

**INFLUENCE OF  
SUSTAINED DEFICIT IRRIGATION  
ON PHYSIOLOGY AND PHENOLIC  
COMPOUNDS IN  
WINEGRAPES AND WINE**

**Yasmin Michelle Chalmers**

School of Agriculture and Wine  
Discipline of Wine and Horticulture  
The University of Adelaide



A thesis submitted to The University of Adelaide in fulfilment of the requirement for the degree of Doctor of Philosophy

**February 2007**

---

## TABLE OF CONTENTS

<b>ABSTRACT</b>	<b>iv</b>
<b>DECLARATION</b>	<b>vii</b>
<b>ACKNOWLEDGEMENTS</b>	<b>viii</b>
<b>LIST OF ABBREVIATIONS</b>	<b>ix</b>
<b>LIST OF FIGURES</b>	<b>xi</b>
<b>LIST OF TABLES</b>	<b>xvi</b>
<b>CHAPTER 1: General Introduction</b>	<b>1</b>
1.1 Background	1
1.2 Deficit Irrigation Strategies for Winegrapes	3
1.3 Water Relations in Grapevines	6
1.3.1 Water deficit effects on grapevine physiology	7
1.4 Grape and Wine Quality	9
1.4.1 Water deficit effects on yield components and berry size	12
1.4.2 Water deficit effects on grape and wine composition	14
1.5 General Conclusions and Aims of the Study	16
<b>CHAPTER 2: General Materials and Methods</b>	<b>17</b>
2.1 Field Sites	17
2.1.1 Trial design	19
2.2 Glasshouse Trials	22
2.3 Definitions	24
2.4 Statistical Analyses	24
<b>CHAPTER 3: Leaf Water Potential, Stomatal Conductance and ABA Responses of Red Winegrapes to Water Deficit</b>	<b>26</b>
3.1 Introduction	26
3.2 Materials and Methods	28
3.2.1 Physiology and hormone measurements	28
3.2.2 Grapevine growth and canopy development	30
3.3 Results	32
3.3.1 Effect of SDI on grapevine physiology and hormonal responses	32
3.3.2 Leaf area index and pruning weights	46
3.4 Discussion	47
3.4.1 Physiological response of grapevine varieties to water deficit	48
3.4.2 Hormonal response of grapevine varieties to water deficit	52

---

---

3.4.3 LAI and pruning weights of SDI-treated vines	56
3.5 Conclusions	58
<b>CHAPTER 4: Changes in Yield Components and Berry Composition of Red Wine Grapes Exposed to SDI</b>	<b>59</b>
4.1 Introduction	59
4.2 Materials and Methods	61
4.2.1 Determination of yield components and berry composition parameters. .	61
4.3 Results	62
4.3.1 Effect of SDI on Cabernet Sauvignon	62
4.3.2 Effect of SDI on Shiraz	66
4.3.3 Interaction between SDI, yield components and berry composition parameters	71
4.4 Discussion	76
4.4.1 Effect of SDI on yield and its components	76
4.4.2 Effect of SDI on berry composition	79
4.4.3 Management of SDI in the vineyard	80
4.5 Conclusions	82
<b>CHAPTER 5: Composition of Phenolic Compounds in Berries from SDI-Treated Vines</b>	<b>83</b>
5.1 Introduction	83
5.2 Materials and Methods	85
5.2.1 Determination of total anthocyanins and total phenolics	85
5.2.2 Extraction of anthocyanins and flavonols from berry skins for HPLC analysis	87
5.2.3 HPLC analysis of anthocyanin and flavonol profiles	87
5.2.4 Total tannin analysis methods for berry skins	90
5.3 Results	91
5.3.1 Changes in phenolic concentration during berry ripening	91
5.3.2 Changes in tannin concentration during berry ripening	94
5.3.3 Differences in anthocyanin and phenolic composition at harvest	94
5.3.4 Differences in total tannin at harvest	100
5.3.5 Differences in flavonol content at harvest	100
5.3.6 Interaction between SDI, berry weight and phenolic composition	102
5.4 Discussion	104
5.4.1 Effect of SDI on anthocyanins and total phenolics	104
5.4.2 Effect of SDI on tannin concentrations	108
5.4.3 Effect of SDI on flavonol levels at harvest	109

---

---

5.4.4 Is it berry weight or SDI influencing phenolic composition of berries?	110
5.5 Conclusions	111
<b>CHAPTER 6: Influence of SDI on Red Wine Composition</b>	<b>113</b>
6.1 Introduction	113
6.2 Materials and Methods	115
6.2.1 Micro-wine ferments	115
6.2.2 Wine analyses	118
6.3 Results	123
6.3.1 Changes in red wine colour composition of SDI-treated wines	123
6.3.2 HPLC anthocyanidin profiles of SDI-treated wines	127
6.3.3 Changes in tannin concentration of SDI-treated wines	130
6.3.4 Influence of SDI on wine copigmentation	130
6.4 Discussion	133
6.4.1 Wine colour	134
6.4.2 Wine phenolic composition	135
6.4.3 Wine copigmentation	136
6.4.4 Influence of berry size on wine composition	138
6.5 Conclusions	139
<b>CHAPTER 7: General Discussion and Conclusions</b>	<b>141</b>
7.1 Physiology and Growth	141
7.2 Yield and Yield Components	144
7.2 Berry Composition	146
7.3 Wine Composition	147
7.5 Management and Economic Implications of SDI	150
7.6 Future Recommendations	154
<b>REFERENCES</b>	<b>156</b>
<b>APPENDICES</b>	<b>172</b>

---

---

## ABSTRACT

Wine grape production in the semi-arid regions of Australia is successful due to the availability of irrigation water. Whilst water is a natural resource it is also becoming extremely valuable. In the hot and semi-arid regions of Australia, the prospect of water restrictions from drought and intensifying horticultural and domestic competition for water has prompted the grape and wine industry to implement strategic deficit irrigation practices to try and maintain sustainable wine grape production. Sustained deficit irrigation (SDI) differs significantly in its management to partial rootzone drying and regulated deficit irrigation and is a technique that could potentially be easily adopted across the winegrape industry if water allocations were reduced. With SDI, the water deficit is not created by withholding water, but rather, by applying a lesser volume of water at each irrigation event for the entire irrigation season.

This study aimed to understand the physiological behaviour of wine grape cultivars to SDI and how this deficit irrigation strategy would influence yield and composition of the grapes and wine. The trials were conducted during 2003-2006 on the cultivars Cabernet Sauvignon and Shiraz grafted to 140 Ruggeri (*V. berlandieri* x *V. rupestris*) rootstock and grown in the Murray-Darling region of Australia. Furthermore, while Cabernet Sauvignon and Shiraz are the main red winegrape varieties grown in the Murray-Darling region, anecdotally they are observed to respond differently to hot, dry conditions when managed under similar irrigation regimes. The vines were drip irrigated providing 100% of estimated  $ET_c$  (control) and three graded sustained water deficits (Cabernet Sauvignon 70%, 52% and 43% of the control; Shiraz 65%, 45% and 34% of the control). For each season, the volume of actual water applied (ML/ha) was calculated for each irrigation treatment and varied depending on seasonal and vineyard conditions. To further explore vine responses to water deficit, glasshouse studies on four own-rooted *Vitis vinifera* L. cultivars, including Cabernet Sauvignon, Shiraz, Grenache and Tempranillo were also conducted.

Deficit irrigation management, whilst controlling vegetative growth and manipulating berry composition, may not always produce consistent outcomes among grapevine varieties. This has led to the observation that deficit irrigation management strategies may need to be tailored to individual grape cultivars. Consequently, an understanding as to how certain

---

---

grapevine varieties respond to water deficit, particularly in relation to physiological responses, could assist with linking any impacts that water deficits may have on grape and wine composition. Field-grown Cabernet Sauvignon and Shiraz exposed to approximately 50% SDI experienced significant reductions in leaf water potential and stomatal conductance compared to the control. By contrast, xylem sap abscisic acid (ABA) levels increased significantly for the SDI-treated vines compared to the control that is probably related to root to shoot signals and canopy-derived ABA. Under field situations, Cabernet Sauvignon displayed physiological responses more typical of an isohydric-like (drought avoiding) vine, compared to the anisohydric-like (drought tolerant) responses of Shiraz. These responses may also be supported by the pattern of xylem sap [ABA] production. The differences in canopy development (leaf area index and pruning weights) for Cabernet Sauvignon and Shiraz may be a reflection of the isohydric-like and anisohydric-like responses of these grape varieties to water deficit, thereby influencing carbohydrate dynamics and long-term viability of vine health under SDI.

After three seasons, the SDI treatments significantly reduced yield of the field-grown vines, primarily due to a reduction in berry weight that tended to occur from the beginning of veraison through to harvest. SDI reduced yield (t/ha) by up to 30% in Cabernet Sauvignon and Shiraz, when applied at approximately 50% of the control irrigation (ML/ha). Irrespective of the yield reductions, water use efficiency was improved between 40-50% for the SDI-treated Cabernet Sauvignon and Shiraz, compared to the control. The lighter berries from SDI-treated vines tended to have increased pH and decreased titratable acid levels than the control. The SDI treatments applied at approximately 50% of the control increased the concentration of total anthocyanins in Cabernet Sauvignon and Shiraz berries by 22% and 15% respectively. As less water was applied there was an increase in total malvidin concentration for both varieties, with less effect on delphinidin, peonidin, petunidin and cyanidin for Cabernet Sauvignon and peonidin, petunidin, delphinidin and cyanidin for Shiraz. The increase in total anthocyanin and total phenolic concentrations for the SDI treatments than the control is attributed more to factors such as water deficit, canopy light penetration and/or changes in phenolic synthesis, than to differences in berry size (skin surface area to pulp volume ratio).

Differences in grape anthocyanins and phenolics between the irrigation treatments were not the same as those measured in the wine. A decrease in berry weight did not alter the skin

---

---

weight to berry weight ratios, and were therefore unlikely to be the cause of the altered composition of SDI wines. The increases in wine colour with SDI treatment may be the result of biochemical changes in the flavonoid pathway as a result of altered grapevine physiology responses to the SDI. Alternatively, the increases in red wine colour could possibly be due to a change in chemical properties of the anthocyanins to copigmented forms that may have influenced extractability efficiency during the winemaking or ageing process.

This research showed that an SDI of approximately 50% less water could be applied over one or two seasons with improvements in water use efficiency (t/ML) and berry composition compared to fully irrigated vines. Furthermore, for Cabernet Sauvignon exposed to 70% and 52% SDI there tended to be improvements in the overall wine composition and sensory ranking than the control. However from an economic perspective, net returns were not largely affected by using SDI based on the current grape prices. If water becomes a more highly valued resource and priced accordingly, then a larger increase in net return will result from SDI. Additionally, wineries would need to offer price incentives to produce lower yields that may result from adopting SDI. Overall, if the wine industry was faced with reductions in water allocations of 50% or more in a particular season, then the adoption of SDI may be a feasible solution to maintaining winegrape production for the short-term. Through understanding the translation of grape composition into wine, these findings should be able to provide additional knowledge to the Australian grape and wine industry as to how SDI can be used to manipulate grape composition for the production of sustainable wine styles.

---

---

## DECLARATION

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

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

Signed: .....

Date:.....

Yasmin Chalmers

---



---

## ACKNOWLEDGEMENTS

- My supervisors Assoc. Prof. Peter Dry, Dr. Brian Loveys, Dr. Mark Krstic and Dr. Mark Downey for their supervision and constructive comments.
  - The Victorian State Government (Our Rural Landscapes) and the Grape and Wine Research and Development Corporation (GWRDC) for financial support.
  - The Department of Primary Industries (DPI-Mildura) for use of the Shiraz trial site and laboratory facilities.
  - Mr. John Webley for collaborative support and management of the Cabernet Sauvignon site, Dareton, NSW.
  - The Victorian and Murray Valley Vine Improvement Association (VAMVVIA) and Mr. Julian Connellean for use of hot-water treatment and glasshouse facilities, and advice on glasshouse grown vines.
  - Ms. Nardia Baker, Ms. Marica Mazza, Ms. Glenda Kelly for their help and enthusiasm with the field, glasshouse and laboratory trials.
  - Dr. Masoud Edraki for management and irrigation technical advice of the DPI Shiraz site.
  - Ms. Debra Partington for assistance with experimental design and biometrics.
  - Ms. Sue Maffei and Dr. Chris Soar for their assistance with ABA analyses and advice on field and glasshouse physiology measures.
  - Dr. Patrick Iland and Dr. Helen Holt for assistance and advice with performing micro-wine ferments.
  - Ms. Lyn McMahon for assistance with proof reading.
  - Ms. Florence Juillet, Ms. Sara Melillo and Mr. Fabien Collerais for their technical assistance with processing grape material.
  - Dr. Fiona Constable for her invaluable technical advice, support and friendship.
  - Thanks to my family and friends for help and encouragement.
  - Finally, I thank my husband and children - Paul, Liam, Niah and Eva for their support, patience and love.
-

---

## LIST OF ABBREVIATIONS

ABA	abscisic acid
au	absorbance units
°C	degrees Celsius
CE	catechin equivalents
cm	centimetres
CS	Cabernet Sauvignon
df	degrees of freedom
Epan	pan evaporation
ET <sub>c</sub>	crop evapotranspiration under
ET <sub>o</sub>	reference crop evapotranspiration (grass reference crop)
g	grams
g <sub>s</sub>	stomatal conductance
GC-MS	gas chromatography/mass spectroscopy
GDD	growing degree days
GR	Grenache
h	hour
ha	hectare
HCl	hydrochloric acid
HPLC	high performance liquid chromatography
kg	kilograms
kPa	kilopascals
L	litre
LAI	leaf area index
LSD	least significant difference
LWP	leaf water potential
m	metre
mg	milligram
mm	millimetres
min	minute
mL	millilitre
ML	megalitre

---

---

MPa	megapascals
n	number of samples
ng	nanogram
nm	nanometre
ns	not significant
NSW	New South Wales
P	probability for data
pH	$-\log[\text{H}^+]$
ppm	parts per million
PRD	partial rootzone drying
r	correlation coefficient
$r^2$	coefficient of determination
RDI	regulated deficit irrigation
rpm	revolutions per minute
s	second
SC	stomatal conductance
SDI	sustained deficit irrigation
s.e.	standard error of the mean
SHZ	Shiraz
t	tonnes
TA	titratable acidity (g/L tartaric acid)
TE	Tempranillo
TSS	total soluble solids ( $^{\circ}$ Brix)
$\mu\text{L}$	microlitre
UV	ultra-violet
Vic	Victoria
VPD	vapour pressure deficit
WUE	water use efficiency
$\Psi_1$	leaf water potential

---

---

## LIST OF FIGURES

- Figure 1.1** Geographic location of the Murray-Darling region in Australia. Map provided by the Murray Valley Winegrape Growers Corporation (2005). 2
- Figure 1.2** Relationship of soil water tension (kPa) to a grapevine's response towards the available soil moisture (adapted from Goodwin, 1995). 4
- Figure 1.3** Schematic representation of the flavonoid pathway showing the production of anthocyanins, tannins and flavonols, including the general structure for each phenolic compound (adapted from Robinson & Walker, 2006). 10
- Figure 1.4** Sigmoidal pattern of canopy growth and grape berry development and ripening. The stages of water application are also depicted for the deficit irrigation techniques of regulated deficit irrigation (RDI), partial rootzone drying (PRD) and sustained deficit irrigation (SDI) (adapted from Coombe, 1992; Coombe & McCarthy, 2000). 13
- Figure 2.1** Satellite image showing location of Shiraz (Irymple, Vic) and Cabernet Sauvignon (Dareton, NSW) vineyards used for the field trials in the Murray-Darling region, Australia. Image provided by ©Google Earth, NASA, 2006. 17
- Figure 2.2** Cabernet Sauvignon (left) and Shiraz (right) are the premium, red wine grape varieties grown in the Murray-Darling region. Cultivars were grafted to 140 Ruggeri rootstock and trained on a two-wire vertical trellis. 18
- Figure 2.3** Irrigation design for the Cabernet Sauvignon and Shiraz SDI trial sites during 2003-2006. The insert shows the number of vines per treatment, with the test vines (shaded) in the middle row surrounded by the buffer vines. 20
- Figure 2.4** Cumulative Enviroscan data showing changes in soil water content (mm) for each irrigation treatment at the Shiraz trial site during 2004-2005. 21
- Figure 2.5** Cumulative Gbug data showing changes in soil matric potential (kPa) for Cabernet Sauvignon (100%, 70%, 52% and 43% irrigation treatments) and Shiraz (100%, 65% and 34% irrigation treatments) during 2004-2005. 22
- Figure 2.6** Glasshouse trials established in August 2004 (left) and August 2005 (right) on own-rooted Shiraz, Cabernet Sauvignon, Grenache and Tempranillo at the Department of Primary Industries. 23
- Figure 3.1** Diurnal changes in stomatal conductance ( $g_s$ ) from Cabernet Sauvignon (CS), Shiraz (SHZ), Grenache (GR) and Tempranillo (TE) glasshouse control (full irrigation) vines measured on 12 November 2005. LSD bars indicate significance at  $P=0.05$ . ( $n=5$ ). 32
- Figure 3.2** Leaf water potential ( $\Psi_l$ ) of leaves of Cabernet Sauvignon (CS), Shiraz (SHZ), Grenache (GR) and Tempranillo (TE) glasshouse vines exposed to a full (control) and deficit irrigation. Measurements were taken on the 22 and 28 November 2005 at A) predawn (0500 h) and B) 1400 h. Means for the control or deficit vines
-

- 
- followed by the same letter are not significantly different at  $P=0.05$ . Data points represent mean values  $\pm$  s.e. ( $n=10$ ). 33
- Figure 3.3** Stomatal conductance ( $g_s$ ) at 1400 h from leaves of Cabernet Sauvignon (CS), Shiraz (SHZ), Grenache (GR) and Tempranillo (TE) glasshouse vines exposed to a full (control) and deficit irrigation. Measurements were taken on the 22 and 28 November 2005. Means for the control or deficit vines followed by the same letter are not significantly different at  $P=0.05$ . Data points represent mean values  $\pm$  s.e. ( $n=10$ ). 34
- Figure 3.4** Petiole xylem sap abscisic acid [ABA] collected from Cabernet Sauvignon (CS), Shiraz (SHZ), Grenache (GR) and Tempranillo (TE) glasshouse vines exposed to a full (control) and deficit irrigation. Measurements were taken on the 22 and 28 November 2005 at A) predawn (0500 h) and B) 1400 h. Means for the control or deficit vines followed by the same letter are not significantly different at  $P=0.05$ . Data points represent mean values  $\pm$  s.e. ( $n=10$ ). 35
- Figure 3.5** Linear regression of leaf water potential ( $\Psi_l$ ) and stomatal conductance ( $g_s$ ) of Cabernet Sauvignon (CS), Shiraz (SHZ), Grenache (GR) and Tempranillo (TE) glasshouse vines measured at 1400 h on the 22 and 28 November 2005. Regression lines represent both control and deficit treatments, ( $n=10$ ). 36
- Figure 3.6** Linear regression of leaf water potential ( $\Psi_l$ ) and xylem sap abscisic acid [ABA] of Cabernet Sauvignon (CS), Shiraz (SHZ), Grenache (GR) and Tempranillo (TE) glasshouse vines measured on the 22 and 28 November 2005 at A) 0500 h and B) 1400 h. Regression lines represent both control and deficit treatments, ( $n=10$ ). 37
- Figure 3.7** Exponential regression of stomatal conductance ( $g_s$ ) and abscisic acid [ABA] of Cabernet Sauvignon (CS), Shiraz (SHZ), Grenache (GR) and Tempranillo (TE) glasshouse vines measured on the 22 and 28 November 2005 at 1400 h. Regression lines represent both control and deficit treatments, ( $n=10$ ). 38
- Figure 3.8** Diurnal leaf water potential ( $\Psi_l$ ) for field-grown A) Cabernet Sauvignon (CS) and B) Shiraz (SHZ) irrigated at a full irrigation (100% control) and a deficit irrigation (43% or 45%). Measurements for Cabernet Sauvignon and Shiraz were taken on the 13 and 18 January 2005 respectively. Bars indicate LSD at  $P=0.05$ . Absence of a bar indicates no significant difference ( $P=0.05$ ) at that time of day, ( $n=8$ ). 39
- Figure 3.9** Diurnal stomatal conductance ( $g_s$ ) for field-grown A) Cabernet Sauvignon (CS) and B) Shiraz (SHZ) irrigated at a full irrigation (100% control) and a deficit irrigation (43% or 45%). Measurements for Cabernet Sauvignon and Shiraz were taken on the 13 and 18 January 2005 respectively. Bars indicate LSD at  $P=0.05$ . Absence of a bar indicates no significant difference ( $P=0.05$ ) at that time of day, ( $n=8$ ). 40
- Figure 3.10** Diurnal leaf water potential ( $\Psi_l$ ) for field-grown Cabernet Sauvignon (CS) and Shiraz (SH) irrigated at a full irrigation (100% control) and deficit irrigation (43% or 45%). Measurements for Shiraz and Cabernet Sauvignon were taken on the 10 and 17 February 2005 respectively. Bars indicate LSD at  $P=0.05$ . Absence of a bar indicates no significant difference at that time of day ( $P=0.05$ ), ( $n=8$ ). 41
-

- Figure 3.11** Diurnal stomatal conductance ( $g_s$ ) for field-grown Cabernet Sauvignon (CS) and Shiraz (SH) irrigated at a full irrigation (100% control) and deficit irrigation (43% or 45%). Measurements for Shiraz and Cabernet Sauvignon were taken on the 10 and 17 February 2005 respectively. Bars indicate LSD at  $P=0.05$ . Absence of a bar indicates no significant difference at that time of day ( $P=0.05$ ), ( $n=8$ ). 41
- Figure 3.12** Diurnal xylem sap abscisic acid [ABA] levels for field-grown Cabernet Sauvignon (CS) and Shiraz (SH) irrigated at a full irrigation (100% control) and deficit irrigation (43% or 45%). Measurements for Shiraz and Cabernet Sauvignon were taken on the 10 and 17 February 2005 respectively. Data points represent mean values  $\pm$  s.e. ( $n=8$ ). 42
- Figure 3.13** Linear regression of leaf water potential ( $\Psi_l$ ) and xylem sap abscisic acid [ABA] of field grown A) Cabernet Sauvignon (CS) and B) Shiraz (SHZ) exposed to a control (100%) irrigation or SDI (43% or 45%). Measurements for Shiraz and Cabernet Sauvignon were taken on the 10 and 17 February 2005 respectively. Regression lines represent both control and deficit treatments, ( $n=8$ ). 43
- Figure 3.14** Linear regression of stomatal conductance ( $g_s$ ) and abscisic acid (ABA) of field grown A) Cabernet Sauvignon (CS) and B) Shiraz (SHZ) exposed to a control (100%) irrigation or SDI (43% or 45%). Measurements for Shiraz and Cabernet Sauvignon were taken on the 10 and 17 February 2005 respectively. Regression lines represent both control and deficit treatments, ( $n=8$ ). 43
- Figure 3.15** Relationship between adjusted leaf water potential (LWP -  $\Psi_l$ ) and abscisic acid (ABA) measured at different times of the day (0900, 1130, 1400 and 1630 h) of field grown A) Cabernet Sauvignon (CS) and B) Shiraz (SHZ). Measurements for Shiraz and Cabernet Sauvignon were taken on the 10 and 17 February 2005 respectively. Regression lines represent both control and deficit treatments, ( $n=8$ ). 44
- Figure 3.16** Relationship between stomatal conductance ( $g_s$ ) and abscisic acid [ABA] measured at different times of the day (0900, 1130, 1400 and 1630 h) of field grown A) Cabernet Sauvignon (CS) and B) Shiraz (SHZ). Measurements for Shiraz and Cabernet Sauvignon were taken on the 10 and 17 February 2005 respectively. Regression lines represent both control and deficit treatments, ( $n=8$ ). 45
- Figure 3.17** Leaf area index (LAI) of field grown A) Cabernet Sauvignon (CS) and B) Shiraz (SHZ) exposed to a control and SDI treatments during 2005/2006 (Year 3). Significance indicated by LSD bar for irrigation treatment at  $P=0.05$ , ( $n=4$ ). 46
- Figure 4.1** Effect of SDI on 2005 and 2006 mean berry ripening parameters for Cabernet Sauvignon exposed to a control and SDI irrigations 70%, 52% and 43%. A + B) total soluble solids, C + D) berry weight, and D + E) titratable acidity (dotted lines) and juice pH. LSD bars indicate treatment significance at  $P=0.05$ , ( $n=4$ ). 65
- Figure 4.2** Effect of SDI on 2005 and 2006 mean berry ripening parameters for Shiraz exposed to control and SDI irrigations (65%, 45% and 34%). A + B) total soluble solids, C + D) berry weight, and D + E) titratable acidity (dotted lines) and juice pH. LSD bars indicate treatment significance at  $P=0.05$ , ( $n=4$ ). 69

- 
- Figure 4.3** Regression analyses of the quantity of irrigation water applied (ML/ha) and A) yield, B) berry weight, C) average bunch weight, D) bunch number, E) juice pH and F) titratable acidity for Cabernet Sauvignon (CS) and Shiraz (SHZ). Data points represent the treatment means for 2005 and 2006 seasons, (n=8). 74
- Figure 5.1** HPLC chromatogram of a Cabernet Sauvignon grape skin extract, recorded at 520nm and illustrating the separation and identification of the A) anthocyanins and B) flavonols measured during the analyses. 88
- Figure 5.2** Standard curve for calculating concentration of mg of malvidin-3-*O*-glucoside per mL of grape skin extract. 89
- Figure 5.3** Standard curve for calculating concentration of mg of quercetin-3-*O*-glucoside per mL of grape skin extract. 89
- Figure 5.4** Effect of SDI during berry ripening on berry total anthocyanin concentration (mg/g) and berry total phenolic concentration (au/g) for Cabernet Sauvignon exposed to a control and SDI irrigations 70%, 52% and 43%. A) 2005 berry total anthocyanin concentration (mg/g), B) 2006 berry total anthocyanin concentration (mg/g), C) 2005 berry total phenolic concentration (au/g) and D) 2006 berry total phenolic concentration (au/g). LSD bar indicates treatment significance at P=0.05, (n=4). 91
- Figure 5.5** Effect of SDI during berry ripening on berry total anthocyanin concentration (mg/g) and berry total phenolic concentration (au/g) for Shiraz exposed to a control and SDI irrigations 65%, 45% and 34%. A) 2005 berry total anthocyanin concentration (mg/g), B) 2006 berry total anthocyanin concentration (mg/g), C) 2005 berry total phenolic concentration (au/g) and D) 2006 berry total phenolic concentration (au/g). LSD bar indicates treatment significance at P=0.05, (n=4). 93
- Figure 5.6** Effect of SDI during berry ripening on the development of total skin tannin concentration (mg catechin equivalent/g skin) from A) Cabernet Sauvignon (CS) and B) Shiraz (SHZ) grape skins exposed to a control and SDI irrigations. Berries were collected between veraison and harvest in 2006. LSD bar indicates treatment significance at P=0.05, (n=4). 94
- Figure 5.7** Linear regression of total flavonols (mg/g of skin) vs leaf area index (leaf area:soil area) for Cabernet Sauvignon berries exposed to a control and SDI irrigations 70%, 52% and 43% during 2004-2006, (n=8). 101
- Figure 5.8** Regression analyses of A), C) and E) total anthocyanins (mg/g) and B), D) and F) total phenolics (au/g) against berry weight, amount of irrigation water applied (ML/ha) and yield per vine (kg) for Cabernet Sauvignon (CS) and Shiraz (SHZ). Data was pooled over 2005 and 2006 seasons, (n=8). 103
- Figure 6.1** Grapes were crushed and fermented in plastic containers with gas traps (above left). Ferments were plunged daily to ensure even skin contact during the maceration process (above right). Wine was pressed off into glass Schott bottles and capped with gas traps to allow the gross lees to settle before racking and cool storage (below left). After 2 weeks cool storage the wine was bottled (below right). 117
-

- 
- Figure 6.2** Standard curve for calculating concentration of mg of malvidin-3-*O*-glucoside equivalents per litre of wine extract. **119**
- Figure 6.3** Development of wine colour from Cabernet Sauvignon micro-ferments at bottling and 6 month age for A) wine colour (au), B) wine hue ( $A_{420}/A_{520}$ ), C) total anthocyanins (mg/L) and D) total phenolics (au). Grapes were collected at the 2006 harvest from Control (100%), 70%, 52% and 43% SDI treatments. Means at bottling or 6 months followed by the same letter are not significantly different at  $P=0.05$ . Data are represented as mean values  $\pm$  s.e. (n=4). **124**
- Figure 6.4** Development of wine colour from Shiraz micro-ferments at bottling and 6 month age for A) wine colour (au), B) wine hue ( $A_{420}/A_{520}$ ), C) total anthocyanins (mg/L) and D) total phenolics (au). Grapes were collected at the 2006 harvest from Control (100%), 65%, 45% and 34% SDI treatments. Means at bottling or 6 months followed by the same letter are not significantly different at  $P=0.05$ . Data are represented as mean values  $\pm$  s.e. (n=4). **126**
- Figure 6.5** Regression analyses of monomeric anthocyanins, anthocyanins in the copigment complex, polymeric pigments and total colour against the amount of irrigation water applied for Cabernet Sauvignon (CS) and Shiraz (SHZ) wines after 6 months. A) monomeric anthocyanins, B) copigment anthocyanins, C) polymeric pigment anthocyanins and D) total colour. (n=4) **131**
- Figure 6.6** Percent colour due to monomeric, copigment complex and polymeric pigment anthocyanins of Cabernet Sauvignon wines at bottling and 6 month age. Grapes were collected at the 2006 harvest from control (100%), 70%, 52% and 43% SDI treatments. **132**
- Figure 6.7** Percent colour due to monomeric, copigment complex and polymeric pigment anthocyanins of Shiraz wines at bottling and 6 month age. Grapes were collected at the 2006 harvest from control (100%), 65%, 45% and 34% SDI treatments. **133**
- Figure 7.1** Net return per hectare for the control and SDI treatments for A) Cabernet Sauvignon and B) Shiraz during 2003-2006. **152**
-



---

## LIST OF TABLES

<b>Table 1.1</b> Percentage of total wine, drying and table grape production for each state of Australia in 2005. Data were compiled from the Australian Bureau of Statistics vineyard survey (Australian Bureau of Statistics (ABS), 2006).	1
<b>Table 2.1</b> Irrigation regimes established for the Cabernet Sauvignon and Shiraz trial sites from November 2003 until December 2006.	19
<b>Table 3.1</b> Mean pruning weights for Cabernet Sauvignon and Shiraz taken during 2004-2006. Means followed by the same letter are not significantly different at $P=0.05$ , ( $n=8$ ). No letters signify ns between irrigation treatments within a row.	47
<b>Table 4.1</b> Yield components and berry composition parameters from Cabernet Sauvignon bunches harvested between 2004-2006 and exposed to a full irrigation (100% control) and SDI irrigations (70%, 52% and 43% of the control). Means followed by the same letter within a row are not significantly different at $P=0.05$ , ( $n=8$ ). No letters signify ns between irrigation treatments within a row.	63
<b>Table 4.2</b> Water applied and WUE for the different irrigation treatments for Cabernet Sauvignon between 2004-2006. Figures followed by the same letter within a row are not significantly different at $P=0.05$ , ( $n=8$ ). No letters signify ns between irrigation treatments within a row.	66
<b>Table 4.3</b> Yield component and berry composition parameters from Shiraz bunches harvested between 2004-2006 and exposed to a full irrigation (100% control) and SDI irrigations (65%, 45% and 34% of the control). Means followed by the same letter within a row are not significantly different at $P=0.05$ , ( $n=8$ ). No letters signify ns between irrigation treatments within a row.	67
<b>Table 4.4</b> Water applied and WUE for the different irrigation treatments for Shiraz between 2004-2006. Means followed by the same letter within a row are not significantly different at $P=0.05$ , ( $n=8$ ). No letters signify ns between irrigation treatments within a row.	70
<b>Table 4.5</b> Correlation matrices of berry composition for Cabernet Sauvignon treated with A) 100% (control) irrigation, B) 70%, C) 52% and D) 43% SDI irrigation. Data were pooled over three seasons from 2004 to 2006. Since the $df = 10$ , then $P<0.05$ when $r>0.576$ (no shade); $P<0.01$ when $r>0.708$ (grey shade).	72
<b>Table 4.6</b> Correlation matrices of berry composition for Shiraz treated with A) 100% (control) irrigation, B) 65%, C) 45% and D) 34% SDI irrigation. Data were pooled over three seasons from 2004 to 2006. Since the $df = 10$ , then $P<0.05$ when $r>0.576$ (no shade); $P<0.01$ when $r >0.708$ (grey shade).	73
<b>Table 5.1</b> Solvent gradient for HPLC to separate anthocyanin profiles in grapes using 10% formic acid (solvent A) and 10% formic acid:methanol (solvent B).	89
<b>Table 5.2</b> Berry total anthocyanin and berry total phenolic content and concentration for Cabernet Sauvignon berries harvested in 2004-2006 and exposed to a full irrigation	

---

(100% control) and SDI irrigations (70%, 52% and 43% of the control). Means followed by the same letter within a row are not significantly different at  $P=0.05$ , ( $n = 8$ ). No letters signify ns between irrigation treatments within a row. 95

**Table 5.3** Berry total anthocyanin and berry total phenolic content and concentration from Shiraz bunches harvested between 2004-2006 and exposed to a full irrigation (100% control) and SDI irrigations (65%, 45% and 34% of the control). Means followed by the same letter within a row are not significantly different at  $P=0.05$ , ( $n = 8$ ). No letters signify ns between irrigation treatments within a row. 96

**Table 5.4** Percent composition of parent anthocyanidin (delphinidin, cyanidin, petunidin, peonidin, malvidin); di- and trihydroxylated anthocyanidin; and -3-*O*-glucoside, acetylglucoside, and coumaroylglucoside anthocyanidin of Cabernet Sauvignon berry skins collected at the 2005 harvest from Control (100%) and SDI treatments 70%, 52% and 43%. Total anthocyanins (mg/g) from harvested berry skins are also included. Means  $\pm$  s.e. ( $n = 8$ ). 97

**Table 5.5** Percent composition of parent anthocyanidin (delphinidin, cyanidin, petunidin, peonidin, malvidin); di- and trihydroxylated anthocyanidin; and -3-*O*-glucoside, acetylglucoside, and coumaroylglucoside anthocyanidin of Cabernet Sauvignon berry skins collected at the 2006 harvest from Control (100%) and SDI treatments 70%, 52% and 43%. Total anthocyanins (mg/g) from harvested berry skins are also included. Means  $\pm$  s.e. ( $n = 8$ ). 98

**Table 5.6** Percent composition of parent anthocyanidin (delphinidin, cyanidin, petunidin, peonidin, malvidin); di- and trihydroxylated anthocyanidin; and -3-*O*-glucoside, acetylglucoside, and coumaroylglucoside anthocyanidin of Shiraz berry skins collected at 2005 harvest from Control (100%) and SDI treatments 65%, 45% and 34% expressed as mg/g of skin. Total anthocyanins (mg/g) from harvested berry skins are also included. Means  $\pm$  s.e. ( $n = 8$ ). 99

**Table 5.7** Percent composition of parent anthocyanidin (delphinidin, cyanidin, petunidin, peonidin, malvidin); di- and trihydroxylated anthocyanidin; and -3-*O*-glucoside, acetylglucoside, and coumaroylglucoside anthocyanidin of Shiraz berry skins collected at 2006 harvest from Control (100%) and SDI treatments 65%, 45% and 34% expressed as mg/g of skin. Total anthocyanins (mg/g) from harvested berry skins are also included. Means  $\pm$  s.e. ( $n = 8$ ). 99

**Table 5.8** Concentration of total tannins from Cabernet Sauvignon and Shiraz berry skins collected at the 2005 and 2006 harvest from Control (100%) and SDI treatments expressed as mg of catechin equivalent/g of skin. Means  $\pm$  s.e. ( $n=8$ ). 100

**Table 5.9** Concentration of skin total flavonols from Cabernet Sauvignon and Shiraz berry skins collected at the 2005 and 2006 harvest from Control (100%) and SDI treatments expressed as mg/g of skin. Significance indicated by different letters. Means followed by the same letter within a row are not significantly different at  $P=0.05$ , ( $n = 8$ ). No letters signify ns between irrigation treatments within a row. 101

**Table 6.1** Mean concentration of total red pigments (au), degree of red pigment colouration (%) and ionised pigments (mg/L) from Cabernet Sauvignon micro-ferments at bottling and 6

---

month age. Grapes were collected at the 2006 harvest from Control (100%), 70%, 52% and 43% SDI treatments. Means followed by the same letter in a row are not significantly different at  $P=0.05$ . (n=4).

125

**Table 6.2** Mean concentration of total red pigments (au), degree of red pigment colouration (%) and ionised pigments (mg/L) from Shiraz micro-wines at bottling and 6 month age. Grapes were collected at the 2006 harvest from Control (100%), 65%, 45% and 34% SDI treatments. Means followed by the same letter in a row are not significantly different at  $P=0.05$ , (n=4). No letters signify ns between irrigation treatments within a row. (n=4).

127

**Table 6.3** Mean concentration of total wine anthocyanins and parent anthocyanidin (delphinidin, cyanidin, petunidin, peonidin, malvidin); di- and trihydroxylated anthocyanidin; and -3-*O*-glucoside, acetylglucoside, and coumaroylglucoside anthocyanidins from Cabernet Sauvignon wines expressed as mg/L of wine at bottling and 6 month age. Grapes were collected at the 2006 harvest from control (100%), 70%, 52% and 43% SDI treatments. Means followed by the same letter in a row are not significantly different at  $P=0.05$ . (n=4).

128

**Table 6.4** Mean concentration of total wine anthocyanins and parent anthocyanidin (delphinidin, cyanidin, petunidin, peonidin, malvidin); di- and trihydroxylated anthocyanidin; and -3-*O*-glucoside, acetylglucoside, and coumaroylglucoside anthocyanidins from Shiraz wines expressed as mg/L of wine at bottling and 6 month age. Grapes were collected at the 2006 harvest from control (100%), 65%, 45% and 34% SDI treatments. Means followed by the same letter in a row are not significantly different at  $P=0.05$ . (n=4).

129

**Table 6.5** Mean concentration of total wine tannins from Cabernet Sauvignon and Shiraz grapes harvested in 2006 from Control (100%) and SDI treatments expressed as mg of catechin equivalent/L of wine. Means followed by the same letter in a row are not significantly different at  $P=0.05$ . (n=4).

130

**Table 6.6** Means of berry weight, total anthocyanins and total phenolics from grapes collected at the 2006 harvest. Total wine anthocyanin and phenolic concentrations are from micro-ferment wines after 6 months ageing. Grapes were collected from Cabernet Sauvignon and Shiraz exposed to a control (100%) and SDI treatments. Means followed by the same letter in a row are not significantly different at  $P=0.05$  (n=8\*, n=4).

139

**Table 7.1** Wine ranking scores for small-scale wines produced from a control (100%) and SDI treated Cabernet Sauvignon (70%, 52%, 43%) and Shiraz (65%, 45%, 34%) grapes harvested in 2006. The lower the score represents the more preferred wine. (n=4).

149