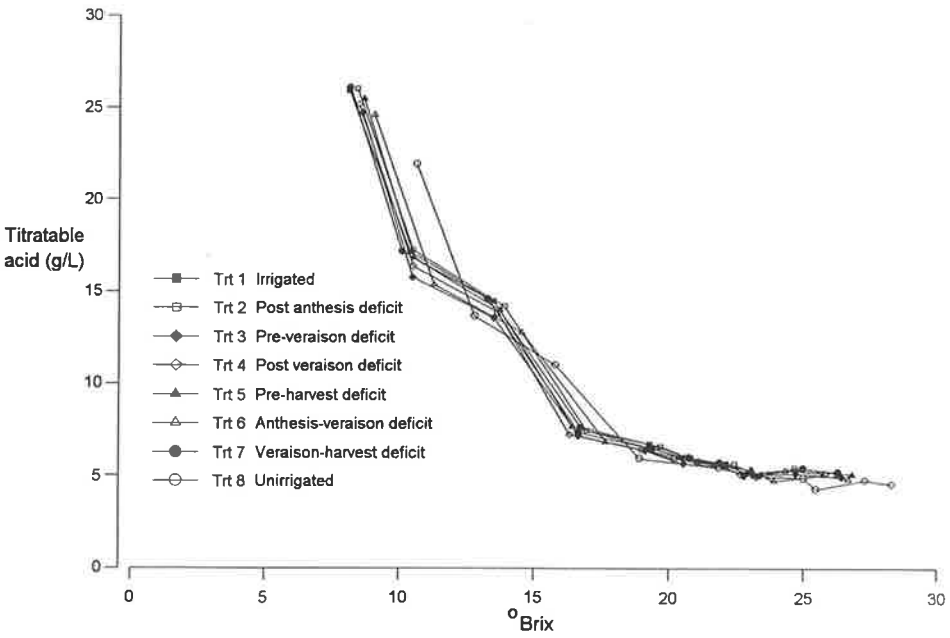

Figure 4.16 Relationship between titratable acid (g/L) and °Brix for all treatments during berry ripening in the 1993-94 season.

4.3.5 Juice pH

As was the case for titratable acid, only data from the 1993-94 season on the effect of irrigation treatment on juice pH are presented. The pH of juice of berries of unirrigated vines was significantly higher than other treatments at each sampling time (Figure 4.17) and irrigated the lowest although similar to pre-veraison, pre-harvest and veraison-harvest deficit treatment. The juice pH of post anthesis deficit and post veraison deficit treatment vines were also similar at each sampling time. When plotted against °Brix (Figure 4.18), treatment differences disappeared and there was an almost linear increase in pH between about 8 and 25 °Brix.

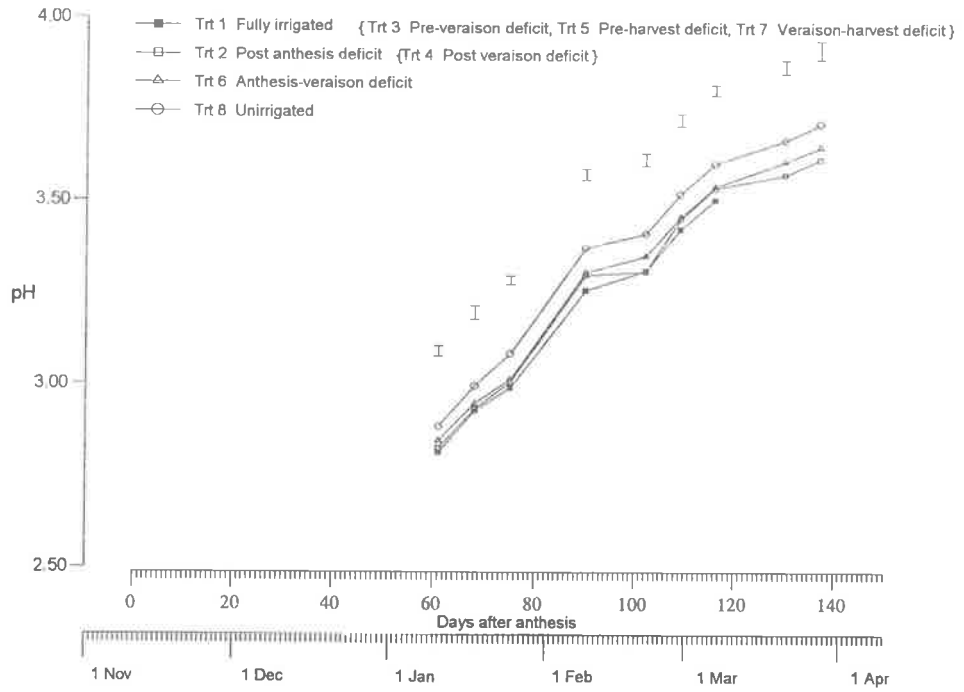

Figure 4.17 Increase in juice pH with days after anthesis during berry ripening in the 1993-94 season.
Vertical bars indicate l.s.d.($p<0.05$) for each sample date. Bracketed treatments indicate those which were similar to plotted treatments at every sample date.

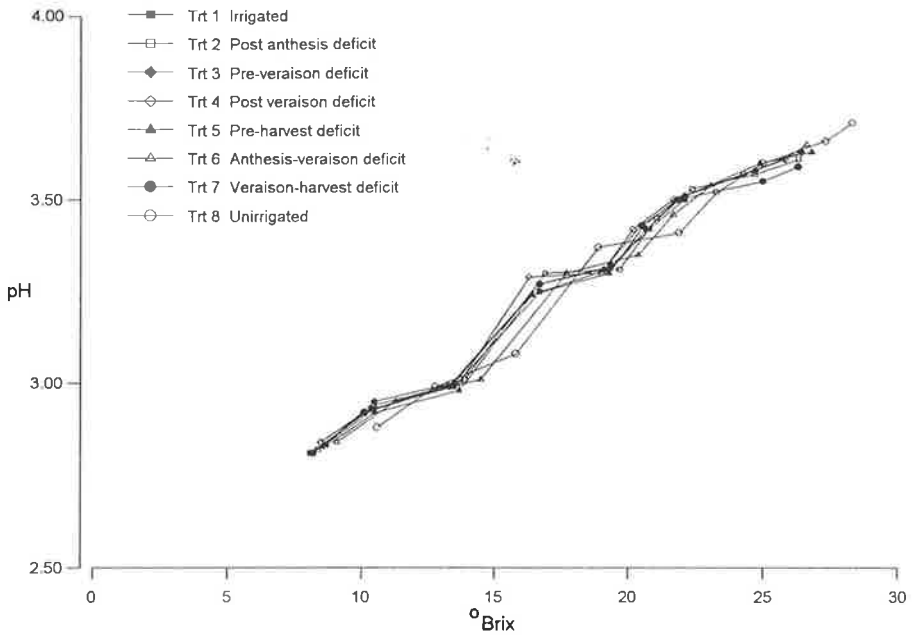

Figure 4.18 Relationship between pH and °Brix for all treatments during berry ripening in the 1993-94 season.

4.3.6 Homogenate chloride concentration

Homogenate chloride concentration was determined on 5 of the 9 field replicates and, as there were some random missing samples due to insufficient sample after G-G analysis (Chapter Five), no statistical analysis of the data was attempted. The chloride concentration of homogenates was determined only on berry samples collected between veraison and maturity for the 1993-94 and 1994-95 seasons. Homogenate chloride concentration varied from week to week, however concentration increased steadily during berry ripening in both seasons. A linear regression was fitted to the plot of homogenate chloride against days after anthesis for each treatment in each year (Figures 4.19 and 4.20). The increase between veraison and the final sampling was about four-fold in 1993-94 and three-fold in 1994-95.

Homogenate chloride concentration was higher in 1994-95 than 1993-94 (note different Y axis scales on Figures 4.19 and 4.20). At the first sampling in 1993-94 the average chloride concentration of Trts 1-7 was about 0.08 mg chloride per g fresh weight compared with about 0.26 at the first sampling in 1994-95. With the exception of the unirrigated treatment, between veraison and maturity in 1993-94, homogenate chloride concentration increased by about 0.02 mg chloride per g fresh weight per week compared with about 0.04 mg chloride per g fresh weight per week during the same period in 1994-95. The homogenate chloride concentration of unirrigated vines was always higher than Trts 1-7 in both seasons especially in 1994-95.

The berries of fully irrigated vines (Trt 1) and pre-harvest deficit vines (Trt 5) had the lowest chloride concentration of the 7 irrigated treatments and the anthesis-veraison deficit treatment (Trt 6) had the highest chloride concentration at all sampling times and, in 1994-95 increased more rapidly than the other irrigated treatments. With the exception of the pre-harvest deficit treatment (Trt 5), which was usually the second-to-lowest in chloride concentration during 1994-95, there was no other consistent pattern in the ranking of the other treatments (Trts 2, 3, 4 and 7).

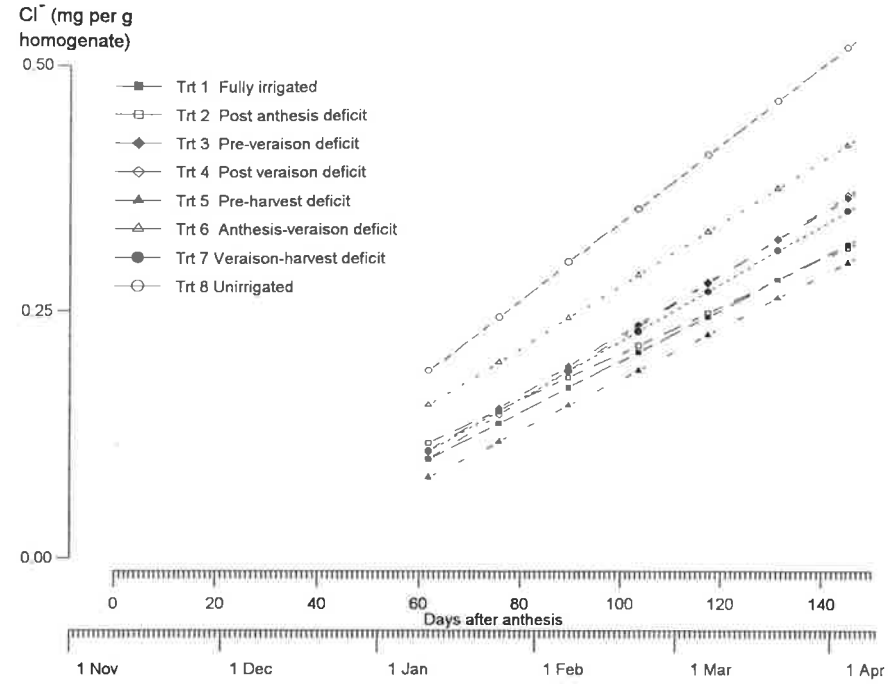

Figure 4.19 Linear regressions of chloride concentration (mg Cl per g homogenate) plotted against time during berry ripening in 1993-94. Treatment symbols are plotted only to indicate treatments and do not represent data points.

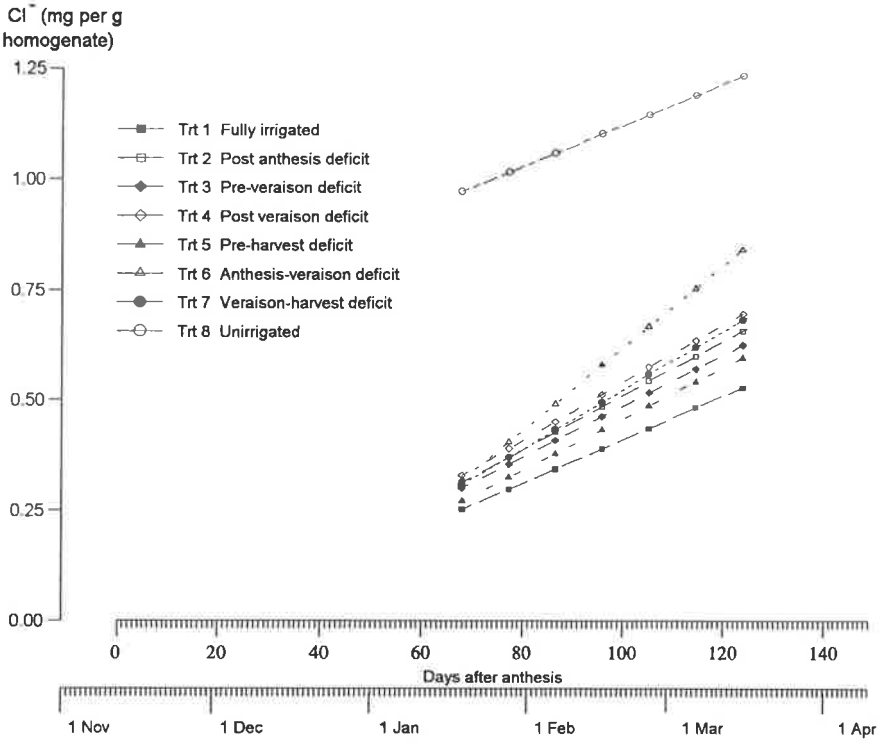

Figure 4.20 Linear regressions of chloride concentration (mg Cl per g homogenate) plotted against time during berry ripening in 1994-95. Treatment symbols are plotted only to indicate treatments and do not represent data points.

4.4 Discussion

4.4.1 Phenological correlates

A schema of the duration in days of most of the phenological stages of fully irrigated vines between budburst and harvest during four years was shown in Figure 3.17. That picture is supplemented by data in Figure 4.21 which more specifically indicates the variation in the time from anthesis of phenological events between veraison and harvest for fully irrigated vines (Trt 1). 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 4.21). 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.

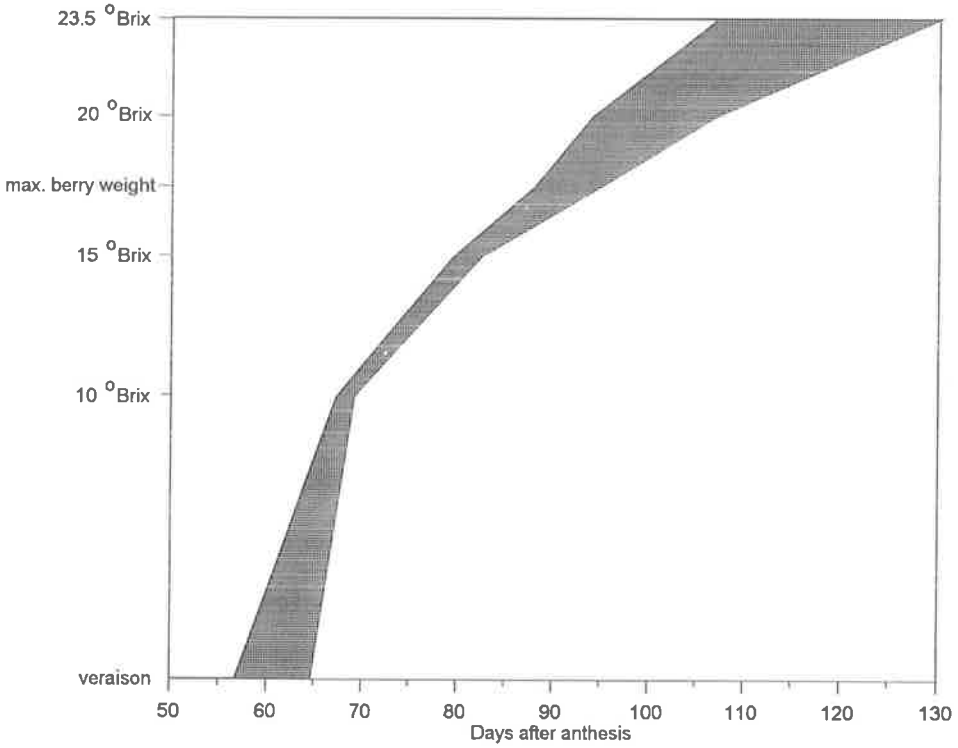

Figure 4.21 Variation in the number of days between anthesis and key phenological events of fully irrigated vines (Trt 1) over the years 1991-92 to 1994-95. Y axis not to scale.

Notwithstanding the increased spread in the number of days after anthesis to specific °Brix levels, a statistically significant model was fitted to the plot of °Brix against the number of days after anthesis. For the combined data of the change in °Brix with days after

anthesis for the 1991-92, 1993-94 and 1994-95 seasons (Figure 4.5) polynomial equation (1) was derived

$$Y = -35.25 + 0.889X - 0.0033X^2 \quad (1)$$

where

X = days after anthesis

Y = °Brix

Freeman and Kliewer (1983) reported that the increase in °Brix with days after anthesis for irrigated Carignane vines was described by the equation:

$$Y = -27.93 + 0.7X - 0.0025X^2 \quad (2)$$

with X and Y as in (1)

A similar equation was derived to describe the relationship between °Brix and days after anthesis for unirrigated Carignane vines in the same experiment was:

$$Y = -34.39 + 0.91X - 0.0035X^2 \quad (3)$$

(there is a discrepancy in the text and figure captions in Freeman and Kliewer (1983) for the value of the Y intercepts for these equations; a negative Y intercept is the correct value as indicated here). The overall equation for the combination of irrigation and thinning treatments was:

$$Y = -31.05 + 0.81X - 0.003X^2 \quad (4)$$

Using equation (3), Carignane grapes at Davis reached 23.5 °Brix about 112 days after anthesis and Shiraz vines (equation 1) at Waikerie, 100 days after anthesis (or 12 days earlier). Gladstones (1992) classified Shiraz as a Group 5 variety and Carignane as Group 7, the latter requiring an additional 100 biologically effective day degrees to ensure ripeness. Although Gladstones noted that day degrees to ripeness did not infer common °Brix the additional 100 day degrees required to ripen Carignane compared with Shiraz would equate to about 12 days at either Davis and Waikerie as both are classified as Region IV (Winkler et al., 1974). As discussed above however, there was a range of about 23 days in the time required to reach 23.5 °Brix for Shiraz at Waikerie which is too wide to be of practical value in predicting harvest date. Nevertheless the data from Waikerie and Davis showed that temperature summation models to predict harvest may perform adequately across regions, provided an adequate data set is used.

GDD did not accurately predict °Brix between 10 and about 22 °Brix but there was a close correlation between GDD and °Brix above 22 °. About 1280 GDD after anthesis were

required to reach 23.5 °Brix in the 1992-93, 93-94 and 94-95 seasons (Figure 4.6). Similarly Williams et al. (1985b) reported a poor correlation between GDD and °Brix in the range of 14-18 °Brix but a closer correlation when between 20 and 21.5 °Brix. Polynomial curves fitted to the plot of °Brix against GDD indicated a range of only 10 GDD to reach 23.5 °Brix in each of these seasons (equations not presented). The variation of about 130 GDD between the minimum and maximum GDD needed to accumulate 20 °Brix at Waikerie is less than the 200 GDD range reported by Williams et al. (1985b) however, those data were from different sites in California within the same year. The equation fitted to the change in °Brix against growing degree days at Waikerie is similar to that reported by Williams (1987) although Williams used GDD from budbreak. For a 100 GDD increase the equation derived by Williams gave about a 0.38 °Brix increase. At Waikerie a similar increase in GDD resulted in a rise of about 0.46 °Brix but with a lower rate of increase than for Williams at high GDD and °Brix.

The close correlation between GDD and maturity for fully irrigated vines in the Waikerie experiment was probably due to a minimisation of the effect of other influences on berry ripening. Williams et al. (1985a, 1985b) reported that factors such as soil water content and crop load were the most likely cause of discrepancies between predicted and actual maturity. Both water stress and low crop resulted in earlier maturity than predicted by their model. At Waikerie, harvest date of treatments 2-8 was either advanced or delayed in comparison with fully irrigated vines. For example, in 1991-92, 1992-93 and 1993-94 unirrigated vines were the first to be harvested, while in 1994-95 excessive water stress delayed harvest compared to fully irrigated. These data suggest that, for non-stressed vines in the vineyard in which this experiment was located, harvest date was closely correlated to GDD after berries reached at least 20 °Brix and GDD predicted harvest date more accurately than days after anthesis. Maturity models based on GDD can only be predictive under average weather conditions and extrapolation beyond seven to ten days is unreliable. GDD models are therefore only useful as a guide to predicting harvest date. Data presented here however showed little variation in the number of days between anthesis and 10 or 15 °Brix; this relationship warrants further examination for predicting harvest.

4.4.2 Timing of water deficit

Water deficit reduced solute content per berry compared to fully irrigated vines, and increased berry sugar concentration. For example, unirrigated berries had a lower solute

content per berry than fully irrigated vines in 1993-94 however, as the berries were smaller, °Brix was higher. There was no change in soluble solids per berry of Thompson Seedless when irrigation was reduced 66 percent although berry weight declined by 9 percent and °Brix increased by 6 percent (Williams and Grimes, 1987). In a similar experiment at another site by these authors, reducing irrigation by the same amount also resulted in smaller berries but °Brix was reduced as the result of lower soluble solids per berry; they suggested this was indicative of excessive water stress. Hardie (1980) also noted that, although water deficit increased berry sugar concentration, sugar content per berry was reduced, especially if vines were water stressed during post veraison. These authors suggested the reduction was caused by stress-induced defoliation as there was no recovery in berry sugar content after water stress was relieved. In the Waikerie experiment post veraison water deficit reduced solute content per berry in 1993-94 and 1994-95 however, there was no apparent defoliation nor recovery in solute content after the deficit period. Solute content was not reduced by pre-harvest water deficit suggesting the post-veraison period is most sensitive to water deficit. This may be due to a non-reversible change in photosynthetic capacity during the senescent phase or to effects on translocation mechanisms.

4.4.3 Maximum berry weight

In Chapter Three, data were presented indicating maximum berry weight occurred approximately 91 days after anthesis in every year (Figures 3.10-3.13) after which there was about a 20 percent loss in berry weight by harvest. 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 (Figure 4.7), in 1994-95 between 18 and 19.5 for Trts 1-7 and 19.5 to 22 for unirrigated (Figure 4.8). Freeman and Kliewer (1983) reported a loss in the weight of unirrigated Carignane berries about 100 days after anthesis when the berries were 20 °Brix and suggested that this loss in weight was the result of water loss from berries. Matthews & Anderson (1988) reported a decline in percent water content of berries commencing before veraison but as berry weight was not reported the actual water content of the berries could not be calculated. In Shiraz the similarity of the curves of berry weight and of non-solute weight per berry (Figures 3.12 and 4.13; 3.13 and 4.14 respectively), 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 thesis, 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. For example, the soluble solids content per berry of well irrigated Thompson Seedless continued to rise during berry ripening and, although the rate of accumulation in water stressed vines slowed towards harvest, a steady increase was maintained (Matthews and Anderson, 1988). Christensen (1975) similarly reported a steady increase in the weight of soluble solids per berry in Thompson Seedless berries up to the stage when berries were riper than 20 °Brix . Solutes per berry of Muscat Gordo Blanco berries continued to increase for 110 to 120 days after flowering at which time berries were between 20 and 30 °Brix (Coombe, 1980).

Several authors have suggested that because of xylem blockage early in phase III both water and sugars are loaded into berry tissue via the phloem during the remainder of phase III. Findlay et al. (1987) reported breakage of the peripheral xylem bundles soon after the inception of rapid sugar accumulation in berries and suggested it was caused by the rapid expansion in berry size. As sugar flow into the berry was maintained, these authors suggested phloem function remained intact, and this was supported by Lang (1987) and Greenspan et al. (1994) who reported that the phloem sap was the major pathway for water movement into the expanding grape berry and transpiration through the skin was the major outflow. The importance of the phloem in water and sugar movement into berries during the ripening phase was further emphasised by Coombe et al. (1987). If it is accepted that the phloem is the main pathway for sugar and water movement into grape berries after veraison, data presented here suggest that at weight-max. phloem transport of water and sugars into Shiraz berries ceased in most plots but that transpiration through the berry skin

continued resulting in a decrease in water content per berry and a consequent increase in °Brix.

4.4.4 Titratable acidity, pH and chloride

There are examples in the literature of irrigation effects on TA and pH but as there was often a treatment effect on °Brix the influence of irrigation on TA and pH was not obvious. For example, Neja et al. (1977) reported "highly significant differences among the four irrigation treatments for °Brix, total acidity and pH" but did not comment that the treatments with the lowest °Brix had the highest titratable acid and the lowest pH. For this reason titratable acid (TA) and pH were plotted against °Brix to aid in the interpretation of the effects of water deficit on TA and pH in the Waikerie experiment. Irrigation treatment had no effect on the rate of decline in TA or the rise in pH when compared at similar °Brix in the 1993-94 season. The rapid decline in TA between the first sampling, when berries were about 8 °Brix, and 16 °Brix is similar to the decline in TA of Carignane berries reported by Freeman and Kliewer (1983) who suggested the slowing in the rate of decline indicated that all the readily available malic acid had been degraded. The slowing in the rate of decline in TA of Shiraz berries from the Waikerie experiment was coincident with weight-max. during the 1992-93 and 1993-94 seasons but less apparent in 1994-95 (data not presented). Irrigation had no effect on the relationship between pH and °Brix, however this relationship was influenced by season (Freeman and Kliewer, 1983). Pre- or post veraison water deficit had no effect on juice pH at harvest and Matthews and Anderson (1988) suggested juice pH to be insensitive to vine water status and may be site- and variety-specific. Data presented here support this suggestion.

The chloride concentration of the berry homogenate represented the sum of the chloride concentration in the seeds, flesh and skin, and in the Waikerie experiment no attempt was made to separate these tissues for analysis. While each segment contained chloride, the concentration in the seeds and skins of Merlot berries did not increase over a five week period prior to harvest, however, there was 65 percent increase in the concentration of chloride in the flesh during this period (M. McCarthy - unpubl.). There was probably a different seed/flesh/skin ratio of berries as a result of irrigation treatment with berries from the more water stressed treatments having less flesh to seed and skin. However there was a uniform increase in homogenate chloride concentration for most treatments in both years. The unexpectedly high chloride concentration of the small berries

of unirrigated vines in 1993-94, and more so during berry ripening in 1994-95, was likely to have been the result of chloride uptake from the regional watertable at about 3 m depth. Above-average rainfall during the 1992-93 season, winter rainfall, and no irrigation since the middle of the 1990-91 season would have resulted in low soil salinity in the soil profile. It seems possible that unirrigated vines extracted soil water at considerable depth since withholding irrigation during the anthesis-veraison period in the 1994-95 season resulted in a decline in soil water content at 2 m (Figure 2.16). Both soil water extraction from more saline layers at depth, and concentration with-in the rootzone as the available soil water content declined when irrigation was withheld, contributed to elevated chloride concentration of berries from the anthesis-veraison deficit treatment. These data indicate that if irrigation water is of similar or lower salinity to that used in the Waikerie experiment (less than 0.5 dSm^{-1}) withholding irrigation for short periods during berry development will not result in a significant increase in juice chloride concentration. The interaction of WI or RDI with water of higher salinity remains to be determined and is of critical importance, especially in many parts of Australia where water quality is often marginal and phylloxera or nematode tolerant rootstocks, many of which have salt-excluding properties, are not used.

4.5 Conclusions

a. *Irrigation treatment had no effect on juice titratable acid or pH when compared at the same juice °Brix level. The berries of unirrigated vines had the highest chloride content which, it is proposed, was the result of uptake from the regional water table.*

b. *Juice °Brix showed a steady rise with days after anthesis, unirrigated vines reaching specific °Brix levels 2-10 days earlier than other treatments within years. Between years there was a notable constancy of the interval from anthesis to 10 ° and to 15 °Brix e.g. in berries of fully irrigated vines the range was only two and three days respectively, while at higher °Brix levels the range increased markedly e.g. to 23 days at 23.5 °Brix.*

c. *The rise in juice °Brix was more closely correlated to growing degree days (GDD) from anthesis than days after anthesis. In three of the four years, a juice °Brix of 23.5 was reached at 1280 GDD from anthesis.*

d. *In years 3 and 4, maximum berry weight (weight-max.) was reached in all treatments at a constant interval after anthesis (91±3 days, see Chapter 3) but at different juice °Brix levels (16.8-19.1°). After weight-max. was attained berry weight declined and °Brix rose to 'mature' levels.*

e. *The increase in solute content per berry was slow in unirrigated berries (small in size) and, in berries of vines that were deficit irrigated in the four weeks after veraison, this increase was slower than fully irrigated.*

f. *The rate of solute accumulation in berries of all treatments slowed after weight-max. in year 3 and ceased in year 4. This suggests a blockage of both phloem water and sugar transport into the berry at this stage.*

Chapter Five - Effect of timing of water deficit on glycosyl-glucose and anthocyanin-glucose

5.1 Introduction

Effect of irrigation deficit on wine quality

There is a paucity of literature on the effect of early or late water deficit on wine quality. Matthews et al. (1990) showed that wine made from fruit of continually irrigated vines was different to wine from early or late season deficit treatments, and there were distinctions evident in appearance, flavour, taste and aroma between 'early season deficit' and 'late season deficit' wines. Tasters of these wines indicated that 'late deficit' wines had a greater intensity of black currant aroma compared with 'fully irrigated' wines. The concentration of anthocyanins and phenolics was higher in 'deficit' wines although levels of residual sugar, titratable acid, pH and ethanol were similar to 'fully irrigated' wines. The volume of water applied weekly to the least-stressed treatment was about 50 percent of ETo (see section 1.2.5 in Chapter One) for the site and the most stressed vines received about 11 percent of ETo (Matthews and Anderson 1988). As no data were given on the effect of the irrigation treatments on soil water content the relative contribution of irrigation water or stored soil water cannot be determined. The authors concluded that, in situations where vine water status can be altered, irrigation is one way in which wine sensory characteristics can be manipulated. Van Zyl (1984) suggested that irrigation during the ripening phase could be used to manipulate wine quality but that such control might only be achieved in the absence of large reservoirs of soil water associated with deep soils.

Manipulation of wine quality by irrigation should be possible in irrigated vineyards in the Murray-Darling Basin in Australia as many are planted on relatively shallow or sandy soils with low water holding capacity. Although the effects of irrigation timing on wine quality could be assessed by large scale experimentation and commercial winemaking, this approach should take account of other complexities such as variation in soil depth etc. Smaller experiments reduce this variability but have the added difficulty of assessment of small-lot wines, a problem that remains to be resolved.

Assessment of wine quality

The effect of irrigation on wine quality is contentious and widely debated. Part of the reason for the protracted discussion on this subject arises from the divergence of opinions and methods for defining grape composition in relation to wine quality. In cool countries the sugar content of the grapes is considered an adequate index of quality (Huglin, 1977) and payment for winegrapes is based on this measure. Ough and Alley (1970) claimed that °Brix/acid was a suitable index for defining optimum maturity of Thompson Seedless grapes. Following suggestions by Somers (1975) that pH was probably more important to winegrape quality than titratable acidity, Coombe et al. (1980) suggested an index of °Brix x pH^2 for defining optimum ripeness. However, Du Plessis and Roussouw (1978) claimed that as irrigation may cause fluctuations in the rise of must pH as berries ripen, indices which include pH may lead to inaccuracies. In Australia it is commonly held that grape quality for wine cannot be adequately described by measurement of °Brix, pH, or titratable acidity, as these measures give little indication of the potential quality of the wine made from a parcel of fruit (Williams, 1996).

Colour and phenolic content are now widely recognised as important quality components of red wine. In the first year of a study by Somers and Evans (1974) the quality rating of Shiraz and Cabernet Sauvignon wines 'of the current vintage' was correlated to wine colour density and the degree of ionisation of anthocyanins. This also held for Cabernet Sauvignon wines in the second year, but the lack of a statistical correlation between wine colour density and the degree of ionisation of anthocyanins for Shiraz wines in the second year indicated that these measures may not be reliable for this purpose.

In Australia the method of Somers and Evans (1977) has been widely adopted to determine the anthocyanin and phenolic profile of young red wines, more specifically for wines of the current vintage. For example, Cirami et al. (1984) used this protocol to examine the effects of nematode tolerant rootstocks on grape juice and wine quality, and McCarthy et al. (1983) used it to test the effects of irrigation and canopy management on Shiraz wine quality. However the method is specific to black grapes.

Aroma and flavour of the fruit or must is used by many winemakers to rate grape quality. Cootes et al. (1981) demonstrated a close correlation between the aroma and flavour quality rating of clarified grape juice and the wine quality score of young white

wines made from 'Riesling' grapes from three sites in the Barossa Valley. Jordan and Croser (1983) reported that, for cultivars such as `Muscat Gordo Blanco' and `Riesling', the use of aroma and flavour assessment of juices was an aid in determining harvest date. Potentially the subjective assessment of juice aroma and flavour has the same problems as wine assessment; for example, McCarthy (1986) reported inconsistencies between judges in the scores assigned to the flavour of Riesling grape juices from an irrigation experiment.

Chemical components of grape berries that contribute directly to flavour may be indicative of wine quality and their measurement may augment subjective assessments of juice and wine. Williams et al. (1993) confirmed the existence of glycosidically bound forms of flavour compounds which, in the bound form, are without flavour and aroma. Acid or enzyme hydrolysis of the sugar-aglycone link releases the flavour and aroma of these aglycones. The concentration of bound forms greatly exceeds that of the free forms. The recognition of the role of glycosidically bound forms of flavour compounds resulted in the development of a measure for the free volatile terpene (FVT) and potential (ie bound) volatile terpene (PVT) content of monoterpene-rich varieties such as the muscat group (Dimitriadis and Williams 1984). McCarthy (1986) analysed FVT and PVT to investigate the effects of irrigation and crop thinning on cv. Riesling and reported that, in addition to significant treatment effects on PVT (but not on FVT), fruit ripening influenced these measures. There were differences in the PVT concentration of a range of clones of cv. Muscat à petite grains blanc (McCarthy, 1992) but not for FVT; moreover, there was no correlation between PVT concentration and juice °Brix. Reynolds and Wardle (1989) reported FVT levels to be unresponsive to fruit exposure although their data showed that FVT concentration of fully shaded berries tended to be lower than that of fully exposed berries. Berries that were fully exposed to the sun were highest in PVT concentration in comparison to berries that were either partially or fully shaded by the leaves. The relationship between FVT or PVT and wine quality was not investigated. While FVT and PVT levels may be indices of wine quality, they are however specific only to fruit and juice samples of the monoterpene-rich varieties (such as muscat) and have given variable results. Their analysis has not been widely used by the wine industry.

The contribution of glycosylated secondary metabolites to wine flavour in varieties that lack high levels of monoterpenes is being investigated. Abbott et al. (1993) reported the development of an assay for the measurement of total glycosylated compounds in the

black grape variety, Shiraz. The assay was used to demonstrate that fruit from vines planted at high density had higher concentrations of glycosidically bound glucose (G-G) than fruit from vines planted at lower density (Abbott, 1991). Viticultural treatments such as root ripping and fruit thinning increased G-G concentrations, although the effects were not always significant. A correlation of G-G concentration with wine quality could not be established because of differences in fruit maturity when fruit was harvested for small-lot winemaking. Abbott et al. (1993) however demonstrated differences in the G-G content of Shiraz fruit from a range of sites known to produce wines of varying wine quality. High quality wines were made from grapes with higher concentrations of total glycosides, a finding which is pioneering in the quest for methods to quantify the quality potential of grapes before vinification.

The contribution of glycosylated secondary metabolites to grape varietal flavour characteristics of wine was established through sensory analysis by Francis et al. (1992, 1996) and Francis (1994); this supports the idea that measurement of the glycosylated secondary metabolites in berries could be an index of the quality of wine made therefrom. A schema of the glycosylated secondary metabolites in grapes is given in Figure 5.1.

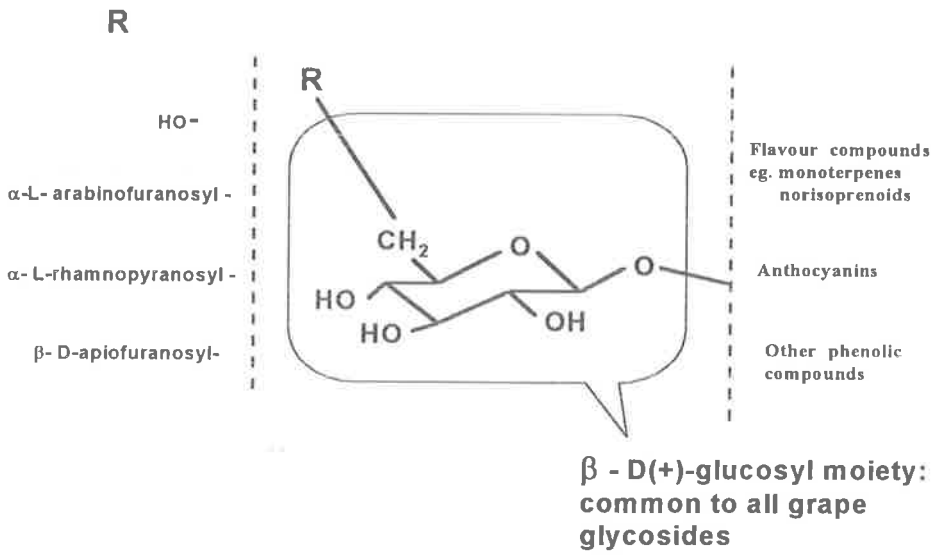

Figure 5.1 Generalised nature of glycosylated secondary metabolites found in grapes.

The G-G assay used by Abbott (1991) was subsequently developed by Williams et al. (1995). These authors noted differences in the G-G content of ripening Shiraz fruit using samples taken from the experiment reported in this thesis. The assay has been further

refined to take account of the glucose derived from red colour compounds which do not contribute directly to flavour; the difference between the total G-G and anthocyanin-glucose represents the non-pigmented glycosides, called red-free G-G, (Iland et al., 1996 a). The G-G assay (representing total glycosides, which in black grapes is predominated by anthocyanins), and the calculated red-free G-G (which in all grape varieties includes, among other glycosides, those of flavour compounds) provide new possibilities in the search for a measurement in grapes that gives an index of wine quality.

The merit of G-G and red-free G-G analyses as an indicator of wine quality is as yet untried. This study represents one of the first field experiments from which these measures are being adjudged; however this cannot be done until small-lot wine quality assessments are available. Small-lot wines were integral to the experiment reported here but, as sensory evaluation and correlations between the G-G and red-free G-G measures and wine sensory evaluations of the 1995 small-lot wines are yet to be completed, these data are not incorporated in this thesis. In the meantime the results will be discussed here on the premise that high levels of G-G and red-free G-G are desirable.

5.2 Materials & Methods

5.2.1 Sampling

Details of the procedure used for berry sampling are described in 4.2.1 in Chapter Four. Briefly, commencing soon after berry softening in January 1994 and 1995, a total of 100 berries, plucked from the three vines in each plot, were collected weekly. On return to the laboratory 50 berries were weighed, placed in labelled screw-top containers and frozen. Juice from the remaining berries was used to determine °Brix, pH and titratable acidity.

5.2.2 Sample preparation

Samples collected in 1994 were stored at approximately -30 °C for nearly 12 months before analysis while 1995 samples were analysed after less than one month of storage at -30 °C. Unless otherwise indicated all procedures were performed at room temperature (~ 20 °C).

Berry samples from five of the nine field replicates were used for G-G analysis. Samples, which were prepared in batches of forty, were thawed at room temperature for about one hour and then whole berries were homogenised (in the container used for their storage) with a blender (Ultra-Turrax) at high speed for approximately 45 seconds. Homogenised samples were stored in a refrigerator while other berries were prepared. After re-mixing the homogenate, approximately 2 g was transferred to a tared 15 ml centrifuge tube. The weight of homogenate taken was recorded and 10 ml of 50% ethanol added. To ensure complete suspension of the homogenate in ethanol, the forty capped tubes were shaken by inversion at about ten minute intervals during one hour. Samples were then centrifuged at 1500 x g for about 7 minutes.

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. (1996a) except that a second Sep-pak was not used and no corrections were made for the approximately six percent loss of anthocyanin-glucose during the analysis procedure. Red-free G-G was calculated using the same method reported by Iland et al. (1996a) ie. by subtraction of anthocyanin-glucose (as µmol glucose) from µmol G-G (per berry or per g

berry weight). A schema of the G-G assay and the methodology for calculating red-free G-G is shown in Figure 5.2.

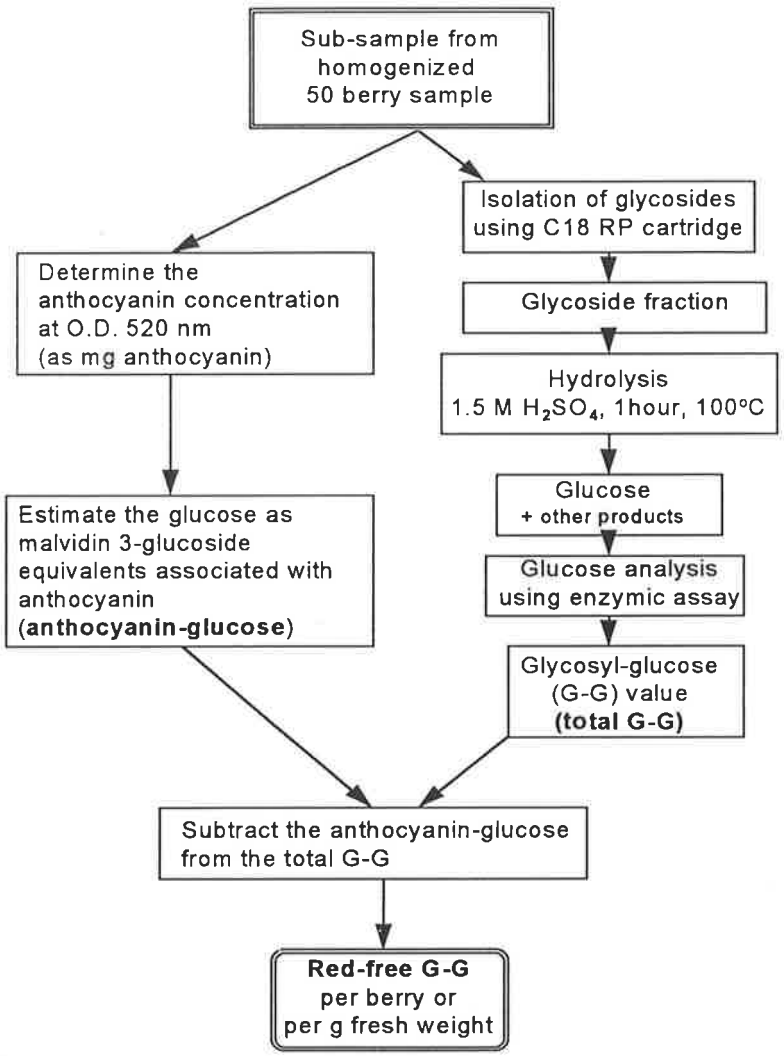

Figure 5.2 Schema for G-G assay of whole Shiraz berries and methodology for calculating red-free G-G.

5.2.3 Statistical analysis

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. Logistic models fitted the data more precisely than either second or third order equations (R. V.

Kenyon - pers. comm). An example of a logistic model derived for the rise in G-G per berry with the increase in °Brix of fully irrigated vines during the 1993-94 season is shown in Figure 5.3 a. Correlation matrices of the differences in slope, inflection point, asymptote and intercept were derived for each set of models.

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 1994-95 season is shown in Figure 5.3 b. 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.

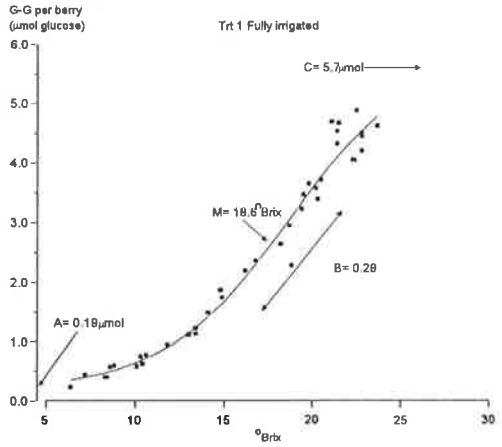

Figure 5.3 a Increase in G-G per berry with the rise in °Brix for fully irrigated vines during berry ripening in the 1993-94 season. Data points indicate G-G per berry and °Brix of each sample comprising 8 sampling times in 5 replicate plots. The fitted logistic model is described by the plotted curve. Constants A, B, C and M are indicated.

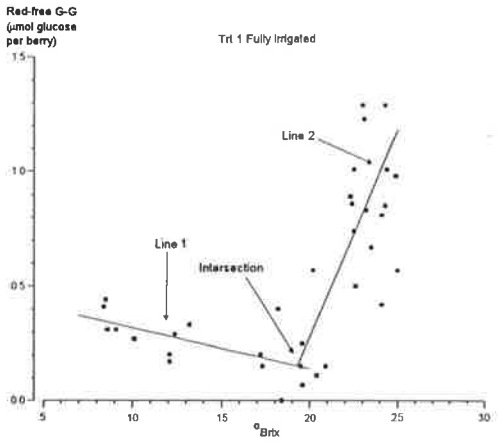

Figure 5.3 b Change in red-free G-G per berry with °Brix for fully irrigated vines during berry ripening in the 1994-95 season. Data points indicate red-free G-G per berry and °Brix of each sample as in Figure 5.3 a. Lines 1 and 2 of the two-phase linear model are described by the two fitted lines.

5.3 Results

Most of the data on independent variables over the two ripening seasons are compared against juice °Brix rather than 'days after anthesis' as the dependent variable. °Brix and time were closely correlated (Figures 4.1-4.4) and comparison of independent variables against °Brix provides a more realistic comparison between years and relates better to composition for winemaking.

Plots of the fitted logistic model of G-G and anthocyanin, two-phase linear regression modelling of red-free G-G per berry and per g berry weight against °Brix for each treatment for 1993-94 and 1994-95 are presented in the Appendix. Also shown there are summary statistics of the logistic modelling and details of the slope and intercept of each fitted line derived from the two phase linear modelling, and summary statistics of the difference in slope of lines 1 and 2 and intercepts between treatments.

There were some significant differences between treatments in either intercept, slope, asymptote or the inflection point and where appropriate these results are included, however, for the purpose of clarity, only the fitted curves that are statistically different in one or more of the four constants to the fully irrigated (Trt 1) are presented in this Chapter. There were minor differences between treatments in the slopes and intercepts for each of the two fitted linear regressions, and the data for all treatments for each year were combined to produce an overall two phase model for the change in red-free G-G per berry or per g berry weight for each year.

5.3.1 G-G per berry, G-G per g berry weight

G-G per berry

Only one treatment, post veraison treatment (Trt 4), was different from fully irrigated (Trt 1) in 1993-94 (Figure 5.4) and 1994-95 (Figure 5.5). In 1993-94 the slope of the fitted curve for the post veraison deficit (Trt 4) was greater than fully irrigated and the inflection point was lower (Figure 5.4 and highlighted figures in Appendix Table 1). The slope of the fitted curve for Trt 4 was also significantly lower than the pre-harvest deficit treatment (Trt 5) and the veraison-harvest deficit treatment (Trt 7). The inflection point of the curve for Trt 4 was significantly lower than pre-harvest deficit, anthesis-veraison deficit and unirrigated treatments (Trt 5, 6 and 8 respectively), (see Appendix

Table 1). There was a lower asymptote of the curve fitted to data for unirrigated vines, not significantly lower than fully irrigated but significantly lower than pre-veraison deficit (Trt 3), pre-harvest deficit (Trt 5) and veraison-harvest deficit (Trt 7) treatments (Appendix Table 1).

In 1994-95 the only significant difference was between the asymptote of veraison-harvest (Trt 7) and unirrigated treatments (Appendix Table 9). The shape of the curve for the post-veraison deficit treatment (Trt 4) was different to other treatments (Figure 5.5) and there was no asymptote or inflection point. The inflection point for the curve fitted to the fully irrigated treatment was significantly higher in 1994-95 compared with 1993-94, however the asymptote was lower. There was a similar pattern for most other treatments. In each year there was a high standard error associated with some of the estimates of the constants and this resulted in a non-significant difference both between treatments and between seasons for each treatment, for example, there was up to a two-fold difference in intercept for some treatments between 1993-94 and 1994-95 however this difference was non-significant (Appendix Table 1).

G-G per g berry weight

There were no differences between treatments in G-G per g berry weight in 1993-94 (Figure 5.6) 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 (Appendix Table 2). 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 5.7), other treatments being similar to fully irrigated (Appendix Table 10). 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. There was a high standard error associated with some of the treatments, for example note Trt 6 in Appendix Table 10.

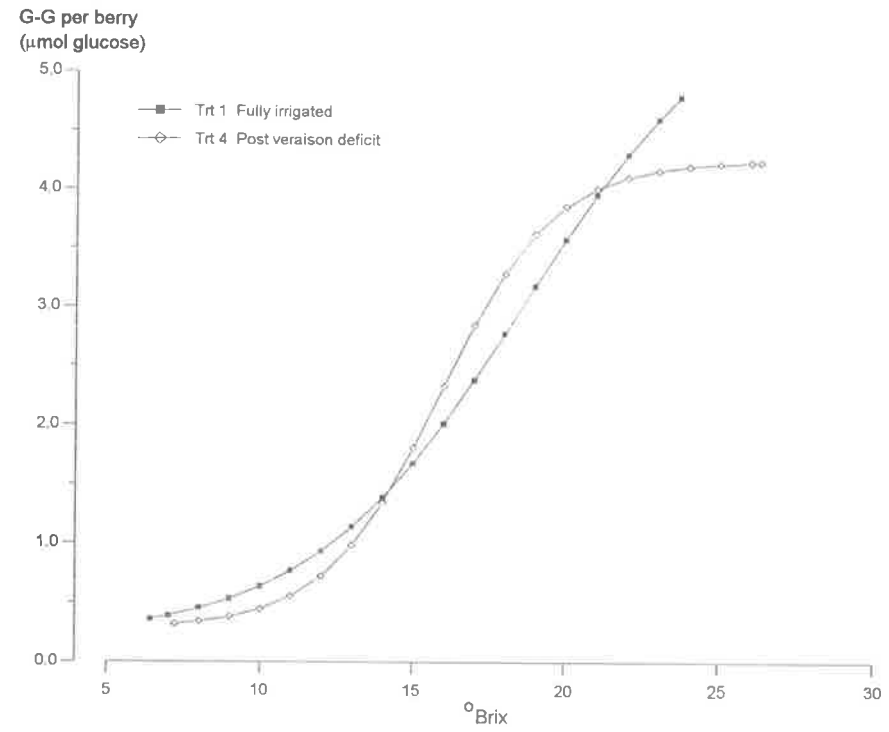

Figure 5.4 Fitted logistic models for G-G per berry plotted against °Brix for fully irrigated and post veraison deficit treatments during the 1993-94 season.
All other treatments were similar to fully irrigated. Actual minimum and maximum x-axis values are plotted but other points are placed at uniformly spaced x-axis values to distinguish treatments.

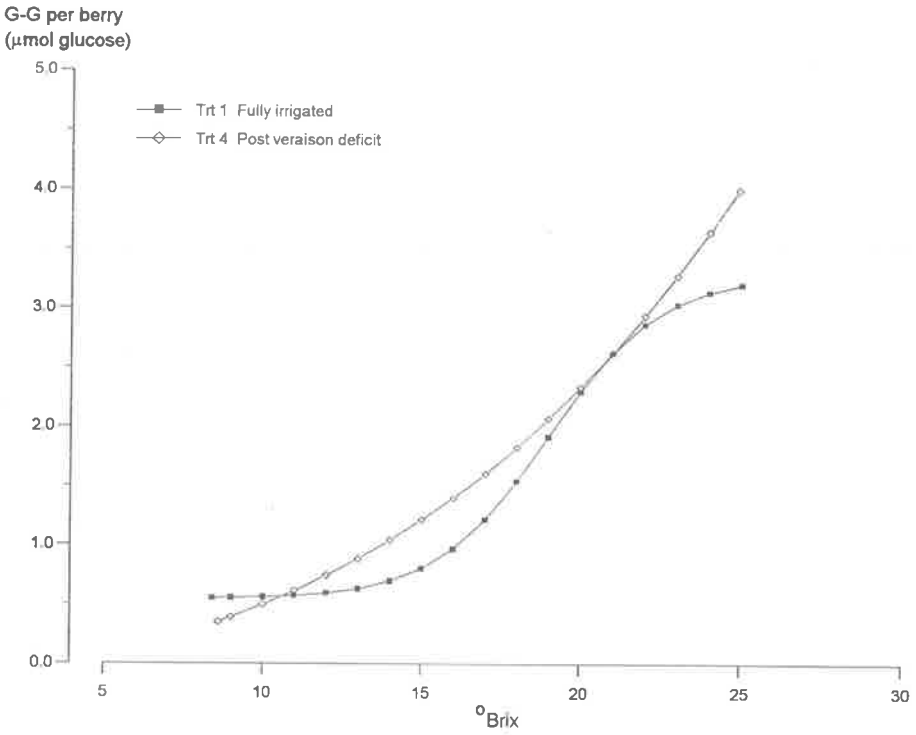

Figure 5.5 Fitted logistic models for G-G per berry plotted against °Brix for fully irrigated and post veraison deficit treatments during the 1994-95 season.
All other treatments were similar to fully irrigated. Actual minimum and maximum x-axis values are plotted but other points are placed at uniformly spaced x-axis values to distinguish treatments.

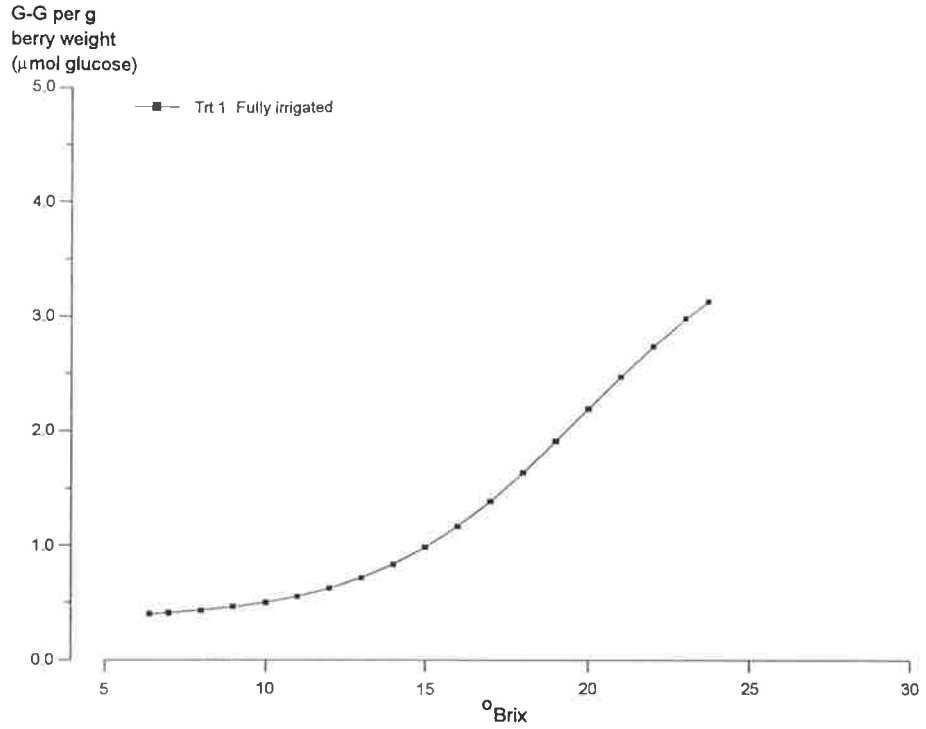

Figure 5.6 Fitted logistic model for G-G per g berry weight plotted against °Brix for the fully irrigated treatment during the 1993-94 season.
Other treatments were similar to fully irrigated. Actual minimum and maximum x-axis values are plotted but other points are placed at uniformly spaced x-axis values.

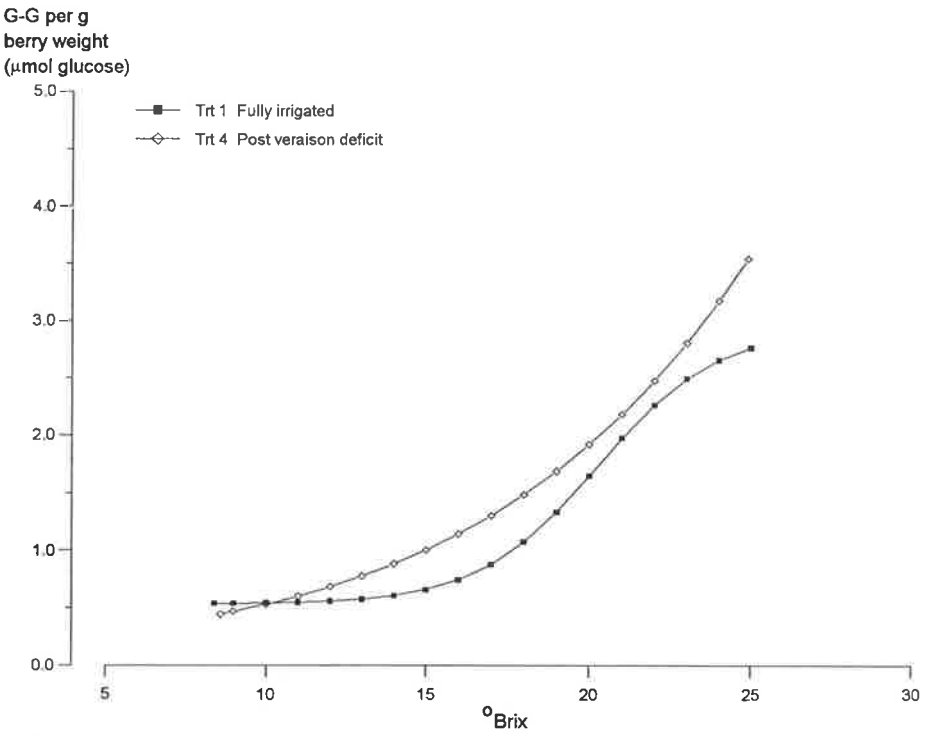

Figure 5.7 Fitted logistic models for G-G per g berry weight plotted against °Brix for the fully irrigated and post veraison deficit treatments during the 1994-95 season.
Actual minimum and maximum x-axis values are plotted but other points are placed at uniformly spaced x-axis values to distinguish treatments.

5.3.2 Anthocyanin per berry and per g berry weight

Anthocyanin per berry

Plots of anthocyanin per berry against juice °Brix are presented in Appendix Figures 4 & 10 and statistical summaries in Appendix Tables 3 & 11. The berries of unirrigated vines (Trt 8) had less anthocyanin per berry at nearly every °Brix level in both years (Figure 5.8 and 5.9) and the anthocyanin content at the asymptote of the curve fitted to Trt 8 was lower than six treatments in each year. In 1993-94 the anthocyanin content at the inflection of the Trt 8 curve was similar to fully irrigated (Trt 1) and lower than Trts 3, 4 and 7. The slope of the curve fitted to the post veraison deficit treatment (Trt 4) was significantly greater than fully irrigated in 1993-94 (Figure 5.8) and the inflection point of Trts 3,4, 7 was significantly lower than Trt 8. In 1994-95 the inflection point of the curve fitted to the post anthesis deficit (Trt 4) and the veraison-harvest deficit (Trt 7) treatments was greater than fully irrigated (Figure 5.9). The asymptote of unirrigated was significantly lower than all treatments except Trt 6 but no other regression constants were different to fully irrigated. The slope of the curve fitted to Trt 2 was lower than Trts 5 and 7, the slope of Trt 5 and 7 was greater than Trt 4 and that of Trt 5 was greater than Trt 6. The anthocyanin content at the asymptote of the fully irrigated treatment was 2.8 mg anthocyanin per berry in 1993-94 compared with 1.2 in 1994-95.

Anthocyanin per g berry weight

Plots of anthocyanin per g berry weight against °Brix are presented in Appendix Figures 5 & 11 and statistical summaries in Appendix Tables 4 & 12. 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. The slope of the Trt 8 curve was lower than the post anthesis deficit treatment (Trt 2) (Appendix Tables 4 & 8). 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 (Figures 5.10 and 5.11). The inflection point in 1993-94 was about 22 °Brix compared with about 18 °Brix in 1994-95(Appendix Tables 4 &12). 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.

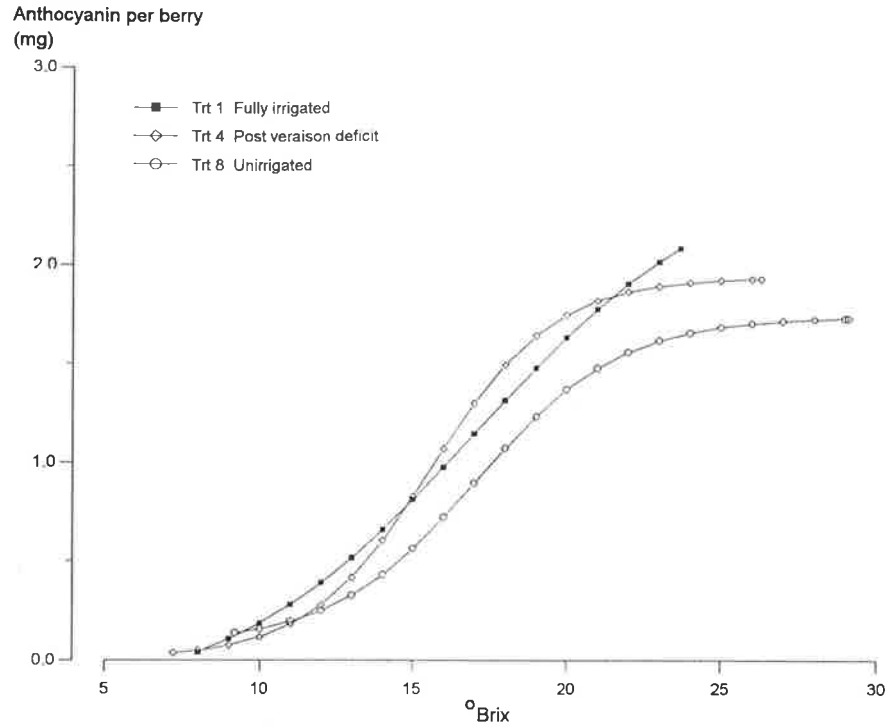

Figure 5.8 Fitted logistic models for anthocyanin per berry plotted against °Brix for fully irrigated, post veraison deficit and unirrigated during the 1993-94 season.
Other treatments were similar to fully irrigated. Actual minimum and maximum x-axis values are plotted but other points are placed at uniformly spaced x-axis values to distinguish treatments.

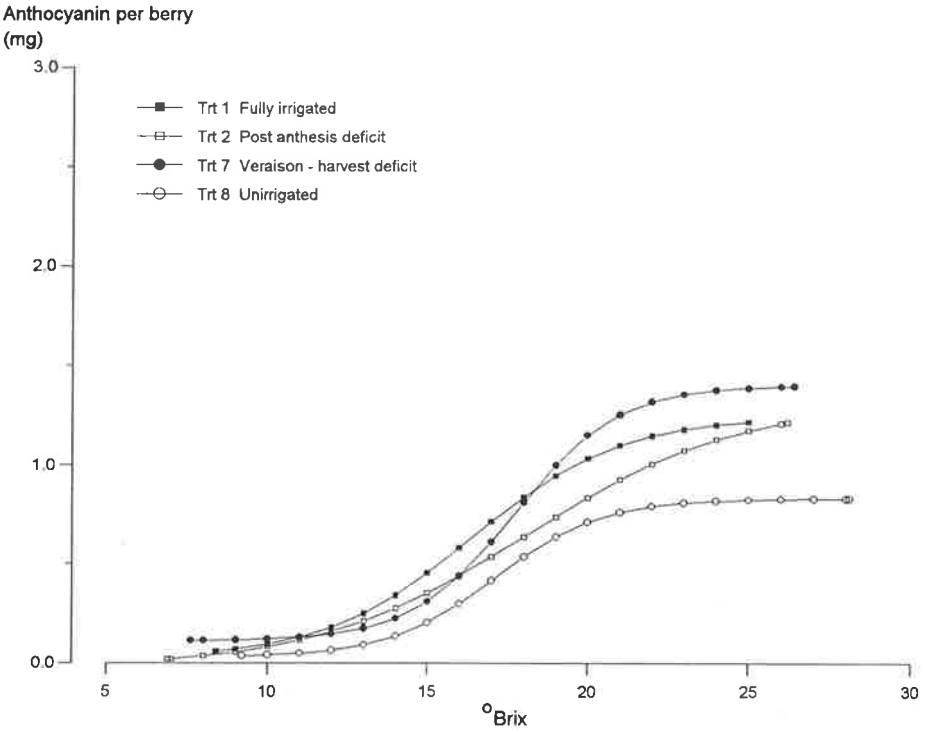

Figure 5.9 Fitted logistic models for anthocyanin per berry plotted against °Brix for treatments indicated in the legend during the 1994-95 season.
Other treatments were similar to fully irrigated. Actual minimum and maximum x-axis values are plotted but other points are placed at uniformly spaced x-axis values to distinguish treatments.

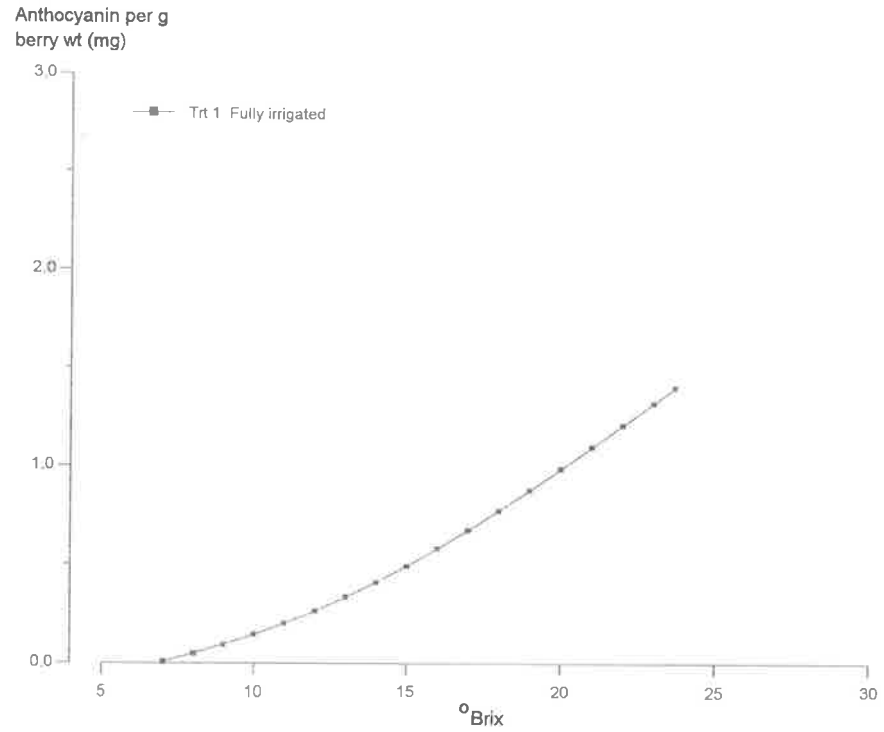

Figure 5.10 Anthocyanin per g berry weight for the fully irrigated treatment plotted against °Brix for the 1993-94 season.
All other treatments were similar to fully irrigated. Actual minimum and maximum x-axis values are plotted but other points are placed at uniformly spaced x-axis values.

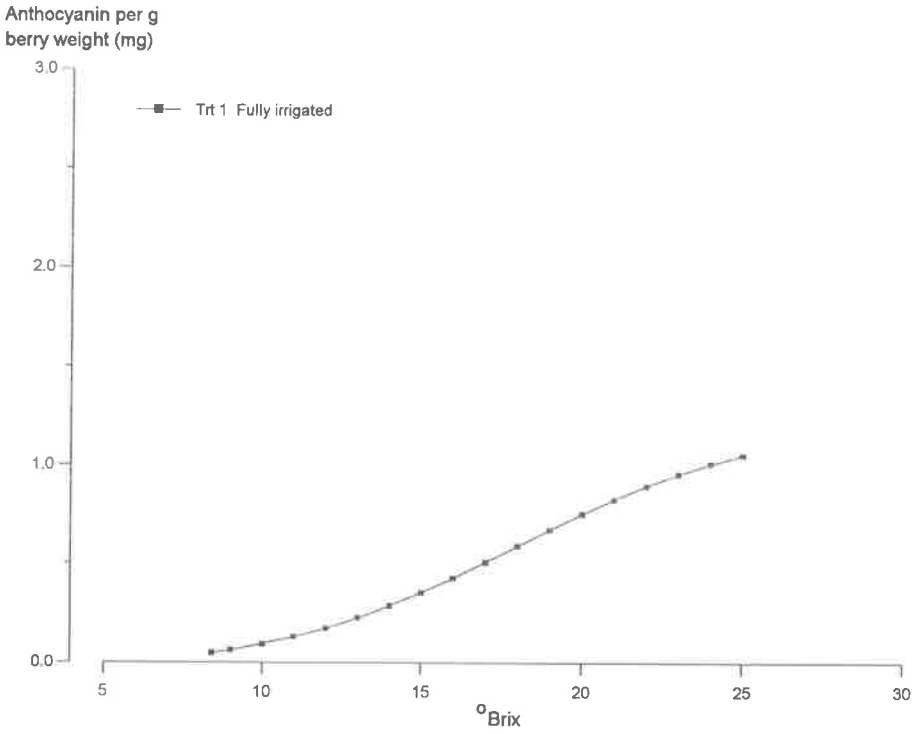

Figure 5.11 Anthocyanin per g berry weight plotted against °Brix for the fully irrigated treatment for the 1994-95 season. All other treatments were similar to fully irrigated. Actual minimum and maximum x-axis values are plotted but other points are placed at uniformly spaced x-axis values.

5.3.3 Red-free G-G per berry and 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); µmol anthocyanin-glucose was derived from mg anthocyanin ÷ 0.529 to allow for the molecular weight of malvidin-3-glucoside (Iland et al., 1996a).

Red-free G-G per berry

The content of red-free G-G content per berry decreased from the first sampling to lower levels at between 14 and 16 °Brix in 1993-94 (Figure 5.12) and 17 to 21 °Brix in 1994-95 (Figure 5.13) after which there was a marked increase (see Appendix Figures 6 and 12 and Appendix Tables 5 and 13 for individual treatments). Irrigation treatment had no effect on red-free G-G content per berry in either 1993-94 or 1994-95 (Appendix Tables 6 and 14). There were variations in the pattern of development of red-free G-G per berry between years, however because of a high standard error, many of the differences were non-significant. For the pooled data (Figure 5.12 and 5.13) the slope and intercept of line 1 of red-free G-G content per berry were similar in both years (Table 5.1) however the °Brix at the intersection of the two lines was significantly higher in 1994-95 compared with 1993-94. Red-free G-G content per berry at the intersection was lower in 1994-95 than in 1993-94. After the intersection, red-free G-G per berry increased 2.7 times faster in 1994-95 than in 1993-94; this difference was significant (slope of 0.121 versus 0.044). In 1993-94 the content of red-free G-G per berry, derived using the regression constants in Table 5.1, was 0.46 µmol glucose at 20 °Brix and 0.68 µmol glucose at 25 °Brix. In 1994-95, comparable values were 0.35 µmol glucose at 20 °Brix and 0.96 µmol glucose at 25 °Brix (Table 5.3).

Table 5.1 Linear regression constants and intersection point for line 1 and 2 for two phase linear regression modelling of red-free G-G per berry 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	0.37	-0.42	0.37	-2.07
slope	-0.009	0.044	-0.009	0.121
°Brix at intersection of lines 1 & 2	15.1		18.8	
Red-free G-G (µ mol glucose) per berry at intersection of lines 1 & 2	0.24		0.19	

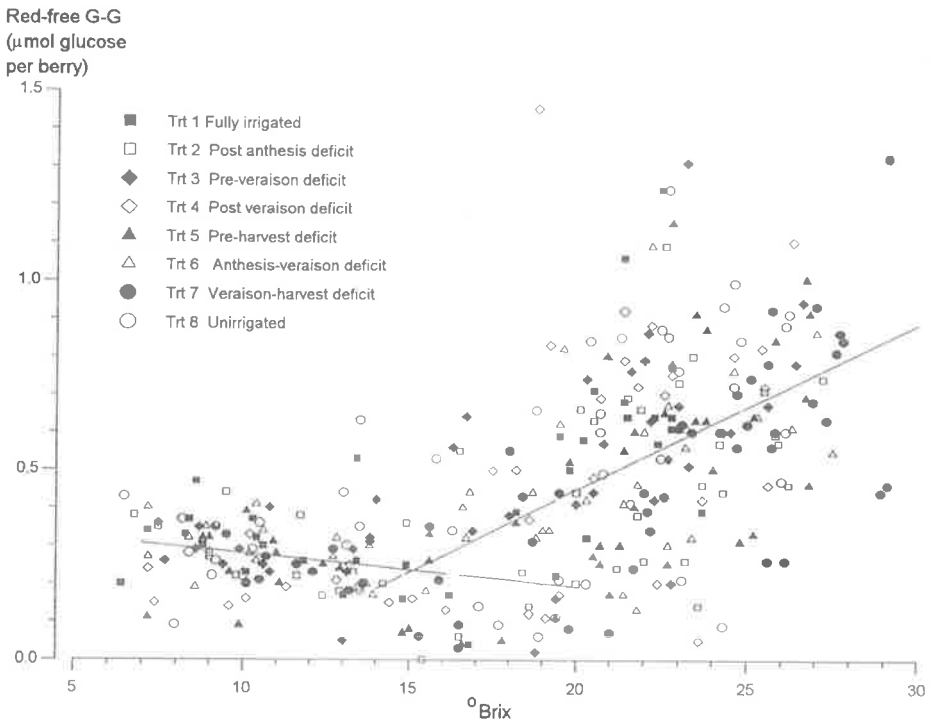

Figure 5.12 Two phase linear regression model of red-free G-G content per berry plotted against °Brix for all treatments for the 1993-94 season.

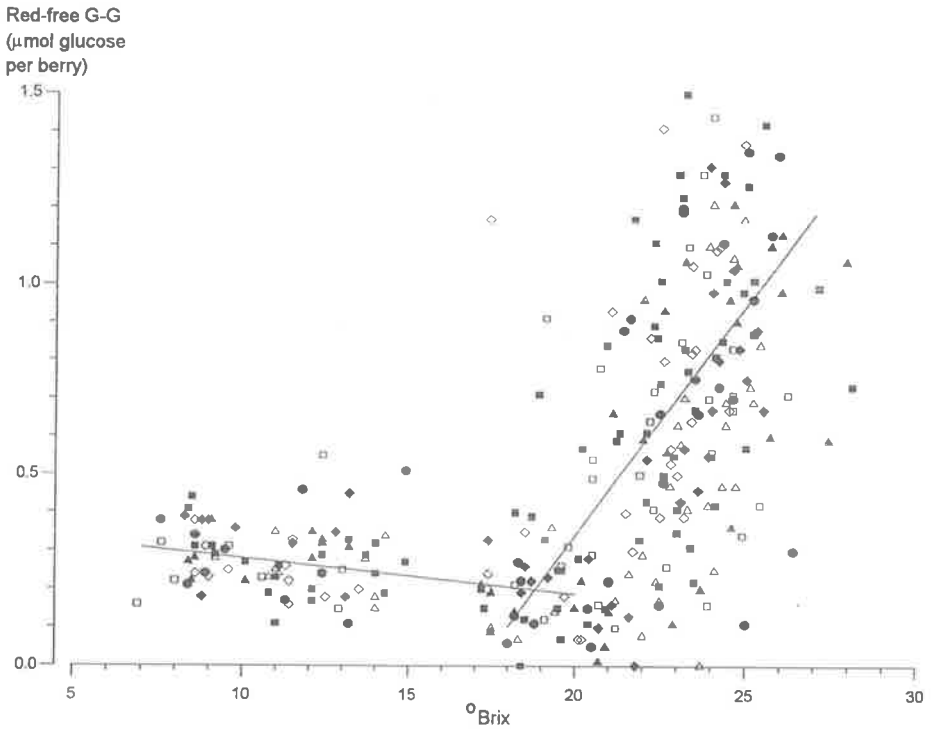

Figure 5.13 Two phase linear regression model of red-free G-G content per berry plotted against °Brix for all treatments for the 1994-95 season.
Data symbols are as described in the previous figure.

Red-free G-G per g berry weight

The pattern of development of red-free G-G per g berry weight was similar to red-free G-G per berry. Plots of red-free G-G concentration for each treatment are presented in the Appendix. 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 Figures 5.14 and 5.15 and summarised statistics of the two phase modelling on the pooled data in Table 5.2. These graphs 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 5.2 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 5.3 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 5.3 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

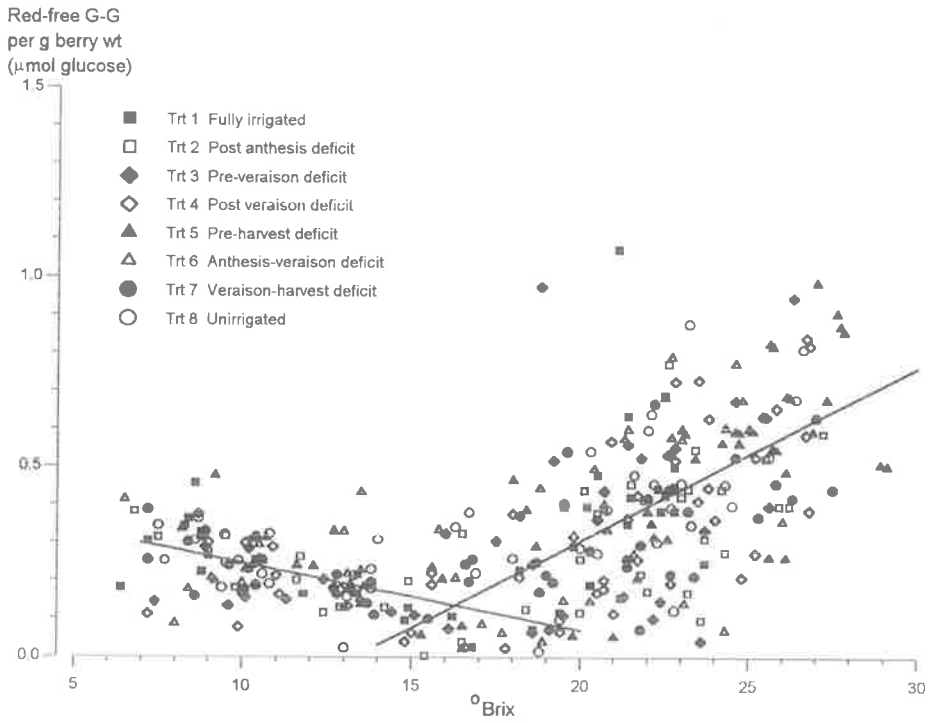

Figure 5.14 Two phase linear regression model of red-free G-G concentration per g berry weight plotted against °Brix for all treatments for the 1993-94 season.

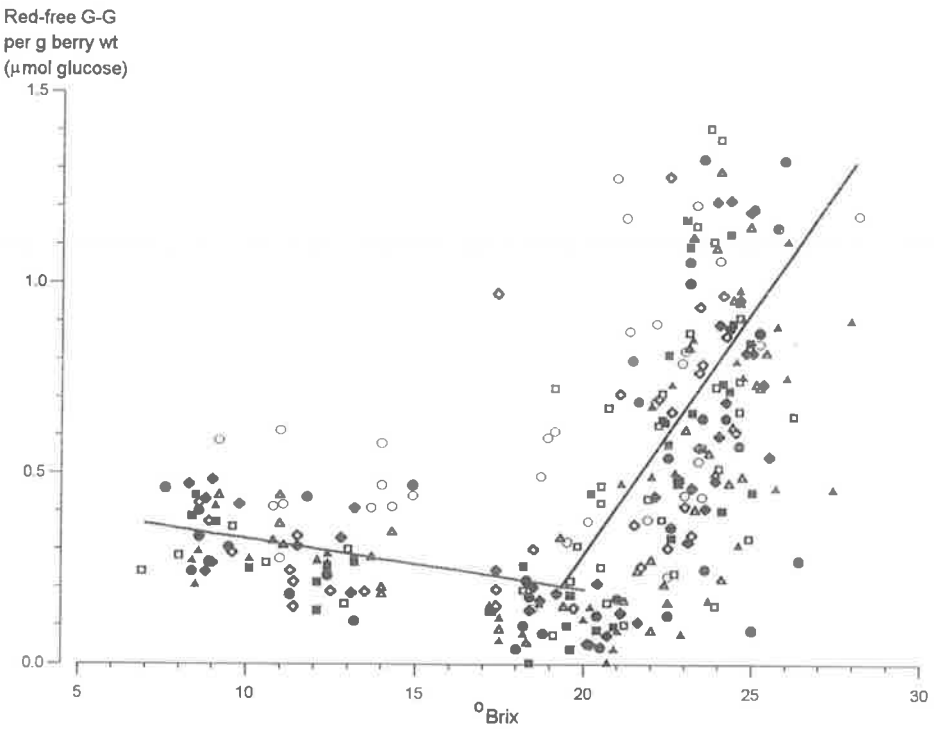

Figure 5.15 Two phase linear regression model of red-free G-G concentration per g berry weight for all treatments plotted against °Brix for the 1994-95 season. Data symbols are as described in previous figures.

5.3.4 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 (the maturity at which fruit was picked for small-lot winemaking) were interpolated from the fitted curves for each treatment and are presented in Table 5.4.

Table 5.4 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 modelling of total G-G and anthocyanin-glucose against °Brix 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 5.5). 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 (Figure 3.12 and 3.13). 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 5.5).

Table 5.5 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 (presented in Table 5.4).
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

The logistic and linear modelling methods are influenced by all of the values in each data set and it is possible that interpolation to a specific °Brix level, eg at 23.5°, may give a false picture of the actual differences in total G-G, anthocyanin-glucose and red-free G-G concentration at that level. Hence it was decided to calculate these values from individual field plots using selected data from ripe grapes.

Samples from all replicates of each treatment near harvest

The smallest °Brix range which included the selected five replicates of each treatment (replicates 1, 2, 3, 4 and 6) that were used for the estimation of G-G was selected to ensure values were not influenced by maturity. In 1993-94 samples in the range 23.0 ± 0.4 °Brix were used and in 1994-95 the range was 23.8 ± 0.3 °Brix. These data were analysed by analysis of variance and results are presented in Table 5.6. In 1993-94, although there were no significant differences between treatments in the concentration of G-G, anthocyanin-glucose and red-free G-G, Trt 4 was 17 percent higher in anthocyanin-glucose concentration compared with fully irrigated, however red-free G-G concentration was nearly half that of fully irrigated (Trt 1). In 1994-95 the berries of unirrigated vines had the highest total G-G, anthocyanin-glucose and red-free G-G concentration being 27, 22 and 39 percent respectively higher than fully irrigated. Total G-G of unirrigated vines was significantly higher than fully irrigated but not significantly different to Trts 4 and 7; anthocyanin-glucose concentration was also higher than fully irrigated but similar to Trts 7,

4 and 2. The red-free G-G concentration of all treatments was not significantly different.

Table 5.6 Concentration (μ mole per g berry weight) of G-G, anthocyanin-glucose and red-free G-G of all treatments at 23.0 ± 0.4 °Brix for the 1993-94 season and 23.8 ± 0.3 °Brix for the 1994-95 season. Numbers followed by the same letter are not significantly different at $p<0.05$ for each season, n. s. = not significantly different at $p<0.05$.

Treatment	1993-94					
	G-G		Anthocyanin-glucose		Red-free G-G	
	per g berry weight	percent of fully irrigated	per g berry weight	percent of fully irrigated	per g berry weight	percent of fully irrigated
Trt 1 Fully irrigated	2.82	100%	2.35	100%	0.47	100%
Trt 2 Post anthesis deficit	2.89	102%	2.50	106%	0.39	83%
Trt 3 Pre-veraison deficit	2.94	104%	2.52	107%	0.42	89%
Trt 4 Post veraison deficit	3.00	106%	2.75	117%	0.25	53%
Trt 5 Pre-harvest deficit	2.81	100%	2.42	103%	0.38	81%
Trt 6 Anthesis-veraison deficit	2.91	103%	2.40	102%	0.51	109%
Trt 7 Veraison-harvest deficit	3.04	108%	2.52	107%	0.51	109%
Trt 8 Unirrigated	3.05	108%	2.63	112%	0.42	89%
	n.s.		n.s.		n.s.	
1994-95						
	G-G		Anthocyanin-glucose		Red-free G-G	
	per g berry weight	percent of fully irrigated	per g berry weight	percent of fully irrigated	per g berry weight	percent of fully irrigated
Trt 1 Fully irrigated	2.64 bc	100%	1.89 c	100%	0.74	100%
Trt 2 Post anthesis deficit	2.92 bc	111%	2.08 abc	110%	0.84	114%
Trt 3 Pre-veraison deficit	3.00 bc	114%	2.03 bc	107%	0.97	131%
Trt 4 Post veraison deficit	3.04 ab	115%	2.22 ab	117%	0.82	111%
Trt 5 Pre-harvest deficit	2.62 c	99%	2.01 bc	106%	0.61	82%
Trt 6 Anthesis-veraison deficit	2.86 bc	108%	2.04 bc	108%	0.82	111%
Trt 7 Veraison-harvest deficit	3.03 abc	115%	2.23 ab	118%	0.80	108%
Trt 8 Unirrigated	3.34 a	127%	2.31 a	122%	1.03	139%
	sig. at $p<0.05$		sig. at $p<0.05$		n.s.	

Notwithstanding the inability to determine significant differences in treatment effects there was a similarity in treatment order between years (Table 5.7). In 1993-94 and 1994-95 the berries of Trt 8 (unirrigated) vines had the highest G-G concentration and highest, or next highest, anthocyanin-glucose concentration. Trts 4 and 7 (post veraison deficit and veraison-harvest deficit respectively) were closely grouped for total G-G and anthocyanin-glucose and to a lesser extent so were Trts 2, 3 and 6 (post anthesis, pre-veraison and

anthesis-veraison deficit). The berries of fully irrigated (Trt 1) and pre-harvest deficit (Trt 5) vines tended to be lowest in total G-G and anthocyanin-glucose concentration.

Table 5.7 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 presented in Table 5.6. 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	8	7	4	3	6	2	1	5
1994-95	8	4	7	3	2	6	1	5
	Anthocyanin-glucose per g berry weight							
1993-94	4	8	7	3	2	5	6	1
1994-95	8	7	4	2	6	3	5	1
	Red-free G-G per g berry weight							
1993-94	7	6	1	8	3	2	5	4
1994-95	8	3	2	4	6	7	1	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 comparison with Table 5.6 the upper limit was 1.3 °Brix higher than in 1993-94 and 0.6 °Brix higher than in 1994-95. 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 5.8). 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 5.16.

Table 5.8 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 5.16). 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 5.17) and from one to ten in 1994-95 (Figure 5.18). 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.

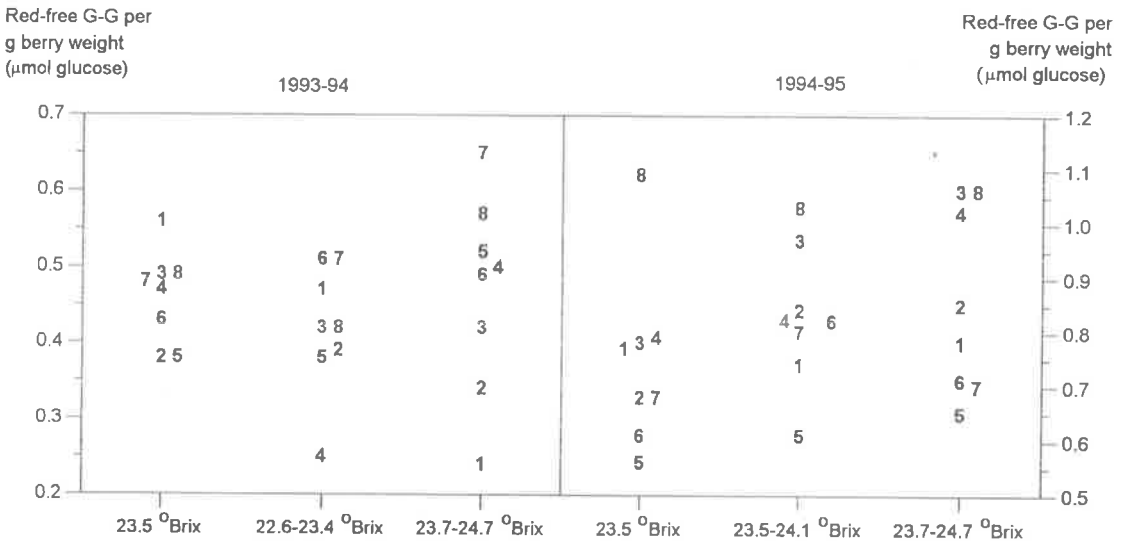

Figure 5.16 Ranking of red-free G-G per g berry weight for all treatments at 23.5 °Brix and two higher °Brix ranges within each year. Horizontal separation within each °Brix range is to distinguish treatment numbers. Treatment ranking at 23.5 °Brix is based on interpolated values. Note the different Y-axis scale for 1993-94 and 1994-95 seasons.

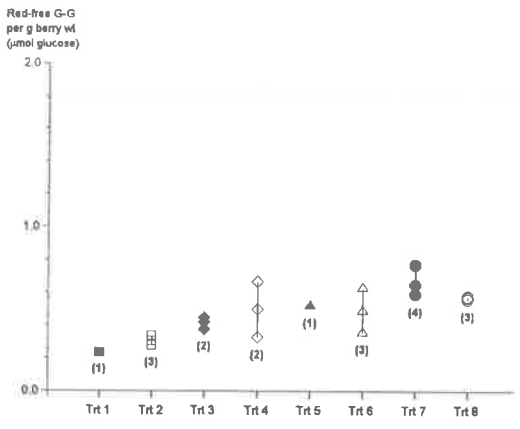

Figure 5.17 Range of red-free G-G per g berry weight between 23.7 and 24.7 °Brix for each treatment in the 1993-94 season. Symbols indicate the minimum, mean and maximum value for each treatment. Numbers in brackets indicate the number of samples for each treatment. Note there was only one datum point for Trt 1 (fully irrigated) and Trt 5 (pre-harvest deficit) within this °Brix range.

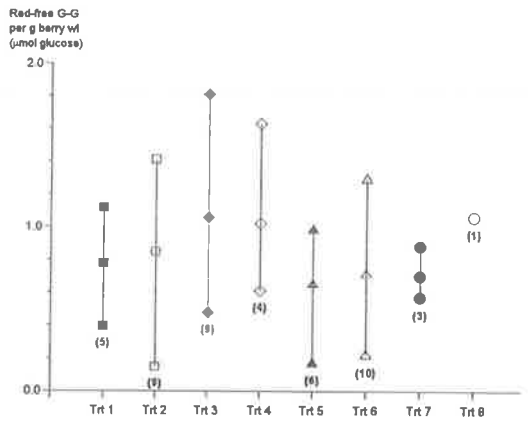

Figure 5.18 Range of red-free G-G per g berry weight between 23.7 and 24.7 °Brix for each treatment in the 1994-95 season. Symbols indicate the minimum, mean and maximum value for each treatment. Numbers in brackets indicate the number of samples for each treatment. Note there was only one datum point for Trt 8 (unirrigated) within this °Brix range.

5.4 Discussion

Williams et al. (1995) recommended that the assay developed for the quantification of glycosyl-glucose needed extensive investigation to establish its usefulness as an index of grape quality for wine. Some preliminary data (based on data from this experiment) have been published (McCarthy et al., 1996; Iland et al., 1996b) however the results presented here on the influence of season and irrigation treatment on G-G accumulation during Shiraz berry ripening represent the first comprehensive testing of the assay. The data indicated a sigmoidal pattern of development for G-G per berry and per g berry weight for all treatments in each season. Data presented on the change in red-free G-G during berry ripening display, for the first time, the pattern of development of total non-pigment glycosides in black grape berries.

The G-G content of Shiraz berries before veraison was not determined in the experiment reported here, however, Gholami et al. (1996) reported that glycosides were present in Muscat Gordo, Flame Seedless and Sultana berries prior to veraison. 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.

The range in G-G concentration reported in this study was similar to the values found in a survey of Shiraz vineyards in the South Australian Riverland (Botting et al., 1996). These authors reported that, between about 15 and 30 °Brix, there was a linear correlation of °Brix with G-G per g berry weight. The data from the Waikerie experiment also indicated a near-linear increase in G-G per berry and G-G per g berry weight between about 15 and 22 °Brix in each season, more so for fully irrigated vines, ($r^2 = 0.81$ and 0.82 for the fully irrigated treatment in 1993-94 and 1994-95 respectively). In each year G-G concentration increased by 0.28 µmol glucose per °Brix between 15 and 25 °Brix (data not presented) which was higher than the 0.22 µmol glucose per °Brix increase for the Riverland study (Botting - pers. comm). Over the wider range of °Brix samples analysed from the Waikerie experiment, using logistic modelling rather than linear regression analysis, 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. (Chapter 4.4.3) of each treatment (Table 5.9).

Table 5.9 °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

At 20 °Brix the G-G content per berry of fully irrigated vines in the Waikerie experiment was at least 3 times greater than G-G content per berry of Muscat Gordo, between 4 and 5 times greater than Flame Seedless berries and about 15 times higher than the G-G content of Sultana berries at similar °Brix during the 1992-93 season (Gholami et al., 1996). G-G content per Muscat Gordo berry approximately doubled between 6 and 23 °Brix, however there was little change in G-G per berry of Sultana vines between 10 and 25 °Brix. In comparison, between the first sampling in the 1994-95 season (when fully irrigated Shiraz berries were 8.2 °Brix) and 23 °Brix there was 5.5 fold increase in G-G content per berry. Although the G-G content of Muscat Gordo berries increased during berry ripening, the rapid increase in berry weight from 1.76 g at 6 °Brix to 3.41 g at 18 °Brix (190 percent increase) resulted in a decrease in G-G concentration. In contrast, over a similar °Brix range, there was about a 50 percent increase in weight for fully irrigated Shiraz berries from the Waikerie experiment and this smaller increase in weight, combined with the large increase in G-G content per berry, resulted in the steady increase in G-G concentration.

In addition to the differences in berry size between treatments, the interpretation of data on the G-G concentration of Shiraz berries from the Waikerie experiment is confounded by the decline in berry weight which commenced about 91 days after anthesis (or when the berries of Trts 1-7 were 16.8 and 18.5 °Brix in the 1993-94 and 1994-95 seasons respectively, Table 5.9). This effect was most apparent for fully irrigated and unirrigated treatments (the treatments that produced the greatest difference in berry size) in the 1994-95 season. During the initial stages of ripening, as the weight of fully irrigated berries increased, G-G content per berry increased at a rate sufficient to cause a steady rise

in G-G concentration (Figure 5.19). The G-G content per berry continued to increase after about 18 °Brix and, although there was about a 20 percent decline in berry weight between 18 and 24 °Brix, there was no acceleration in rate of increase in G-G concentration per berry during the latter stages of ripening. While berries increased in weight between the first sampling and about 19 °Brix, the rate of increase in G-G content per berry was sufficient to result in an overall increase in G-G concentration. After 19-20 °Brix, although the rate of increase in G-G content per berry slowed (Figure 5.19), the loss in berry weight resulted in a continued steady increase in G-G concentration per berry. There was a similar correlation between anthocyanin-glucose per berry and anthocyanin-glucose per g berry weight for all treatments in both years.

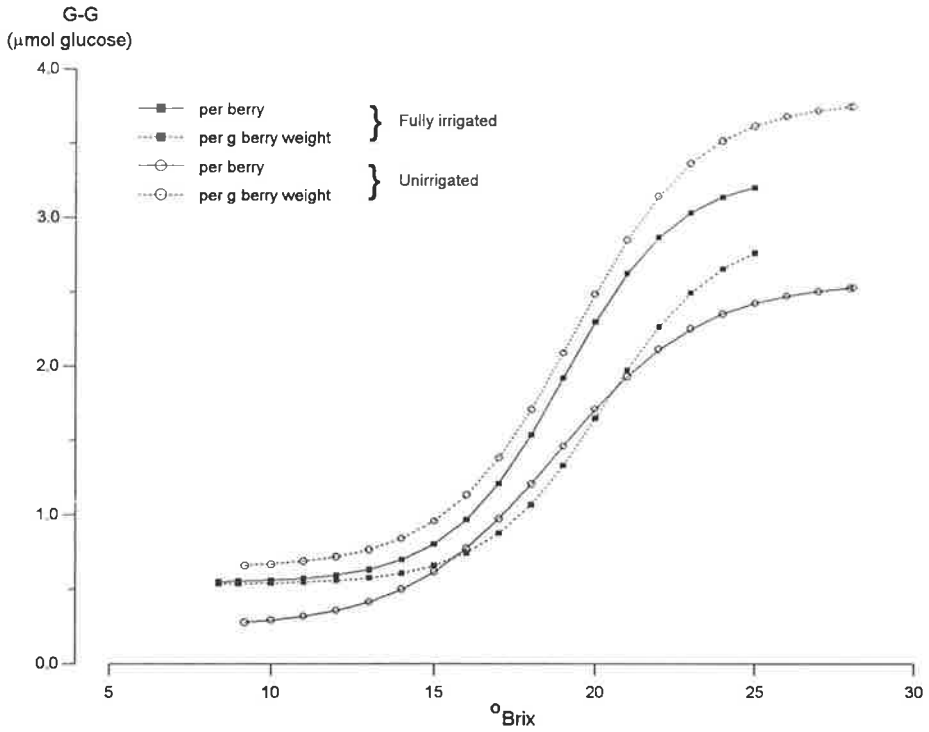

Figure 5.19 Fitted logistic models for G-G per berry and per g berry weight for fully irrigated and unirrigated treatments plotted against °Brix during the 1994-95 season.

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 (Chapter 4). 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.

The greater G-G content of Shiraz berries compared with Muscat Gordo, Sultana and Flame Seedless was partly attributable to glycosylated red-pigments which were absent or at low levels in the varieties tested by Gholami et al. (1996). There were highly significant linear correlations between G-G and anthocyanin-glucose content per Shiraz berry in 1993-94 and 1994-95 for all samples, displayed in Figure 5.20. 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. 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. Seasonal conditions may account for the differences between the two years.

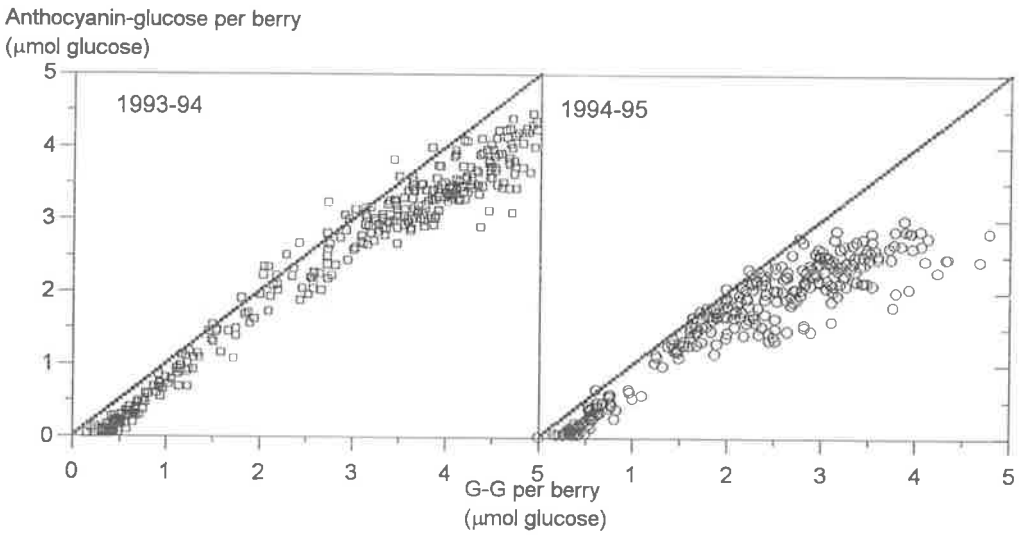

Figure 5.20 Relationship between anthocyanin-glucose content per berry and G-G content per berry for all samples of all treatments for the 1993-94 and 1994-95 seasons. Diagonal line represents the case of all G-G per berry being anthocyanin-glucose.

At 23.5 °Brix the G-G and anthocyanin-glucose content and concentration of Shiraz berries in this experiment were in the upper range of values for other Shiraz vineyards in the South Australian Riverland (Botting et al., 1996). These authors reported a range in G-G content of between 1.4 to 3.3 μmol glucose per berry when collected between 20 and 25

°Brix from a wide range of Shiraz vineyards in the South Australian Riverland. For berries of 23.0 ± 0.5 °Brix, there was a positive correlation between G-G content and concentration per berry when bunch irradiances were between 115 to 343 μmol. m^{-2}. s^{-1} (measured in bright sunshine on cloudless days around midday). In addition G-G content and concentration per berry were positively correlated with berry size. They suggested that in order to achieve adequate wine colour, irradiance of bunches should be greater than 300 μmol. m^{-2} .s^{-1}. In the Waikerie experiment the lack of significant irrigation effects on G-G and anthocyanin-glucose could in part be due to adequate levels of bunch exposure in all treatments including the most vigorous fully irrigated vines. Bunch exposure soon after veraison in the 1993-94 season ranged from an irradiance measure of about 200 μmol. m^{-2} .s^{-1} for fully irrigated vines to greater than 600 μmol. m^{-2} .s^{-1} for unirrigated (Iland et al., 1995) and was higher at harvest (Botting -pers. comm). The unanswered question is, therefore, would a larger range of vigour and vine training produce significant differences in G-G measures, or does the growing environment (locality and season) have an over-riding influence ?

The red-free G-G measure gave an estimate of the concentration of glycosides other than anthocyanidin glycosides (Iland et al., 1996a). For cv. Shiraz in 1994-95, the concentration of the non-anthocyanin glycosides as a percent of the total G-G concentration varied from between nearly 100 percent when G-G per g berry weight was low, declined to low levels and then increased to between forty and fifty percent of the total G-G per g berry weight in ripe berries (Figure 5.21).

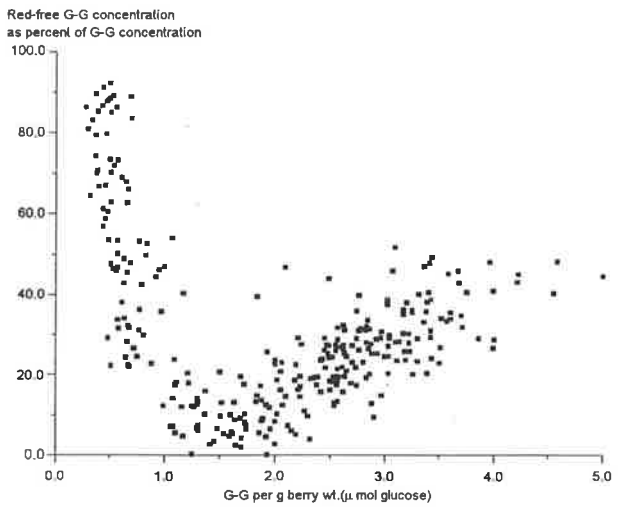

Figure 5.21 Red-free G-G per g berry weight expressed as a percent of G-G per g berry weight for all samples from the 1994-95 season.

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. While the increase in berry size during the initial stages of berry ripening would contribute to the decline in red-free G-G concentration per berry it does not account for the decrease in red-free G-G content per berry. A decline in red-free G-G content as shown could only occur through metabolism to non-glycosides or translocation out of the berry; it is considered unlikely to be due to the method of measurement and calculation. Notwithstanding, red-free G-G per berry declined at a similar rate in each year. The constancy of this decline is surprising in view of the wide range in soil water deficit, seasonal conditions, and a difference between seasons of 3.7 °Brix at the minimum red-free G-G. 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).

Winemakers are mainly interested in grape berry concentrations rather than content per berry, and in particular would appreciate knowing °Brix, TA, pH, anthocyanin and red-free G-G. In this experiment two methods were used to determine the concentration of G-G, anthocyanin-glucose and red-free G-G at harvest, – interpolation from statistically fitted curves or from values from individual field plots. Both methods resulted in an approximately similar ranking of treatments based on G-G or anthocyanin-glucose indicating that either approach could be used to determine the effect of treatment on G-G or anthocyanin-glucose concentration. This comparison was, however, only possible because a large number of samples were available from which similar °Brix could be selected. These data indicate that regular sampling prior to and during harvest is necessary to ensure that treatments are compared at similar °Brix not only for red-free G-G concentration but also for other berry components.

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 5.18). 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 5.18). 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. High variance has been demonstrated before in measurements of monoterpene concentration in ripening Riesling berries (McCarthy, 1986) and in Muscat Blanc berries (P. J. Williams- pers. comm), however the cause of the variability was not determined. Clearly this phenomenon deserves concerted investigation and, with the knowledge that monoterpene glycosides are synthesised in the berries (Gholami et al., 1995), should be attempted.

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.

Data presented in the preceding Chapter indicated a significant change in berry metabolism about 91 days after anthesis, this being characterised by a decline in berry weight due to water loss from berries and a cessation in solute accumulation during one season. This was identified as weight-max. and it was proposed that phloem blockage may be the trigger for these events. In this Chapter evidence is presented of an additional significant change in berry metabolism at weight-max., that being the increase in red-free G-G content. Coombe (1976) suggested that during the initial rise in ABA concentration as berries began to ripen there was a close correlation between ABA concentration and hexose accumulation until midway through ripening whereafter ABA declined. The decline started after about 15 °Brix, a stage similar to weight max. and the onset of red-free G-G accumulation. It is possible that all of these events may be linked.

5.5 Conclusions

a. *Using juice °Brix as an index of Shiraz berry ripening, the levels during ripening of total glycosides (G-G) and anthocyanin-glucose (red colour), both per berry (content) and per g berry weight (concentration) showed sigmoidal forms of development in all treatments and years.*

b. *Anthocyanin-glucose was the predominant component of glycosyl-glucose throughout berry development, its percentage being close to 100 % at weight-max. but declining thereafter. The decline was especially marked in year 4.*

c. *There was no consistent treatment effect on anthocyanin-glucose concentration when compared at the same °Brix level, however, anthocyanin-glucose content and concentration were significantly lower in year 4 compared with year 3 (Table 5.4).*

d. *Red-free G-G (which is the difference between total and anthocyanin G-G and includes flavour compounds as well as other secondary metabolites) showed a two-stage development, declining from medium levels early to almost nil at the time of weight-max. after which levels rose sharply during the latter stages of berry ripening.*

e. *High variability between samples within the same treatment (unrelated to days after anthesis or °Brix) precluded the discrimination of significant irrigation treatment effects. As with anthocyanin-glucose accumulation, there was a significant difference between seasons and, during the latter stages of ripening in year 4, red-free G-G accumulated at three times the rate compared with the same period in year 3. Thus year 4 berries, compared with year 3, had lower G-G and anthocyanin, but higher red-free G-G.*

f. *Weight-max., the cessation of solute accumulation and water loss from berries and onset of rapid red-free G-G accumulation all appear to be linked and are tied more to time after anthesis than to juice °Brix.*

Chapter Six - Concluding Remarks

6.1 The experiment

A comprehensive experiment was established at Waikerie to test the hypothesis:

"That water deficit applied to fruiting grapevines influences fruit development and that the amount of the effect depends upon the timing of the deficit."

The Waikerie site was chosen for its uniform deep soil profile, the absence of a shallow water table, mature Shiraz vines and ease of re-design of the irrigation system from over-canopy sprinklers to under-canopy micro-jet sprinklers.

The experiment comprised nine replicates of eight treatments designed such that test vines were buffered on all four sides with vines that received the same level of irrigation; this ensured lateral water movement did not affect the test vines. The whole of the experiment was bounded by buffer vines to reduce the impact of the surrounding irrigation. The under-canopy micro-jet irrigation system was designed to minimise spatial differences in water application and all irrigations were based on the volume of water delivered.

Few other irrigation experiments have included the multiplicity of assessment methods used at Waikerie and over four consecutive seasons. Intensive measurement of soil water content with a neutron probe provided a detailed account of the daily change in soil water content in all treatments and soil matric potential was calculated from soil water content. The level of soil water deficit achieved in each treatment varied between years as the four seasons were climatically different; this enabled treatment discrimination and examination of the long-term effects of each irrigation deficit treatment. Shoot growth, leaf water potential and stomatal conductance were measured on a regular basis in each season. Berry development and berry composition of all treatments were measured weekly during berry ripening in each year and berry sampling continued past normal harvest time. The effect of irrigation treatment on berry composition during ripening was assessed weekly by measuring juice °Brix, pH, titratable acid, glycosyl-glucose and anthocyanin; red-free G-G was calculated. Yield and its components were measured at harvest in each year and the weight of prunings removed in winter was recorded. The weather and soil water content was continuously monitored with an automatic weather station and capacitance sensors

respectively, however the latter were subject to some inconsistencies. In summary, a large and comprehensive data set was compiled.

6.2 The results

Soil aspects of site selection for irrigation experiments involves a compromise between soil type and depth and the presence of any water-table. At Waikerie most of the available soil water was held at a low soil matric potential in the freely draining sandy soil, however, because of the soil depth, there was a large volume of available soil water. During irrigation deficit periods, the large soil water reservoir provided considerable buffering capacity and soil water deficit was achieved only during periods of high evaporative demand. This occurred at least once for all deficit irrigated treatments although the level of soil water deficit and plant water stress was probably lower than if the experiment had been established on a shallower soil profile. The above-average rainfall during the first two years of the experiment ensured the survival of unirrigated vines; during this time they probably developed an extensive root system to depth which enabled their continued growth, albeit restricted, in subsequent years.

The date of budburst, anthesis, and veraison varied between seasons but the duration between these phenological stages was not affected by irrigation deficit. In one season (1993-94), anthesis on unirrigated vines may have been advanced as berries were significantly heavier than fully irrigated for the first two samplings. Although harvest date (23.5 °Brix) varied by up to three weeks within a season the constancy of the duration between stages for all treatments suggested that the weather was the major influence on vine development. The number of days between anthesis and 10 or 15 °Brix and anthesis and maximum berry weight for fully irrigated vines (Ch 4.5 b) showed little variation and it is suggested this was a genotypic response.

All deficit treatments reduced yield per vine when weather conditions were conducive to the development of soil water deficit and this loss was primarily due to smaller berries. Irrigation deficit during the post anthesis period reduced shoot growth and berry size throughout their development. Water deficit during the pre-veraison, post veraison and pre-harvest periods also reduced berry size but not to the same degree as post anthesis deficit. There appeared to be a threshold level below which the effects of water stress during the post veraison deficit were reversible. The calculated soil matric potential

required to reduce berry size was lower than the critical level for shoot growth as, in some years, shoot growth was reduced with no loss in berry weight.

°Brix was often enhanced by irrigation deficit but the total amount of solutes per berry were reduced. Juice titratable acid or pH were similar for all treatments when compared at the same °Brix level. Berries from unirrigated vines had the highest chloride concentration in their homogenate.

Anthocyanin-glucose, which was the predominant component of glycosyl-glucose throughout berry development, showed a sigmoidal form of development for content and concentration in all treatments and years, and there were only minor differences between treatments within a year when compared at the same °Brix (Ch 5.5 a, b, c). High variability in red-free G-G concentration between samples precluded discrimination of treatment effects (Ch 5.5 e) however there was a large difference in the rate of accumulation of red-free G-G between the two years it was measured. Compared with year 3, berries accumulated less G-G and anthocyanin in year 4 but more red-free G-G. The content of glycosylated secondary metabolites was less sensitive to water deficit than solute content per berry and in the two seasons that comparisons were possible, irrigation deficit reduced solute content but not red-free G-G content per berry.

The single result that transcended all irrigation and seasonal effects was the occurrence of maximum berry weight at about day 91 after anthesis (weight-max.), the subsequent loss in water, the cessation of solute accumulation, and the onset of rapid red-free G-G accumulation. Loss in weight during berry ripening has been reported in other experiments, but as the majority of these spanned only one growing season compared with the four seasons of the Waikerie experiment, the consistency of the onset of weight loss over differing seasons and differing vine vigors has not previously been reported. The sudden cessation of water and solute movement into ripening berries was proposed to be due to phloem blockage.

The data indicate that solute and glycosylated secondary metabolite accumulation are independent. Weight loss after 91±3 days, and the coincident start of glycosylated secondary metabolite accumulation (Ch. 5.5 f) were features of the results shown here. Weight loss may not be as pronounced in the latter stages of berry ripening in other varieties

but it is possible that the late and rapid accumulation of glycosylated secondary metabolites is a general phenomenon in winegrape ripening.

In conclusion, the hypothesis that water deficit applied to fruiting grapevines influences fruit development and that the amount of the effect depends upon the timing of the deficit is accepted with qualification. Little effect on glycosylated secondary metabolite accumulation was demonstrated and water deficit did not influence loss in berry weight which commenced in all treatments about 91 days after anthesis.

6.3 Further research

In the Waikerie experiment daily cumulative soil water deficit was used as a stress index to examine the relationship between irrigation deficit and berry growth and a susceptibility index was established. An index based on soil matric potential rather than soil water content should also be attempted as this would permit extrapolation to other sites. This index could be based on direct measurement of soil matric potential rather than calculated from soil water content using a soil water retention curve.

Several questions about grape berry development are prompted by the present results. Post anthesis deficit reduced growth of both shoots and berries, a result which warrants the examination of the effect of water deficit on cell division in relevant tissues.

The dramatic change in cv. Shiraz berry function at about 91 days after anthesis suggests several lines for further work, for example:

- A similar program of intensive measurement to test if a similar pattern of weight loss and the onset of glycosylated secondary metabolite accumulation occurs in other varieties.

- A testing of the proposal that solute and water transport into berries ceases at day 91.

The control of the biosynthesis of glycosylated secondary metabolites should be pursued. The red-free G-G measure provided a relatively simple analytical method to investigate the changes in non-anthocyanin glycosylated secondary metabolites during berry ripening. The deficit treatments imposed in the Waikerie experiment resulted in a significantly smaller berries, lower yield, shorter shoots and changes in sugar accumulation

but not in the concentration of glycosylated secondary metabolites in berries. In addition the seasonal effect on the rate of accumulation of red-free G-G outweighed any treatment effect and was independent of °Brix. The more rapid rise in red-free G-G in year 4 appeared to be linked to a latter and lower value at the intersection point. This suggested an unusual control of glycosylated secondary metabolite accumulation which, in turn, may account for the high variability between samples within the same treatment. The source of this high variability requires examination; possible sources may be asynchronous berry development, berry position on a bunch or bunch position on a vine, or the leaf area per bunch. If the cause of this variability can be identified and reduced, the effect of cultural practices such as irrigation, canopy configuration, crop load, season and region could be investigated and thus help establish the relationship, if any, between red-free G-G and wine quality.

6.4 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.

6.4.1 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.

6.4.2 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.

6.4.3 Indices of wine quality

No conclusions on the merit of the red-free G-G measure as an index of wine quality can be drawn from this thesis. 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.

Fully irrigated vines (Trt 1) were trained on a quadrilateral cordon and were of moderate vigour which resulted in an 'open' canopy and fruit was well exposed to direct solar radiation. Yield per ha of fully irrigated vines in the Waikerie experiment was about 20.8 T/ha (Table 3.7) which is slightly higher than the district average but lower than

calculated yields from previously reported experiments in which there were significant responses to irrigation, for example 30.9 T/ha reported by Kliewer et al. (1983) and 34.3 T/ha reported by Bravdo et al. (1984). Perhaps with higher yield on a restricted trellis the effects of the irrigation treatments in the Waikerie experiment on wine quality indices may have had a chance to show significance.

Although there were no significant differences in analytical measures of grape quality used in the Waikerie experiment there may be significant differences between treatments when small-lot wines are ranked on wine aroma and flavour (data not presented in this thesis). 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.

Appendix

List of Figures

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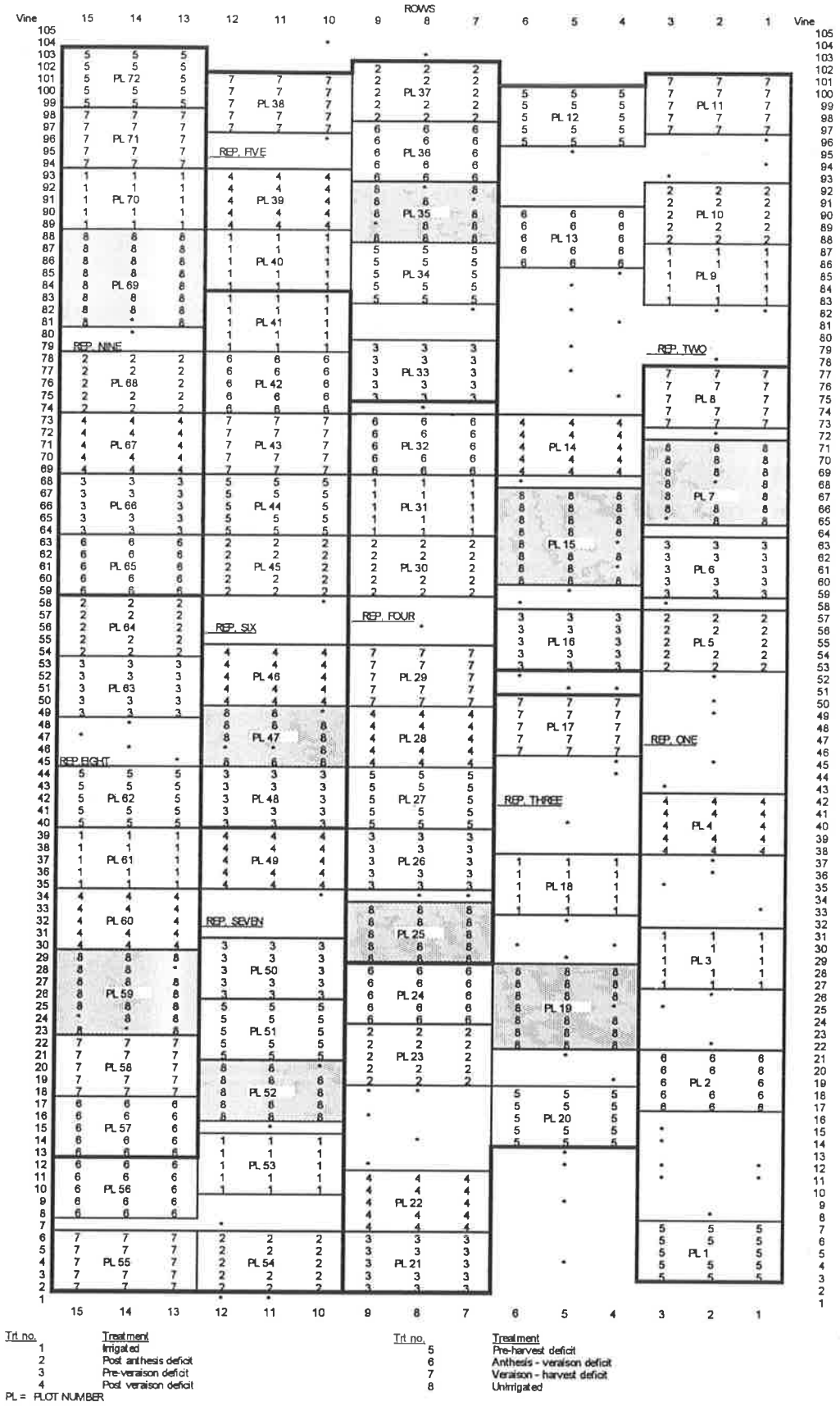
In each table of summary statistics values greater than ± 1.96 in the comparisons matrix indicate a significant difference (shaded cells) between the two treatments.



Trt no.	Treatment
1	Irrigated
2	Post anthesis deficit
3	Pre-veraison deficit
4	Post veraison deficit

Trt no.	Treatment
5	Pre-harvest deficit
6	Anthesis - veraison deficit
7	Veraison - harvest deficit
8	Unirrigated

PL = PLOT NUMBER

Figure 1 Plan of experimental site located in a block of Shiraz vines in a commercial vineyard at Sunlands, South Australia.

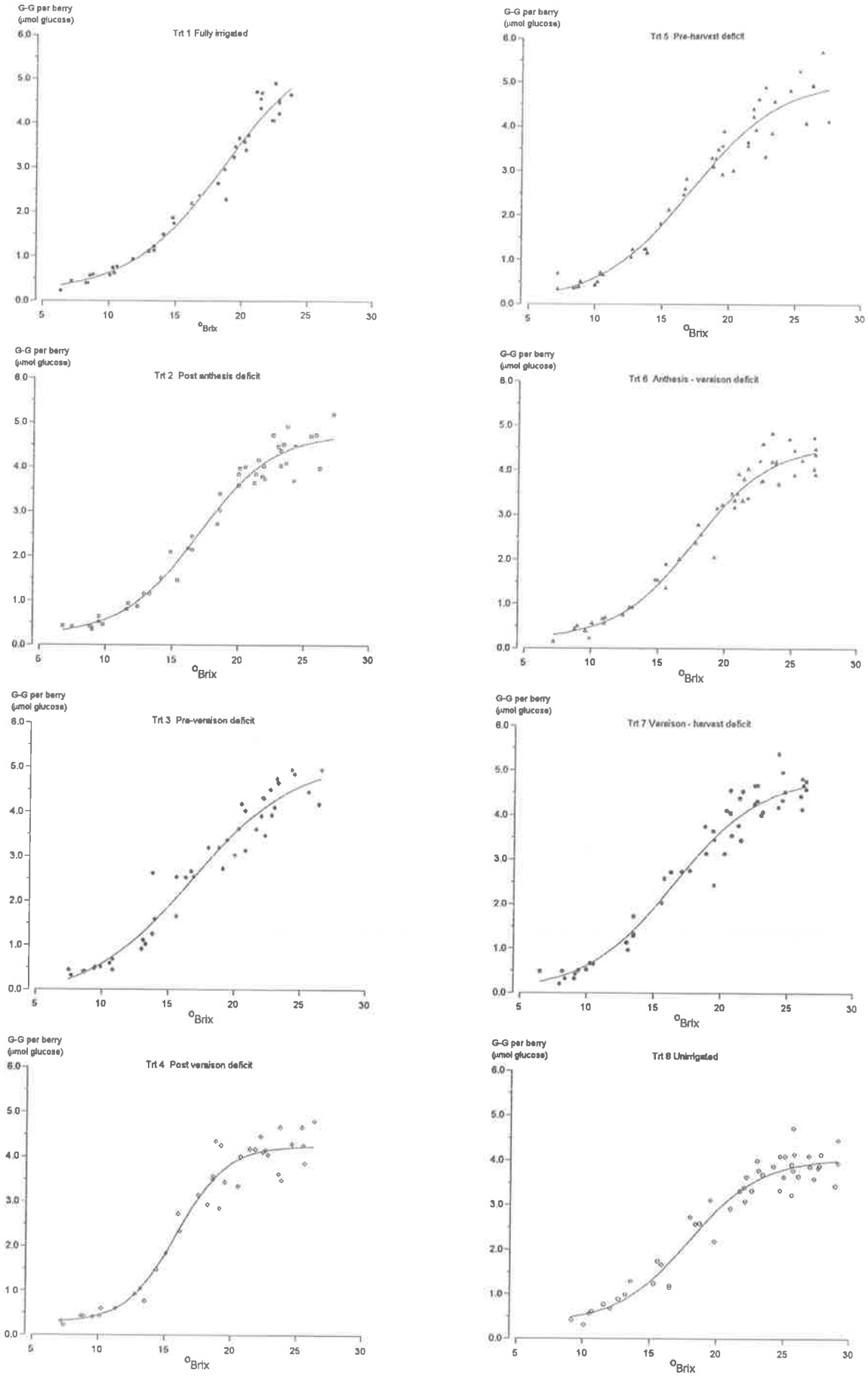


Figure 2 G-G per berry of all treatments during berry ripening in the 1993-94 season.

Table 1 Summary statistics of the difference between treatments in slope, inflection point, asymptote and intercept of the logistic models fitted to describe the relationship between G-G per berry and °Brix for all treatments in the 1993-94 season.

B=slope		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
0.2850	0.0717	1							
0.3545	0.0573	2	-0.76						
0.2581	0.0544	3	0.30	1.22					
0.5370	0.0801	4	-2.34	-1.85	-2.88				
0.2976	0.0498	5	-0.14	0.75	-0.54	2.54			
0.3524	0.0565	6	-0.74	0.03	-1.20	1.88	-0.73		
0.3192	0.0496	7	-0.39	0.47	-0.83	2.31	-0.31	0.44	
0.3757	0.0708	8	-0.90	-0.23	-1.32	1.51	-0.90	-0.26	-0.6

M=Inflection		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
18.650	1.090	1							
16.963	0.432	2	1.44						
16.722	0.631	3	1.53	0.32					
15.880	0.325	4	2.44	2.00	1.19				
17.129	0.488	5	1.27	-0.25	-0.51	-2.13			
17.699	0.428	6	0.81	-1.21	-1.28	-3.38	-0.88		
16.499	0.462	7	1.82	0.73	0.29	-1.10	0.94	1.91	
17.911	0.517	8	0.61	-1.41	-1.46	-3.33	-1.10	-0.32	-2.0

C=Asymptote		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
5.700	1.120	1							
4.548	0.363	2	0.98						
5.370	0.731	3	0.25	-1.01					
3.966	0.216	4	1.52	1.38	1.84				
4.989	0.466	5	0.59	-0.75	0.44	-1.99			
4.374	0.346	6	1.13	0.35	1.23	-1.00	1.06		
4.832	0.394	7	0.73	-0.53	0.65	-1.93	0.26	-0.87	
3.693	0.329	8	1.72	1.75	2.09	0.69	2.27	1.43	2.2

A=Intercept		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
0.188	0.271	1							
0.212	0.207	2	-0.07						
-0.226	0.403	3	0.85	0.97					
0.282	0.157	4	-0.30	-0.27	-1.17				
0.057	0.259	5	0.35	0.47	-0.59	0.74			
0.205	0.206	6	-0.05	0.02	-0.95	0.30	-0.45		
0.039	0.250	7	0.40	0.53	-0.56	0.82	0.05	0.51	
0.354	0.239	8	-0.46	-0.45	-1.24	-0.25	-0.84	-0.47	-0.9

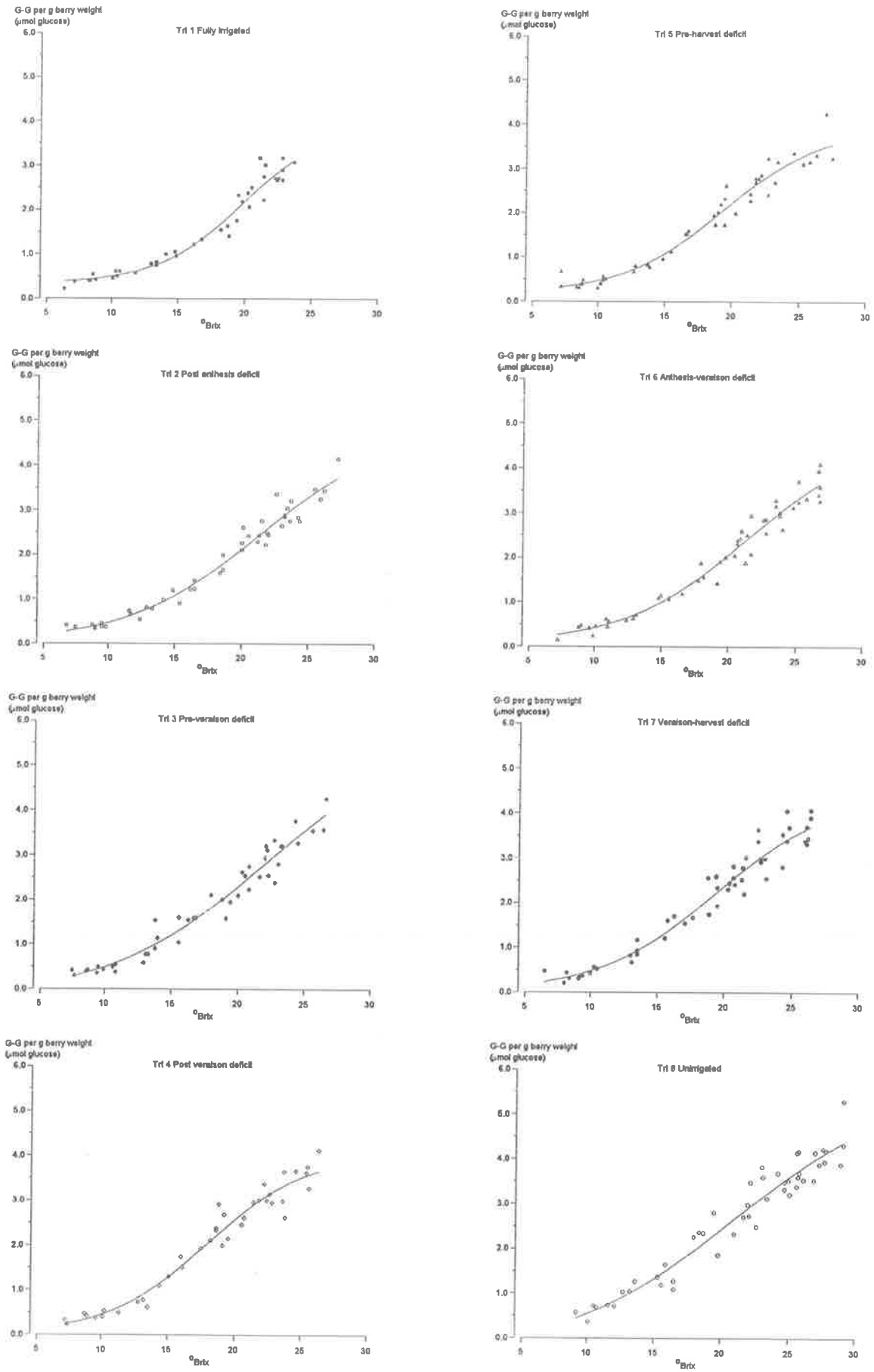


Figure 3 G-G per g berry weight for all treatments during berry ripening in the 1993-94 season.

Table 2 Summary statistics of the difference between treatments in slope, inflection point, asymptote and intercept of the logistic models fitted to describe the relationship between G-G per g berry weight and °Brix for all treatments in the 1993-94 season.

B=slope		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
0.3167	0.0965	1							
0.2017	0.0597	2	1.01						
0.1719	0.0612	3	1.27	0.35					
0.2717	0.0611	4	0.39	-0.82	-1.15				
0.2699	0.0560	5	0.42	-0.83	-1.18	0.02			
0.2205	0.0578	6	0.86	-0.23	-0.58	0.61	0.61		
0.2283	0.0527	7	0.80	-0.33	-0.70	0.54	0.54	-0.10	
0.1601	0.0551	8	1.41	0.51	0.14	1.36	1.40	0.76	0.89

M=Inflection		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
19.830	1.510	1							
21.330	1.820	2	-0.63						
21.960	2.810	3	-0.67	-0.19					
17.887	0.623	4	1.19	1.79	1.42				
19.365	0.695	5	0.28	1.01	0.90	-1.58			
21.370	1.270	6	-0.78	-0.02	0.19	-2.46	-1.38		
19.406	0.820	7	0.25	0.96	0.87	-1.48	-0.04	1.30	
20.990	1.320	8	-0.58	0.15	0.31	-2.13	-1.09	0.21	1.02

C=Asymptote		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
3.590	0.957	1							
4.820	1.260	2	-0.78						
5.940	2.100	3	-1.02	-0.46					
3.987	0.549	4	-0.36	0.61	0.90				
3.708	0.485	5	-0.11	0.82	1.04	0.38			
4.671	0.978	6	-0.79	0.09	0.55	-0.61	-0.88		
4.441	0.715	7	-0.71	0.26	0.68	-0.50	-0.85	0.19	
5.980	1.670	8	-1.24	-0.55	-0.01	-1.13	-1.31	-0.68	-0.8

A=Intercept		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
0.347	0.153	1							
0.030	0.295	2	0.95						
-0.180	0.445	3	1.12	0.39					
0.026	0.253	4	1.09	0.01	-0.40				
0.197	0.178	5	0.64	-0.48	-0.79	-0.55			
0.070	0.260	6	0.92	-0.10	-0.49	-0.12	0.40		
0.013	0.260	7	1.11	0.04	-0.37	0.04	0.58	0.16	
-0.334	0.707	8	0.94	0.48	0.18	0.48	0.73	0.54	0.4

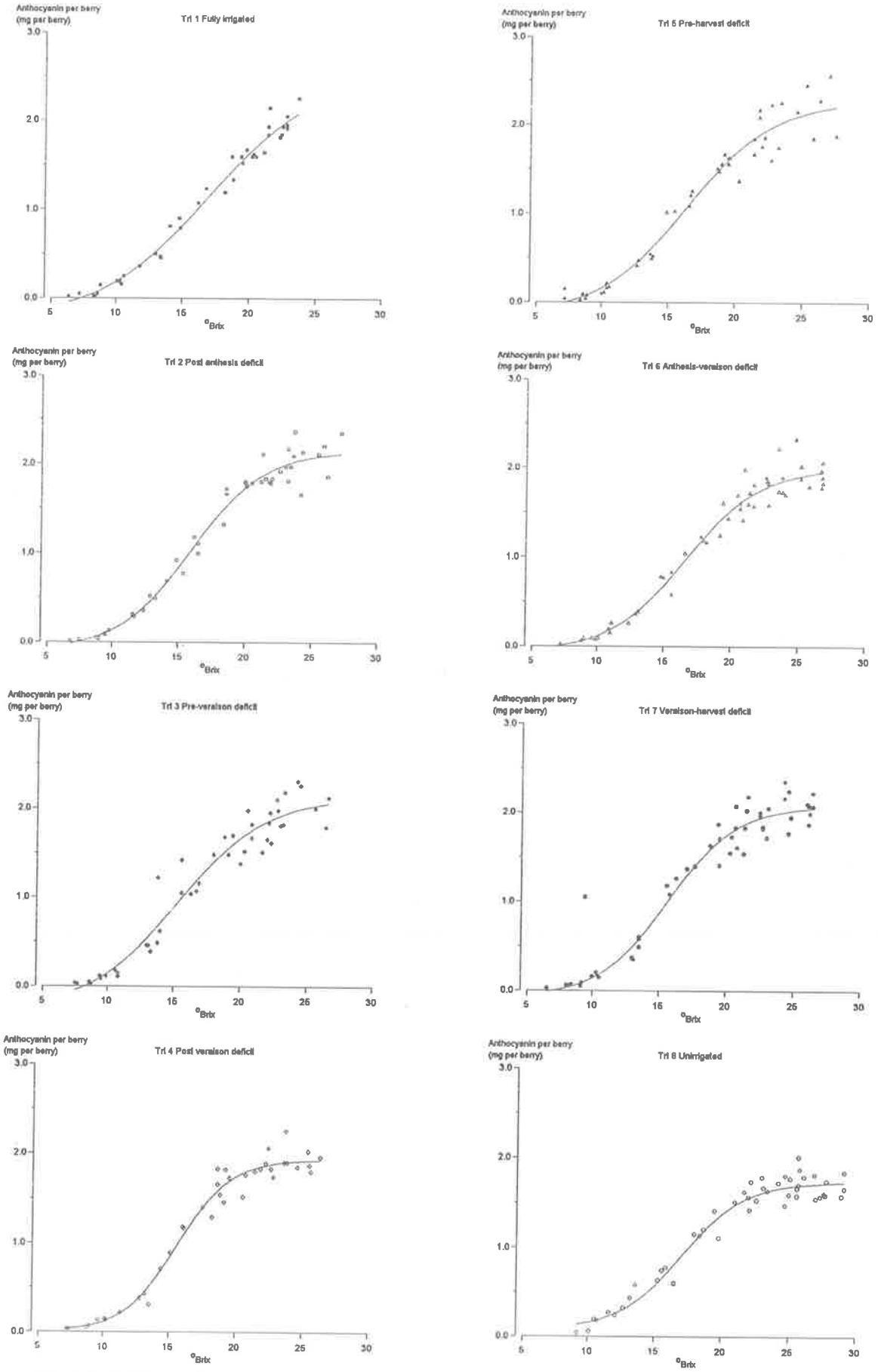


Figure 4 Anthocyanin per berry for all treatments during berry ripening in the 1993-94 season.

Table 3 Summary statistics of the difference between treatments in slope, inflection point, asymptote and intercept of the logistic models fitted to describe the relationship between anthocyanin per berry and °Brix for all treatments in the 1993-94 season.

B=slope		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
0.2445	0.0663	1							
0.3676	0.0529	2	-1.45						
0.3030	0.0532	3	-0.69	0.86					
0.5027	0.0703	4	-2.67	-1.54	-2.27				
0.3051	0.0452	5	-0.76	0.90	-0.03	2.36			
0.3581	0.0536	6	-1.33	0.13	-0.73	1.64	-0.76		
0.3925	0.0507	7	-1.77	-0.34	-1.22	1.27	-1.29	-0.47	
0.4278	0.0762	8	-1.81	-0.65	-1.34	0.72	-1.38	-0.75	-0.39

M=Inflection		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
17.034	0.930	1							
15.996	0.377	2	1.03						
15.311	0.522	3	1.62	1.06					
15.598	0.319	4	1.46	0.81	-0.47				
16.385	0.443	5	0.63	-0.67	-1.57	-1.44			
16.642	0.427	6	0.38	-1.13	-1.97	-1.94	-0.42		
15.662	0.363	7	1.37	0.64	-0.55	-0.13	1.26	1.75	
17.084	0.455	8	-0.05	-1.84	-2.56	-2.67	-1.10	-0.71	-2.44

C=Asymptote		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
2.767	0.551	1							
2.236	0.154	2	0.93						
2.380	0.249	3	0.64	-0.49					
1.928	0.104	4	1.50	1.66	1.68				
2.417	0.198	5	0.60	-0.72	-0.12	-2.19			
2.060	0.154	6	1.24	0.81	1.09	-0.71	1.42		
2.152	0.127	7	1.09	0.42	0.82	-1.36	1.13	-0.46	
1.655	0.129	8	1.97	2.89	2.59	1.65	3.22	2.02	2.75

A=Intercept		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
-0.233	0.206	1							
-0.086	0.101	2	-0.64						
-0.249	0.169	3	0.06	0.83					
0.008	0.076	4	-1.10	-0.74	-1.38				
-0.143	0.122	5	-0.38	0.36	-0.51	1.05			
-0.057	0.105	6	-0.76	-0.20	-0.97	0.50	-0.53		
-0.070	0.092	7	-0.72	-0.12	-0.93	0.65	-0.48	0.09	
0.082	0.103	8	-1.37	-1.16	-1.67	-0.58	-1.41	-0.95	-1.10

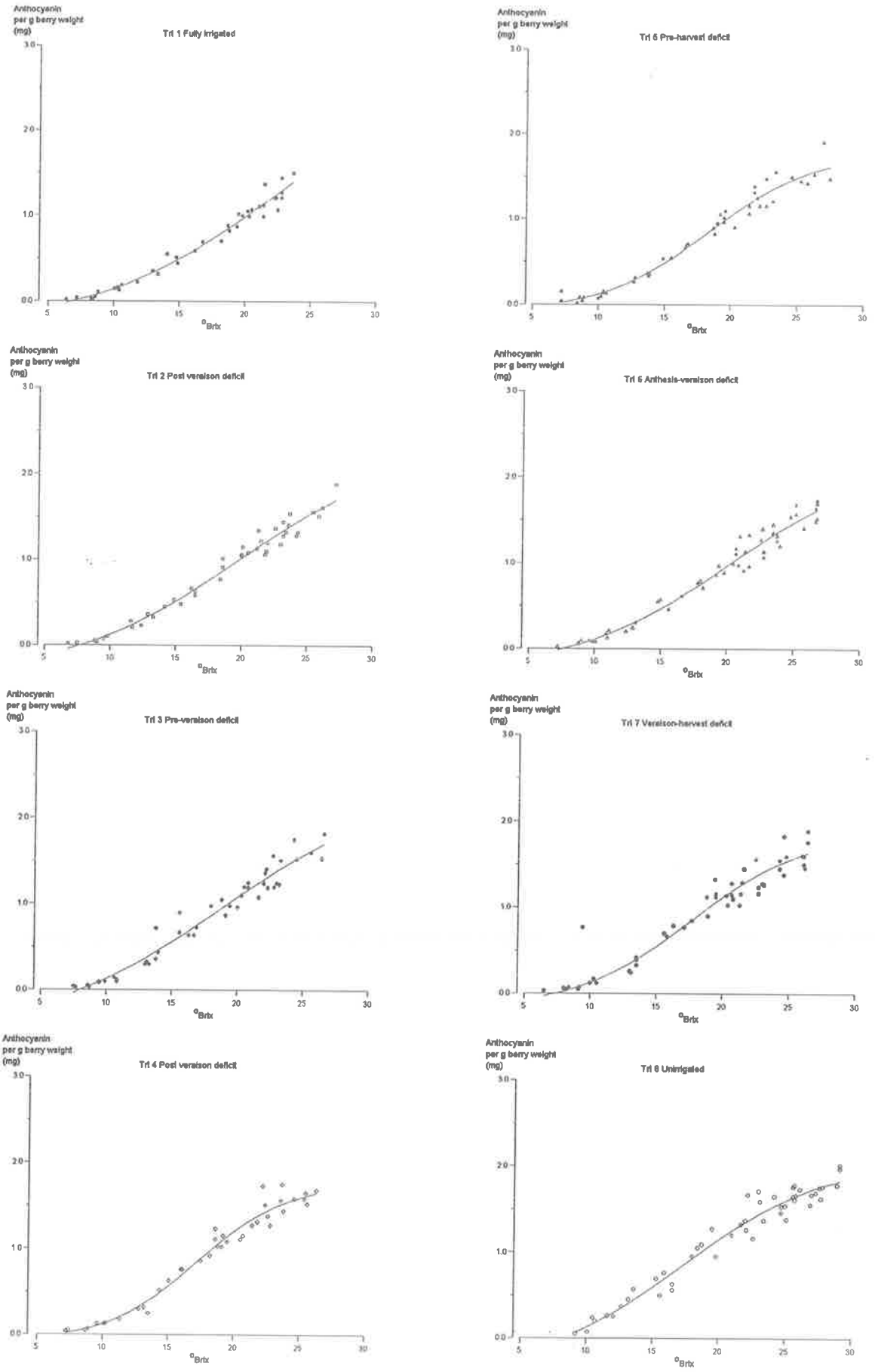


Figure 5 Anthocyanin per g berry weight for all treatments during berry ripening in the 1993-94 season.

Table 4 Summary statistics of the difference between treatments in slope, inflection point, asymptote and intercept of the logistic models fitted to describe the relationship between anthocyanin per g berry weight and °Brix for all treatments in the 1993-94 season.

B=slope		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
0.1483	0.0999	1							
0.1572	0.0545	2	-0.08						
0.1479	0.0580	3	0.00	0.12					
0.2891	0.0525	4	-1.25	-1.74	-1.80				
0.2461	0.0468	5	-0.89	-1.24	-1.32	0.61			
0.1773	0.0532	6	-0.26	-0.26	-0.37	1.50	0.97		
0.2277	0.0477	7	-0.72	-0.97	-1.06	0.87	0.28	-0.71	
0.1786	0.0489	8	-0.27	-0.29	-0.40	1.54	1.00	-0.02	0.72

M=Inflection		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
22.160	8.310	1							
19.740	1.780	2	0.28						
18.740	1.670	3	0.40	0.41					
17.179	0.484	4	0.60	1.39	0.90				
18.347	0.603	5	0.46	0.74	0.22	-1.51			
19.980	1.220	6	0.26	-0.11	-0.60	-2.13	-1.20		
17.619	0.599	7	0.55	1.13	0.63	-0.57	0.86	1.74	
17.250	1.260	8	0.58	1.14	0.71	-0.05	0.79	1.56	0.26

C=Asymptote		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
3.020	2.530	1							
2.684	0.799	2	0.13						
2.865	0.964	3	0.06	-0.14					
1.848	0.194	4	0.46	1.02	1.03				
1.882	0.230	5	0.45	0.96	0.99	-0.11			
2.414	0.579	6	0.23	0.27	0.40	-0.93	-0.85		
2.060	0.268	7	0.38	0.74	0.80	-0.64	-0.50	0.55	
2.517	0.551	8	0.19	0.17	0.31	-1.15	-1.06	-0.13	0.75

A=Intercept		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
-0.284	0.366	1							
-0.353	0.278	2	0.15						
-0.478	0.392	3	0.36	0.26					
-0.082	0.103	4	-0.53	-0.91	-0.98				
-0.092	0.103	5	-0.50	-0.88	-0.95	0.07			
-0.241	0.217	6	-0.10	-0.32	-0.53	0.66	0.62		
-0.180	0.137	7	-0.27	-0.56	-0.72	0.57	0.51	-0.24	
-0.415	0.375	8	0.25	0.13	-0.12	0.86	0.83	0.40	0.59

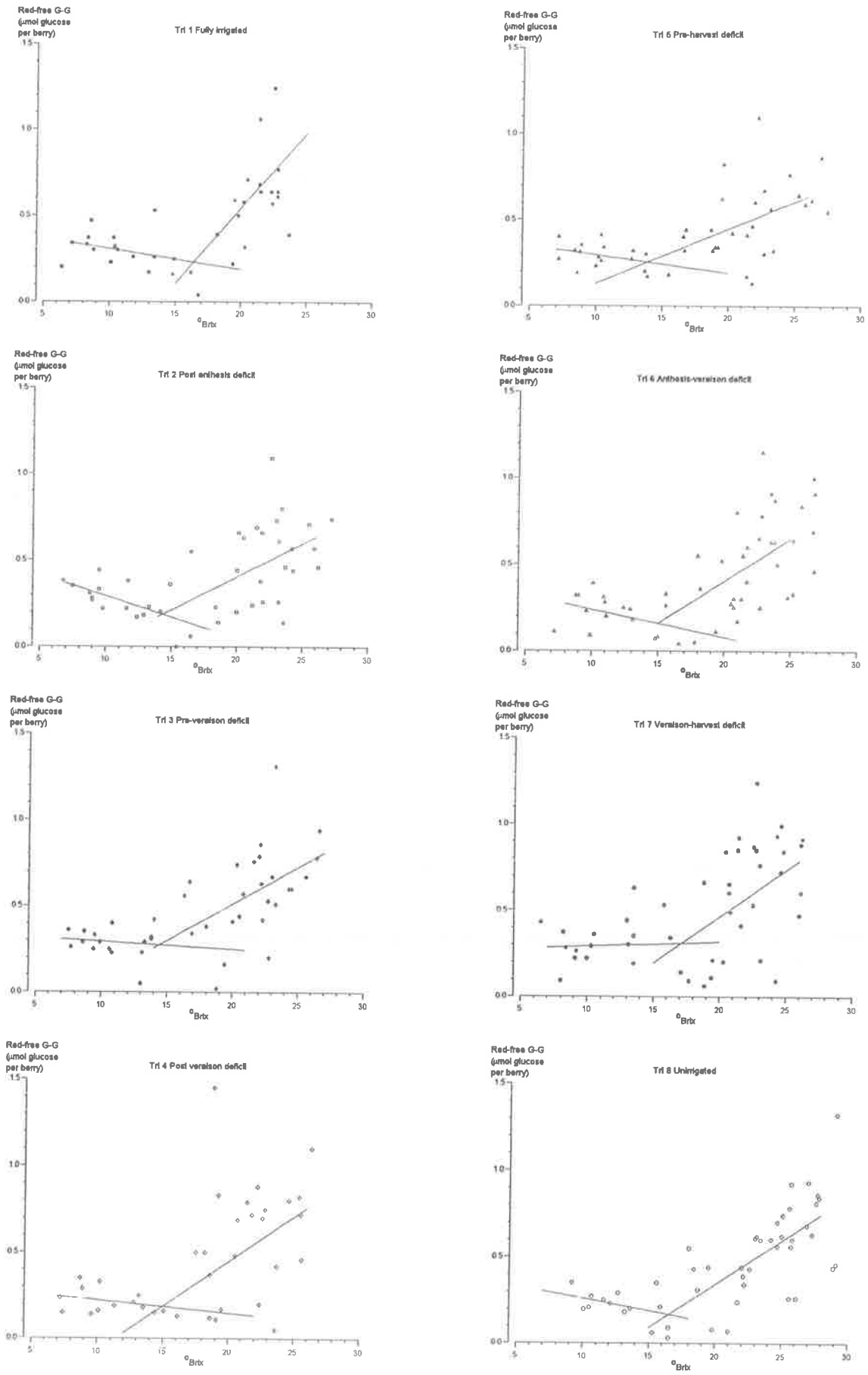


Figure 6 Regression of red-free G-G per berry against °Brix for all treatments in the 1993-94 season.

Table 5 Regression constants for two phase linear modelling of red-free G-G per berry against °Brix for the 1993-94 season.
Line 1 represents the left hand line, Line 2 represents the right hand line.

	Trt 1 Irrigated	
	Line 1	Line 2
Slope	-0.012	0.087
Intercept	0.436	-1.20
Intersection		
°Brix	16.3	
Red-free G-G	0.23	

	Trt 2 Post anthesis deficit	
	Line 1	Line 2
Slope	-0.024	0.039
Intercept	0.54	-0.36
Intersection		
°Brix	14.4	
Red-free G-G	0.19	

	Trt 3 Pre-veraison deficit	
	Line 1	Line 2
Slope	-0.004	0.043
Intercept	0.39	-0.34
Intersection		
°Brix	14.4	
Red-free G-G	0.27	

	Trt 4 Post veraison deficit	
	Line 1	Line 2
Slope	-0.008	0.05
Intercept	0.30	-0.59
Intersection		
°Brix	14.9	
Red-free G-G	0.19	

	Trt 5 Pre-harvest deficit	
	Line 1	Line 2
Slope	-0.01	0.03
Intercept	0.39	-0.19
Intersection		
°Brix	13.9	
Red-free G-G	0.25	

	Trt 6 Anthesis-veraison deficit	
	Line 1	Line 2
Slope	-0.016	0.049
Intercept	0.39	-0.58
Intersection		
°Brix	15.0	
Red-free G-G	0.16	

	Trt 7 Veraison -harvest deficit	
	Line 1	Line 2
Slope	0.002	0.054
Intercept	0.267	-0.613
Intersection		
°Brix	17.1	
Red-free G-G	0.309	

	Trt 8 Unirrigated	
	Line 1	Line 2
Slope	-0.014	0.05
Intercept	0.405	-0.665
Intersection		
°Brix	16.5	
Red-free-G-G	0.167	

Table 6 Summary statistics of the difference between treatments in the Y intercept of line 2, slope of line 1 and 2 and the °Brix of the intersection of lines 1 and 2 respectively for two phase linear modelling of red-free G-G per berry against °Brix for all treatments for the 1993-94 season.

		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
-1.2002	0.6994	1							
-0.3662	0.2504	2	-1.12						
-0.3421	0.3093	3	-1.12	-0.06					
-0.5928	0.3150	4	-0.79	0.56	0.57				
-0.1850	0.2169	5	-1.39	-0.55	-0.42	-1.07			
-0.5787	0.2303	6	-0.84	0.62	0.61	-0.04	1.24		
-0.6128	0.3755	7	-0.74	0.55	0.56	0.04	0.99	0.08	
-0.6648	0.2519	8	-0.72	0.84	0.81	0.18	1.44	0.25	0.12

B1=slope 1		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
-0.0119	0.0215	1							
-0.0244	0.0237	2	0.39						
-0.0045	0.0225	3	-0.24	-0.61					
-0.0076	0.0272	4	-0.12	-0.47	0.09				
-0.0104	0.0190	5	-0.05	-0.46	0.20	0.08			
-0.0160	0.0290	6	0.11	-0.22	0.31	0.21	0.16		
0.0025	0.0248	7	-0.44	-0.78	-0.21	-0.27	-0.41	-0.48	
-0.0144	0.0205	8	0.08	-0.32	0.33	0.20	0.14	-0.05	0.53

B2=slope 2		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
0.0876	0.0332	1							
0.0385	0.0115	2	1.40						
0.0427	0.0142	3	1.24	-0.23					
0.0522	0.0146	4	0.98	-0.74	-0.47				
0.0316	0.0100	5	1.62	0.45	0.64	1.16			
0.0492	0.0104	6	1.10	-0.69	-0.37	0.17	-1.22		
0.0539	0.0166	7	0.91	-0.76	-0.51	-0.08	-1.15	-0.24	
0.0504	0.0103	8	1.07	-0.77	-0.44	0.10	-1.31	-0.08	0.18

G=X intercept		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
16.348	2.115	1							
14.353	2.224	2	0.65						
14.415	3.050	3	0.52	-0.02					
14.929	2.823	4	0.40	-0.16	-0.12				
13.900	2.690	5	0.72	0.13	0.13	0.26			
15.000	2.397	6	0.42	-0.20	-0.15	-0.02	-0.31		
17.100	3.867	7	-0.17	-0.62	-0.55	-0.45	-0.68	-0.46	
16.500	1.872	8	-0.05	-0.74	-0.58	-0.46	-0.79	-0.49	0.14

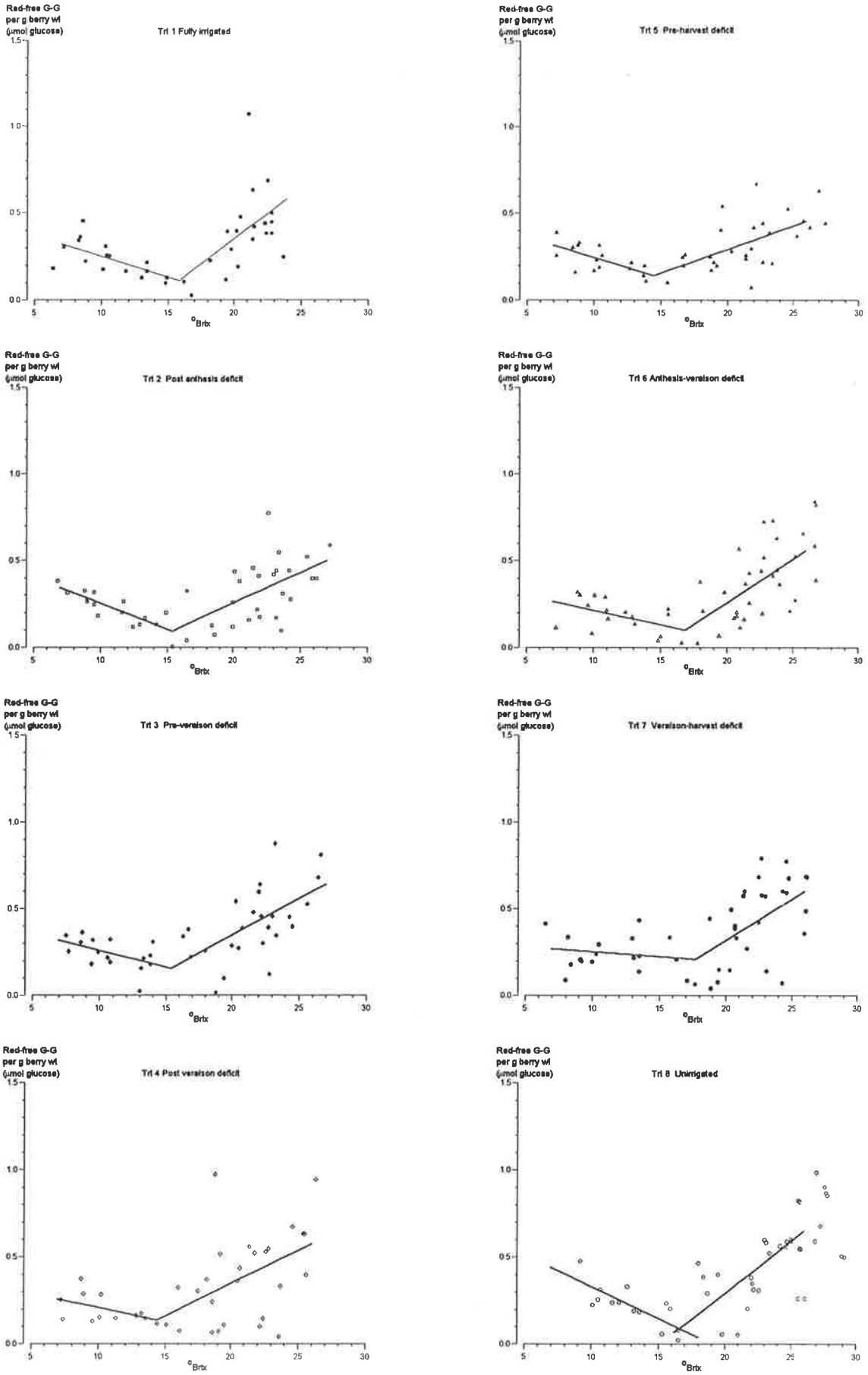


Figure 7 Regression of red-free G-G per g berry weight against °Brix for all treatments in the 1993-94 season.

Table 7 Regression constants for two phase linear modelling of red-free G-G per g berry weight against °Brix for the 1993-94 season.
Line 1 represents the left hand line, Line 2 represents the right hand line.

	Trt 1 Irrigated	
	Line 1	Line 2
Slope	-0.024	0.058
Intercept	0.489	-0.808
Intersection		
°Brix	15.9	
Red-free G-G	0.106	

	Trt 2 Post anthesis deficit	
	Line 1	Line 2
Slope	-0.029	0.035
Intercept	0.550	-0.449
Intersection		
°Brix	15.4	
Red-free G-G	0.092	

	Trt 3 Pre-veraison deficit	
	Line 1	Line 2
Slope	-0.019	0.042
Intercept	0.452	-0.492
Intersection		
°Brix	15.4	
Red-free G-G	0.154	

	Trt 4 Post veraison deficit	
	Line 1	Line 2
Slope	-0.016	0.038
Intercept	0.374	-0.405
Intersection		
°Brix	14.4	
Red-free G-G	0.137	

	Trt 5 Pre-harvest deficit	
	Line 1	Line 2
Slope	-0.023	0.027
Intercept	0.48	-0.252
Intersection		
°Brix	14.5	
Red-free G-G	0.140	

	Trt 6 Anthesis-veraison deficit	
	Line 1	Line 2
Slope	-0.016	0.050
Intercept	0.379	-0.745
Intersection		
°Brix	16.8	
Red-free G-G	0.099	

	Trt 7 Veraison -harvest deficit	
	Line 1	Line 2
Slope	-0.006	0.047
Intercept	0.309	-0.628
Intersection		
°Brix	17.7	
Red-free G-G	0.207	

	Trt 8 Unirrigated	
	Line 1	Line 2
Slope	-0.037	0.059
Intercept	0.698	-0.898
Intersection		
°Brix	16.6	
Red-free G-G	0.09	

Table 8 Summary statistics of the difference between treatments in the Y intercept of line 2, slope of line 1 and 2 and the °Brix of the intersection of lines 1 and 2 respectively for two phase linear modelling of red-free G-G per g berry weight against °Brix for all treatments for the 1993-94 season.

A2=intercept 2		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
-0.8085	0.3829	1							
-0.4488	0.1853	2	-0.85						
-0.4925	0.2239	3	-0.71	0.15					
-0.4054	0.2698	4	-0.86	-0.13	-0.25				
-0.2518	0.1387	5	-1.37	-0.85	-0.91	-0.51			
-0.7447	0.2320	6	-0.14	1.00	0.78	0.95	1.82		
-0.6276	0.2930	7	-0.38	0.52	0.37	0.56	1.16	-0.31	
-0.8980	0.2674	8	0.19	1.38	1.16	1.30	2.15	0.43	0.68

B1=slope 1		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
-0.0240	0.0158	1							
-0.0298	0.0140	2	0.27						
-0.0193	0.0163	3	-0.21	-0.49					
-0.0165	0.0253	4	-0.25	-0.46	-0.09				
-0.0233	0.0121	5	-0.04	-0.35	0.20	0.24			
-0.0166	0.0136	6	-0.35	-0.68	-0.13	0.00	-0.37		
-0.0057	0.0118	7	-0.93	-1.32	-0.68	-0.39	-1.04	-0.61	
-0.0366	0.0218	8	0.47	0.26	0.64	0.60	0.53	0.78	1.2

B2=slope 2		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
0.0576	0.0183	1							
0.0351	0.0084	2	1.12						
0.0420	0.0103	3	0.74	-0.52					
0.0376	0.0127	4	0.90	-0.16	0.27				
0.0271	0.0064	5	1.57	0.76	1.23	0.74			
0.0500	0.0101	6	0.36	-1.13	-0.55	-0.76	-1.92		
0.0472	0.0128	7	0.47	-0.79	-0.32	-0.53	-1.40	0.17	
0.0594	0.0109	8	-0.08	-1.77	-1.16	-1.30	-2.56	-0.63	-0.7

G=X intercept		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
15.909	1.638	1							
15.400	1.461	2	0.23						
15.399	1.752	3	0.21	0.00					
14.403	2.693	4	0.48	0.33	0.31				
14.478	1.474	5	0.65	0.44	0.40	-0.02			
16.860	1.503	6	-0.43	-0.70	-0.63	-0.80	-1.13		
17.700	2.019	7	-0.69	-0.92	-0.86	-0.98	-1.29	-0.33	
16.615	1.349	8	-0.33	-0.61	-0.55	-0.73	-1.07	0.12	0.4

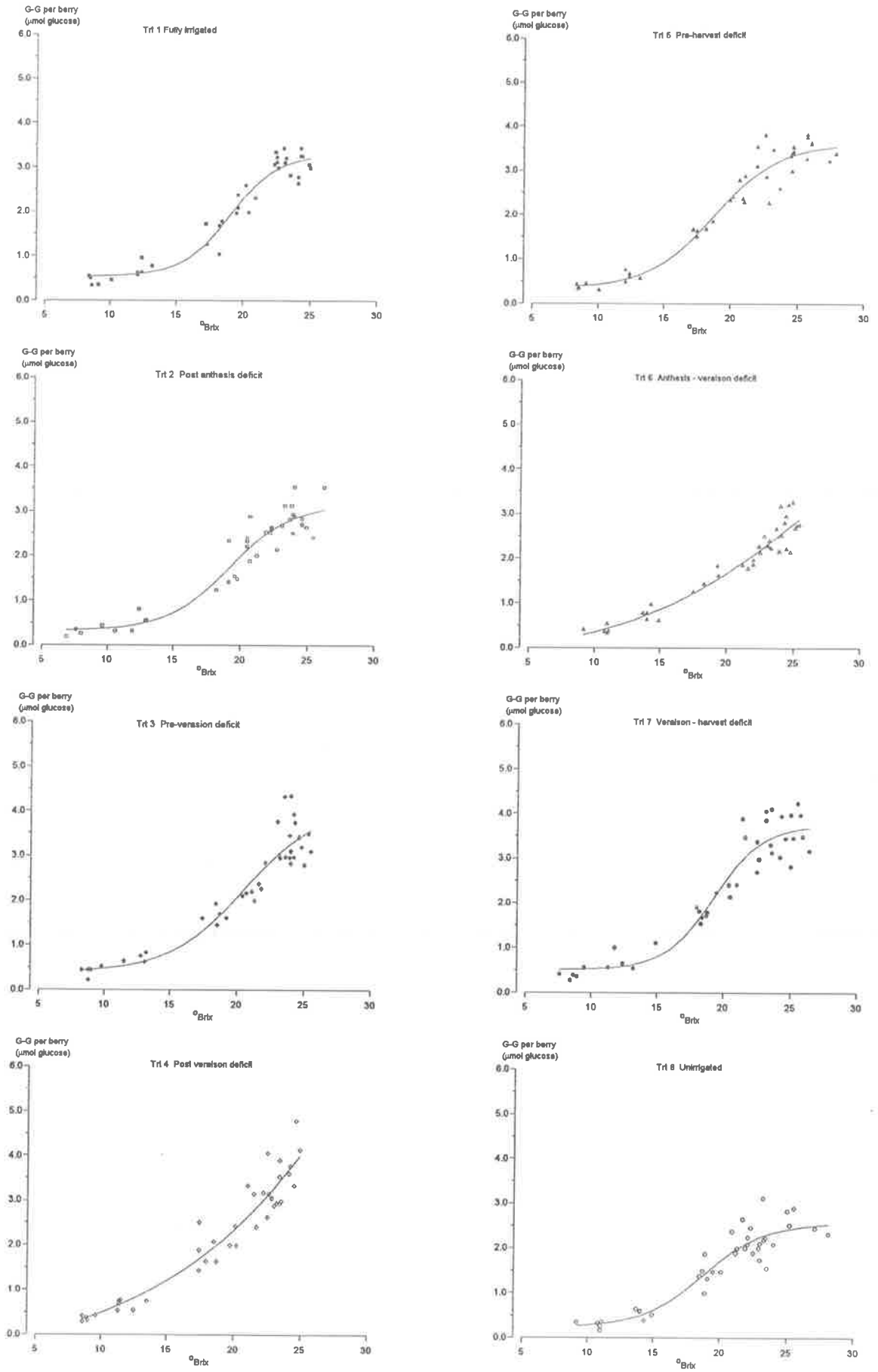


Figure 8 G-G per berry for all treatments during berry ripening in the 1994-95 season.

Table 9 Summary statistics of the difference between treatments in slope, inflection point, asymptote and intercept of the logistic models fitted to describe the relationship between G-G per berry and °Brix for all treatments in the 1994-95 season.

B=slope		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
0.5670	0.1670	1							
0.4320	0.1980	2	0.52						
0.3590	0.1420	3	0.95	0.30					
*	*	4	*	*	*				
0.4090	0.1190	5	0.77	0.10	-0.27	*			
0.1320	0.2220	6	1.57	1.01	0.86	*	1.10		
0.5480	0.1450	7	0.09	-0.47	-0.93	*	-0.74	-1.57	
0.4390	0.1840	8	0.52	-0.03	-0.34	*	-0.14	-1.06	0.47

M=Inflection		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
18.998	0.432	1							
19.173	0.696	2	-0.21						
20.520	1.230	3	-1.17	-0.95					
*	*	4	*	*	*				
18.772	0.607	5	0.30	0.43	1.27	*			
28.579	36.100	6	-0.27	-0.26	-0.22	*	-0.27		
19.283	0.425	7	-0.47	-0.13	0.95	*	-0.69	0.26	
18.774	0.858	8	0.23	0.36	1.16	*	0.00	0.27	0.53

C=Asymptote		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
2.750	0.275	1							
2.830	0.504	2	-0.14						
3.700	0.895	3	-1.01	-0.85					
*	*	4	*	*	*				
3.252	0.380	5	-1.07	-0.67	0.46	*			
7.987	23.700	6	-0.22	-0.22	-0.18	*	-0.20		
3.234	0.287	7	-1.22	-0.70	0.50	*	0.04	0.20	
2.323	0.435	8	0.83	0.76	1.38	*	1.61	0.24	1.75

A=Intercept		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
0.541	0.123	1							
0.324	0.199	2	0.93						
0.394	0.193	3	0.64	-0.25					
*	*	4	*	*	*				
0.344	0.202	5	0.83	-0.07	0.18	*			
-0.279	1.680	6	0.49	0.36	0.40	*	0.37		
0.513	0.147	7	0.15	-0.76	-0.49	*	-0.68	-0.47	
0.241	0.244	8	1.10	0.26	0.49	*	0.33	-0.31	0.95

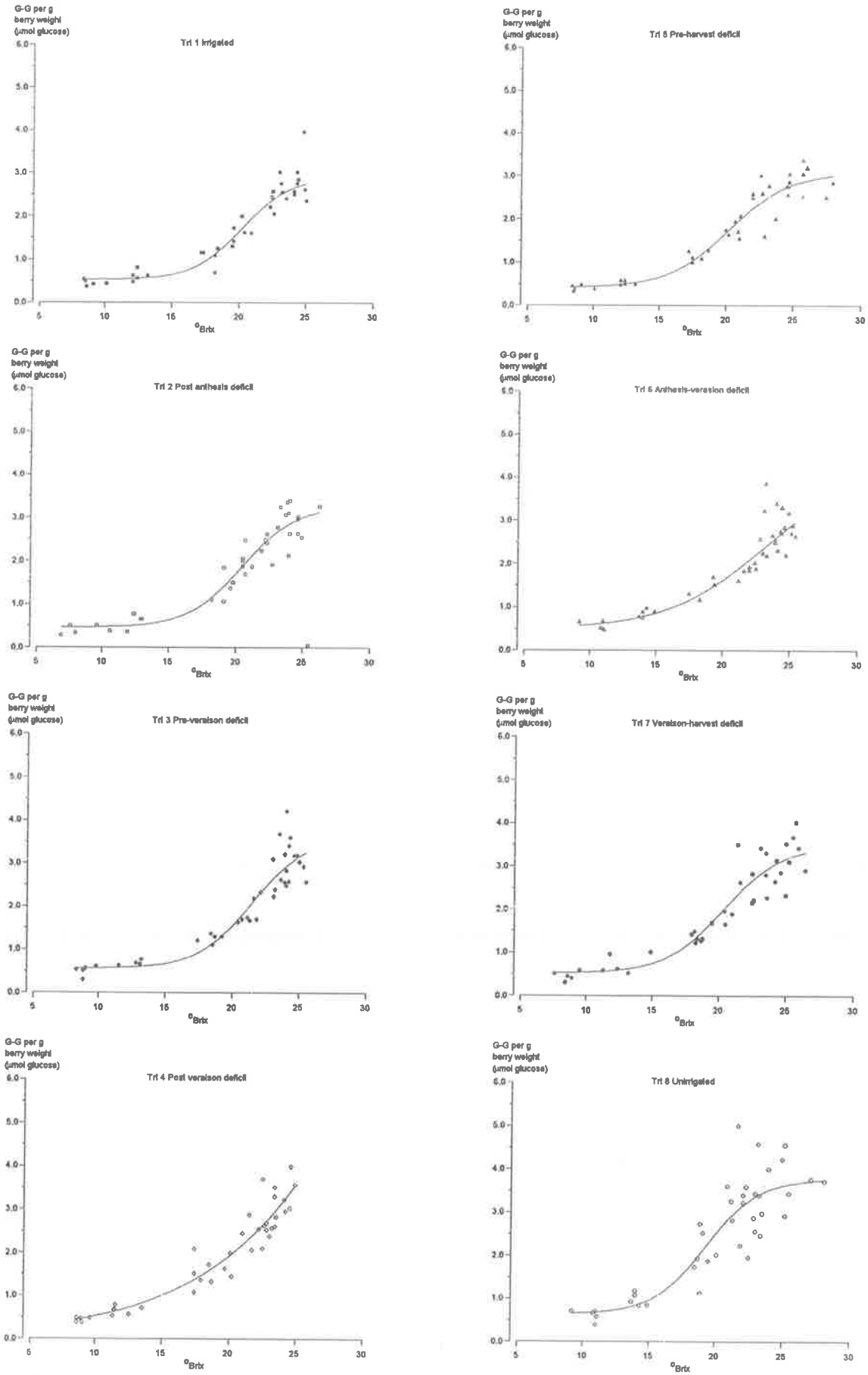


Figure 9 G-G per g berry weight for all treatments during berry ripening in the 1994-95 season.

Table 10 Summary statistics of the difference between treatments in slope, inflection point, asymptote and intercept of the logistic models fitted to describe the relationship between G-G per g berry weight and °Brix for all treatments in the 1994-95 season.

B=slope		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
0.5510	0.2160	1							
0.5020	0.1980	2	0.17						
0.4990	0.1830	3	0.18	0.01					
*	*	4	*	*	*				
0.4420	0.1400	5	0.42	0.25	0.25	*			
0.2730	0.2060	6	0.93	0.80	0.82	*	0.68		
0.4650	0.1380	7	0.34	0.15	0.15	*	-0.12	-0.77	
0.5090	0.1410	8	0.16	-0.03	-0.04	*	-0.34	-0.95	-0.22

M=Inflection		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
20.244	0.826	1							
20.455	0.724	2	-0.19						
21.490	0.948	3	-0.99	-0.87					
*	*	4	*	*	*				
20.250	0.678	5	-0.01	0.21	1.06	*			
23.210	5.240	6	-0.56	-0.52	-0.32	*	-0.56		
20.373	0.679	7	-0.12	0.08	0.96	*	-0.13	0.54	
19.303	0.484	8	0.98	1.32	2.05	*	1.14	0.74	1.28

C=Asymptote		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
2.392	0.438	1							
2.815	0.496	2	-0.64						
3.059	0.633	3	-0.87	-0.30					
*	*	4	*	*	*				
2.677	0.363	5	-0.50	0.22	0.52	*			
3.830	3.180	6	-0.45	-0.32	-0.24	*	-0.36		
2.970	0.411	7	-0.96	-0.24	0.12	*	-0.53	0.27	
3.141	0.347	8	-1.34	-0.54	-0.11	*	-0.92	0.22	-0.32

A=Intercept		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
0.530	0.137	1							
0.460	0.148	2	0.35						
0.558	0.128	3	-0.15	-0.50					
*	*	4	*	*	*				
0.413	0.154	5	0.57	0.22	0.72	*			
0.490	0.366	6	0.10	-0.08	0.18	*	-0.19		
0.518	0.149	7	0.06	-0.28	0.20	*	-0.49	-0.07	
0.641	0.181	8	-0.49	-0.77	-0.37	*	-0.96	-0.37	-0.52

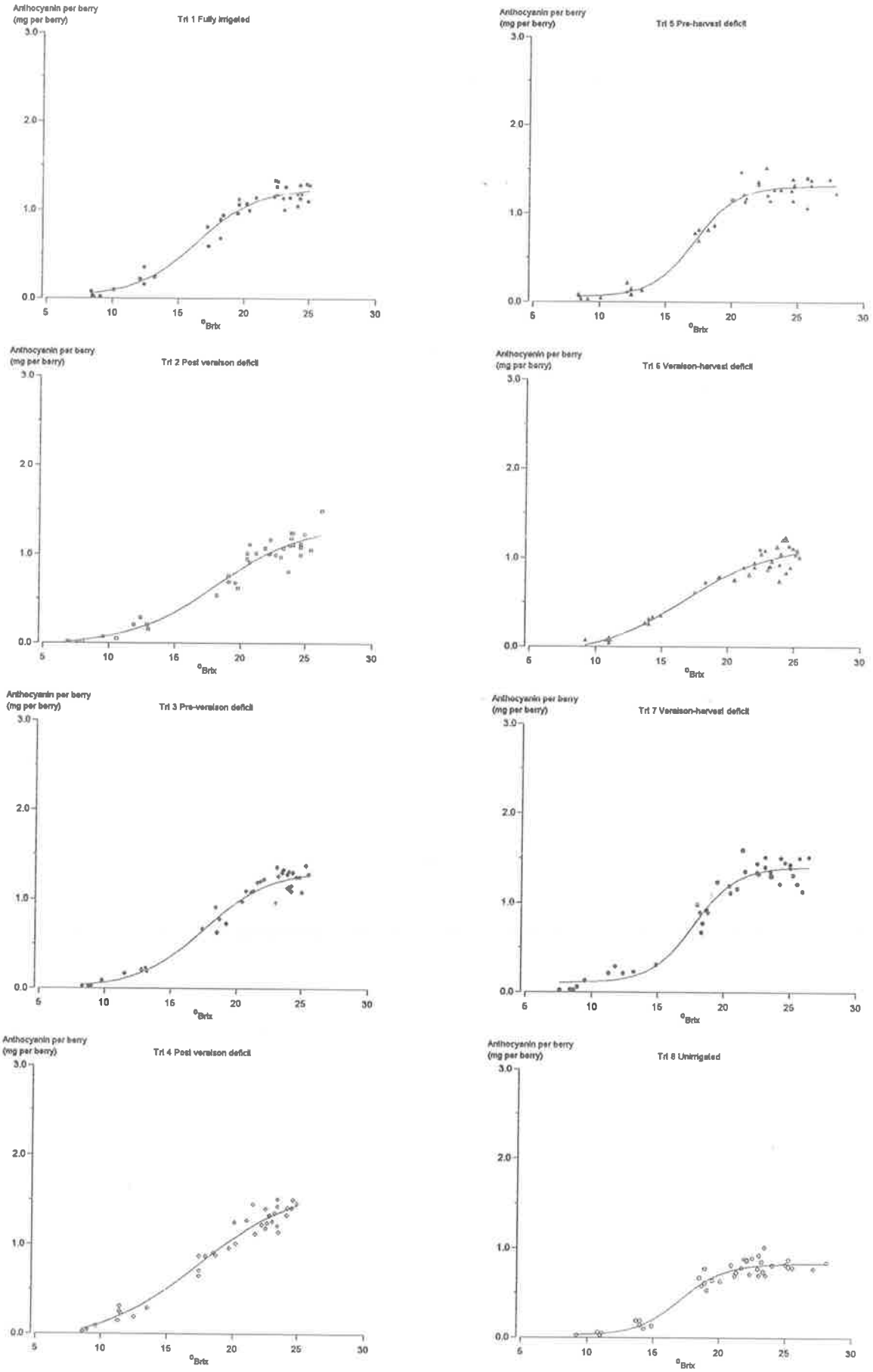


Figure 10 Anthocyanin per berry for all treatments during berry ripening in the 1994-95 season.

Table 11 Summary statistics of the difference between treatments in slope, inflection point, asymptote and intercept of the logistic models fitted to describe the relationship between anthocyanin per berry and °Brix for all treatments in the 1994-95 season.

B=slope		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
0.4355	0.0907	1							
0.3034	0.0832	2	1.07						
0.3989	0.0879	3	0.29	-0.79					
0.2658	0.0777	4	1.42	0.33	1.13				
0.6560	0.1330	5	-1.37	-2.25	-1.61	-2.53			
0.3000	0.1000	6	1.00	0.03	0.74	-0.27	2.14		
0.6260	0.1200	7	-1.27	-2.21	-1.53	-2.52	0.17	2.09	
0.6050	0.1550	8	-0.94	-1.71	-1.16	-1.96	0.25	-1.65	0.1

M=Inflection		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
16.400	0.524	1							
18.115	0.678	2	-2.00						
17.515	0.468	3	-1.59	0.73					
17.336	0.689	4	-1.08	0.81	0.21				
17.179	0.302	5	-1.29	1.26	0.60	0.21			
16.600	1.020	6	-0.17	1.24	0.82	0.60	0.54		
17.728	0.271	7	2.25	0.53	-0.39	-0.53	-1.35	-1.07	
17.112	0.598	8	-0.90	1.11	0.53	0.25	0.10	-0.43	0.9

C=Asymptote		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
1.223	0.106	1							
1.347	0.198	2	-0.55						
1.314	0.114	3	-0.58	0.14					
1.737	0.327	4	-1.50	-1.02	-1.22				
1.249	0.057	5	-0.22	0.48	0.51	1.47			
1.244	0.266	6	-0.07	0.31	0.24	1.17	0.02		
1.292	0.059	7	-0.57	0.27	0.17	1.34	-0.53	-0.18	
0.803	0.074	8	3.25	2.57	3.76	2.79	4.77	1.60	5.1

A=Intercept		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
0.022	0.074	1							
-0.025	0.095	2	0.39						
0.006	0.062	3	0.17	-0.27					
-0.098	0.163	4	0.67	0.39	0.59				
0.060	0.041	5	-0.45	-0.82	-0.73	-0.94			
-0.106	0.181	6	0.66	0.40	0.58	0.03	0.90		
0.110	0.040	7	-1.04	-1.30	-1.40	-1.24	-0.85	-1.16	
0.028	0.058	8	-0.06	-0.47	-0.26	-0.73	0.46	-0.70	1.1

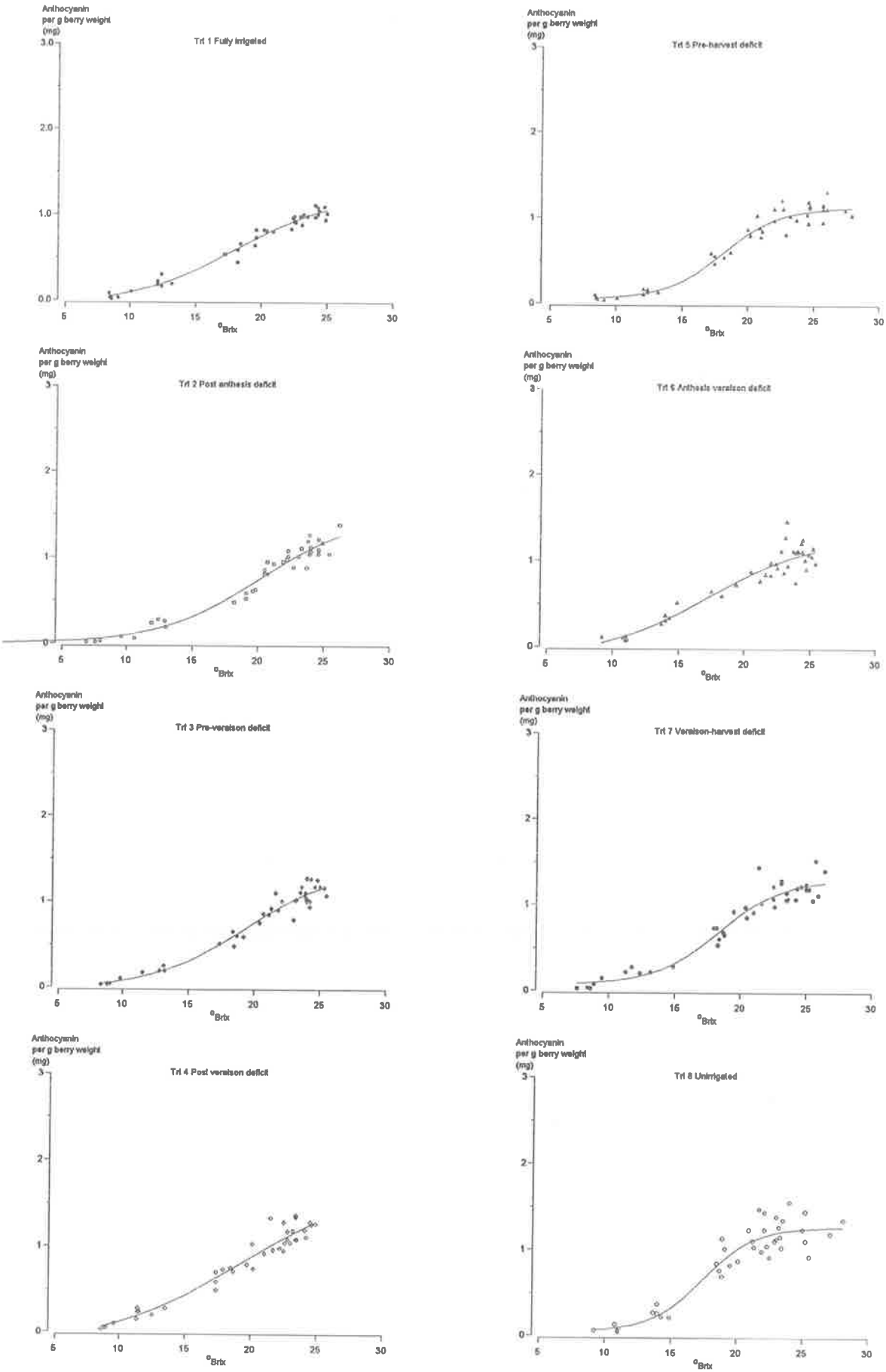


Figure 11 Anthocyanin per g berry weight for all treatments during berry ripening in the 1994-95 season.

Table 12 Summary statistics of the difference between treatments in slope, inflection point, asymptote and intercept of the logistic models fitted to describe the relationship between anthocyanin per g berry weight and °Brix for all treatments in the 1994-95 season.

B=slope		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
0.2570	0.1140	1							
0.2618	0.0996	2	-0.03						
0.2810	0.1030	3	-0.16	-0.13					
0.1900	0.1110	4	0.42	0.48	0.60				
0.4680	0.1080	5	-1.34	-1.40	-1.25	-1.80			
0.2520	0.1120	6	0.03	0.07	0.19	-0.39	1.39		
0.4152	0.0983	7	-1.05	-1.10	-0.94	-1.52	0.36	-1.10	
0.5110	0.1020	8	-1.66	-1.75	-1.59	-2.13	-0.29	-1.71	-0.6

M=Inflection		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
18.010	1.090	1							
20.090	1.290	2	-1.23						
19.320	1.050	3	-0.87	0.46					
19.270	2.400	4	-0.48	0.30	0.02				
18.073	0.455	5	-0.05	1.47	1.09	0.49			
17.270	1.290	6	0.44	1.55	1.23	0.73	0.59		
18.317	0.434	7	-0.26	1.30	0.88	0.39	-0.39	-0.77	
17.400	0.475	8	0.51	1.96	1.67	0.76	1.02	-0.09	1.4

C=Asymptote		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
1.288	0.372	1							
1.505	0.392	2	-0.40						
1.405	0.322	3	-0.24	0.20					
1.933	0.946	4	-0.63	-0.42	-0.53				
1.069	0.085	5	0.57	1.09	1.01	0.91			
1.376	0.429	6	-0.15	0.22	0.05	0.54	-0.70		
1.221	0.113	7	0.17	0.70	0.54	0.75	-1.07	0.35	
1.211	0.099	8	0.20	0.73	0.58	0.76	-1.09	0.38	0.0

A=Intercept		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
-0.054	0.166	1							
-0.003	0.111	2	-0.26						
-0.017	0.102	3	-0.19	0.09					
-0.161	0.317	4	0.30	0.47	0.43				
0.049	0.052	5	-0.59	-0.42	-0.57	-0.65			
-0.109	0.256	6	0.18	0.38	0.33	-0.13	0.60		
0.070	0.058	7	-0.70	-0.58	-0.74	-0.72	-0.27	-0.68	
0.051	0.072	8	-0.58	-0.41	-0.54	-0.65	-0.03	-0.60	0.2

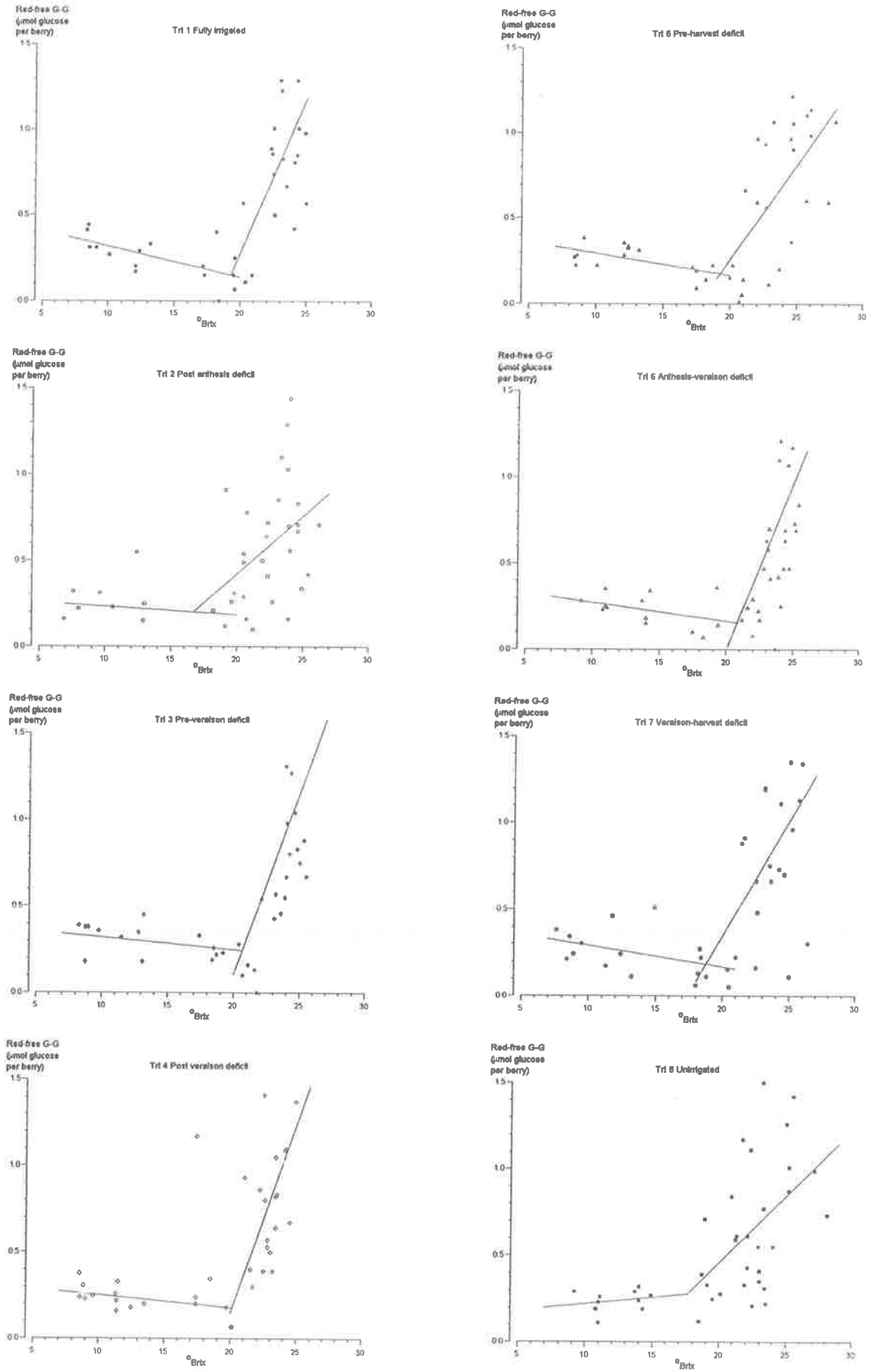


Figure 12 Regression of red-free G-G per berry against °Brix for all treatments in the 1994-95 season.

Table 13 Regression constants for two phase linear modelling of red-free G-G per berry against °Brix for the 1994-95 season.
Line 1 represents the left hand line, Line 2 represents the right hand line on each graph.

	Trt 1 Irrigated	
	Line 1	Line 2
Slope	-0.018	0.182
Intercept	0.490	-3.360
Intersection		
°Brix	19.3	
Red-free G-G	0.15	

	Trt 2 Post anthesis deficit	
	Line 1	Line 2
Slope	-0.005	0.067
Intercept	0.280	-0.920
Intersection		
°Brix	16.7	
Red-free G-G	0.20	

	Trt 3 Pre-veraison deficit	
	Line 1	Line 2
Slope	-0.007	0.021
Intercept	0.390	-4.12
Intersection		
°Brix	20.65	
Red-free G-G	0.24	

	Trt 4 Post veraison deficit	
	Line 1	Line 2
Slope	-0.007	0.22
Intercept	0.330	-4.25
Intersection		
°Brix	20.16	
Red-free G-G	0.18	

	Trt 5 Pre-harvest deficit	
	Line 1	Line 2
Slope	-0.013	0.11
Intercept	0.42	-1.95
Intersection		
°Brix	19.25	
Red-free G-G	0.18	

	Trt 6 Anthesis-veraison deficit	
	Line 1	Line 2
Slope	-0.01	0.19
Intercept	0.380	-3.89
Intersection		
°Brix	20.8	
Red-free G-G	0.16	

	Trt 7 Veraison -harvest deficit	
	Line 1	Line 2
Slope	-0.01	0.13
Intercept	0.410	-2.30
Intersection		
°Brix	18.8	
Red-free G-G	0.18	

	Trt 8 Unirrigated	
	Line 1	Line 2
Slope	0.007	0.08
Intercept	0.150	-1.07
Intersection		
°Brix	17.6	
Red-free G-G	0.28	

Table 14 Summary statistics of the difference between treatments in the Y intercept of line 2, slope of line 1 and 2 and the °Brix of the intersection of lines 1 and 2 respectively for two phase linear modelling of red-free G-G per berry against °Brix for all treatments for the 1994-95 season.

A2=intercept 2		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
-3.3583	0.8194	1							
-0.9200	0.5851	2	-2.42						
-4.1182	1.5812	3	0.43	1.90					
-4.2512	1.1412	4	0.64	2.60	0.07				
-1.9547	0.5600	5	-1.41	1.28	-1.29	-1.81			
-3.8750	2.2030	6	0.22	1.30	-0.09	-0.15	0.84		
-2.3106	1.0682	7	-0.78	1.14	-0.95	-1.24	0.30	-0.64	
-1.0660	0.5302	8	-2.35	0.18	-1.83	-2.53	-1.15	-1.24	-1.04

B1=slope 1		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
-0.0180	0.0230	1							
-0.0048	0.0490	2	-0.24						
-0.0072	0.0228	3	-0.33	0.04					
-0.0073	0.0165	4	-0.38	0.05	0.00				
-0.0128	0.0181	5	-0.18	0.15	0.19	0.22			
-0.0109	0.0443	6	-0.14	0.09	0.07	0.08	-0.04		
-0.0122	0.0238	7	-0.18	0.14	0.15	0.17	-0.02	0.03	
0.0075	0.0508	8	-0.46	-0.17	-0.26	-0.28	-0.38	-0.27	-0.3

B2=slope 2		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
0.1818	0.0361	1							
0.0672	0.0260	2	2.58						
0.2113	0.0671	3	-0.39	-2.00					
0.2198	0.0497	4	-0.62	-2.72	-0.10				
0.1106	0.0237	5	1.65	-1.23	1.42	1.98			
0.1935	0.0933	6	-0.12	-1.30	0.15	0.25	-0.86		
0.1326	0.0453	7	0.85	-1.25	0.97	1.30	-0.43	0.59	
0.0763	0.0234	8	2.45	-0.26	1.90	2.61	1.03	1.22	1.1

G=X intercept		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
19.307	1.100	1							
16.687	5.409	2	0.47						
20.649	1.321	3	-0.78	-0.71					
20.155	0.891	4	-0.60	-0.63	0.31				
19.249	1.405	5	0.03	-0.46	0.73	0.54			
20.826	2.125	6	-0.63	-0.71	-0.07	-0.29	-0.62		
18.800	1.939	7	0.23	-0.37	0.79	0.63	0.19	0.70	
17.618	4.492	8	0.37	-0.13	0.65	0.55	0.35	0.65	0.2

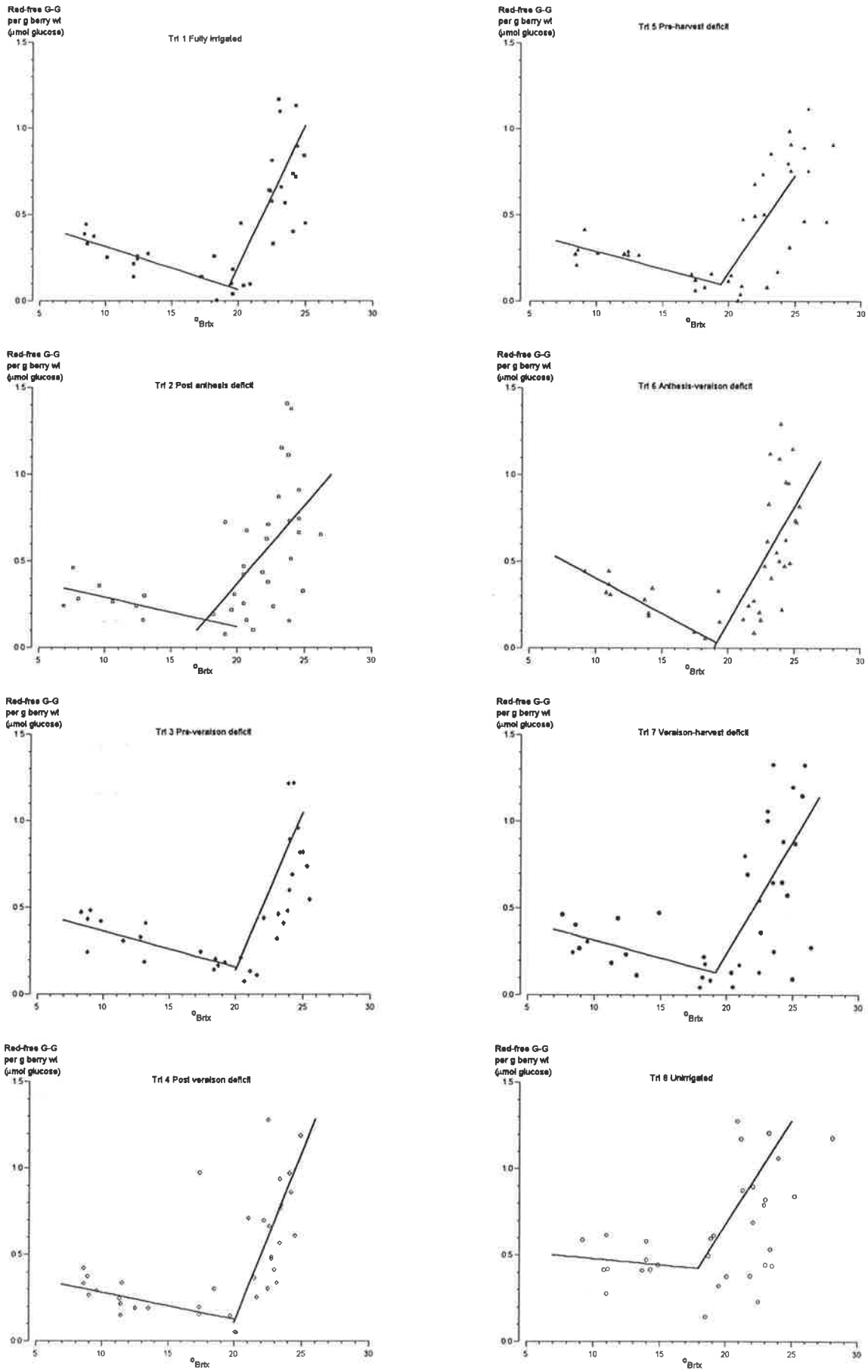


Figure 13 Regression of red-free G-G per g berry weight against °Brix for all treatments in the 1994-95 season.

Table 15 Regression constants for two phase linear modelling of red-free G-G per g berry weight against °Brix for the 1994-95 season.
Line 1 represents the left hand line, Line 2 represents the right hand line on each graph.

	Trt 1 Irrigated	
	Line 1	Line 2
Slope	-0.025	0.164
Intercept	0.566	-3.079
Intersection		
°Brix	19.3	
Red-free G-G	0.08	

	Trt 2 Post anthesis deficit	
	Line 1	Line 2
Slope	-0.017	0.090
Intercept	0.463	-1.427
Intersection		
°Brix	17.7	
Red-free G-G	0.16	

	Trt 3 Pre-veraison deficit	
	Line 1	Line 2
Slope	-0.021	0.182
Intercept	0.571	-3.51
Intersection		
°Brix	20.1	
Red-free G-G	0.15	

	Trt 4 Post veraison deficit	
	Line 1	Line 2
Slope	-0.015	0.196
Intercept	0.435	-3.82
Intersection		
°Brix	20.1	
Red-free G-G	0.12	

	Trt 5 Pre-harvest deficit	
	Line 1	Line 2
Slope	-0.020	0.113
Intercept	0.49	-2.091
Intersection		
°Brix	19.42	
Red-free G-G	0.096	

	Trt 6 Anthesis-veraison deficit	
	Line 1	Line 2
Slope	-0.041	0.134
Intercept	0.815	-2.54
Intersection		
°Brix	19.2	
Red-free G-G	0.03	

	Trt 7 Veraison -harvest deficit	
	Line 1	Line 2
Slope	-0.020	0.130
Intercept	0.519	-2.361
Intersection		
°Brix	19.2	
Red-free G-G	0.13	

	Trt 8 Unirrigated	
	Line 1	Line 2
Slope	-0.007	0.120
Intercept	0.548	-1.732
Intersection		
°Brix	17.9	
Red-free G-G	0.42	

Table 16 Summary statistics of the difference between treatments in the Y intercept of line 2, slope of line 1 and 2 and the °Brix of the intersection of lines 1 and 2 respectively for two phase linear modelling of red-free G-G per g berry weight against °Brix for all treatments for the 1994-95 season.

A2=intercept 2		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
-3.0787	0.7051	1							
-1.4277	0.5990	2	-1.78						
-3.5103	1.2802	3	0.30	1.47					
-3.8202	0.9682	4	0.62	2.10	0.19				
-2.0918	0.5328	5	-1.12	0.83	-1.02	-1.56			
-2.5384	0.7031	6	-0.54	1.20	-0.67	-1.07	0.51		
-2.3625	0.9526	7	-0.60	0.83	-0.72	-1.07	0.25	-0.15	
-1.7321	0.8241	8	-1.24	0.30	-1.17	-1.64	-0.37	-0.74	-0.50

B1=slope 1		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
-0.0249	0.0198	1							
-0.0172	0.0451	2	-0.16						
-0.0207	0.0220	3	-0.14	0.07					
-0.0154	0.0140	4	-0.39	-0.04	-0.20				
-0.0203	0.0175	5	-0.17	0.06	-0.01	0.22			
-0.0410	0.0270	6	0.48	0.45	0.58	0.84	0.64		
-0.0204	0.0212	7	-0.16	0.06	0.00	0.20	0.00	-0.60	
-0.0070	0.0789	8	-0.22	-0.11	-0.17	-0.10	-0.16	-0.41	-0.1

B2=slope 2		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
0.1637	0.031	1							
0.0898	0.027	2	1.80						
0.1824	0.054	3	-0.30	-1.53					
0.1963	0.042	4	-0.62	-2.13	-0.20				
0.1127	0.023	5	1.33	-0.65	1.18	1.75			
0.1339	0.030	6	0.69	-1.09	0.78	1.21	-0.56		
0.1297	0.040	7	0.67	-0.82	0.78	1.14	-0.37	0.08	
0.1230	0.036	8	0.85	-0.73	0.91	1.32	-0.24	0.23	0.1

G=X intercept		Comparisons							
Estimate	Std Error	Irrig	1	2	3	4	5	6	7
19.302	1.003	1							
17.674	3.560	2	0.44						
20.094	1.336	3	-0.47	-0.64					
20.100	0.816	4	-0.62	-0.66	0.00				
19.417	1.256	5	-0.07	-0.46	0.37	0.46			
19.175	1.269	6	0.08	-0.40	0.50	0.61	0.14		
19.192	1.618	7	0.06	-0.39	0.43	0.50	0.11	0.00	
17.924	3.909	8	0.34	-0.05	0.53	0.54	0.36	0.30	0.3

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