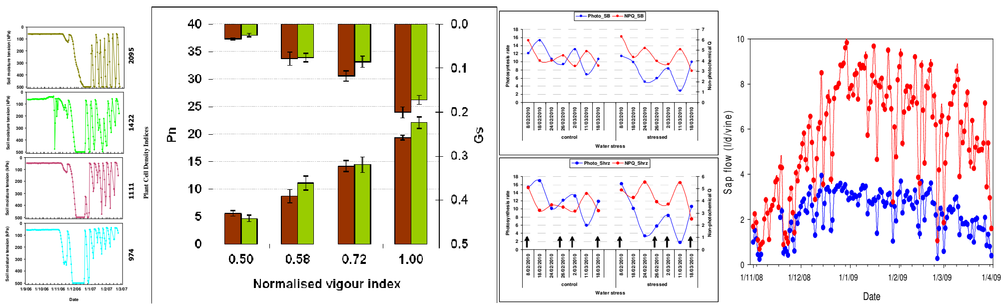
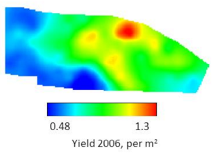
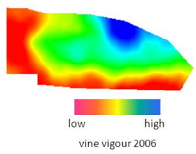
Optimising the recovery of vine performance following irrigation during extended periods of water deficit







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FINAL REPORT to
GRAPE AND WINE RESEARCH & DEVELOPMENT CORPORATION

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1. Abstract

The project reported here was undertaken in a commercial Shiraz vineyard in the Great Southern wine region of WA. Production in this region is predominantly rain-fed with less than 1 ML/ha supplementary irrigation input. In such systems with limited irrigation water availability, irrigation is necessarily applied at low volumes and infrequently – i.e., vines can become water stressed for extended periods of water deficits. The severity of stress may vary spatially within a vineyard block. These production systems, in particular vine functioning under such operational practices, have received little research attention.

This project was thus aimed at examining vine physiological performance during extended periods of water deficits and recovery following small volume irrigation application (under commercial management practice). Variables examined included leaf level gas exchange, light energy utilisation/dissipation, leaf water status, sap flow and utilisation of applied irrigation water. Additionally, wine quality assessments were carried out in collaboration with a co-located and linked GWRDC Soil and Water Initiative project.

The study vineyard block had considerable spatial variation in vine vigour. Variation in vigour had significant influence on nearly all attributes examined. For example, vines from the higher end of the vigour spectrum showed higher leaf photosynthesis and stomatal conductance rates, utilisation of absorbed light energy in photochemistry, sap flow rates and leaf water status than vines from the low vigour zones of the vineyard. At least in terms of leaf water status, low vigour vines showed rapid recovery following small volume irrigation although the recovery lasted for only a short period. A further consistent and notable finding was an apparently reduced capacity of vines from the low vigour zones of the vineyard to utilise applied water. Multivariate analyses of wine quality measures (sensory attributes and chemistry) showed significant differences between vintages, while there were also consistent "quality" differentiations between high and low vigour zones within vintages.

2. Executive Summary

In predominantly rain-fed viticultural systems located in relatively low rainfall regions, water deficit is an ever present limitation to productivity. As the water available for supplemental irrigation is low, irrigation is used strategically for avoiding excessive vine stress while also supporting and ripening an economic crop. When available water for irrigation is limited, applications necessarily occur infrequently, or at low volumes or both. Any of these regimens poses a risk that vines may at times experience extended spells of water deficits that severely limit vine functioning. The severity can vary spatially within a vineyard block (e.g. as a function of soil depth/topography) and temporally (e.g. periods of high *versus* low evaporative demand). The effects on vine functioning can also be compounded when periods of soil water deficit coincide with other stressful conditions such as high temperatures, high photon flux densities, and a dry atmosphere.

This project examined spatial variation in water deficits using $\delta^{13}C$ from winter bud samples and berry soluble solids at harvest. Leaf physiological functioning during extended periods of stress as well as recovery following small volume irrigation applications were monitored in different vine vigour zones. Spatial variations in irrigation water utilisation, as well as productivity of applied water were also examined. Furthermore, the site served as one of the nodes of another GWRDC Soil and Water Initiative project (Goodwin et al., DPI 04/04), which assessed wine quality attributes from different vigour zones.

The $\delta^{13}C$ values of winter buds showed clear spatial trends (-22 ‰ in the higher elevation part of the block and -25 and ‰ at the lower elevation sections). The berry soluble solids results varied between seasons: in 2006, which experienced wet conditions closer to harvest, the spatial trends were less clearly defined, whereas in 2007, which was a dry vintage, there was a distinct north-south gradient that was consistent with the bud sample results from the winter of 2005. These results highlight that tissue samples that incorporate carbon from multiple seasons are more suitable for revealing underlying spatial trends in water deficits than samples whose carbon largely originates from a single season.

Leaf gas exchange rates (photosynthesis and stomatal conductance) varied considerably between high and low vigour zone vines. Vines from the high vigour zones had higher rates for most of the growing season compared to vines from the low vigour zones. This included during periods of water deficits as well as following irrigation application.

Regardless of vine vigour or water stress, between 55 and 84% of the absorbed light energy was thermally dissipated via non-photochemical quenching processes. At summer midday conditions, the proportion of absorbed radiation used in photochemical processes was ≤ 26%, generally being highest early in the growing season and declining with the progression of the season. Nonetheless, the proportion used in photochemical processes was mostly higher in high vigour vines than in low vigour vines. Water stress experiments in Shiraz and Sauvignon Blanc vines also showed similar results to the vineyard observations. In this case, however, there were highly synchronised events: when photosynthesis was high, non-photochemical quenching was low and vice versa. The effect of water stress was largely in modulating the amplitude of the response. These results clearly suggest that under moderate levels of water deficits ($\Psi_{L\text{-}noon}$ = -1.0 MPa), grapevines (at least the varieties evaluated here) can effectively deploy non-photochemical quenching processes to dissipate excess energy that may otherwise damage the photosynthetic machinery of leaves.

Similar to gas exchange rates, vines from the low and high vigour zones of the vineyard showed differences in their water status: low vigour vines generally had lower midday leaf and stem water potentials than high vigour zone vines. This is in spite of the low vigour zones vines receiving more frequent albeit low volume drip irrigation. Recovery of tissue water potentials in low vigour vines following irrigation, however, was at least as quick as those of high vigour vines, yet, low vigour vines return to lower water potentials earlier, and thus seem to experience a greater duration of stress.

Vine-level water use (sap flow) also varied considerably in accord with variation in vine vigour. Depending on season, there were up to five-fold differences in rates of transpiration between individual vines from the highest and lowest vigour zones. When scaled up to block level, water use (Nov-Mar inclusive) in the lowest vigour zone was about half that in highest vigour zones.

Consistent with vine transpiration results, utilisation of soil moisture (applied irrigation water) was also spatially different. The seasonally integrated drawdown of applied water was tightly related with effective canopy cover as well as yield. These results indicate spatially non-optimal utilisation of applied water (and variable water productivity). Further work is recommended to elucidate why low vigour zone vines fail to fully utilise applied water even when these seem to show signs of water stress.

In terms of wine quality (sensory and chemistry) attributes, multivariate analyses revealed highly significant differences between vintages. For example, wines from the relatively wet 2006 vintage were different from the 2007 and 2008 wines in being low in total red pigments, total phenolics and for lacking in body; while the warm vintage of 2007 differed from the average 2008 vintage on the basis of high alcohol content, colour density, body and ripe berry aroma. In terms of the impact of vigour, within in each vintage, the low and high vigour zones were separated primarily on the basis of on wine composition. Sensory attribute differences, though apparent, were not significant. These results are based on harvests made on the same day, as is the norm. It is thus unclear whether these wine composition and sensory differences would still occur if harvests are staggered to achieve near identical maturity between vigour zones.

3. Background

Water deficits are a characteristic feature of most winegrape producing regions of Australia. In many instances, water deficits can have favourable outcomes on quality and water use efficiency. Indeed, in “highly” irrigated systems water deficits are deliberately imposed (regulated deficits irrigation) or ‘simulated’ (partial root zone drying). There have been a considerable number of studies on vine performance under water deficits in these systems. The foci have been on elucidating treatment responses and determining influences of water deficits on yield and quality parameters. The consensus is that water deficits, when imposed deliberately, can be useful ‘tools’ for manipulating vine performance.

In other instances, viticulture is established in areas where rainfall is low and water for irrigation is rather limited. In these predominantly rain-fed systems, production is heavily reliant on stored soil water, occasional rainfall incident during the growing season, and low volume supplemental irrigation. Often, there may be insufficient water even for supplemental irrigation such that vines are irrigated at low volumes and infrequently and can experience extended spells of water deficits. Under such conditions, there is a risk that vines may be severely stressed and recovery can be very slow leading to low yield, potentially reduced grape quality and impact on long term vine health/vigour. A further significant and exacerbating factor is spatial variation in soil water deficit and how this influences recovery of vine physiological functioning following infrequent application of small volume irrigation. Surprisingly, there has been limited, if any, research which has taken account of within block variation in water deficits (and attendant variation in vine vigour) and investigation of the physiological recovery of vines from water deficits and the impacts on resource utilisation.

The study was undertaken in the Great Southern wine region of Western Australia. Production in this region is predominantly rain-fed with an average annual rainfall of 600 mm and irrigation inputs of about 1 ML/ha or even considerably less in drier vintages. Predominantly rain-fed production systems account for about a third of the nation's viticultural production and are poorly studied compared to the highly irrigated production systems. It is expected that the outcomes of this project will have relevance to predominantly rain-fed production systems in other wine regions. It needs to be noted that the study was not an irrigation treatment experiment (as is often the case in highly irrigated viticultural systems). Rather it was intended to examine within vineyard variation in vine physiological performance (as well as resource use) and its recovery following infrequent low volume irrigation, under prevailing commercial management conditions in rain-fed systems. The study was co-located and shared some resources with another GWRDC Soil and Water Initiative project (Goodwin et al. 2009).

4. Project Aims and Performance Targets

1) To develop practical limits for the application of water deficits to grapevines by determining the point at which the economic benefits of improved quality are offset by the risk of long term damage to the vine.
2) To define the role of spatial variation in water deficits in the determination of financial returns by:
    a) Development of an index (and the assignment of vines to stress categories) based on vigour and stable isotope discrimination measurements to identify spatial variation in the long term probability and severity of water deficits within a block of grapevines.
    b) The comparison of variation in water deficits across the site with data on yield and (grape and wine) quality obtained from vines assigned to stress categories.

3) To examine the dynamics and limitations of recovery of vine performance (leaf gas exchange, chlorophyll fluorescence and sap-flow) following irrigation imposed against a background of severe water deficit.
4) To examine the physiology associated with exposure to high light levels during water deficits and to seek to understand the alternative energy dissipation pathways which appear to be available to stressed grapevine leaves.

4.1 Planned Project Outputs

Outputs and Performance Targets 2005-06

Outputs	Performance Targets
1. Select and establish Great Southern field site	Negotiate and establish vineyard site in the great Southern Region. MOU with wine company signed by 15 August 2005.
2. Appoint staff	Staff appointed by 1 October, 2005
3. Site variation in carbon isotope discrimination quantified	Carbon isotope discrimination samples collected from cane and trunk material, prepared and analysed by 1 November, 2005
4. First year data on vine performance and physiology obtained	Measurements for vine performance(yield and berry maturation) and leaf physiology (leaf gas exchange, water relations and preliminary chlorophyll fluorescence studies) complete and data summarised for presentation by 1 June 2006
5. Small-scale wines from stress categories completed	24 small scale wine lots manufactured from vines selected from across the stress categories completed by 30 June 2006.
6. Article in industry journal	Contribute to authorship of one article published by June 2006
7. Review article	Review article on the role of chlorophyll fluorescence in grapevine leaf responses to stress drafted by 30 June 2006

Outputs and Performance Targets 2006-07

Outputs	Performance Targets

1. Assessment of wines from 2005/2006 vintage	Sensory evaluation, chemical analysis and price point assignment of wines produced from 2005/2006 vintage completed by 1 December 2006
2. Assessment of vine water use.	Sapflow probes installed in typical vines across a range of stress categories by 1 October 2006. Variation in vine water use among vines of various stress categories described and related to soil and quality factors by 30 June 2007.
3. Second year data on vine performance and physiology obtained	Measurements for vine performance(yield and berry maturation) and leaf physiology (leaf gas exchange, water relations and detailed chlorophyll fluorescence studies) complete and data summarised for presentation by 1 June 2007
4. Small-scale wine production.	Second year of wines made from zones within each site to quantify spatial variability in wine composition completed by 30 June 2007
5. Publication of results	Outcomes from physiology measurements submitted for publication in scientific journals by 30 June 2007

Outputs and Performance Targets 2007-08

Outputs	Performance Targets
1. Assessment of wines from 2006/2007 vintage	Sensory evaluation, chemical analysis and price point assignment of wines produced from 2006/2007 vintage completed by 1 December 2007
2. Industry extension of results	Field day including the presentation of results to date and wine tasting from stress categories completed by 1 December 2007. Active involvement in the 2007 AWITC.
3. Assessment of vine water use (year 2)	Sapflow probes installed in ‘typical’ vines across a range of stress treatments by 1 October 2007. Variation in vine water use among vines of various stress categories described and related to soil and quality factors by 30 June 2008.

4. Balance between leaf carbon fixation and respiratory carbon losses for sun-exposed and shaded leaves	Spatial and temporal influences on vine water deficit and $^{13}CO_2$-labelling utilised to examine the short and medium term responses of leaf carbon fixation, respiration and photo-respiration to supplementary irrigation by 1 April 2009.
5. Semi-commercial wines	Semi-commercial wines (250 to 500L ferments) produced from stress categories completed by 30 June 2008

Outputs and Performance Targets 2008-09

Outputs	Performance Targets
1. Assessment of wines from 2007/2008 vintage	Sensory evaluation, chemical analysis and price point assignment of wines produced from 2007/2008 vintage completed by 1 December 2008
2. Balance between leaf carbon fixation and respiratory carbon losses for sun-exposed and shaded leaves	Spatial and temporal influences on vine water deficit and $^{13}CO_2$-labelling utilised to examine the short and medium term responses of leaf carbon fixation, respiration and photorespiration to supplementary irrigation. Data collection to be completed by 1 April 2009.
3. Extension of outcomes to industry	Presentation of draft strategy for the optimal use of irrigation during conditions of extended water deficits by 30 Jan 2009. Refinement of strategy following industry input by 30 June 2009. Development of information material for industry extension officers and consultants completed by 30 June 2009
4. Publication of results	Results prepared for publication in scientific journals by 30 June 2009
5. Final Report	Final report to be submitted by 30 June 2009

5. Materials and Methods

5.1 Study site location, climate and vine

The study was carried out in a commercial vineyard, planted with own-rooted *Vitis vinifera* L. cv. Shiraz vines, in the Great Southern wine region (34º23'11"S, 116º57'50"E, elevation 240 m) of Western Australia. Vines were planted in an east-west row orientation at a spacing of 1.8 m along and 3.6 m between rows (1543 vines/ha). Vines were trained to a single layer of bilateral cordons at 90 cm height. Canes were spur-pruned to two-bud spurs with eight spurs on each cordon with developing shoots trained to the vertical-shoot-positioning system. The average, 1977-2006, annual rainfall (Silo data) at the site was 586 mm, of which about one-third (192 mm) fell during the growing season (October-April inclusive) (Table 1). By contrast, some four-fifths (1070 mm) of the annual evaporative demand occurs during the growing season. Thus, there is a substantial disparity between evaporative demand and the amount of rainfall incident during the growing season. Part of this deficit was offset by providing vines with supplemental irrigation which, depending on season and vineyard zone varied, from 11 to 50 mm. The soil texture varied from 18% clay, 24% silt and 58% at the surface (0-100 mm) to 48% clay, 10% silt and 42% sand at depth (700-800 mm). Gravel (Ø ≥ 2mm) content of the top 100 mm soil of the vineyard block had a clear east-west spatial pattern (Fig. 3a).

Table 1. General characteristics of the study site climate, soil and management. Climate data are averages for 1977-2006 (from Silo). §growing season here refers to Oct-April inclusive.

Climate	average rainfall (mm)	Annual	586
		Growing season§	192
	pan evaporation (mm)	Annual	1356
		Growing season§	1072
	temperature (ºC)	minimum	9
		maximum	21
Altitude	260 m (north – south height range 12 m, Fig. 3b)		
Soil texture	at 0-100 mm depth	18% clay, 24% silt and 58% sand	
	at 700-800 mm depth	48% clay, 10% silt and 42% sand	
Gravel (Ø ≥ 2 mm)	at 0-100 mm depth	Varied spatially (10-70 %) (Fig. 3a)	
Canopy management	cordon	Single bilateral at 900 mm height	
	training	vertical-shoot positioning	
	pruning	hand pruned; two-bud spurs; eight spurs per cordon	

5.2 Zonation of vineyard block into vine vigour classes

The data and procedures used for dividing the vineyard block into distinct vigour zones were obtained as part of a co-located and linked GWRDC Soil Water Initiative project (Goodwin et al. 2009). Full details are given in Lanyon et al. (2008) and Zerihun et al. (2009). Briefly, the study block was divided into six vigour zones using vine and soil data. The vine data consisted of a plant cell density metric derived from air-borne high resolution multi-spectral digital imaging of the vineyard block at veraison of the preceding year (SpecTerra Services, Leederville, WA) , and the soil property data were obtained from γ-radiometric survey of the block (Baigent Geosciences, Banjup, WA). These two data-streams (vine and soil properties) were used in conjunction to divide the vineyard block into six vine vigour zones using K-means clustering procedures.

5.3 Soil moisture monitoring

In four vigour zones of the study vineyard block, under-vine soil moisture status was continuously monitored using gypsum blocks (Measurement Engineering Australia, Magill, South Australia). At each location, soil moisture monitoring was done at four depths in the soil profile (10, 25, 45, and 80 cm).

5.4 Leaf gas exchange and chlorophyll fluorescence measurements

Leaf gas exchange rates were carried out using a Li-6400-02B open gas exchange system (Li-Cor Inc, Nebraska, USA). Measurements were made on fully expanded and sun-exposed leaves under the following conditions: light level, 1500-1800 μmol/m^2/s supplied from the instruments red and blue light source; CO_2, 400 μmol/mol in the reference cell; leaf temperature was maintained close to the prevailing ambient air temperature via block temperature control. Vines used for leaf gas exchange measurement were selected from within the different vigour zones.

On several occasions, chlorophyll fluorescence was determined concurrently with leaf photosynthesis rate measurement using an integrated gas exchange and fluorescence measurement system (Li-6400-40 LCF, Li-Cor Inc, Nebraska, USA). Minimum and maximum chlorophyll fluorescence yields, F_o and F_m, respectively, of dark adapted leaves were determined at predawn on overnight dark-adapted leaves. F_o was determined under conditions of a short duration (1 s) pulse of a very low intensity (non-actinic) measuring light, ~20 $nmol/m^2/s$, modulated at a frequency of 250 Hz. F_m was determined by exposing leaves to a short duration (0.8 s) saturating pulse light (>6000 $\mu mol/m^2/s$) modulated at a frequency of 20 kHz. Minimal and maximal fluorescence of light-adapted leaves, F'_o and F'_m respectively, as well as steady state fluorescence, F_s, were determined as described in Genty et al. (1989) using the routines implemented in Li Cor 6400-40_LCF. F_s readings were recorded when the chlorophyll fluorescence of a leaf adapted to the ambient light level, typically 1500-1800 µmol/m2/s, was stable: $-5 < dF/dt < 5$. Following the Fs recording, F'_m was determined by exposing the same measurement leaf to a 0.8 s flash of >6000 $\mu mol/m^2/s$ modulated at a frequency of 20 kHz. F'_o was determined by employing the “dark pulse” routine of the instrument. For this, the instrument’s far red light source (λ_{peak}= 740 nm, 7 µmol/m2/s) was turned on about 1 s prior to turning off the actinic light (for ~ 6 s). The far red light stayed on for 6 s in order to preferentially excite photosystem I (PSI) which leads to a rapid draw down of electrons from PSII to PSI thereby fully oxidising (opening) photosytem II reaction centres (e.g. Baker, 2008). The far red light was then turned off 1 s before the actinic light came on. During this brief dark adaptation, pulse modulation frequency was maintained at 250 Hz. From these measurements, the following “parameters” were calculated as in Baker (2008):

Maximal photosystem II efficiency (of dark adapted leaves), $\frac{F_v}{F_m} = \frac{(F_m - Fo)}{F_m}$

Maximum efficiency of PSII in light adapted leaves, $\frac{F\prime_v}{F\prime_m} = \frac{(F\prime_m - F\prime_o)}{F\prime_m}$

Quantum yield of photosystem II, $\Phi PSII = \frac{(F\prime_m - F_s)}{F\prime_m}$

Photochemical quenching of Chl fluorescence, $\mathrm{qP} = \frac{(F\prime_m - F_s)}{(F\prime_m - F'_o)}$

Nonphotochemical quenching of Chl fluorescence, $NPQ = \frac{(F_m - F\prime_m)}{F\prime_m}$

Partitioning of “absorbed” light energy among competing sinks (e.g., utilisation in PSII photochemistry, ΦPSII; trans-thylakoid proton gradient- and xanthophyll cycle-dependent thermal dissipation, ΦNPQ; and a combination of other process such as constitutive non-photochemical thermal dissipation and through fluorescence, Φf,D) were computed as in Hendrickson et al. (2004). Whole chain electron transport from fluorescence data was calculated as in von Caemmeer (2000).

5.5 Sap flow measurement

Sap flow, on up to 16 vines from different vigour zones of the vineyard block, was estimated by the heat pulse/compensation method using the Greenspan SF100 and/or SF300 sap flow sensor units with associated data loggers (Greenspan Technology, Warwick, Queensland). Sensors were installed in vine trunks at least 50 cm above ground level. Following installation, the probes and a section of the trunk ± 15 cm from the point of probe implantation were insulated using a sisalation® wrap. Data were logged at 15 min intervals. Measurements typically started in November and continued until a week or so prior to harvest. For the purpose of this work, when calculating sap flow, logs exceeding 150 s (i.e., the time taken for the up- and down-stream thermistors to equilibrate following a pulse of heat from the heating probe) were assumed to show “zero” flow.

5.6 Leaf and stem water potential measurements

Leaf and stem water potential were measured using a Plant Water Status Console 3000 Series (Soilmoisture Equipment Corporation, Santa Barbara, California, USA) connected to a compressed air cylinder. For leaf water potential (Ψ_L) measurement, leaves were enclosed in plastic bags immediately before excision of petioles, with sharp scalpels, about 10 mm from cane junctions. The tiime elapsed from petiole/leaf excision to insertion in pressure chamber and pressurisation was ≤ 30 s.

Stem water potential (Ψ_S) was determined similarly to leaf water potential, except that leaves selected for Ψ_S measurement were enclosed in aluminium foil cloaked plastic bags for at least 2 h before measurements were taken. Generally, both Ψ_L and Ψ_S were measured diurnally. Pre-dawn measurements of Ψ_L were typically made between 03:00 and 05:00 h.

5.7 Carbon stable isotope analysis

Bud samples (EL 1) from the 2005 season and freeze dried, centrifuged aliquots of berry juices from 2005/06 as well as 2006/07 seasons were analysed for $\delta^{13}C$ and $\delta^{15}N$. The analyses were carried out at the Western Australia Organic and Isotope Geochemistry Centre (Curtin University) for bud samples and berry sugars from the 2006 harvest; and at the West Australian Biogeochemistry Centre (University of Western Australia) for the 2007 samples. ^{13}C values are given in per mil (‰, VPDP) according to delta notation (Paul et al., 2007).

Cumulative soil moisture tension was estimated analogously to the plant water stress integral metric devised by Myers (1988):

$$C_{\Psi}, k = \sum_{d=1}^{d=120} \left(S - \overline{S}_{\Psi}, k, d\right)$$

Where $C_{\Psi,\,k}$ is the cumulative soil moisture tension for location *k* in the vineyard during the monitoring period (approximately from flowering to harvest); *S* is soil water tension (S_{Ψ}) at field capacity; $\overline{S}_{\Psi}$ is average S_{Ψ} for location *k* and day *d*. For all locations, a value of -0.04 MPa was used for *S* since this was the maximum value (≈ field capacity) that was recorded during the monitoring period. For this analysis, data logged at 25 cm depth were used. For some dates, the soil moisture data were missing due to fox damage to cables. For such dates, the missing data were estimated as follows. Firstly, a relationship between the daily cumulative potential evapotranspiration (ETo) derived from an onsite automatic weather station (Measurement Engineering Australia) data and the daily gypsum block readings was developed for the days immediately preceding the missing data periods. Because of vine vigour differences, function parameters were estimated separately for each of the zones. In each case however, the relationship between soil moisture depletion and ET_o was well described (adjusted-$r^2 > 0.993$) by a sigmoid curve of the form:

$$SMT = a + b \times \left(1 + exp\left(-\left(\frac{ET_o - c}{d}\right)\right)\right)^{-1}$$

where *SMT* is soil moisture tension; *a*, *b*, *c* and *d* are parameter estimates. Secondly, these vigour-specific relations were used to estimate daily soil moisture tension for the dates with missing data based on the respective ET_o values derived from the onsite weather station. Overall, the missing and thus estimated data accounted for less than 5% of the observations. An example of model fit for one vigour zone is shown in Fig. 1.

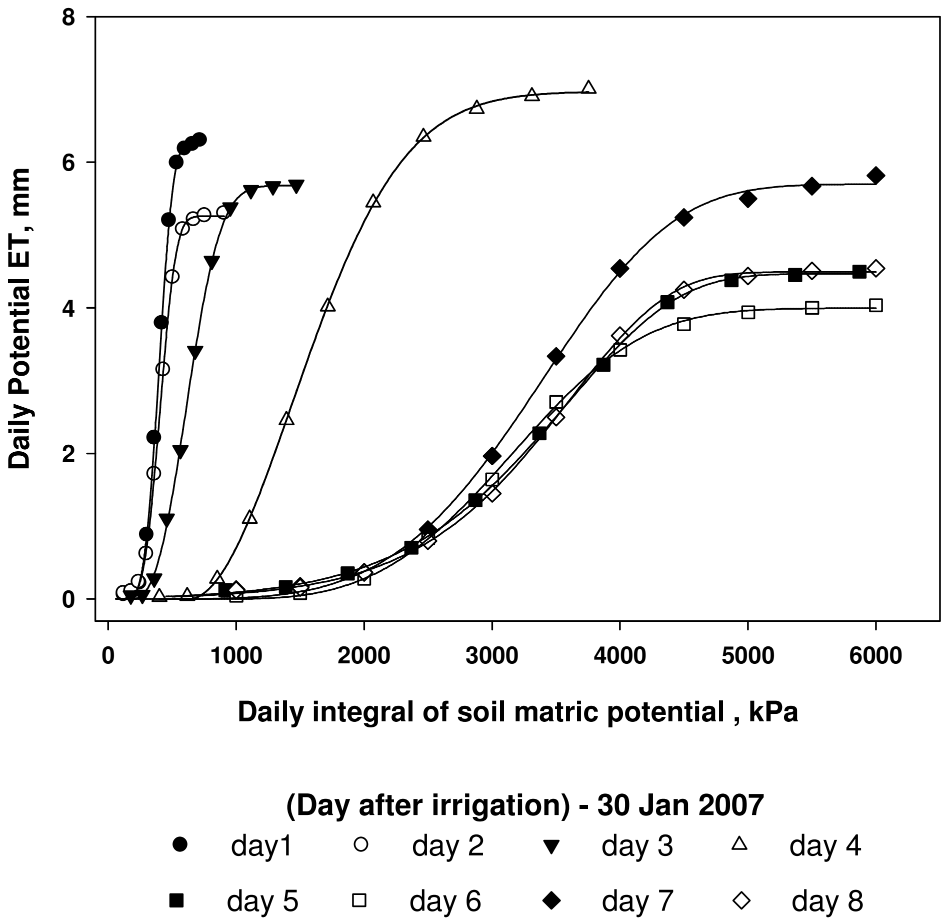


Fig. 1. Relationship between potential ET and under-vine soil moisture tension. Note that for plotting purposes, the predictand and the predictor are reversed.

5.8 Data analysis

Data were analysed using GenStat 13th edition (VSN International Ltd) and IBM SPSS Statistics 20. Most of the measured attributes were spatially non-contiguous. Thus, where spatial pattern visualisation from point measurements is presented, it is based on krigged estimates from best fit variogram models. Vesper 1.6 provided by the Australian Centre for Precision Agriculture (Minasny et al. 2002) was used for generating estimates.

6. Results and Discussion

6.1 C stable isotope discrimination as an indicator of spatial variation in the water deficits

The $\delta^{13}C$ of bud samples showed a clear north-south gradient whereby vines in the southern section of the block were enriched with ^{13}C compared to those in the northern section (Fig. 2a). Since the carbon in bud samples is likely to originate from multiple seasons (Zapata et al., 2004), the pattern revealed in Fig. 2a provides an integrated picture of long-term (inherent) soil water deficits in different parts of the block.

In exclusively rain-fed viticultural production systems, van Leeuwen et al. (2007) showed that the spatial pattern of $\delta^{13}C$ of berry sugars at harvest closely mirrored vine (hence soil) water status. Our results for berry sugar $\delta^{13}C$ for 2006 harvest however show that strong spatial patterns (such as those depicted in Fig. 2a) can be masked when the berry-ripening period experiences an unusually wet spell (Fig. 2b and Fig. 7). On the other hand, the $\delta^{13}C$ of berry sugars from the drier 2007 vintage showed moderately strong spatial patterns that were similar to those of bud samples. However, the east and west sections of the vineyard block were split drip-irrigated with the west side receiving 42 mm while the eastern section got 30 mm during the growing season. This differential irrigation slightly distorted the spatial water deficit pattern; nonetheless, the drier and warmer conditions in the latter part of the 2007 vintage prevailed in partially revealing the underlying pattern of variation in soil water deficits (Fig. 3c).

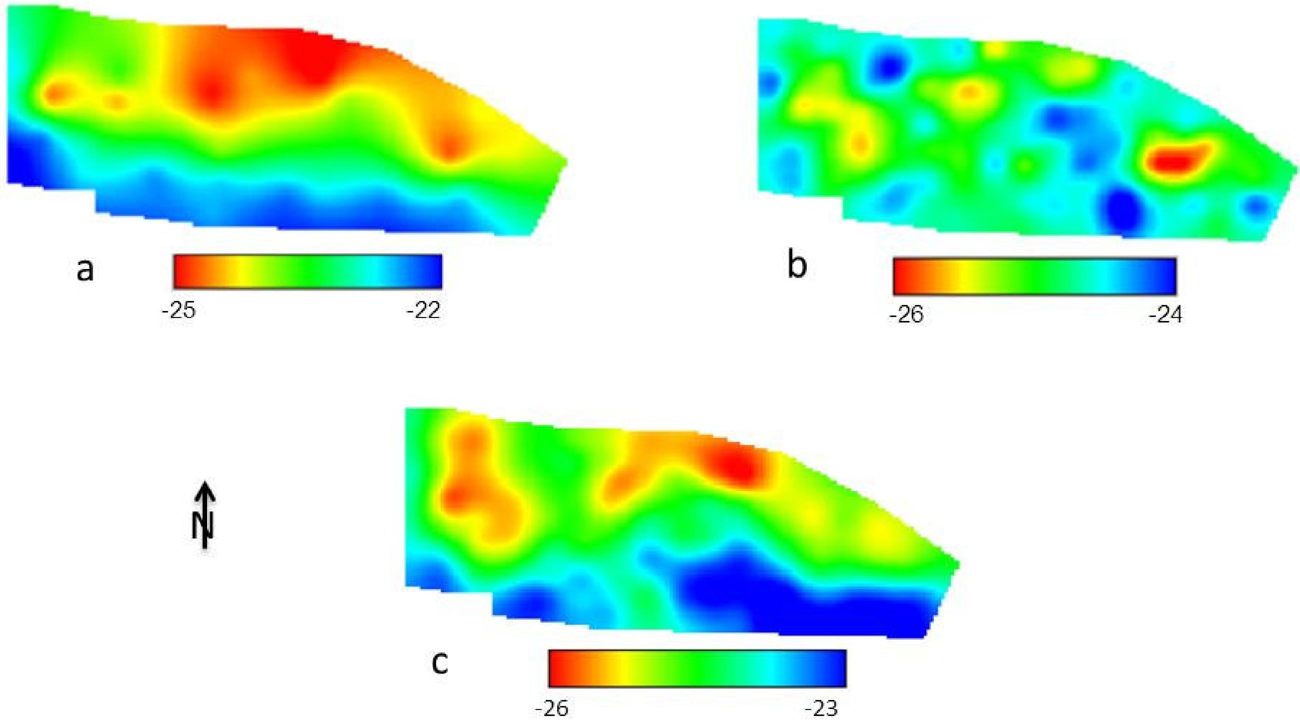


Fig. 2. Spatial pattern of $\delta^{13}C$ within a 6.4 ha study block. a) of bud samples collected at stage EL 1 in 2005, b) and c) respectively of freeze dried berry juice samples at harvest 2006 and 2007.

The bud $\delta^{13}C$ patterns were further examined in relation to some (semi)-permanent features of the block that may influence soil water levels such as topography and gravel content. Interestingly, the bud $\delta^{13}C$ spatial patterning appears to bear a resemblance to the north-south topographic gradient of the vineyard block whereas there was rather poor similarity to the pattern of gravel content of the top 100 mm of soil (*cf*. Fig. 2a, Fig. 3a, b). This is suggestive of moisture levels in subsurface (> 100 mm depth) as being more influential.

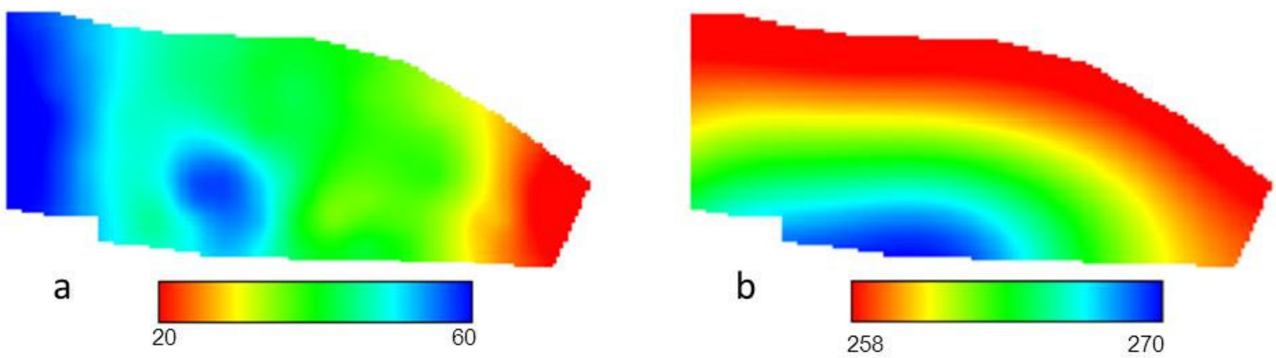


Fig. 3. a) Spatial pattern of gravel content (%) in the top 100 mm of the soil profile; b) within in block variation in elevation. The block has a 12 m north-south relative height range.

Interestingly, results from these analyses revealed relatively strong similarity between the bud $\delta^{13}C$ patterns and vine vigour patterns in the subsequent season (cf. Fig. 2a and 5a). Vineyard sections with vines depleted in ^{13}C, had low vigour vines the following season, while sections which were relatively more enriched in ^{13}C produced vigorous vines. This is further illustrated in Fig. 4 using point (individual vine) measurements showing strong association between $\delta^{13}C$ of buds and the vine canopy density resulting from it. This provides a clear indication of the effect of long-term water deficits on carbon fixation patterns (hence carbohydrate reserves) and its impact on subsequent season vine growth. Unlike the bud samples, there was little similarity between spatial patterns of $\delta^{13}C$ of berry soluble solids from 2006 or 2007 harvests and subsequent season vine vigour (*cf*. Fig 2b-c and Fig 5a-b).

A moderately strong ($r = 0.58$, $p < 0.001$) relationship was observed between $\delta^{13}C$ of berry soluble solids from 2006 and 2007 harvests (Fig. 6). Although care is needed in comparing between seasons (e.g., possible vapour pressure deficit (VPD) difference impacts unrelated to soil water), the observed relationship indicates that the general spatial pattern of vine water deficits was conserved, albeit modestly, between seasons. However, a lower ^{13}C discrimination (compare with blue line) was apparent in 2007 (which had a drier and warmer berry ripening period) than in 2006 which had a wetter ripening period (Fig. 7).

In summary, carbon stable isotope data may be used for identifying water deficit patterns in a vineyard block. However, in blocks that are variably irrigated, berry sugar $\delta^{13}C$ values are poorly suited for discerning underlying soil water deficit patterns. Instead, it is suggested that vine tissues that integrate/incorporate carbon from multiple seasons are more likely to reveal inherent soil water deficit patterns. If the water deficit level patterns that emerge from such analyses are coterminous and sufficiently large, these may provide a mechanistic/sound basis for delineating irrigation management zones.

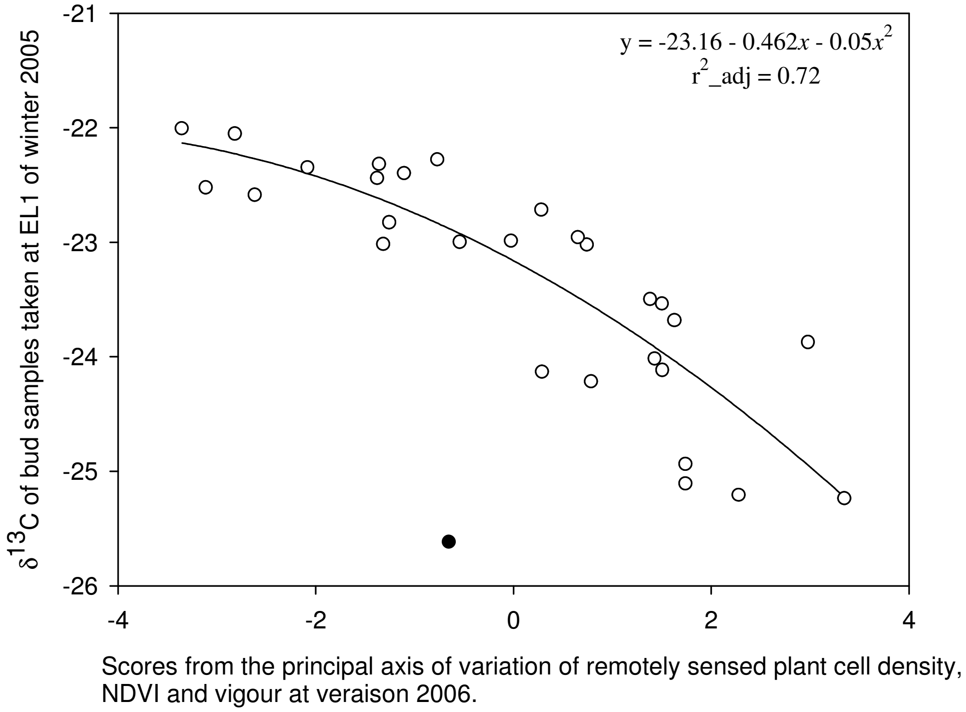


Fig 4. Relationship between the level of bud (stage EL 1) $\delta^{13}C$ (an integrated indicator of relative water stress) and subsequent season vigour of vines. Note the axes are reversed. The equation shown excludes the observation represented by the solid circle.

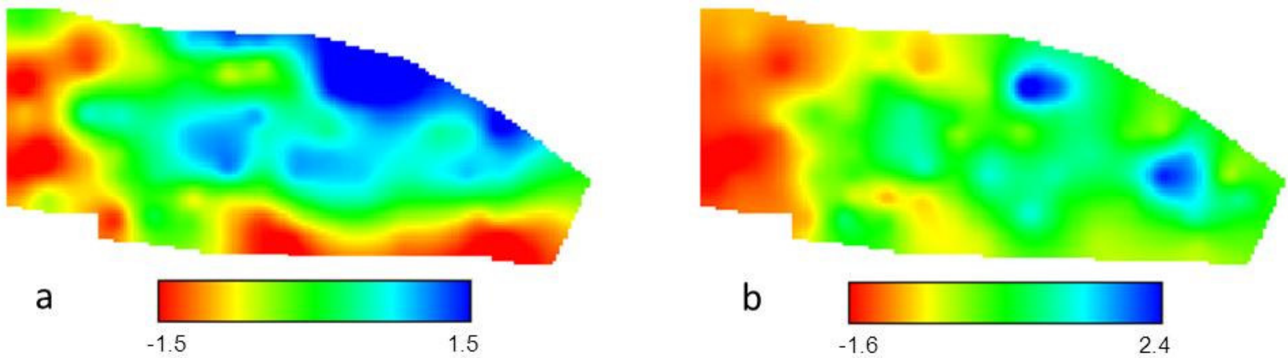


Fig. 5. Patterns in vine canopy density/size around veraison in a) 2006 and b) 2007. The data used for these displays are principal axis scores extracted from three canopy vigour indices (plant cell density, normalised difference vegetation index and vigour).

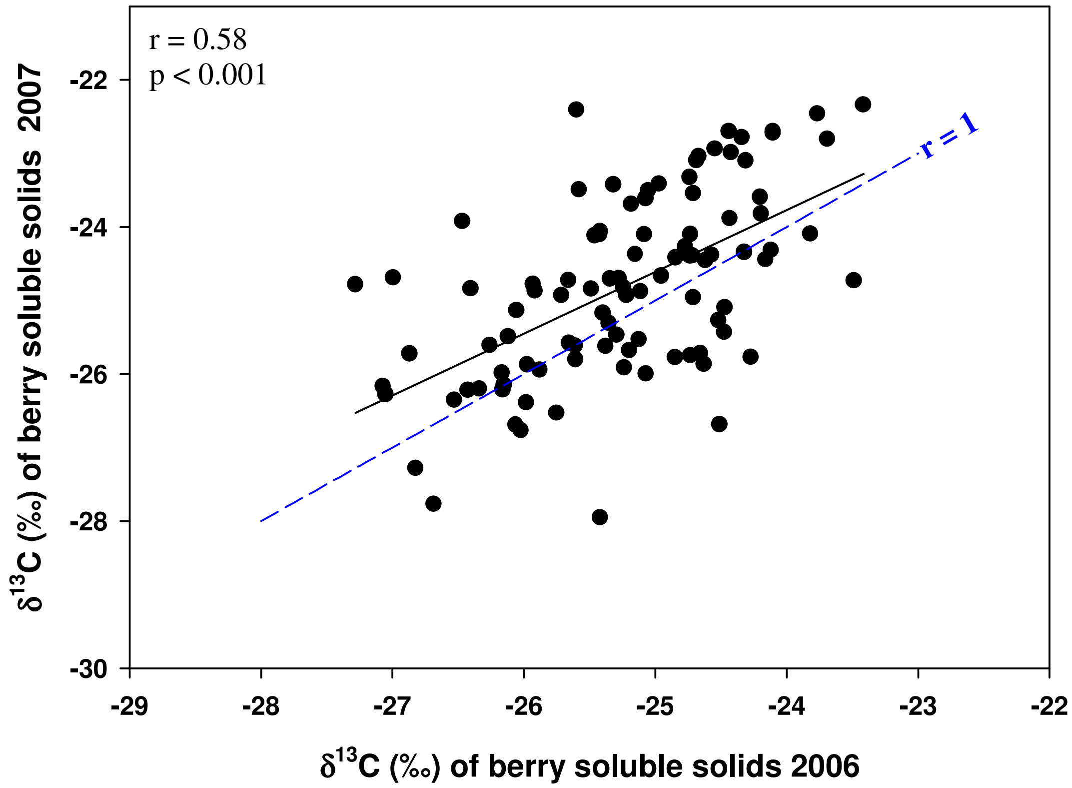


Fig. 6. Relationship between δ[13]C of berry soluble solids, at harvest, of two consecutive seasons. Blue line represents perfect correlation.

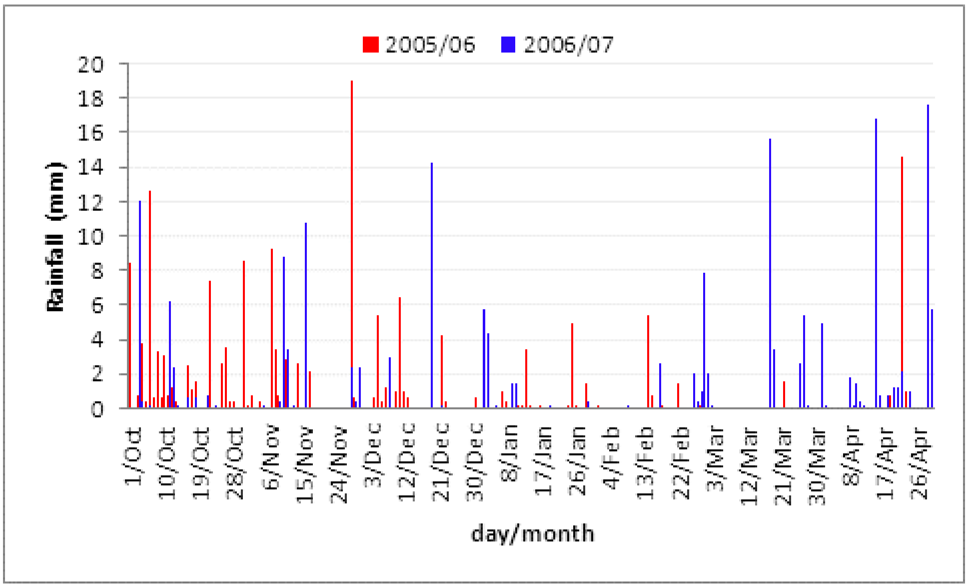


Fig 7. Rainfall during the growing season (1 Oct – 30 April) showing the relatively wet spell during the berry ripening phase in 2005/06 and 2006/07.

6.2 Dynamics of recovery of vine function following irrigation application

(a) Gas exchange 2006/07 season

Survey of gas exchange in the 2006/07 season indicated significant differences in rates of leaf level photosynthesis and stomatal conductance among vines from the different vigour zones (Fig. 8).

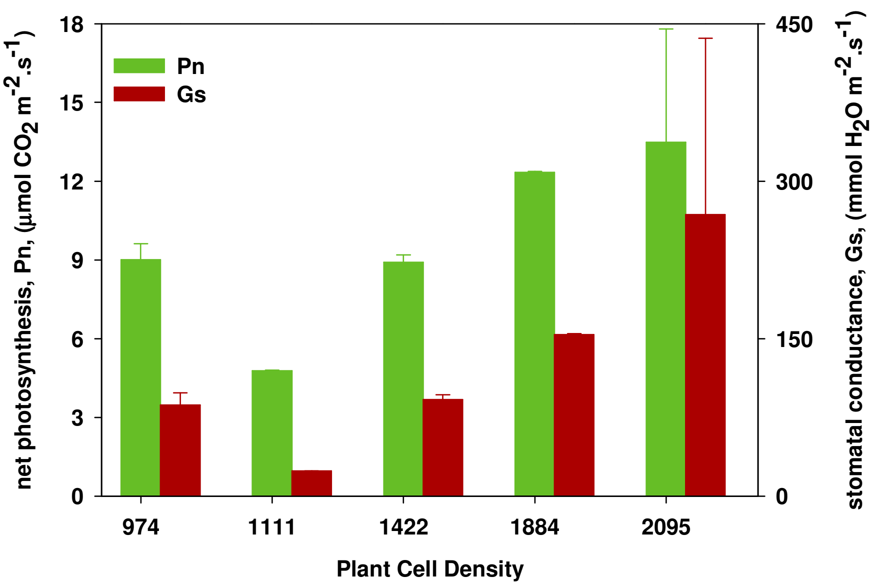


Fig. 8. Vine-vigour related variation in leaf net photosynthesis (Pn) and stomatal conductance (Gs) within in a vineyard block.

Subsequently, intensive measurements were carried out to examine whether the dynamics of recovery of leaf gas exchange from water stress also varied in relation to vine vigour. For this, vines from only the highest and lowest vigour zones were used. The results showed that rates of leaf photosynthesis and stomatal conductance were consistently high in vines from high vigour zones compared to those from the low vigour zones (Fig. 9). These differences between high and low vigour vines were apparent during the soil profile drying and re-wetting cycles (cf. Fig 9, 10). The failure of gas exchange rates of low vigour vines to reach the levels observed in the high vigour vines does not appear to be due to low root zone soil moisture. As shown in Fig. 10, low vigour zone vines had two extra irrigation events compared to the high vigour zone vines in the two weeks prior to start of measurements. This was reflected in the root zone moisture tension (at 25 cm depth) data showing considerably drier soil in the high than the low vigour vines zones (Fig. 10). This suggests factors other than availability of water were limiting the gas exchange rates of vines in the low vigour zones of the vineyard block. From this work, it was not possible to identify the precise mechanism(s) for the low rates of photosynthesis in low vigour vines. Zerihun et al. (2009) speculated the timing of start of irrigation, nutritional limitation especially phosphorus (extreme case shown Table 2) and sink-limitation as potential factors, and these warrant further investigations.

Regardless of vine vigour, there was a muted recovery of gas exchange following small volume drip irrigation (compare rates pre- and post-irrigation, Fig. 9). However, this may be due to hotter (up to 5^{o}C) and drier conditions (VPD increases of up to 2 kPa beyond an already high level) prevailing on the two days immediately after irrigation application (Fig. 11). Thus, although the post-irrigation gas exchange rates were lower than the pre-irrigation levels, given the atmospheric conditions, irrigation application probably significantly mitigated the decline that would have ensued otherwise. This is, thus, an important management intervention that safeguards canopy function.

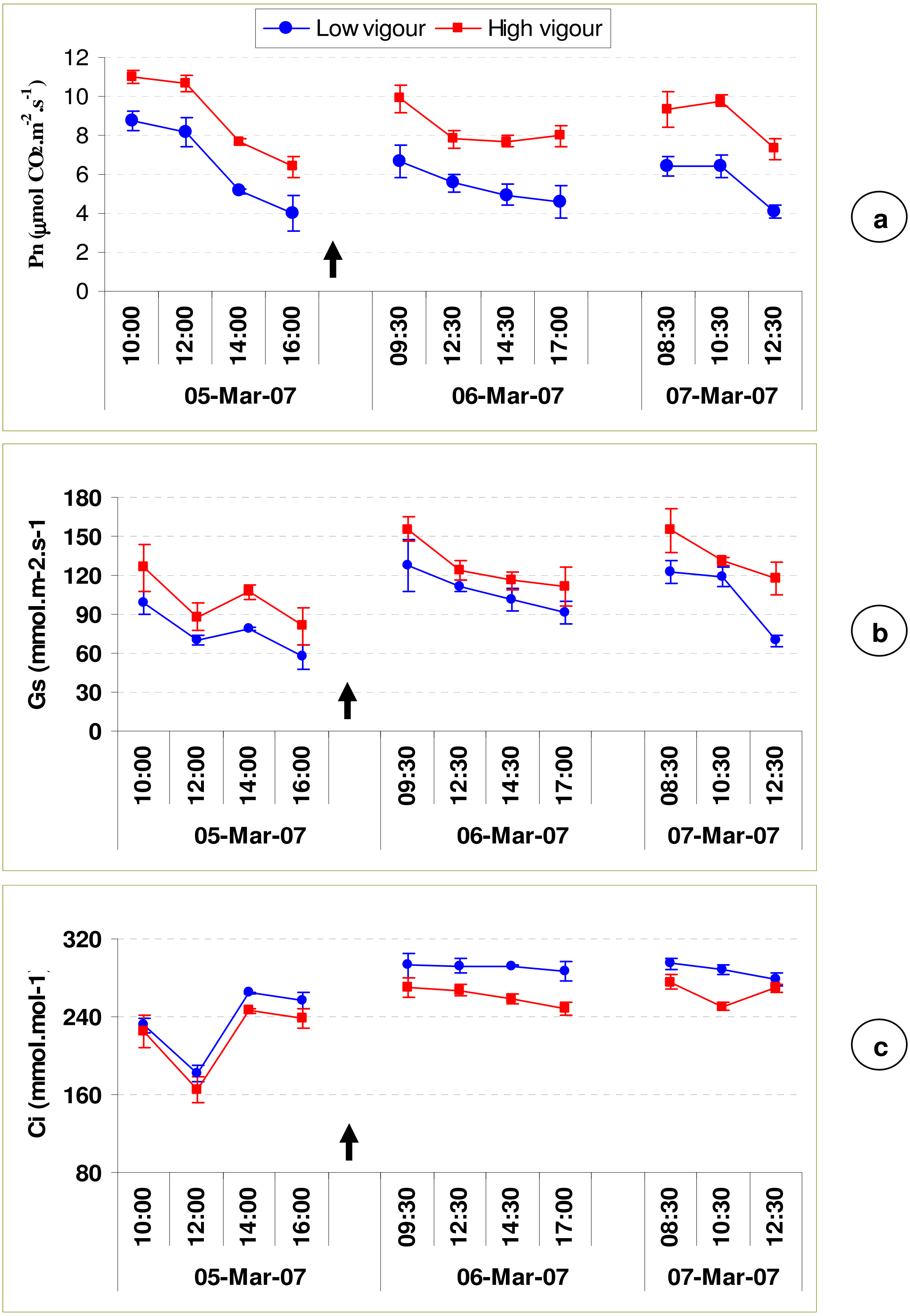


Fig. 9. Diurnal patterns of a) leaf net photosynthesis (Pn), b) stomatal conductance (Gs), and c) internal [CO_2] (Ci). Arrows indicate irrigation application on the night of 05 March.

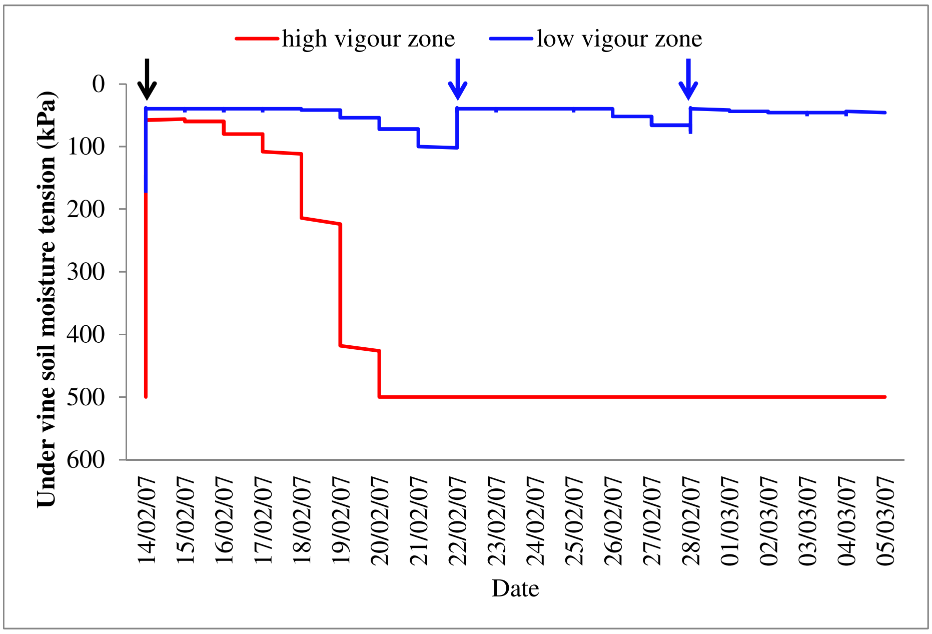
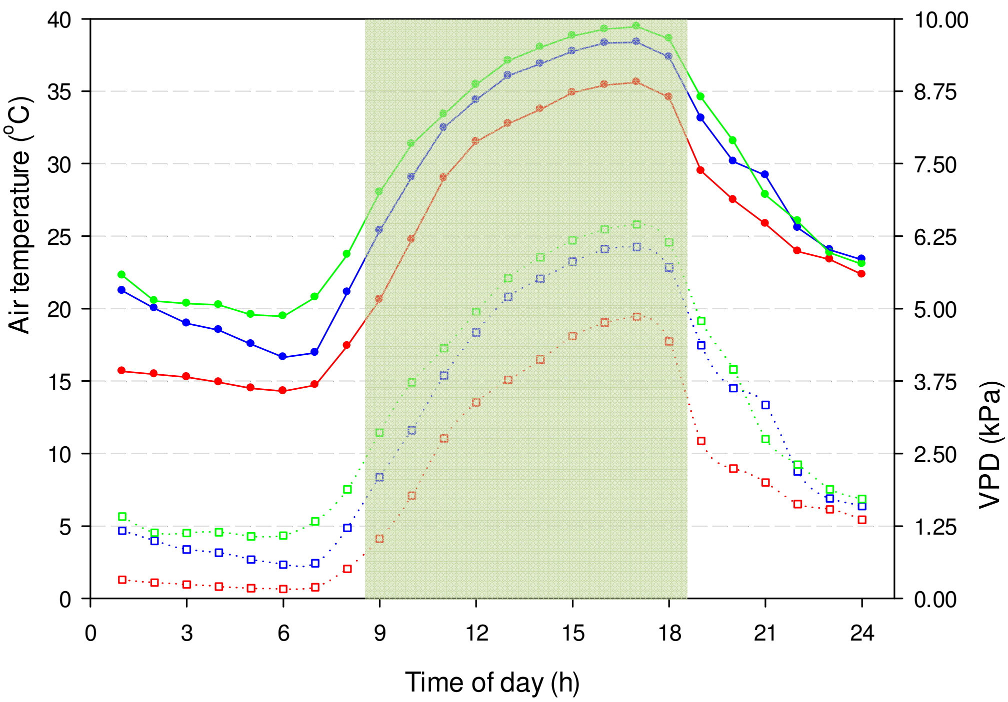


Fig 10. Irrigation history (and under vine soil mositure status at 25 cm depth) of the low and high vine vigour zones during the three weeks prior to diurnal gas exchange measurements, shown in Fig. 9. Note that on 14 Feb, both the high and low vigour zones were irrigated (30 L/vine). On 22 and 28 Feb, however, only the low vigour zone vines were irrigated at 30 l/vine on each occasion. Diurnal gas exchange measurements were started on 05-Mar (representing conditions under soil drying phase); irrigation at 30 l/vine applied to both vigour zones on the night of 06-Mar (data not shown) and measurements continued until 07-Mar. Measurements on the the latter two dates represent "recovery" following extended water stress.



Air temparature (circles) and vapour presure deficit (squares) on gas exchange measurement dates: on 5 March (red), 6 March (blue) and 7 March 2007 (green).

Fig. 11. Weather conditions during the diurnal measurement periods (shown in shades).

(b) Gas exchange 2007/08 season

The results from the 2006/07 season raised questions as to whether the observed differences in photosynthetic performance of low versus high vigour vines were also apparent early in the growing season. Consequently, measurements were carried out starting from the time of flowering and continued until harvest at regular intervals as weather conditions permitted. The measurements at the time of flowering clearly indicated that vigour-dependent differences in vine physiological performance were indeed present even early in the growing season (Fig. 12) when soil moisture status was still sufficient (Fig. 13), thus reinforcing the previous season conclusions.

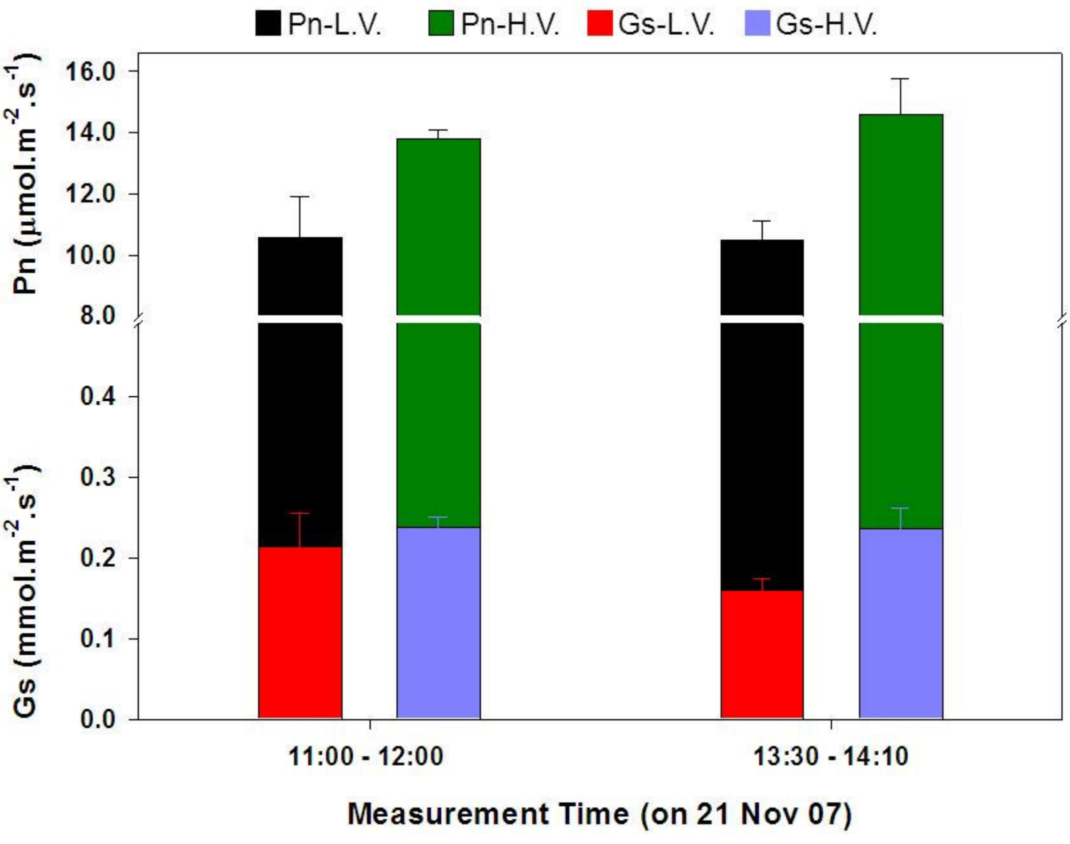


Fig. 12. Rates of leaf photosynthesis (Pn) and stomatal conductance (Gs) in low vigour (LV) and high vigour (HV) vine zones of the vineyard taken at flowering.

Further measurements around veraison confirmed the existence of considerable variation in gas exchange rates across the different vigour zones of the vineyard block (Fig. 14). These results, as in the results from the preceding season, suggest that factors other than soil moisture deficits may be limiting leaf photosynthetic activity in the low vine vigour zones. This suggestion is based on the observation that at least up to this point in the growing season, the rhizospheric moisture tension was similar between the low and high vigour zones (Fig. 13).

In terms of recovery of gas exchange rates following irrigation (15 L/vine) application, there was no significant response in photosynthesis rates although contrasting responses were apparent between the extreme vigour classes (compare pre- and post-irrigation results, Fig. 14). Stomatal conductance rates however were on average 17% lower ($p = 0.04$) after irrigation. It needs to be noted, however, that the maximum air temperature on the 17 Jan (post-irrigation measurement date) was nearly 8 ^{o}C higher than that on 16 Jan, the pre-irrigation measurement date (see also section on fluorescence). The maximum VPD also higher by 2 kPa. It is thus probable that the elevated temperature and VPD on the post-irrigation day may have contributed to a lack of positive response to irrigation. Although the expected increase did not eventuate, it is clear that the small volume irrigation event enabled the vines to offset the potential impacts of the rather large increases in temperature and VPD on carbon assimilation. The commercial operational conditions did not create an opportunity to examine what might have happened if a replicate of the block was not irrigated prior to a "heat spike event" such as that occurred on 17 January. Nonetheless, it may be argued that strategic interventions such as this are key risk management tools in preventing serious damage to vine physiological functioning that could otherwise take longer to recover and potentially impact on final output.

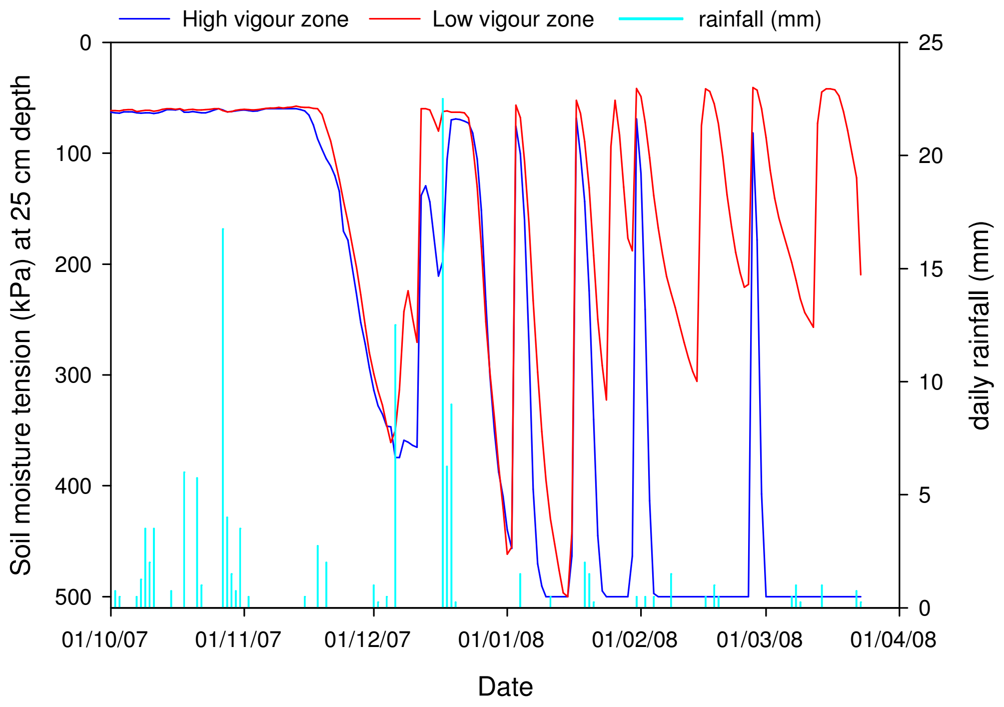


Fig. 13. Under vine soil moisture tension in highest and lowest vigour zones and rainfall during the 2007/08 growing season. Spikes in soil moisture correspond to irrigation application dates (except the spike during 17-19 Dec, which was due to rainfall events). Note that the high vigour zone vines had two fewer spikes (infrequently irrigated); furthermore, the total quantity applied over the entire season was only 50% of the amount applied to the low vigour zone vines.

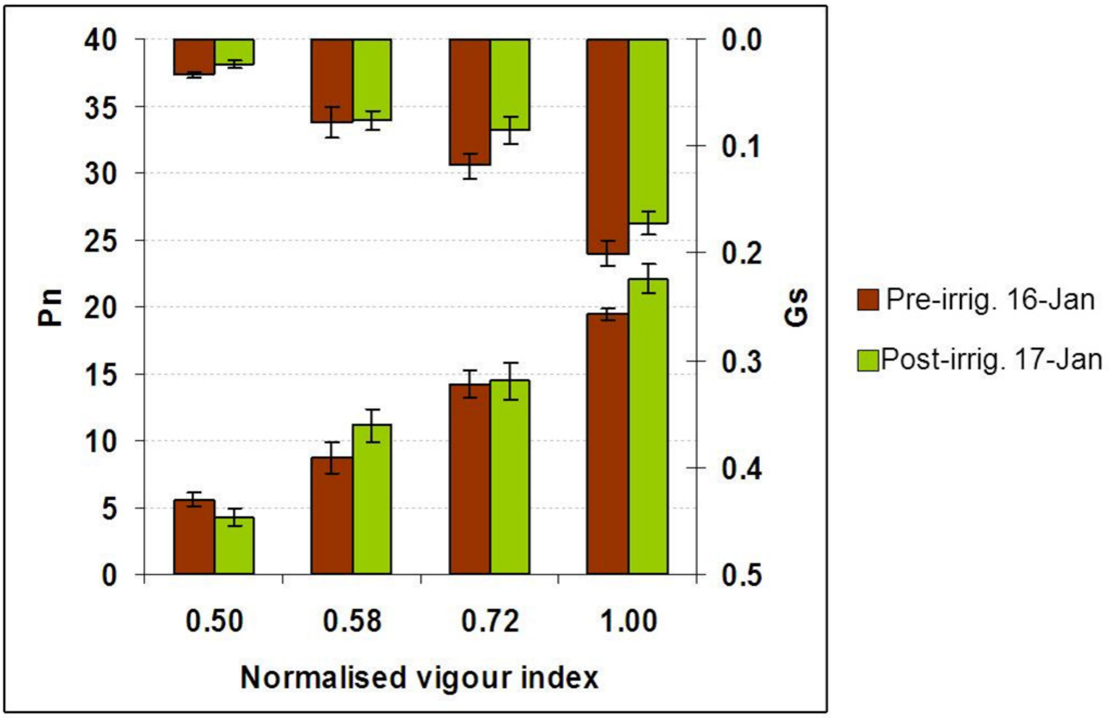


Fig. 14. Variation in leaf gas exchange rates across different vigour zones of the study vineyard block in mid-January 2008 (around veraison). Vine size is normalised to the highest vigour. The lowest and highest indices are the same as those shown in Fig. 12.

Additional intensive measurements in the highest and lowest vigour zones taken during berry ripening in late February (26-29) provided further confirmation that leaf gas exchange in low vigour vines operated at lower rates than those of the high vigour zones (Fig. 15). Indeed, this was so on all measurement occasions throughout the growing season (Figs. 12, 14-16). Furthermore, this occurred despite the low vigour zones vines receiving 50% more irrigation water (Fig.13) via more frequent and/or volume application.

In terms of recovery response, gas exchange rates of low vigour vines in late February responded positively to the small volume irrigation applications (Fig. 15). The gas exchange rates of the low vigour vines on 26 Feb were extremely low (e.g. leaf photosynthesis diurnal average of 1.7 $\mu mol/m^2/s$, Fig. 15) despite receiving 30 L/vine 10 days prior. Over the two days (27 and 28 Feb) following 15 L/vine application, the rate of carbon fixation rose to an average of 5.1 $\mu mol/m^2/s$ (+190%). This is a considerable recovery although it is still less than 50% of the pre-irrigation rate in high vigour zones (i.e., vines that were not irrigated for more than three weeks).

On the 26 Feb the high vigour vines, despite not receiving irrigation for 4 weeks, were still photosynthesising at high levels (diurnal average 10.6 $\mu mol/m^2/s$). The average response to irrigation over two days (27 and 28 Feb) was +24%. While this relative response is clearly less than that of the lower vigour vines, it is a reflection of the high operating base level of photosynthesis in these vines. It thus appears that at least on this particular occasion, the low vigour vines benefited considerably more from irrigation than the high vigour vines.

It is worth noting that in each vigour zone gas exchange rates remained relatively stable, albeit at different levels, until December and started to decline thereafter with the progression of the growing season, with the relative decline being greater in the low vigour zones.

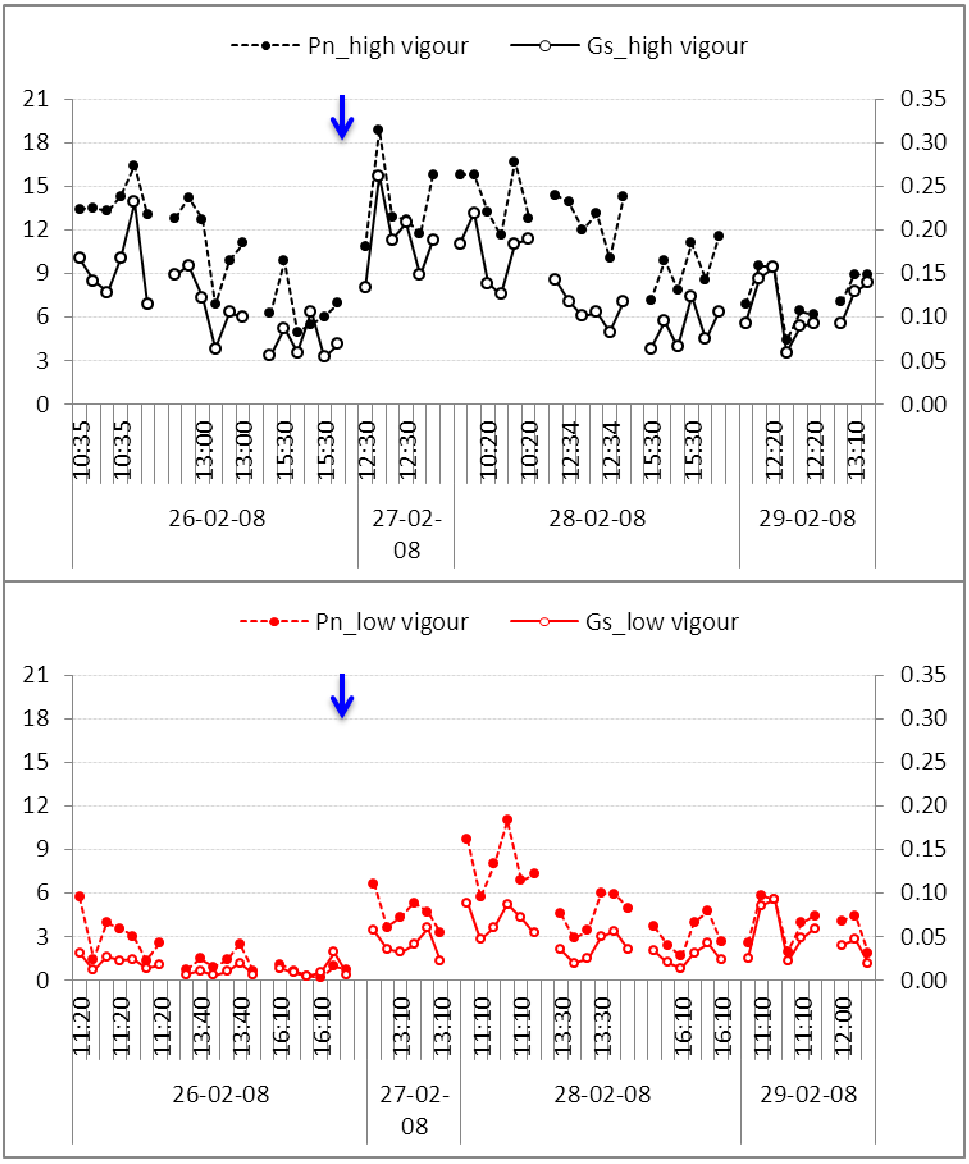


Fig. 15. Responses of leaf photosynthesis (µmol/CO_2 m^2/s, left axis) and stomatal conductance (mmol H_2O/m^2/s, right axis) rates to irrigation in the lowest and highest vigour zones. Arrow indicates irrigation application (15 L/vine).

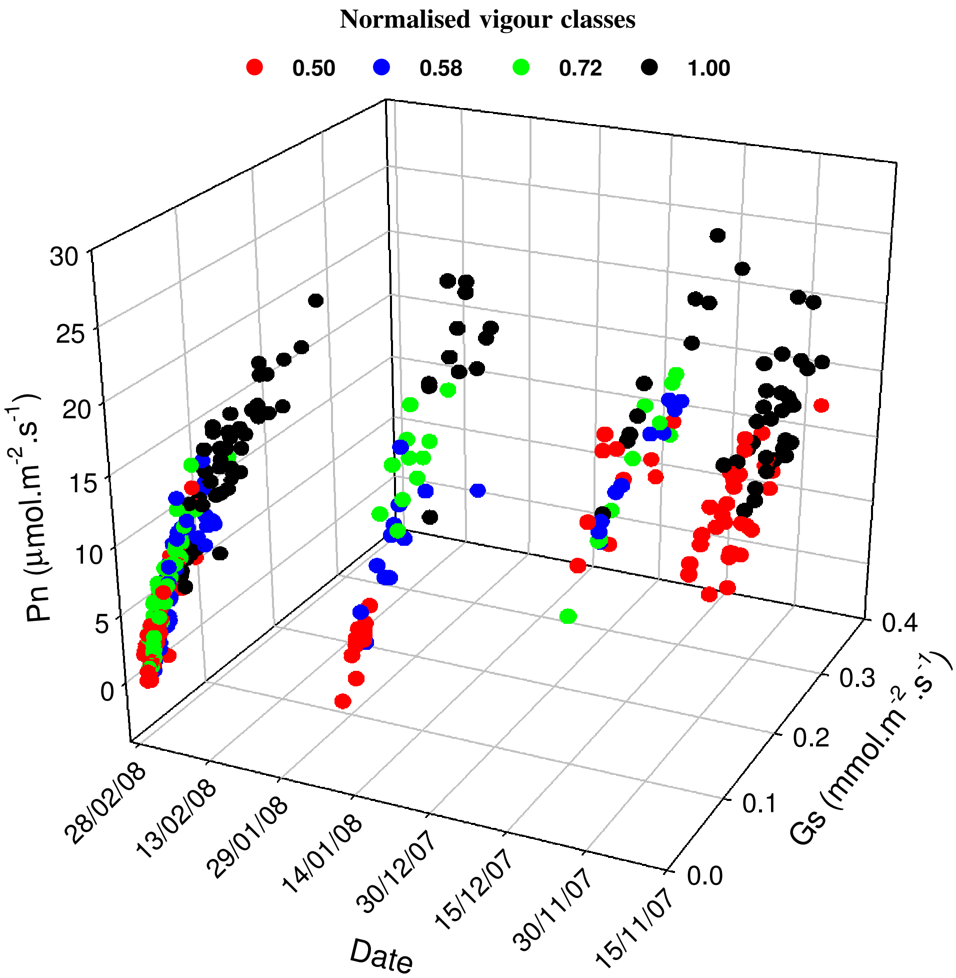


Fig. 16. Seasonal trends of leaf photosynthesis rates in relation to stomatal conductance in various vigour zones of the study vineyard. Note the vigour persisting throughout the monitoring period (flowering to harvest).

6.3 Chlorophyll fluorescence analysis

Chlorophyll fluorescence was measured simultaneously with gas exchange on seven occasions during the 2007/08 growing season (Fig. 17). As was the case with the gas exchange results, all the fluorescence derived variables reported here were consistently different between the lowest and highest vigour zone vines throughout the monitoring period (Fig. 17c-h). Vines from the lowest vigour zone compared to those from the highest vigour zone were characterised by a low: (1) maximum PSII efficiency of full sunlight adapted leaves, (2) photochemical quenching, (3) PSII quantum yield, (4) hence whole chain electron transport rate, and by a high: (5) non-photochemical quenching and a corresponding (6) quantum yield.

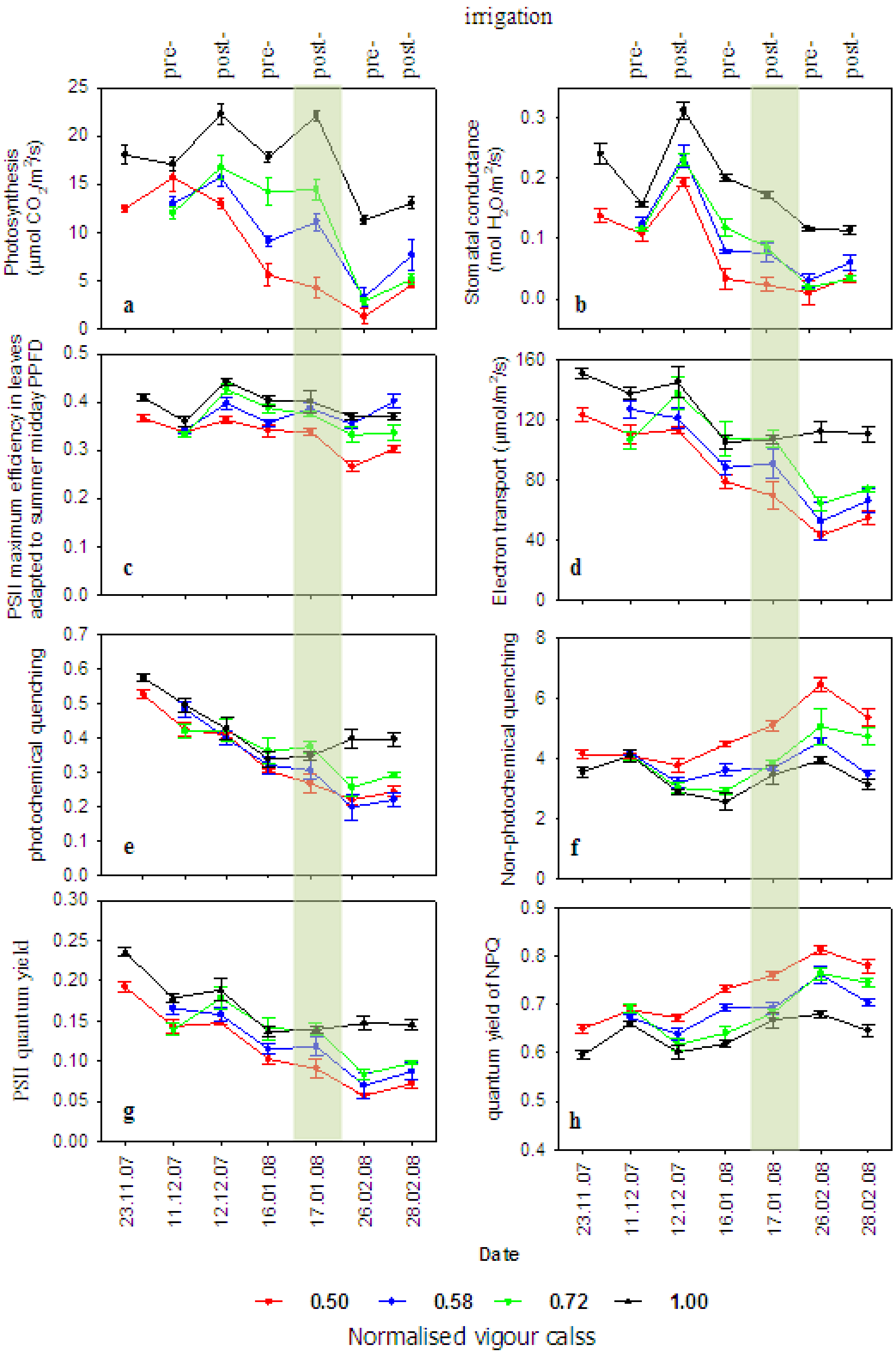


Fig. 17. Leaf gas exchange and chlorophyll fluorescence derived indicators of photosynthetic performance in relation to vine vigour. Data (mean ± 1s.e; n = 6 vines) shown are for measurements taken at midday on the indicated dates. For some dates and variables, diurnal trends were also assessed (see Fig. 18).

A second general observation was the contrasting temporal trends between photochemical (Fig. 17c-e, g) and non-photochemical processes (Fig. 17 f, h). While the photochemistry-related variables displayed a declining trend, the non-photochemical quenching processes progressively increased with the advancement of the growing season. These generally inverse relationships were also evident over the diurnal course (Fig. 18). One again, the differences between vigour zones were clearly seen.

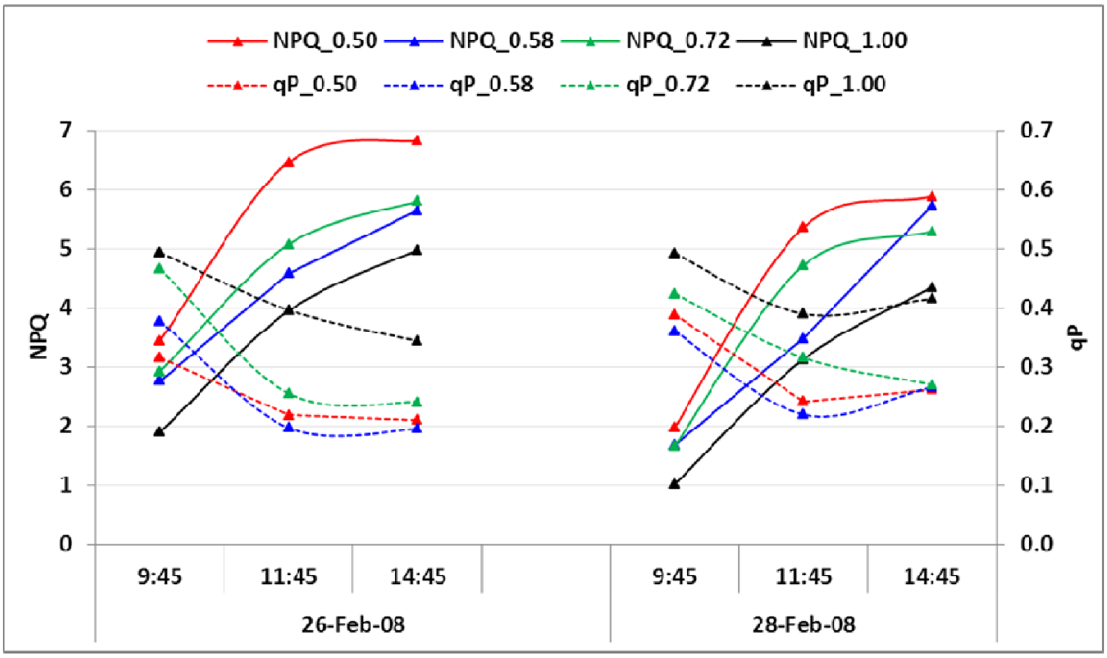


Fig. 18. Diurnal patterns in photochemical (qP) and non-photochemical quenching (NPQ) before (26- Feb-08) and after (28-Feb-08) small volume irrigation (15 L/vine equivalent to 2.3 mm). The numbers suffixed to the legends are vine vigour classes normalised to the most vigorous vines. Note that vines from the highest vigour zone (shown in black) did not receive irrigation for 4 weeks prior to the night of 26-Feb, while all the other vines got 30 L/vine on 15-Feb.

The increase in non-photochemical quenching with advancement the growing season is likely to provide protection from photo-oxidative damage to PSII reaction centres thereby enabling the foliage to stay in functional state for a longer time than would be possible otherwise. This, in addition to enabling leaves to maintain a positive carbon balance during post-harvest period that facilitates for carbohydrates reserves to be built up for the subsequent season, caters for effective resorption of phloem mobile nutrients from the foliage back into the storage structures.

Compared to the vigour- and seasonal-related differences, irrigation effects were relatively modest. Nonetheless, the small volume irrigation applications generally appeared to reduce the proportion of absorbed photon energy dissipated thermally (Fig. 19), except when irrigation applications were followed by high temperature days (Fig. 20).

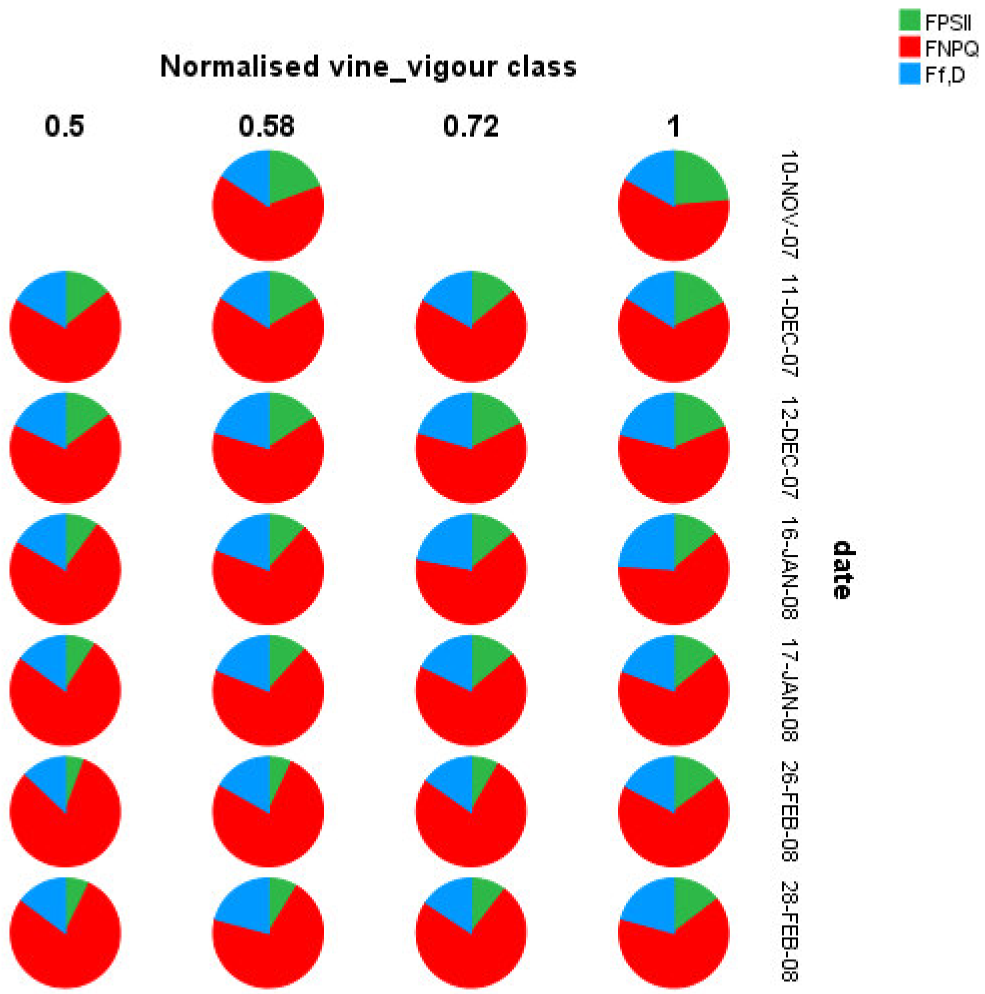


Fig. 19. Seasonal trends in the fraction of light energy absorbed by leaves that was used in driving photochemistry (green sector), thermally dissipated by energy-dependent and xanthophyll cycle-dependent mechanisms (red sector) and that lost via a combination of processes including fluorescence (blue sector). Note that, as the season progresses, the proportion of light energy that is used via photosynthesis declines while that dissipated thermally increases, and these shifts appear to be greater in low than in high vigour vines.

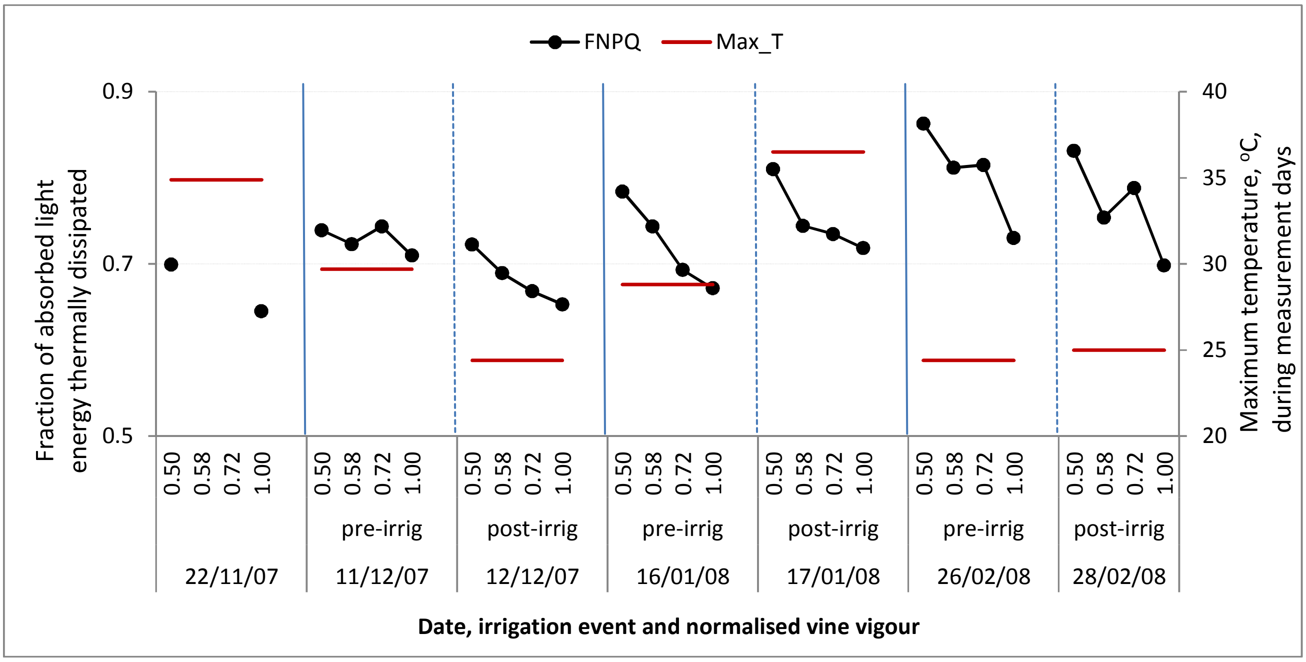


Fig. 20. Small volume irrigation application appears to reduce the proportion of absorbed energy dissipated thermally, except on days when air temperature following irrigation application becomes highly elevated. Note the increasing trend in thermal dissipation of absorbed energy with the progression of the growing season.

6.4 Outdoor pot experiment study of photosynthesis recovery from water stress

Being a typically winter-deciduous and hence summer active plant, a major proportion of the annual net primary production of grapevines occurs during the late spring to summer months of the year. With the progression of the season from spring to summer vines experience sustained levels of high radiation load, increasing temperatures and water deficits, with the latter likely to be more severe and frequent under primarily rain-fed viticultural production systems. These conditions can disrupt normal leaf physiological function with a consequent impact on leaf photosynthetic activity.

One of the aims of this project was to gain some understanding of physiological mechanisms that enable grapevines to maintain physiological competence of their leaves under conditions of moderate to severe water deficits while temperatures and radiation loads remain high. Towards addressing this aim, two grapevine varieties (Shiraz and Sauvignon Blanc) were grown from cuttings in 75 L pots and kept outdoors. During the subsequent season, a replicated water stress experiment was initiated in which these varieties were exposed to water deficit cycles and their leaf physiology (photochemistry and water status) monitored periodically – seven times.

Water deficits cycles (replete- and deficit-states) were generated over ~6 weeks for both varieties (Fig 21). Regardless of variety, leaf photosynthesis rate was strongly modulated by water deficit (*cf*, Fig 21 and 22).

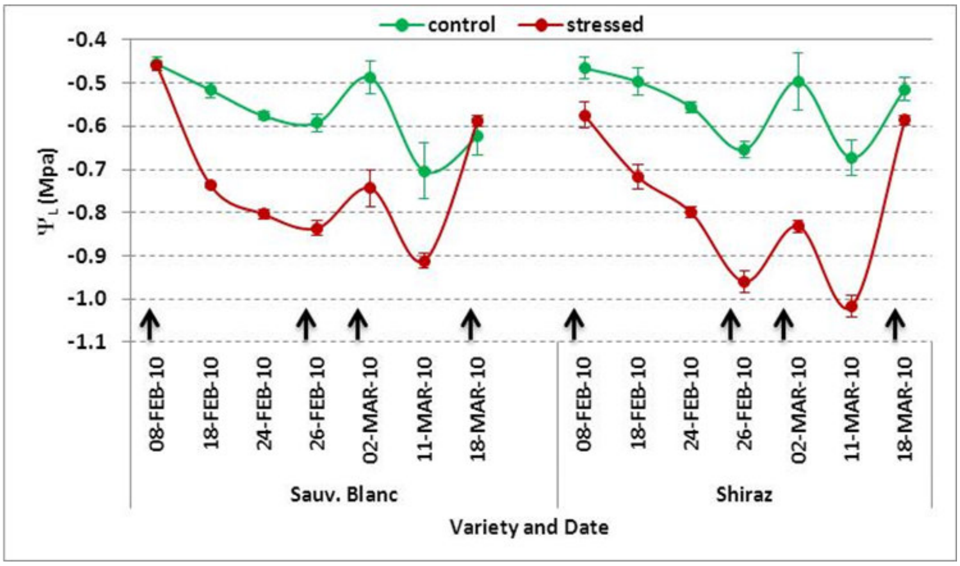


Fig. 21. Midday leaf water potentials of Sauvignon Blanc and Shiraz varieties in control and stress treatments. Data are mean ± 1 s.e.; n = 6-8 vines. Arrows are represent irrigation events.

Although photosynthesis of the vines maintained under water-replete state also showed rises and falls in concert with leaf water status, the amplitude was substantially greater in the water-stressed treatments (Fig. 22).

In both varieties, there was a clear evidence of an elevated level of engagement of the xanthophyll-cycle dependent non-photochemical quenching (NPQ) in water stressed vines compared with water-replete vines. The non-photochemical thermal dissipation of excess absorbed radiation as heat was found to occur as a mirror image of photosynthesis (Fig. 22) thus potentially protecting oxidative damage to the photosynthetic machinery of leaves. These results suggest that active deployment of the xanthophyll-cycle dependent NPQ is one of the key mechanisms that enables rapid recovery of grapevine leaf photosynthesis following small-volume irrigation during extended water stress.

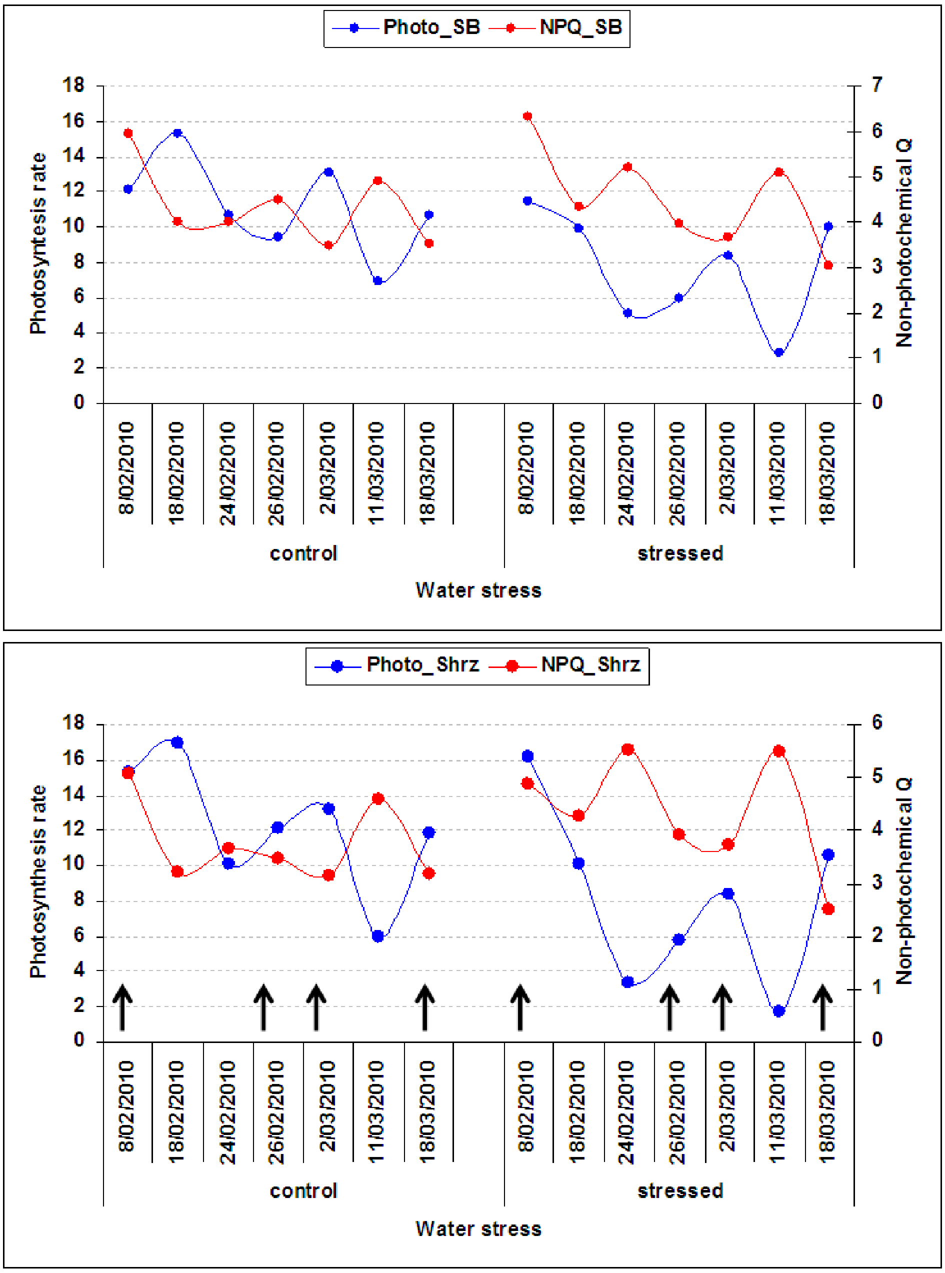


Fig. 22. Responses of leaf photosynthesis rates and non-photochemical quenching in water stressed and unstressed (control) Sauvignon Blanc (SB) and Shiraz (Shrz) vines.

6.5 Vine water relations and its response to small volume irrigation events

Vine water status was monitored from pre-flowering (EL 17) to harvest/berry maturity (EL 38) during the 2007/08 season. When weather conditions allowed, leaf water potentials at pre-dawn ($\Psi_{L,PD}$), at various times during the photoperiod including at midday ($\Psi_{L,MD}$), and stem water potential (Ψs) at midday and mid-after noon were measured (Fig. 23-25). Also, when weather permitted, diurnal measurements were carried out to examine the dynamics of recovery of leaf water status after a small pulse of irrigation.

6.6 General observations (seasonal trends) of vine water status

One of the most noticeable observations was the progressive decline of vine water status with the advancement of the growing season (Fig. 23-25). According to van Leeuwen *et al.* (2007), grapevines which maintain $\Psi_{L,PD}$, $\Psi_{S,MD}$ and $\Psi_{L,MD}$ respectively above -0.2, -0.6 and -0.9 MPa are not water stressed. On the bases of these benchmarks, all three sets of measurements ($\Psi_{L,PD}$, $\Psi_{L,MD}$ and $\Psi_{S,MD}$) indicated that all vines regardless of their vigour were not water stressed until mid-December (fruitset stage, EL 27) (Fig. 23-25). Post-fruitset, however, the water status of vines alternated between stressed and unstressed depending on whether measurements were done pre- or post-irrigation application. During the post-fruitset to harvest period, the pre-irrigation measurements (i.e., measurements after "extended" period of soil drying) indicated that high vigour vines generally maintained higher leaf and/or stem water status than low vigour vines. This was despite the high vigour vines being irrigated at half the frequency of the low vigour vines (Fig. 23-25).

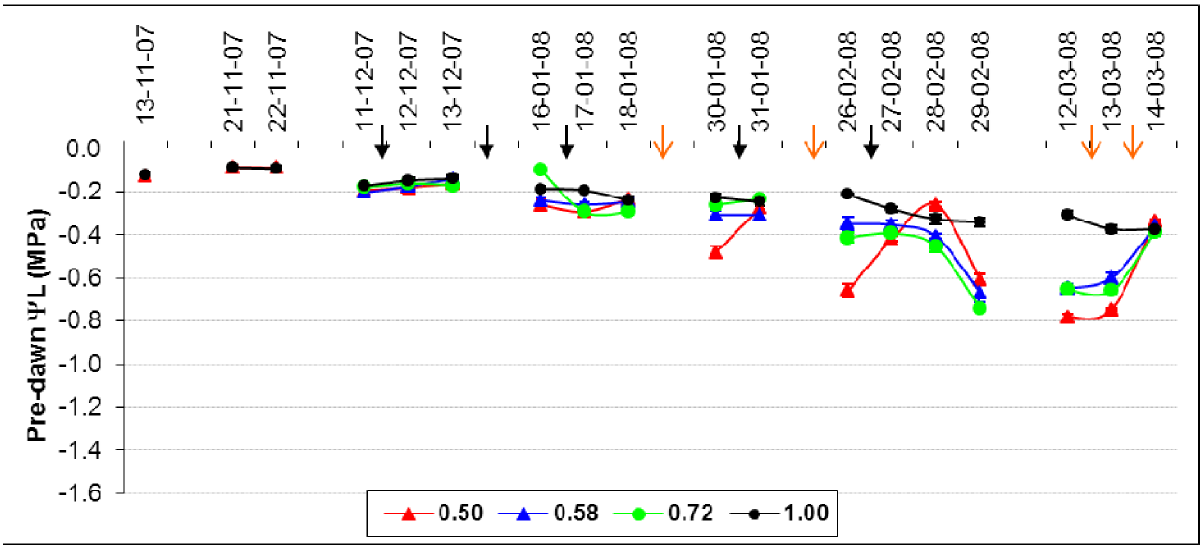


Fig. 23. Seasonal trends in pre-dawn leaf water potentials of Shiraz vines of varying vigour and their response to small volume irrigation pulses. Data are mean ± 1 s.e. (where larger than symbol). Arrows indicate irrigation events. In about half of the irrigation events, only one half of the vineyard block was irrigated (shown by orange arrows) while the vigorous vines, represented by the black line (vigour class 1.00), were not irrigated; black arrows indicate dates on which irrigation was applied to the entire block.

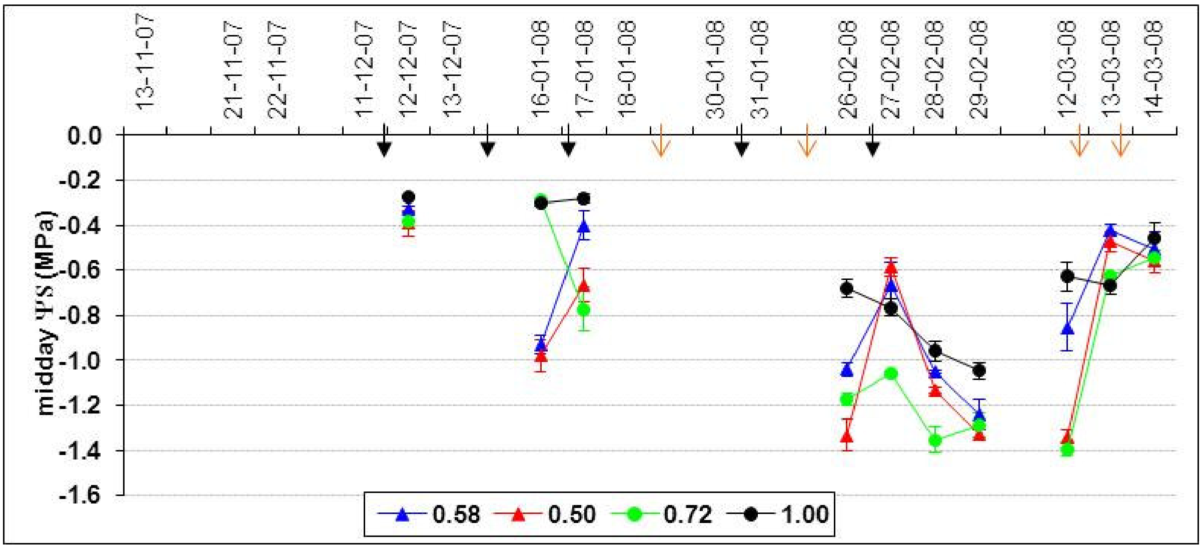


Fig. 24. Seasonal trends in stem water potentials and response to small volume irrigation pulses. Other details are as in Fig. 23.

6.7 Recovery response of vine water status to irrigation (diurnal and diel patterns)

<u>11-Nov 2007</u>

The first water status assessment was carried out on 11-Nov (EL stage 17, when 12 leaves or single flowers were separated). At this stage, supplementary irrigation of the season had not yet started, but there was moderate level of spring rainfall and the rhizospheric moisture tension was high (see Fig. 13). Consequently, the $\Psi_{L,PD}$ was high (-0.13 MPa) and similar across all vigour zones of the vineyard (Fig. 23). No further (diurnal) measurements could be done on this trip due to unsuitable weather.

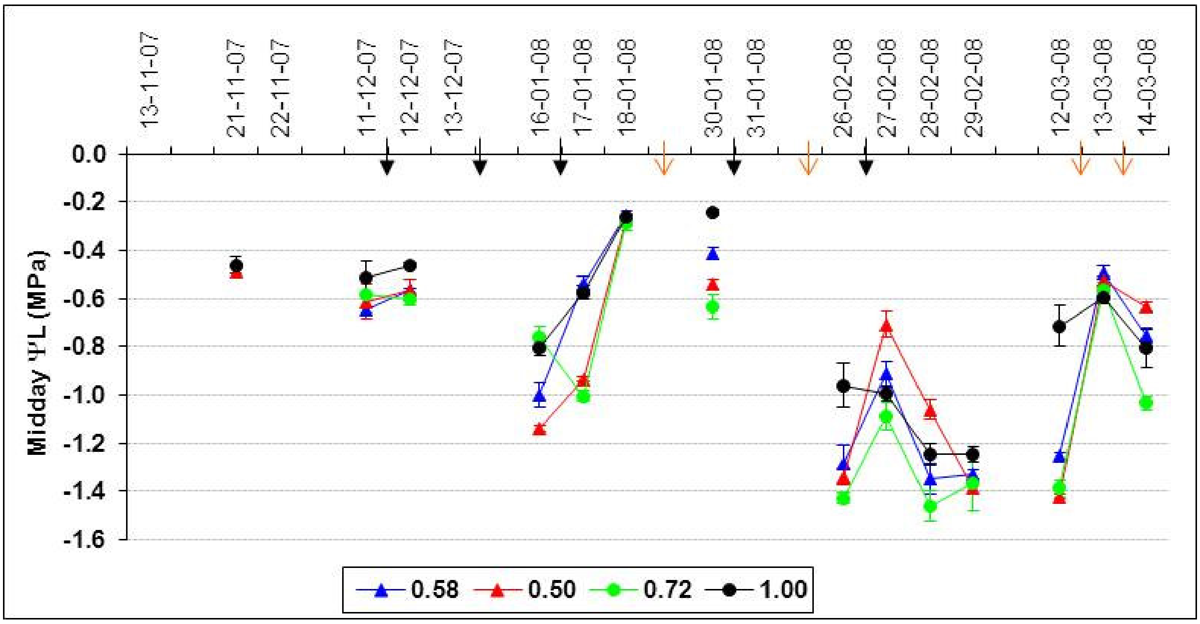


Fig. 25. Seasonal trends of midday leaf water potential and its response to supplementary irrigation. Other details are as in Fig. 23. For diurnal trends, see Figs. 26-30. Note the sharp increase of Ψ_L on 18-Jan coincided with full cloud cover and near saturating humidity.

21-22 Nov 2007

The second measurement campaign was 10 days later (21-22 Nov 2007) at EL stage 22 or 50% cap fall. At this time too, the soil moisture status was still adequate (Fig. 13), and $\Psi_{L,PD}$ was uniformly high (about -0.10 MPa) between the highest and lowest vigour zones of the vineyard (Fig. 23). On this occasion, it was possible to take extra measurements at midmorning and midday to capture the diurnal dynamics of $\Psi_{L.}$ The results showed:

- $\Psi_{L,MD}$ of vines from the highest and lowest vigour zones maintained comparable water status (about -0.5 MPa, Fig. 23, 26; note that as described above, a vine with a midday water potential of this magnitude is considered unstressed), and
- The low vigour vines reached this value earlier in the day compared to the high vigour vines (Fig. 26).

Thus, although both the low and high vigour zone vines were relatively unstressed, there was indication that the low vigour vines were reaching the daily minimum water potential much earlier in the diurnal cycle. This means that even if the high and low vigour vines attain the same low water potential, the high vigour vines experienced a lower level of water stress integral given that the minimum value evolves at a slower pace and lasts for a shorter fraction of the photoperiod period.

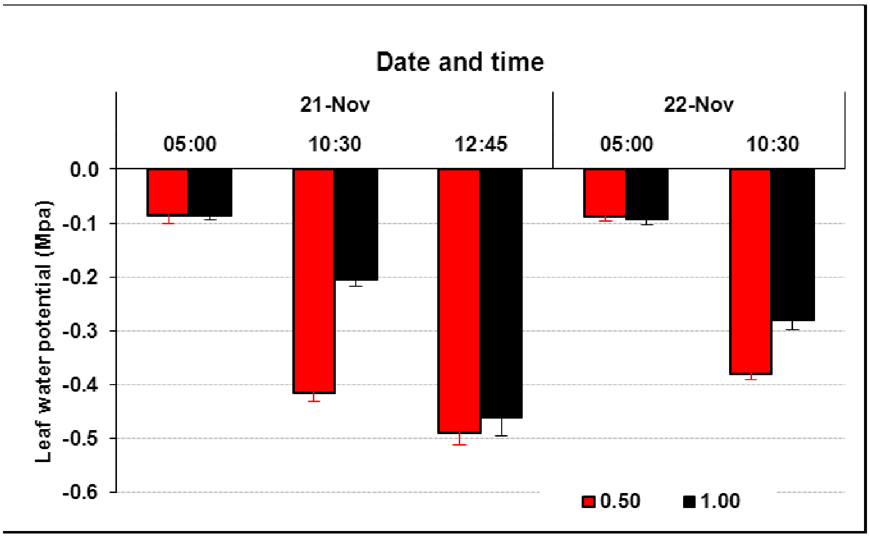


Fig. 26. Evolution of leaf water potential over the diurnal period in Shiraz vines from the lowest and highest vigour zones.

<u>11-13 Dec 2007</u>

The first supplemental irrigation event of the season was on the night of 11-Dec. Measurements were therefore carried out from 11-13 Dec to capture both the pre-irrigation vine water status as well as its response to an irrigation pulse (15 L/vine).

The pre-irrigation $\Psi_{L,PD}$ values (11-Dec) were still high (≥ -0.2 MPa) for all vigour classes across the vineyard probably due to a significant, 15 mm, rainfall in the preceding week (see Fig. 13). The $\Psi_{L,MD}$, depending on vigour, ranged from showing weakly stressed vines in low vigour zones to unstressed vines in high vigour zones (*sensu* van Leeuwen *et al*. 2007).

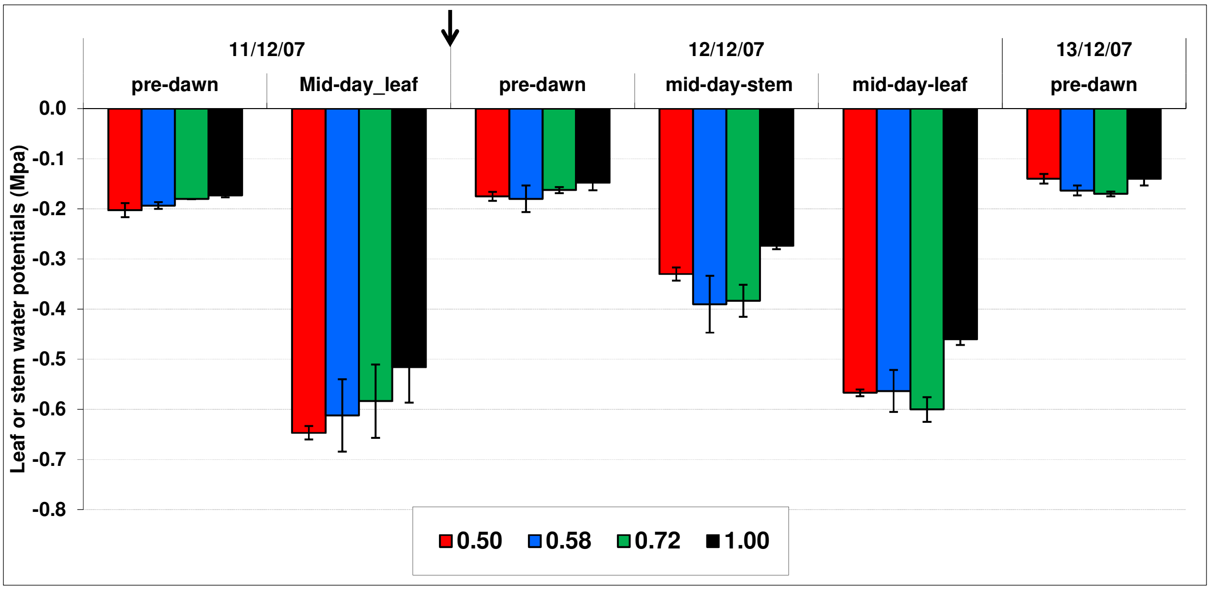


Fig. 27. Response of water status of Shiraz vines of varying vigour to a small volume (15 L/vine) irrigation pulse during fruit set (EL stage 27). Arrow denotes irrigation application on the night of 11-Dec-2007, the first application for the season.

The $\Psi_{L,PD}$ measurements following the overnight irrigation (about 2 h after drip irrigation ceased), showed similar values and patterns to the previous day (pre-irrigation) values. Thus, the effect on $\Psi_{L,PD}$, if any, of 15 L/vine irrigation that was completed a few hours prior was not detected. However, by midday, the overnight irrigation led to a very modest improvement in vine water status. On 12-Dec, stem water potential ($\Psi_{s,MD}$) was also measured. As expected, $\Psi_{s,MD}$ was significantly higher than $\Psi_{L,MD}$ regardless of vigour class. These data support the $\Psi_{L,MD}$ results in showing vines from highest vigour zones had higher water status the vines from the less vigorous zones.

The $\Psi_{L,PD}$ measurements on the second day after irrigation were generally high (~ -0.2MPa) with no difference among vines.

In summary, the results from the 11-13 December series of measurements showed that: 1) the first supplemental irrigation of the season gave only modest improvements in water relations regardless of vigour, which is not surprising given that all vines were either not stressed or only weakly stressed prior to irrigation; and 2) there was evidence, from the $\Psi_{L,MD}$ and $\Psi_{s,MD}$ data of both pre- and post-irrigation, that the high vigour vines were maintaining slightly better water status than the low vigour vines at or up to the fruitset stage.

<u>16-18 Jan 2008</u>

The next set of measurements occurred about 4 weeks later 16-18 Jan (EL 33, berries still green and hard). At this stage, the $\Psi_{L,PD}$ of the pre-irrigation day (16-Jan) were about -0.3 MPa or higher across all four vigour zones (Fig. 23, 28) – showing little sign of water stress. Pre-dawn measurements taken on the two days subsequent to irrigation showed no significant change (Fig. 23, 28).

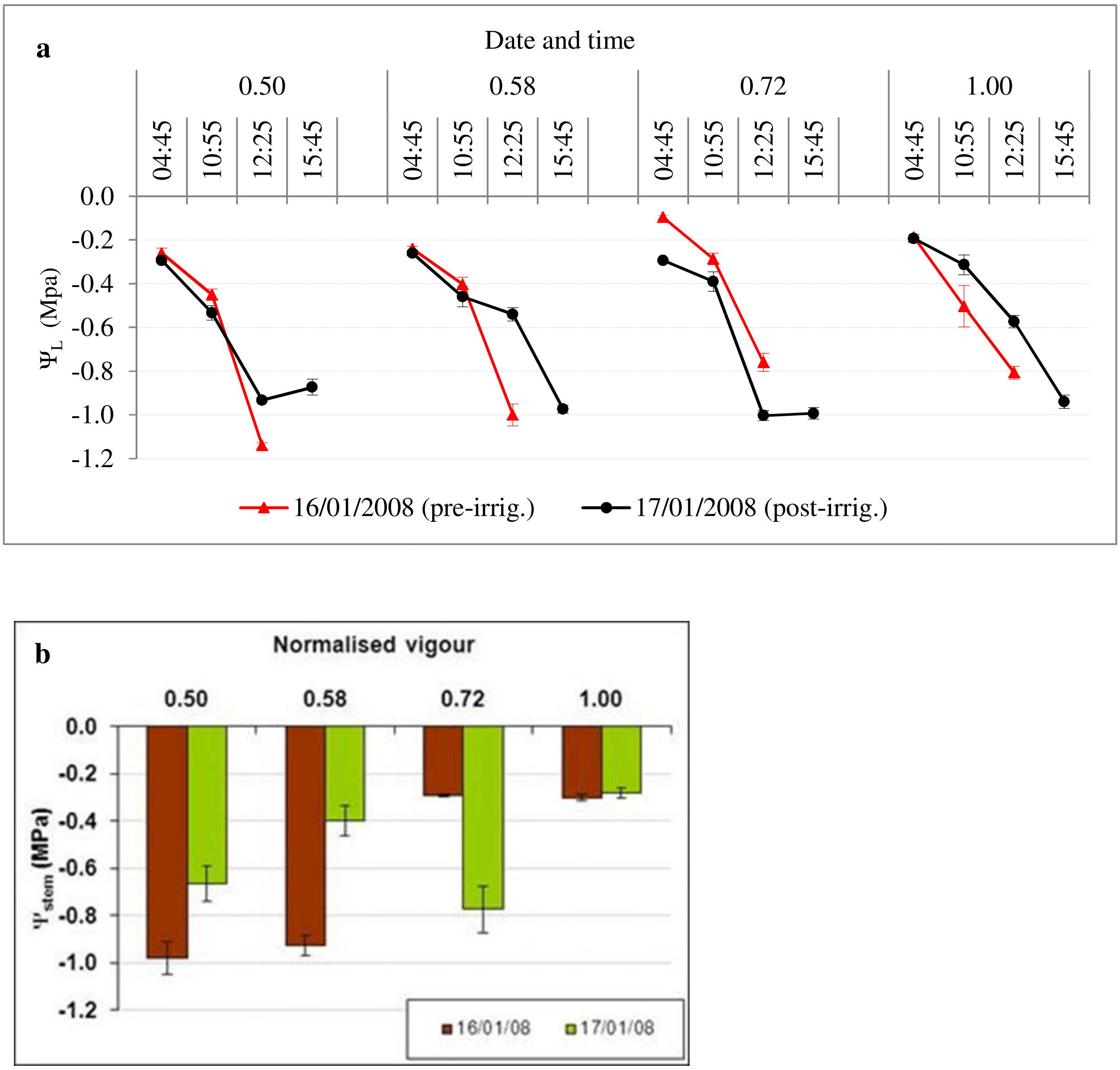


Fig. 28. Responses of (a) leaf and (b) stem water potentials to small volume irrigation application during pre-veraison period.

Contrary to the pre-dawn values, the pre-irrigation (16-Jan) midday Ψ_L indicated all vines were experiencing moderate levels of water stress. Nonetheless, vines from the vigorous zones still had higher leaf water status than those from the less vigorous zones of the vineyard (-0.81 to -0.76 MPa *vs* -1.14 to -1.00 MPa) (Fig. 25, 28).

On 16-Jan, $\Psi_{S,MD}$ were also measured. These data substantiated the $\Psi_{L,MD}$ (Fig. 24,25,28) in that medium and high vigour vines had higher values than the low vigour vines (-0.30 vs -0.95 MPa). These data also indicated two divergent trends: the midday stem water potentials of medium and high vigour vines were very high and approached the pre-dawn leaf water potentials. By contrast, the $\Psi_{S,MD}$ of the low vigour vines were low and comparable to the $\Psi_{L,MD}$. Thus, both the $\Psi_{L,MD}$ and $\Psi_{S,MD}$ indicated that the low vigour vines were water stressed whereas the medium to high vigour vines were still maintaining high water status.

It is interesting to note, from the above divergent responses, that assuming the $\Psi_{L,PD}$ values approach equilibrium with the soil moisture (the soil-root gradient is dissipated at night), the closeness of $\Psi_{S,MD}$ to $\Psi_{L,PD}$ in high vigour vines suggests a quick (within 2 h, i.e. duration that leaves were covered with foils) restoration of hydraulic balance with the soil which was lacking (or at least there was a prolonged hysteresis) in the low vigour vines. It needs to be noted that at this stage the vines did not get the small volume irrigation for two weeks.

The $\Psi_{L,MD}$ on the 17 Jan showed that all but one of the vines responded positively to the overnight irrigation despite worsening atmospheric conditions [e.g. midday Tmax increased by >7 ^{o}C (from 28.8 on 16 Jan, pre-irrigation, to 36.5 ^{o}C on 17 Jan, post-irrigation) while VPDmax rose from 2.9 to 4.9 kPa]. The $\Psi_{L,MD}$ response ranged from 0.22 to 0.46 MPa. For one of the vines the post-irrigation $\Psi_{L,MD}$ dropped further than the values recorded pre-irrigation (showed greater stress), due to dripper blockage which went on unnoticed for several weeks.

By 15:00 local time all vines had a similarly low leaf water potential of about -0.9 MPa. Support for the argument that high vigour vines reach the daily minimum at a slower pace is equivocal based on the observations here (upheld from post-irrigation data but not clear from the pre-irrigation data).

The responses of $\Psi_{S,MD}$ to irrigation measured at the same time as the $\Psi_{L,MD}$ were generally consistent (*cf.* Fig. 23 and 24). In high vigour vines, the $\Psi_{S,MD}$ did not respond to irrigation since it was already high. By contrast, the low vigour vines benefited from the irrigation since their $\Psi_{S,MD}$ rose considerably post-irrigation. Nonetheless, even after irrigation, $\Psi_{S,MD}$ did not reach the levels observed in the highest vigour vines.

Inadvertently, the observations from the “0.72” vigour zone (which got very limited, if any, water due to blocked drippers) provided opportunity for examining the “comparative” influences of atmospheric and soil-moisture conditions on leaf water relations. This vine and its neighbours had high water status ($\Psi_{S,MD}$ and $\Psi_{L,MD}$) pre-irrigation. On the following day, its irrigation input failed while the atmospheric demand conditions became markedly worse relative to the previous day (see above). Soil moisture is unlikely to drop markedly in one day, but $\Psi_{S,MD}$ and $\Psi_{L,MD}$ did – indicating the influence of atmospheric conditions on water relations. The $\Psi_{L,PD}$ also remained unchanged before and after irrigation (Fig. 23) providing credence to this proposition.

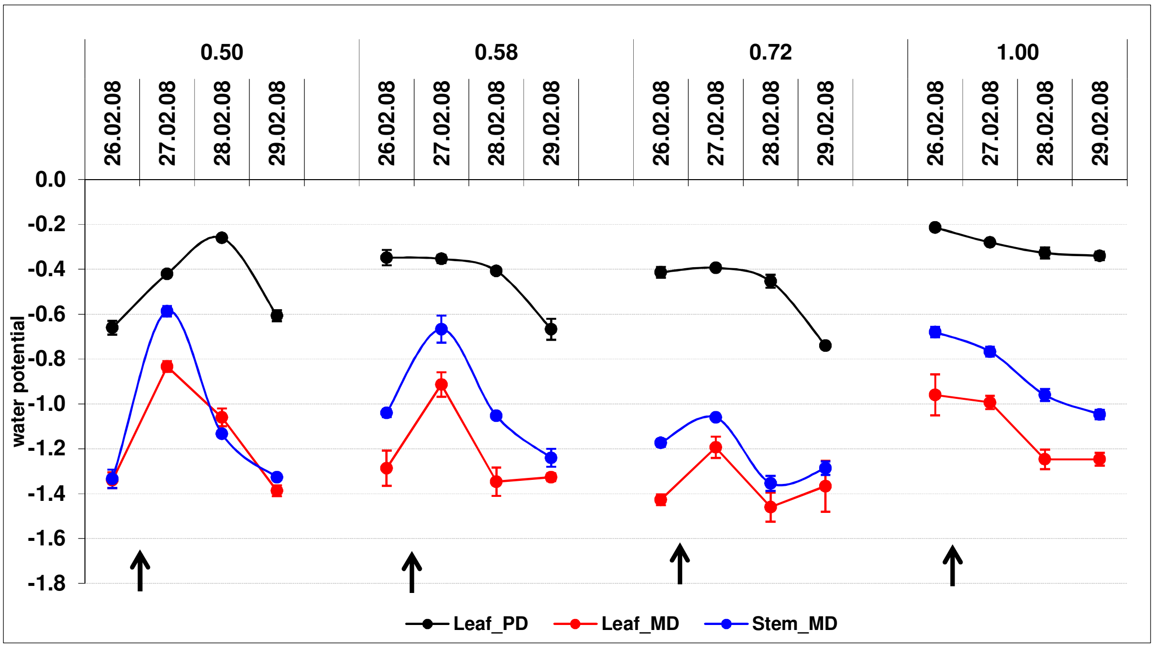


Fig. 29. Responses of daily pre-dawn (black), midday stem (blue) and midday leaf (red) water potentials to small volume (15 L/vine) irrigation application. Arrows indicate date of application.

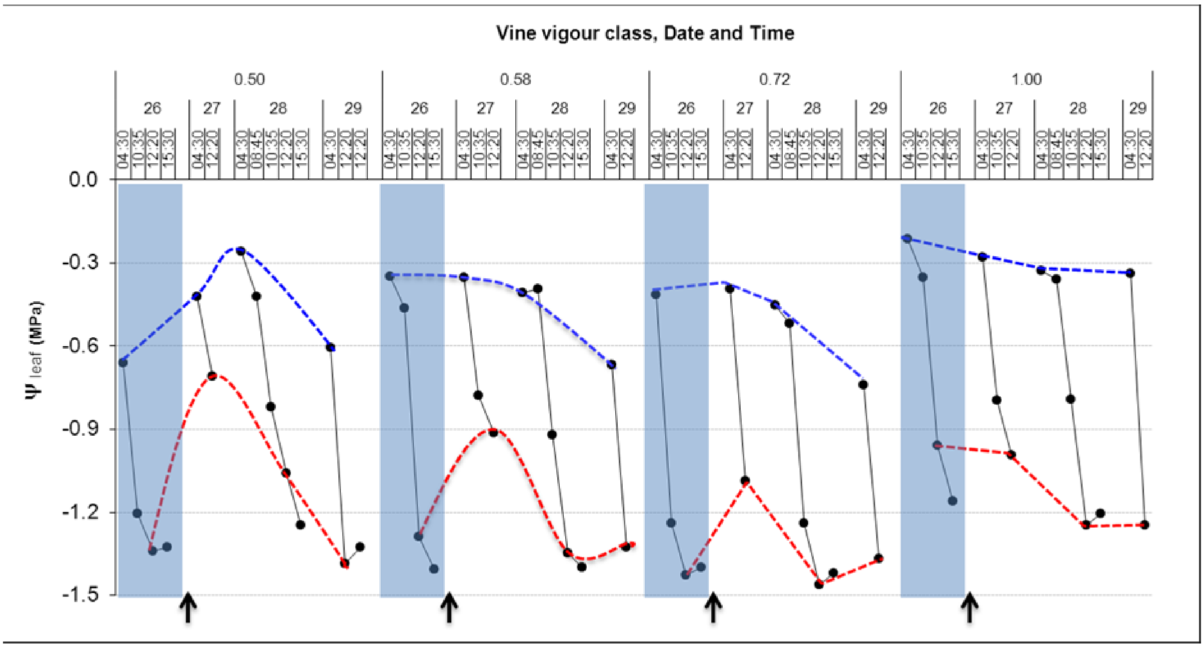


Fig. 30. Responses of $\Psi_{L,PD}$ and Ψ_L to irrigation (during the later stages of berry ripening) across different vine vigour zones. The blue line joins the $\Psi_{L,PD}$ while the red connects $\Psi_{L,MD}$. Measurements at other times during the diurnal course are also shown. The data within the shaded rectangle are for the pre-irrigation date. Arrow irrigation application on the night of 26-Feb.

<u>30-31 Jan 2008</u>

The next measurement campaign was carried out during 30-31 January 2008, although only a limited set of measurements could be completed due to unfavourable weather. On 30 Jan, $\Psi_{L,PD}$ for vines from all vigour zones ranged from -0.48 MPa for the lowest vigour vines to -0.23 MPa for the highest vigour vines. The $\Psi_{L,MD}$ also varied among vines ranging from -0.63 MPa in the lower vigour vines to -0.24 MPa for the highest vigour vines. Once again, these data indicate the high vigour vines were able to maintain high leaf water potential at least until early afternoon.

Pre-dawn values of 31 January, following overnight irrigation, were generally comparable across all vine vigour classes at about -0.27 MPa. Vines from the lowest vigour zone showed a 50% increase in their $\Psi_{L,PD}$ in response to the small volume irrigation. The rest of the vines already had high $\Psi_{L,PD}$ prior to irrigation, and thus showed no response to irrigation.

<u>26-29 Feb 2008</u>

The second last set of measurements for the season was carried out four weeks later, from 26 to 29 February 2008. By this stage, the most vigorous section of the block had not received irrigation for four weeks while the rest were irrigated two weeks prior. Despite this differential irrigation, the pre-irrigation $\Psi_{L,PD}$ (26-Feb) showed that vines from the most vigorous zone were showing little sign of water stress ($\Psi_{L,PD}$ about -0.21 MPa) whereas the least vigorous vines were experiencing moderate to severe stress ($\Psi_{L,PD}$ of -0.66) (Fig.30-31). Further diurnal measurements showed that all zones except those in the most vigorous section had similar level of water stress of about -1.4 MPa by 15:00. Thus, once again, vines from the lowest vigour class were sustaining a greater stress integral than the more vigorous vines. The diurnal response pattern of Ψ_s paralleled that of Ψ_L (Fig. 30), and thus, the Ψ_L data of the respective vine vigour classes.

Irrigation (15 L/vine) was applied overnight on 26-Feb and into the very early hours of 27-Feb. The $\Psi_{L,PD}$ taken following overnight irrigation showed an increase only in vines from the least vigorous zone while vines from the other vigour classes did not respond (Fig. 30-31) – in part because the pre-irrigation values were relatively high. It should be emphasized however that the positive response (recovery) was only ephemeral since the $\Psi_{L,PD}$ returned to the pre-irrigation level within two days (Fig. 29-30).

The $\Psi_{L,MD}$ responded positively to the overnight irrigation in all zones except those in the most vigorous sections of the block. The magnitude of the response was once again the highest for the least vigorous part of the block (Fig. 29-30). The $\Psi_{S,MD}$ data also generally supported the leaf water potential results (Fig. 29).

A key and consistent observation from all three sets of measurements ($\Psi_{L,PD}$, $\Psi_{S,MD}$ and $\Psi_{L,MD}$) is that the small volume irrigation can lift the water status of vines, particularly those from the low end of the vigour continuum, but the recovery from stress is of the order of 48 hours or less depending on vigour. The transient nature of the response is understandable given the quantum of water applied. Even if it can be assumed, although unlikely, that all the applied water is captured by the roots, as shown in the section on sap-flow, a vigorous vine can transpire almost all the 15 L applied water over a course of a single day, and a less vigorous vine over 2 to 3 days under high atmospheric demand conditions which is when the supplemental irrigation is typically applied.

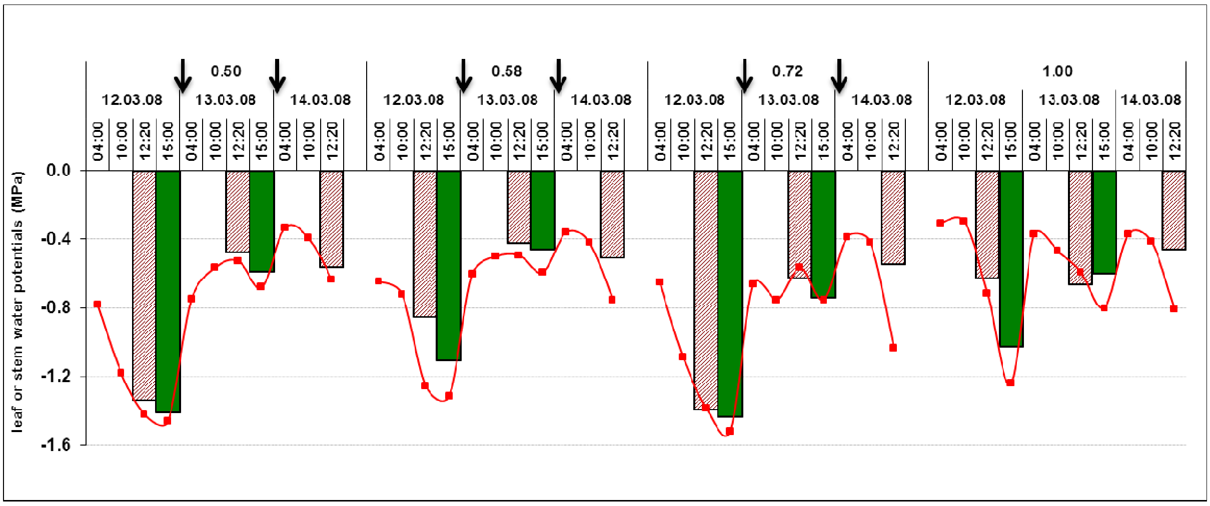


Fig. 31. Responses of leaf and stem water potentials to repeated irrigation events. Arrows denote irrigation dates. Note, however, the highest vigour zone vines were not irrigated. Red line, leaf water potential; hashed bar, midday stem water potential; and solid green bar, stem water potential at 15:00.

<u>12-14 March 08</u>

During this period, the most vigorous zone was not irrigated, whereas all the other three zones received irrigation on March 13 and 14. The measurements taken on the pre-irrigation day (12-Mar) showed that the $\Psi_{L,PD}$ ranged from -0.80 MPa in vines from the least vigorous zones to -0.3 MPa in the highest vigour zone (Fig. 31). Thus, all vines except those in the most vigorous zones showed signs of moderate to severe water stress. The $\Psi_{L,MD}$ ranged from -1.42 to -1.25 MPa for three of the vigour classes whereas the most vigorous vines had -0.71 MPa, thus reinforcing the pattern of observations from the pre-dawn measurements. The mid-afternoon data showed, in all zones, the leaf water potential declined further than those recorded at midday, but there was evidence that by this time a stable minimum was reached at least in the low vigour vines. There was also some indication that even the high vigour vines were approaching the minimum values observed in the low vigour vines.

The above results emphasize that an important aspect of the difference between the high and low vigour vines (and for that matter any plant) is not necessarily in the minimum value reached, but in the rate at which the fall in water status proceeds, and hence in the resulting stress integral. In terms of the comparison at hand, the low vigour vines reached the daily minimum value rapidly thereby experiencing a greater magnitude and duration of stress while the high vigour vines experience values as low as those of the low vigour vines (if at all) for a shorter duration.

On 13 Mar, $\Psi_{L,PD}$ values obtained about two hours after irrigation (15 L/vine) was applied, showed little improvement in vine water status – suggesting there was not sufficient time for the vines respond to the applied water. By mid-morning, however, the Ψ_L all vines from the low-vigour zones positively responded to the applied irrigation. By contrast, the Ψ_L of vines from the most vigorous zone of the block showed a drop compared to the previous day; however, this zone was not irrigated. Yet, the water status of vines from this zone was still comparable to the water status of the irrigated zone vines.

The midday and mid-afternoon results confirmed the positive responses to irrigation (improvement in vine water status) for the low vigour vines. In effect, what the 15 L/vine irrigation did for the low vigour vines was to raise the vine water status to the levels of the high vigour zone vines.

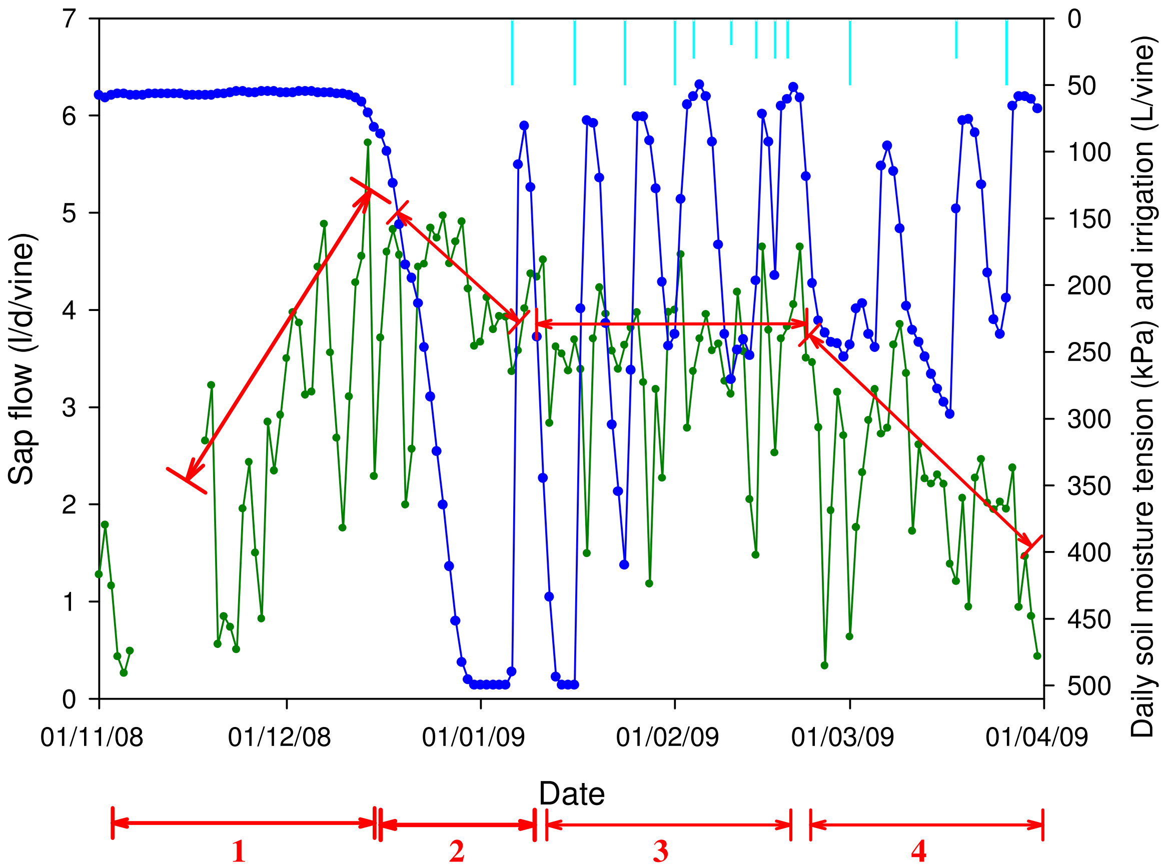
The irrigation event on the following day (on the night of 13-Mar) enabled the low vigour zone vines to sustain the gain from the previous day's irrigation. Thus, from a purely water relations aspect, these results suggest that for the lowest vigour zone vines to maintain a non-stressed water status, the small volume irrigation events need to be applied frequently.

Collectively, the vine water relations results can be summarised as follows:

- The water status of lowest vigour zone vines starts to deviate from those of highest vigour zone vines from flowering and becomes progressively stronger (more stressed) with the progression of the growing season, particularly from veraison onwards.
- The lowest compared to highest vigour vines also appear to reach the daily minimum leaf water potential earlier in the diurnal cycle. Thus, even if both vine vigour classes end up reaching a similar minimum water potential, the low vigour vines will have experienced greater integrated stress duration.
- The leaf water potential of the lowest vigour vines appears to respond quickly to the applied small volume irrigation, and benefits from it. However, the gain is transient and generally lasts about 48 hours or less.
- From a water relations point of view, maintaining the benefit of the small volume irrigation would entail a more frequent application than is practiced currently.

6.8 Sap flow (vine transpiration)

Vine transpiration was monitored in various vigour zones of the study block typically for most of the growing season. The season-long transpiration data indicated three (four) water uptake phases (see Fig. 32 for details) in this predominantly rain-fed system with a modest level of supplementary irrigation input. Phases 2 and 3 may merge into a single phase if water can be supplied to maintain transpiration rates seen at end of phase 1.



1. Soil moisture adequate; water use limited by canopy development;
2. Canopy approached maximal size; water use limited by rapidly drying soil profile;
3. Water use dictated by frequency and amount of drip irrigation;
4. Steady decline in water use during latter stages of berry ripening due to infrequent drip irrigation as well as leaf aging.

Green - water use by vine; blue - soil water tension; cyan - irrigation water applied.

Fig. 32. Pattern of transpiration rates of Shiraz vines in a predominantly rain-fed production system with a small volume and intermittently irrigated vineyard.

As was the case with nearly all the physiological processes examined in this study, vine vigour/canopy size exerted considerable influence on sap flow rates (Fig. 33-35). Low vigour vines transpired at much lower rates than the high vigour vines. However, one aspect that was a shared feature irrespective of vigour was the recovery response to the intermittent and small volume irrigation as well as the occasional rainfall events (Fig. 33-35). Even after seemingly prolonged soil profile drying, transpiration rates of both the low and high vigour zone vines, increased (recovered) rapidly in response to irrigation or rainfall events. This is clearly illustrated in Fig. 34. In this figure, one can see rapid increases of rhizospheric moisture levels following irrigation or rainfall which are then observed as transpiration responses (peaks) within a day, in both vigour classes.

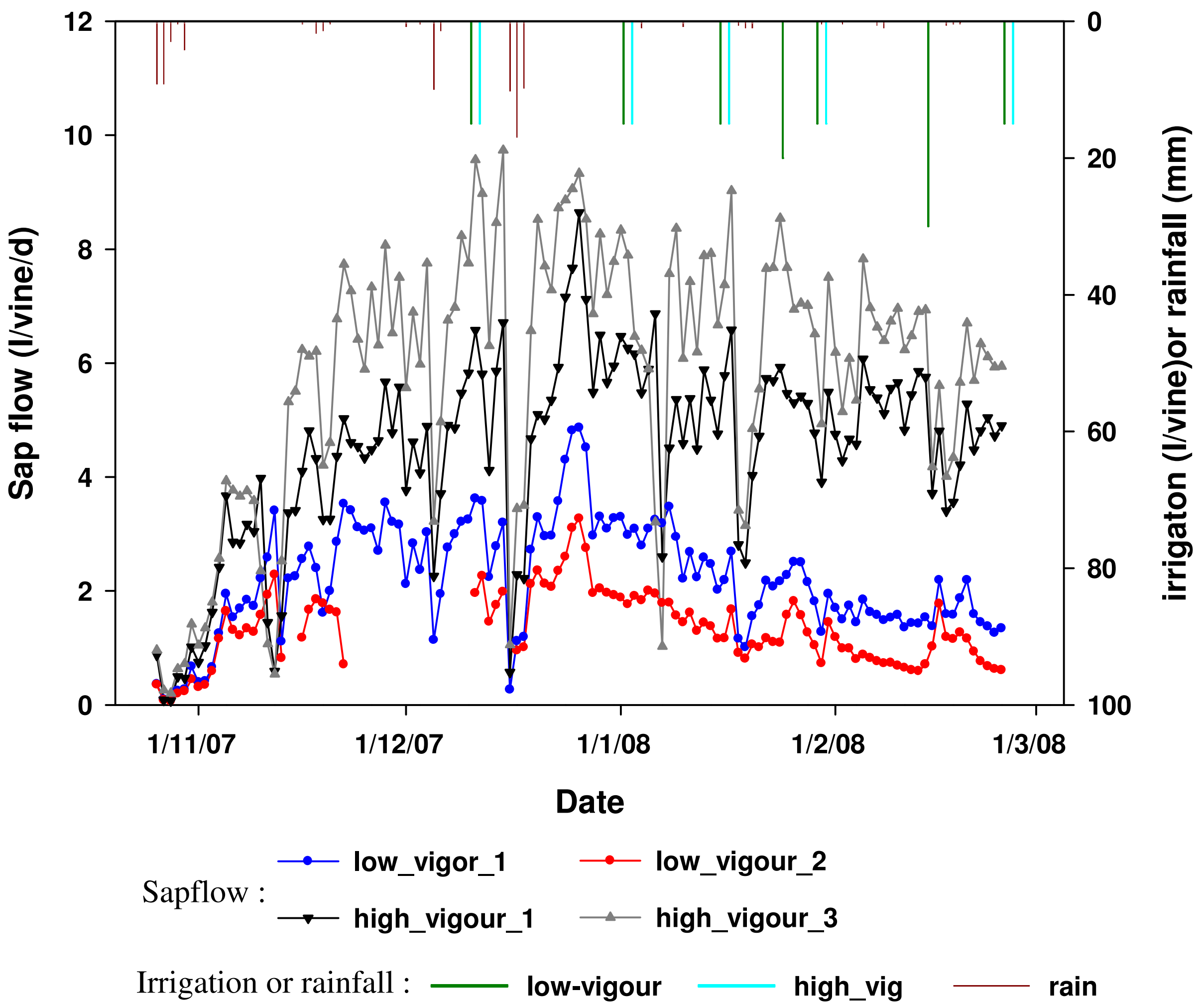


Fig. 33. Sap flow rates in low and high vigour zones of the study block during the 2007/08 growing season. Note response of sap flow rates to the small volume irrigation and rainfall events.

Sap flow rates, as would be expected, were positively related with reference crop evapotranspiration (ETo) estimates from an onsite weather station data (Fig. 36). Although there was a scatter about the least squares line relating sap flow to ETo, some points were evident: (1) over the course of a growing season transpiration rates, depending on canopy size or effective area of shade (EAS), ranged from 9 to 17% of ETo, and (2) while transpiration rates generally increased with EAS as has been reported (e.g., Williams and Ayars, 2005; Goodwin *et al*. 2006, McClymont *et al*. 2009) , this holds when water supply is uniform across a block. That is, when water supply varies, the relationship between sap flow and ETo can be different (Fig 36). While acknowledging this potential weakness, estimates of block-wide water use were made from EAS and ETo for a significant portion of the growing season. A moderately strong positive relationship (r = 0.84) between NDVI and EAS (Fig. 37) was used to estimate EAS for 100 vines spread across the study block. Water use was calculated from these EAS estimates and ETo estimated from an onsite weather station data similarly to that reported in Goodwin et al. (2006, 2009). The results indicate up to a 1.9-fold variation in vine water use between different sections of the vineyard (Fig. 38) and there was also vintage difference. The calculated variations in within a given year are certainly a reflection of canopy (EAS) variations across the block since ETo is constant, while the between years difference is part canopy size and part ETo differences between the growing seasons.

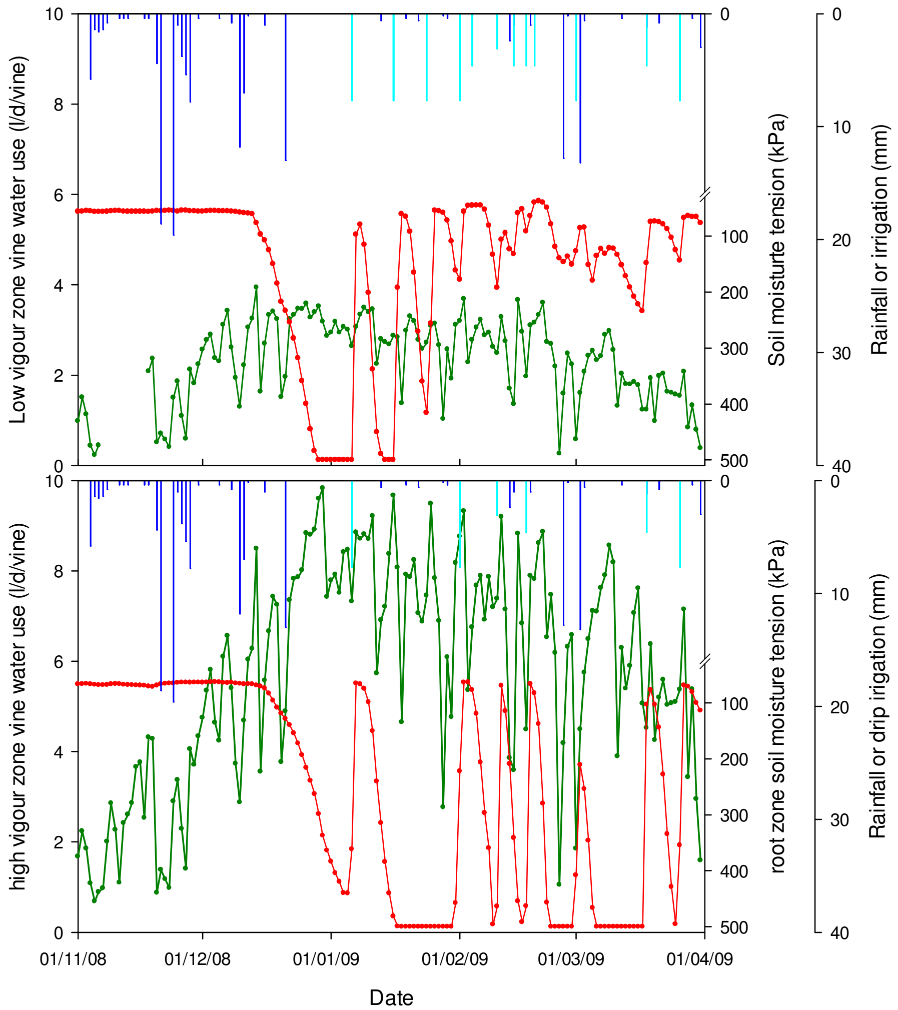


Fig. 34. Recovery of vine sap flow (transpiration) rates in low (top panel) and high (bottom panel) vigour zones of the vineyard from the 2008/2009 season. Note the synchronicity of transpiration rate peaks following rainfall events or when the whole vineyard was irrigated uniformly. Green, sap flow; red, under-vine soil moisture tension; blue, rainfall; and cyan, irrigation. Note that low vigour zones vines received more frequent irrigation the high vigour zones (6 *vs*. 12 events).

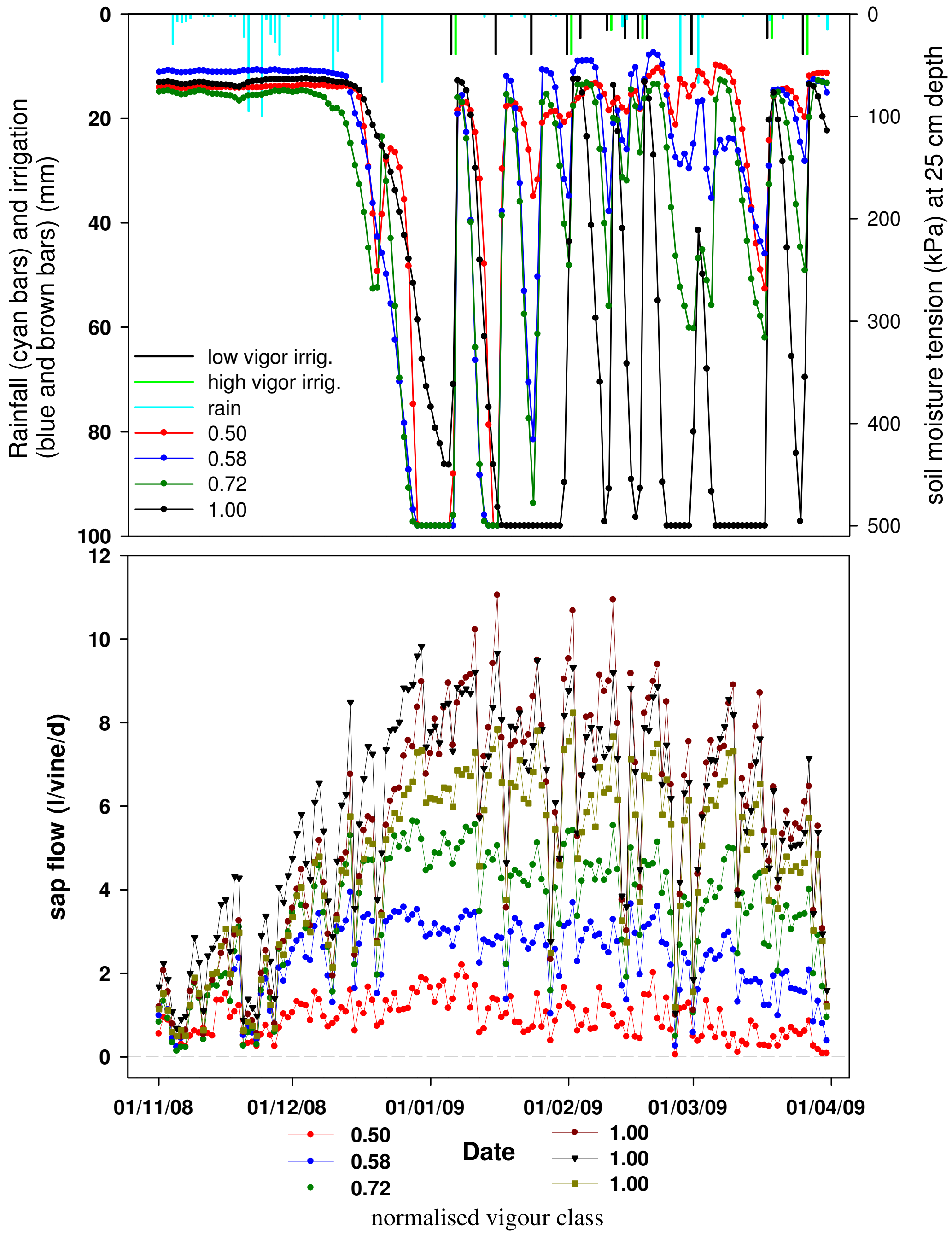


Fig. 35. Sap flow rates in low and high vigour zones of the study block during the 2008/09 growing season. Here too, notice the quick recovery of transpiration rates in response to irrigation and/or rainfall, across all vigour classes. Note the steady increase in sap flow rates earlier in the growing season as the canopy develops while the soil profile is still sufficiently moist. Peak water use was attained by late December- early January. However, although the soil profile appeared moist, there was strong fluctuation in daily vine water use during the November and December period as well as occasionally after January. These sharp falls in transpiration rates were caused by weather events which reduced atmospheric water demand (high cloud cover/rainy and low VPD and radiation days, data not shown).

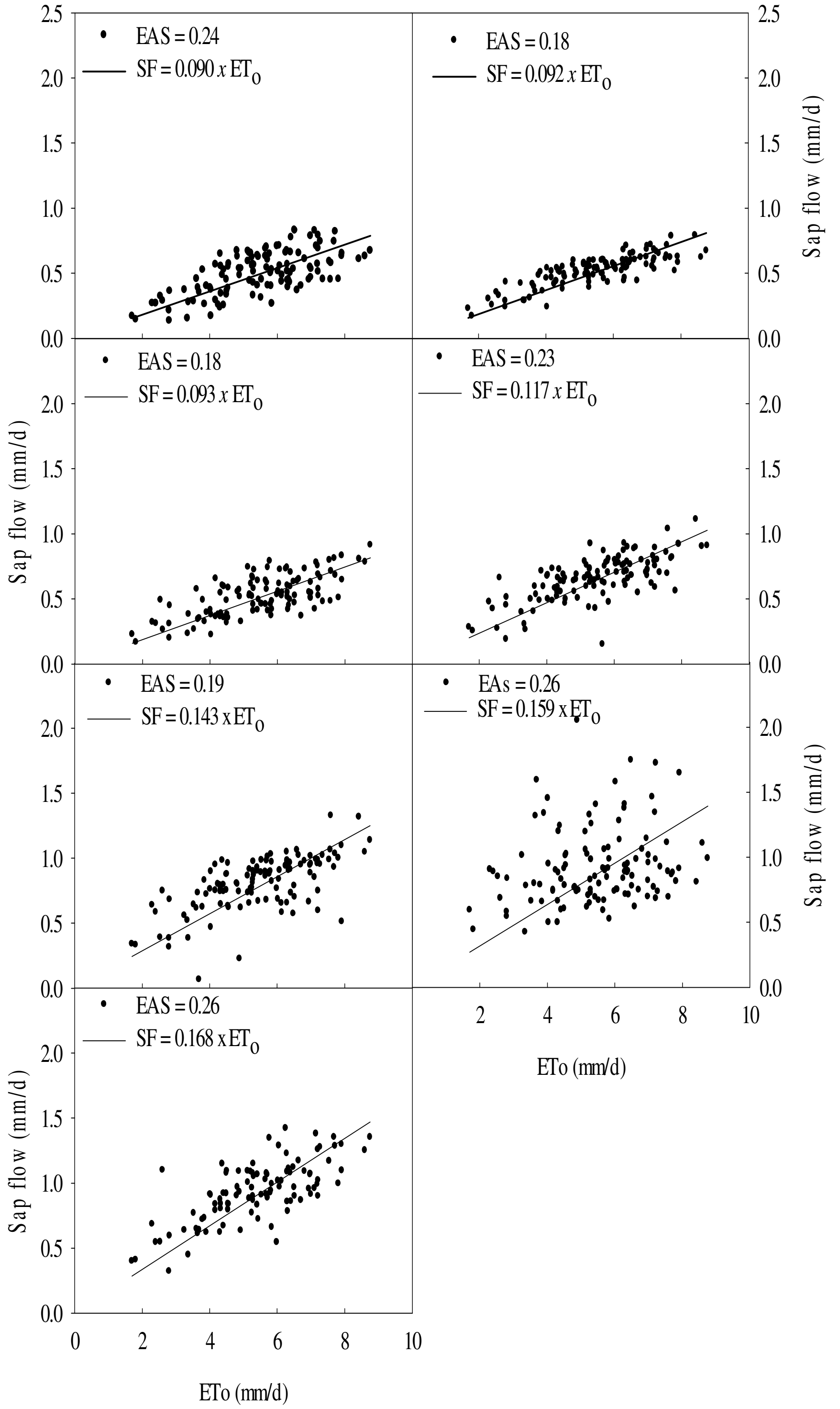


Fig. 36. Relationship between vine transpiration (sap flow) rates and reference crop evapotranspiration in a range of vines with differing effective area of shade (EAS).

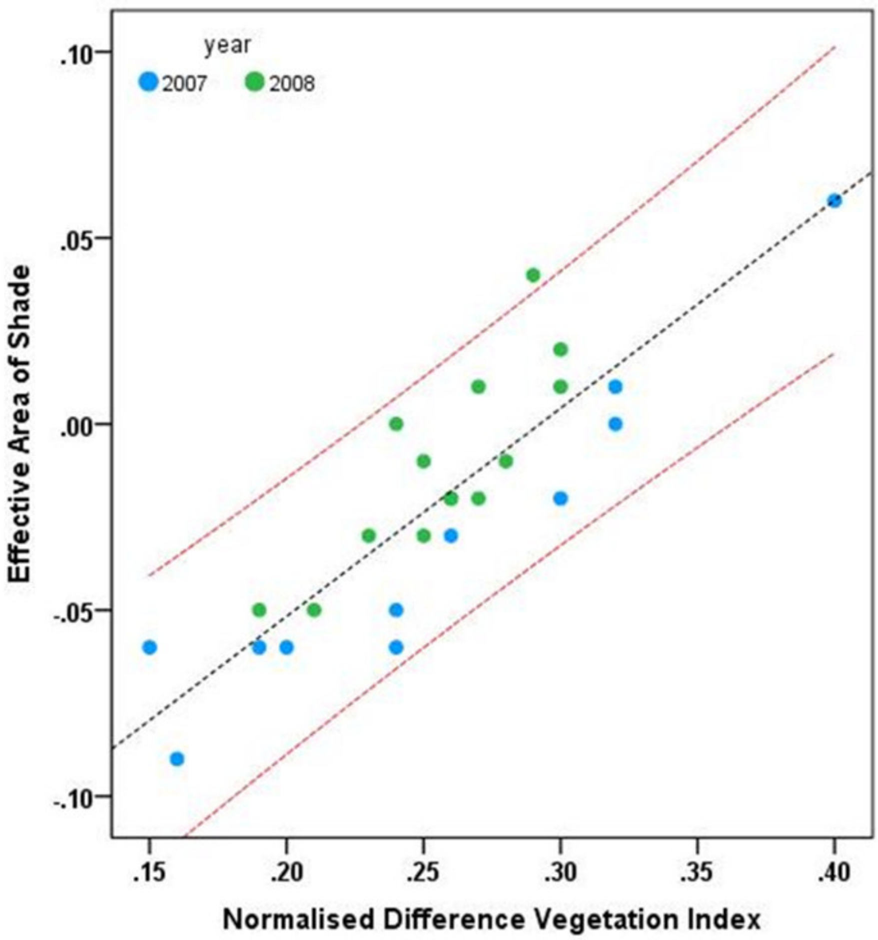


Fig. 37. Relationship between effective area of shade and normalised difference vegetation index. The red lines are 95% confidence bands; Season had no significant effect on the relationship between EAS and NDVI and thus the pooled regression line (EAS = 0.276 + 1.157NDVI, r^2_adj = 0.70) is shown. Axis labels are swapped.

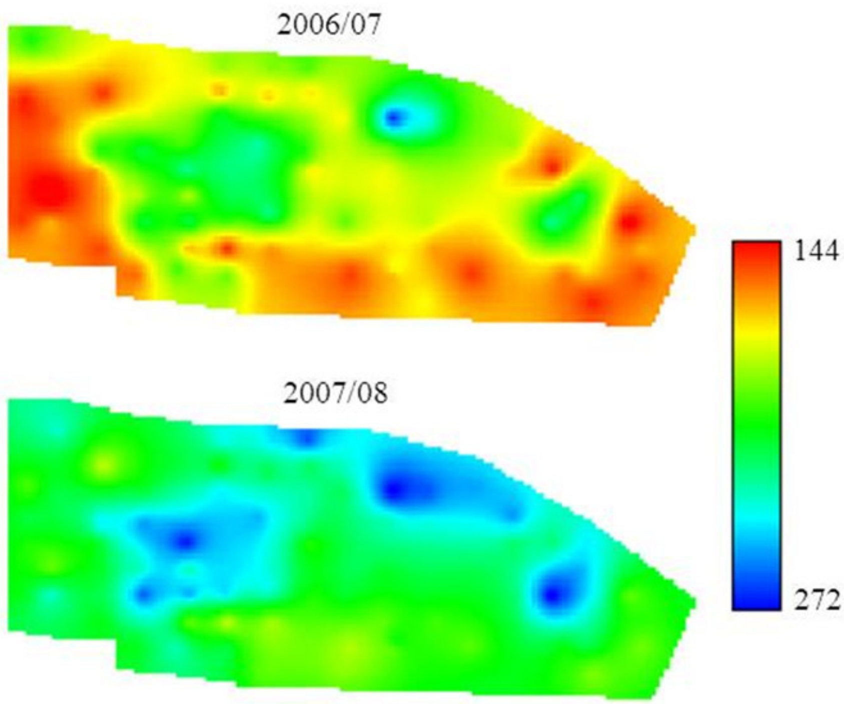


Fig. 38. Spatial patterns of estimated vine water use (mm) during November-March inclusive over two seasons. Values were calculated as products of effective area of shade (EAS) and ETo (calculated from weather data recorded at the onsite weather station) with EAS estimated from NDVI using the relation given in Fig. 37.

6.9 Resource (irrigation water) utilisation

Depending on availability, irrigation use may be rationalised to maximise yield or manage risks. As outlined at the outset, in this predominantly rain-fed viticultural production system, water resources for irrigation are limited, and the available water is a means for buffering production risks. Irrespective of its role, efficient acquisition and/or utilisation of water

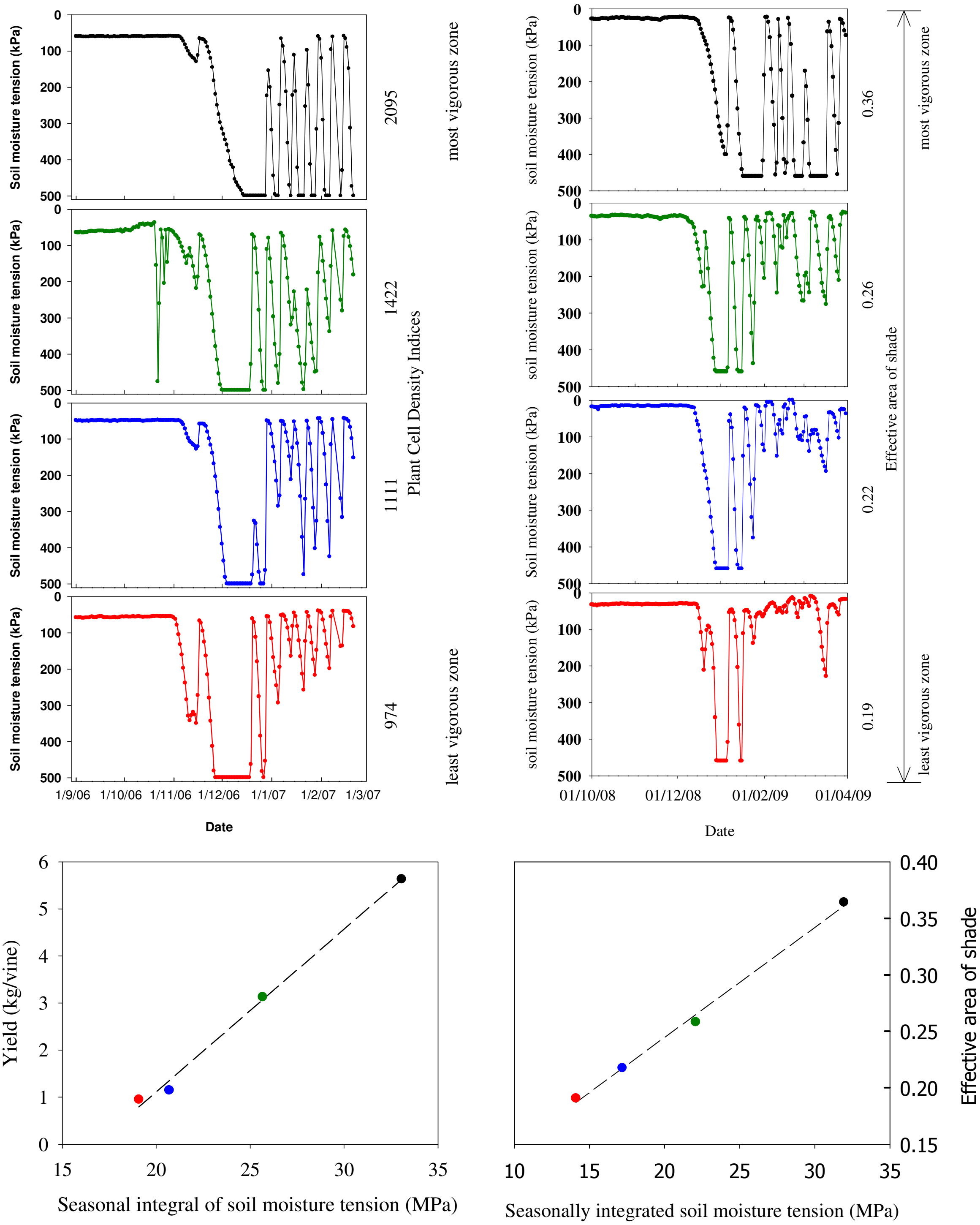


Fig. 39. Daily average soil moisture tension in the soil profile during the growing season at four locations in the vineyard. Left panel is for 2006/07 and right panel for 2008/09 seasons. The graphs from the top to the bottom panel correspond to the highest through to the lowest vigour zones of the vineyard. The bottom row of graphs show: left panel relationship between seasonal integral of soil moisture tension and yield (left) and canopy cover (right). Note that for the graph shown at the bottom right, strictly, canopy cover should be on the abscissa as it is the driver variable, but instead is shown on the ordinate for consistency with the graph shown on the left panel. Yield was not used as it was not recorded.

(applied or otherwise) is a key and integral component of sustainable production. In a production sense, for a given crop and growing season, acquisition of applied resources by the crop can be considered efficient if acquisitions are complete and homogeneous across an area occupied by the crop. Whether this was the case at the trial block was examined as described below.

In this project, under-vine soil moisture was monitored at four vigour zones which represented the range of vigour variation in the study vineyard block. Admittedly, these data are spatially discrete. However, given that the monitoring locations were selected to capture the range of block-wide variation in vine vigour, the data enabled an ad hoc evaluation of effectiveness of irrigation water use over the study block. The results from this monitoring indicated that the extent of acquisition of the applied irrigation water varied markedly with vigour of vines (Fig. 39). Vines from the highest vigour zone acquired the applied water completely while in the low vigour zones the acquisition of the irrigation water was rather incomplete (Fig. 39). This observation revealed two related points:

- There was a high degree of zonal heterogeneity (spatial inefficiency) in irrigation water utilisation across the vineyard block,
- The variation in water acquisition, if not exclusively, at least in a significant way, was driven by variation in vigour.

These observations which were based on soil water monitoring strongly supported the results obtained from sap flow estimates of spatial patterns of water use (see section on sap-flow).

Table 2a. Blade nutrient levels at veraison for some of the vines used in gas exchange in each vigour zone. These are based on 20 leaves sampled from opposite bunches (typically located in the interior of the vine canopy). Data collected as part of a linked GWRDC SWI project DPI 04/04.

Season	Vigour class	N	P	K	Ca	Mg	S	Na	B	Cu	Fe	Mn	Zn
		%							mg/kg				
2006	0.50	1.70	0.05	1.21	1.34	0.25	0.11	0.10	31	104	36	22	19
	0.58	1.53	0.06	1.04	1.71	0.33	0.15	0.08	49	115	120	29	28
	0.72	1.79	0.09	1.04	1.99	0.36	0.14	0.09	34	144	149	26	27
	1.00	1.96	0.18	1.07	2.54	0.43	0.28	0.08	43	237	127	57	47
2007	0.50	1.32	0.06	1.08	1.81	0.28	0.14	0.13	54	245	135	97	82
	0.58	1.96	0.06	1.07	2.05	0.39	0.16	0.10	78	238	97	94	31
	0.72	1.67	0.08	0.95	2.42	0.45	0.17	0.11	48	305	114	112	52
	1.00	1.65	0.11	1.06	2.64	0.49	0.25	0.11	53	302	109	137	79
2008	0.50	1.22	0.07	1.14	2.31	0.37	0.19	0.13	41	278	170	64	36
	0.58	1.58	0.08	1.02	2.53	0.48	0.19	0.10	48	225	138	62	29
	0.72	1.77	0.09	1.17	2.09	0.42	0.21	0.10	40	241	145	46	30
	1.00	2.01	0.14	0.89	2.30	0.57	0.29	0.08	51	255	119	79	32

Examination of the seasonally integrated changes in soil moisture tension as a proxy for water use in relation to yield indicated a strong association between yield and a vine's capacity to use the applied water (Fig. 39). Although water use and production showed proportionality regardless of vigour, productivity in terms of the applied water differed considerably (Fig. 40). Thus, as suggested in

Zerihun et al. (2009), increasing yield and water productivity require increasing capacity of the low vigour vines to utilise the applied water. This has potential to minimise "wastage" of the applied water and deliver uniformity in block-wide resource use efficiency.

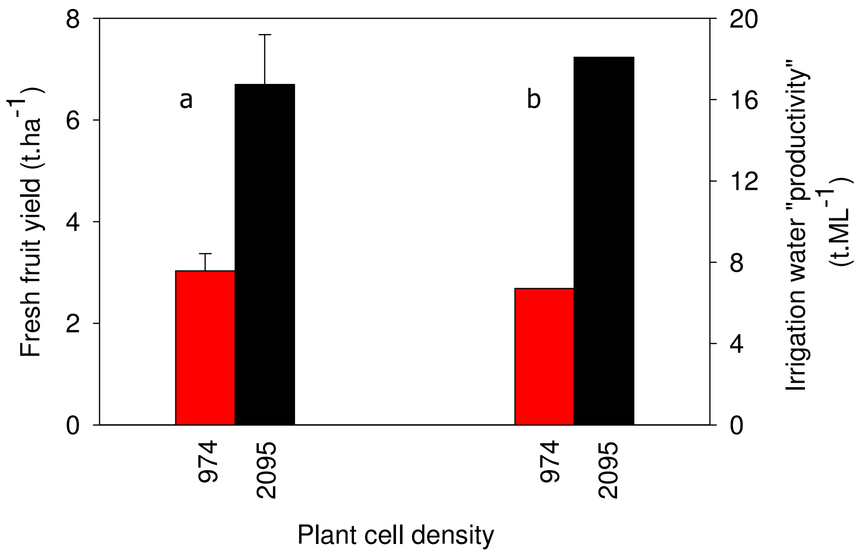


Fig. 40. Fruit yield (a) and irrigation water productivity (b) of vines from the least and highest vigour zones of the vineyard block in 2006/07. The yield and plant cell density data shown are average values for the respective vigour zones.

From the current work, it was not possible to identify unequivocally the limitations to effective acquisition of the applied water in the lower vigour zones of the vineyard. Clearly, given the dependence of water uptake on canopy size, it appears that attention be paid to factors that influence canopy development. In addition to the points raised in Zerihun et al. (2009), closer attention to nutritional limitations, especially phosphorus, may be warranted (Table 2a-b).

Table 2b. Three-year (2005/06-2007/08) average petiole nutrient levels at flowering and veraison for some of the vines used in gas exchange in each vigour zone. These are based on 20 leaves sampled from opposite bunches (typically located in the interior of the vine canopy). Data collected as part of a linked GWRDC SWI project DPI 04/04.

	%							mg/kg				
	N	P	K	Ca	Mg	S	Na	B	Cu	Fe	Mn	Zn
vigour class	at flowering											
0.50	0.79	0.12	1.73	1.42	0.57	0.14	0.11	45	52	34	16	34
0.58	0.84	0.11	1.51	1.48	0.64	0.15	0.09	49	52	27	15	29
0.72	0.93	0.16	2.15	1.48	0.74	0.16	0.11	47	46	28	11	30
1.00	1.37	0.48	1.68	1.46	0.86	0.22	0.09	41	54	27	18	43
	at veraison											
0.50	0.40	0.04	2.34	1.29	0.84	0.11	0.17	40	27	31	6	26
0.58	0.41	0.04	2.01	1.32	1.04	0.10	0.13	44	23	35	5	24
0.72	0.42	0.04	2.52	1.24	1.03	0.10	0.15	37	21	30	3	19
1.00	0.57	0.12	2.74	1.42	1.28	0.17	0.15	37	36	30	8	38

In summary, considerable variation in the acquisition of the applied water was observed which was closely associated with the variation in vine vigour. It follows that the greater the spatial variation in vine vigour, the greater the variation in utilisation of water (and by implication other resources), the greater the spread in resource use efficiency (in this case productivity of the applied water). Therefore, identifying and managing factors that cause differential vigour expression across a block will help achieve lift block-wide production, resource use and efficiency, and contribute to sustainability of the enterprise.

6.10 Wine composition and sensory

Wine quality assessments were carried out over three vintages in collaboration with a linked and co-located GWRDC SWI project (DPI 04/04). For this purpose, the vineyard block was delineated into six zones based on vine vigour (plant cell density) and soil property (γ-radiometric survey) at the start of the project (for details see Lanyon et al. 2008; Goodwin et al 2009; Zerihun et al. 2009). For consistency, the same six zones were used for harvesting fruit for wine making in all three vintages. The wines were assessed for their composition (colour density, total anthocyanins concentration, total phenolics, total red pigments and alcohol content) and sensory properties (body, drying, fruit flavour, and ripe berry, spicy and confectionery aromas).

Necessarily, the sample sizes were small relative to the number of variables measured on them, thus limiting the rigour of analyses. Nonetheless, the data still revealed some worthwhile information as described below. Multivariate analysis of variance (MANOVA) indicated highly significant effects of vintage on wine composition (Rao $F = 50.4$; $p < 0.0001$) as well as on sensory attributes (Rao F 17.3, $p < 0.0001$) (note that the analyses were done separately, due to insufficient degrees of freedom for combined analyses). Following the MANOVA results, canonical variate analyses (CVA) were performed to identify which vintages were different as well as to identify discriminating variables. The CVA results showed an identical pattern of separation for the vintages on the basis of wine chemical composition or wine sensory attributes (Fig. 41, 42).

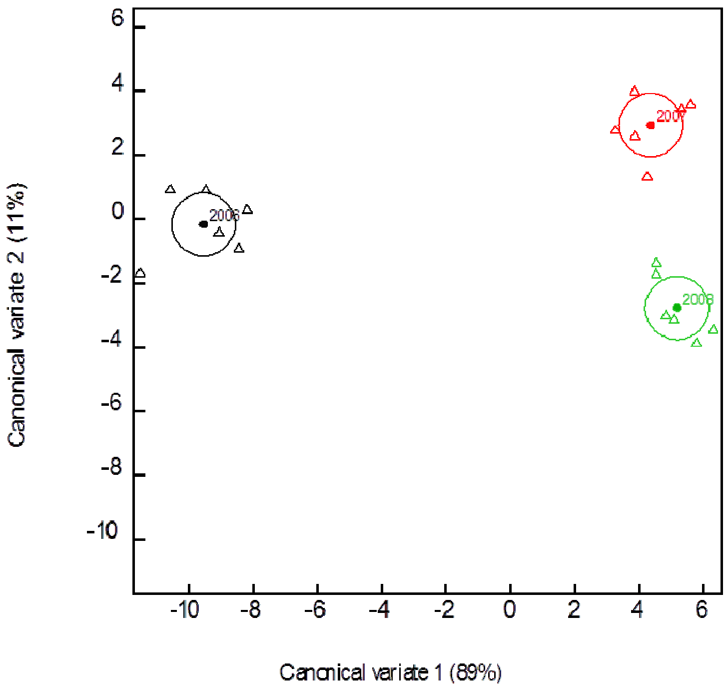


Fig. 41. Effect of vintage on wine composition (see text for list). The large circles circumscribing the small solid circles are 95% confidence regions for the vintage mean scores (solid circles). The points around each centroid are unit scores of wines from each vigour zone. Non-overlapping means are different ($p < 0.05$).

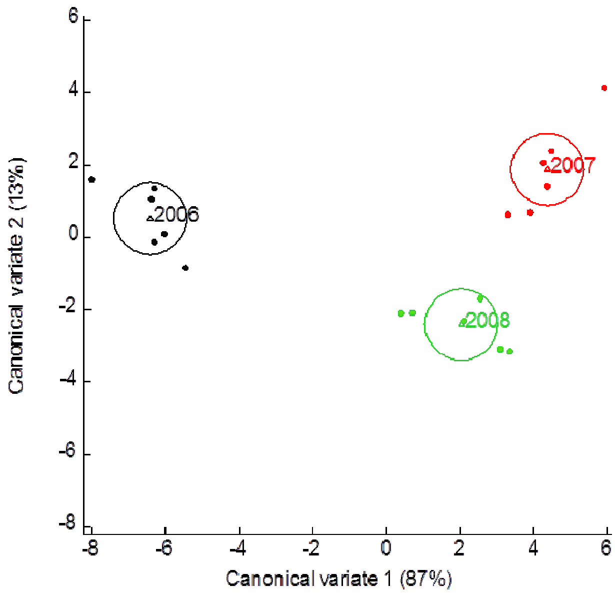


Fig. 42. Effect of vintage on wine sensory properties (see text for the list). The circles around the multivariate means (shown by triangles) are 95% confidence regions. Non-overlapping means are different ($p < 0.05$). The solid circles around each vintage's centroid are scores for wines from each vigour zone.

A separate canonical correlation, distinct from canonical variate, analysis revealed that the basis for the near identical patterning was the high degree of association between the wine chemistry and the sensory sets of variables (Fig. 43).

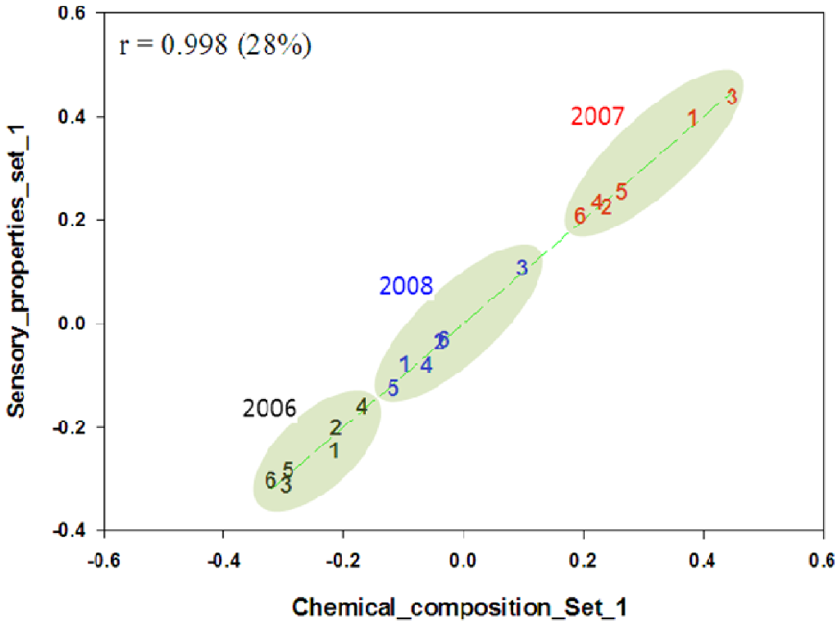


Fig. 43. Canonical correlations between the wine composition set of variables and the wine sensory properties set of variables. Note the vintage separations. The numbers within each vintage are the vineyard zones from which fruit was harvested for wine making.

Both the wine composition and sensory attributes showed that the wines from the 2006 vintage, which experienced late season rainfall, were significantly different from the 2007 and 2008 wines. In terms of sensory attributes, the separation of vintages was due to the 2006 wines being low in fruit flavour, body and ripe berry aromas while the 2007 and 2008 had high scores on these attributes (Fig. 44).

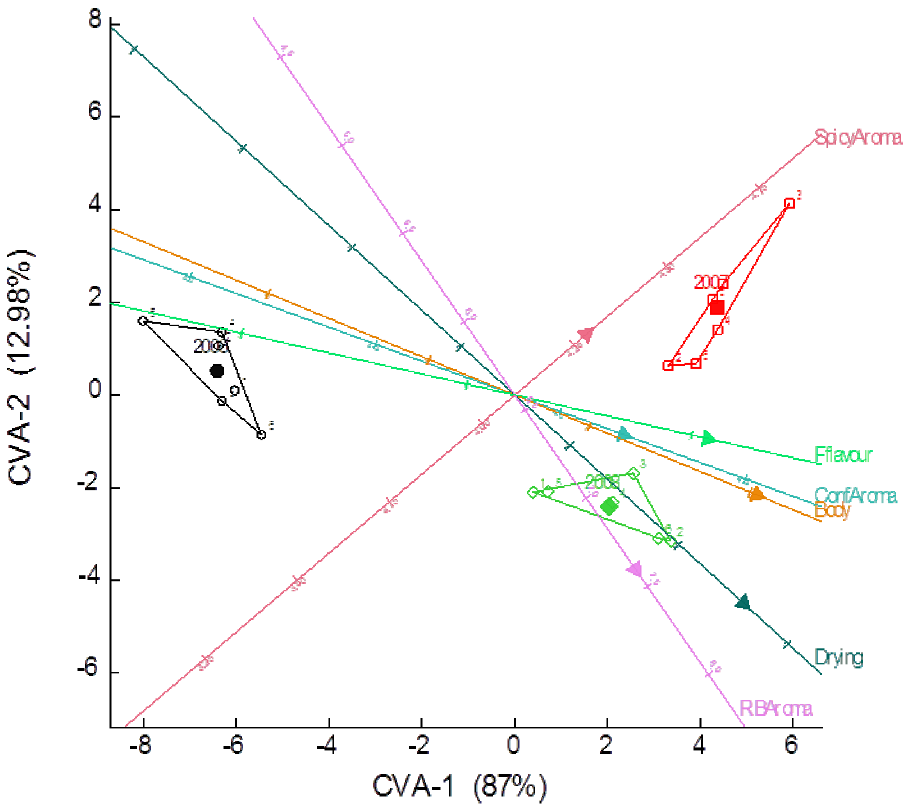


Fig. 44. Biplot from canonical variate analysis showing the relationships between observations and between sensory variables. The numbers (observations) within each vintage are vigour zones from which fruit was taken for wine making.

In terms of wine composition, the 2006 wines were different from the rest for having lower levels of all chemical attributes considered here (lower total phenolics, total anthocyanins, total red pigments, colour density and alcohol content) (Fig. 45).

The wine composition data, in addition to showing differences between vintages, revealed consistent within-year segregation of vigour zones, at least between the most and least vigorous zones (Fig. 46). This is in agreement with our earlier results from multiple sites showing vine size as an important variable influencing wine composition and sensory properties (Lanyon et al., 2010).

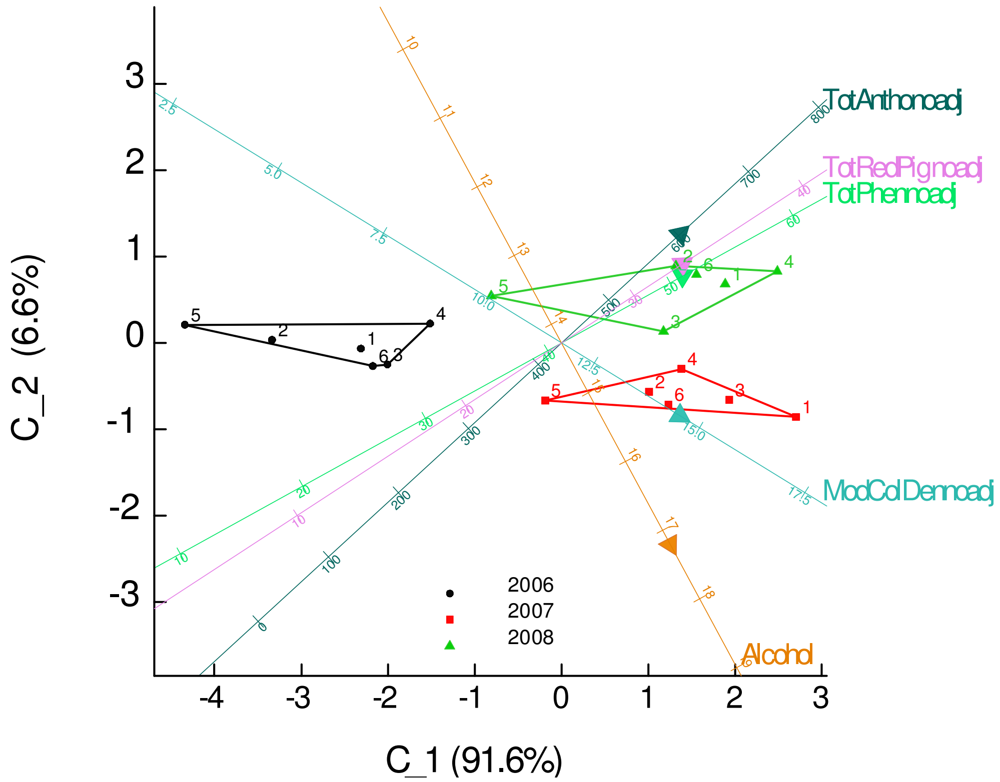


Fig. 45. Biplot from canonical variate analysis showing relationships between observations and between wine composition variables. The numbers (observations) within each vintage represent vigour zones from which fruit was harvested for wine making.

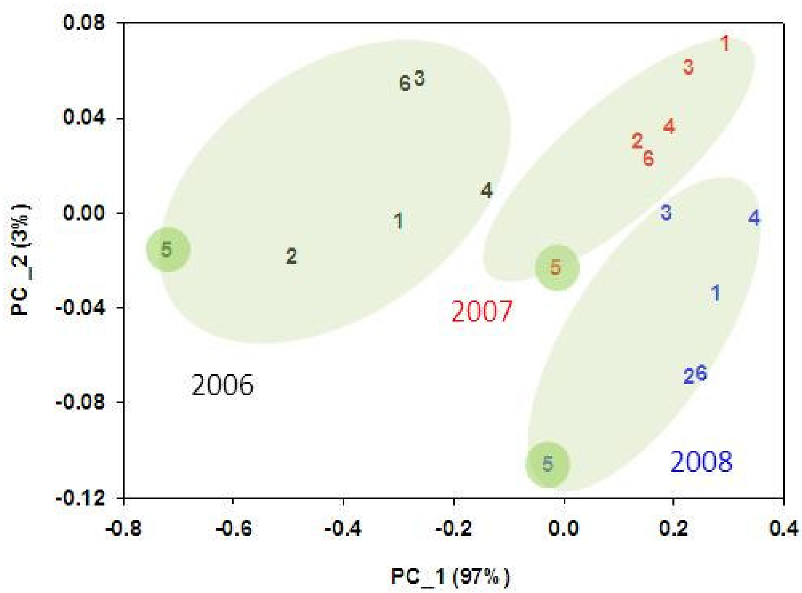


Fig. 46. Plot of principal component scores of wine composition data showing that in each vintage, wines from the most vigorous vineyard zone (5) were segregated from the rest. This is also apparent in Fig. 45.

Multivariate ANOVA of the combined wine chemical composition variables indicated a weak but significant vigour zone effect (Rao F 1.9, p = 0.045; Fig. 47). The largest inter-group distances (separations) were between the most vigorous (zones 5 & 2) and least vigorous zones (zone 4) (Fig. 47.). The dominant contributors to this zonal separation were concentrations of total red pigments, total phenolics and alcohol content - all these being low in wines from the high vigour zones compared to the low vigour zone wines. On the other hand, vine vigour had no significant effect on wine sensory properties (p = 0.195).

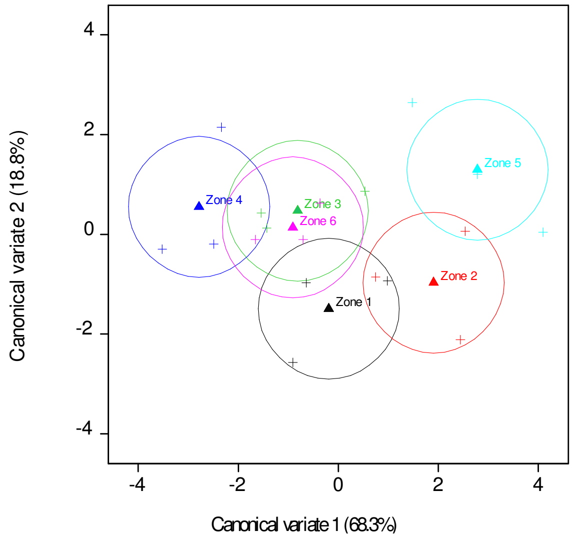


Fig. 47. Separation of wines from different vigour zones based on wine chemical composition. The circles are 95% confidence regions for the zonal mean scores. The "+" symbols represent vintage score.

In summary, this analysis showed a strong year-to-year variation in wine chemical composition as well as sensory properties. However, the pattern of variation was similar for both sets. This was due to the strong relationship between wine chemistry and sensory attributes (at least among those reported here). In spite of the marked annual variation, the overall impact of vine vigour was significant on wine composition (instrument measures) though not on sensory characteristics (subjective measures). In terms of chemical composition, the wines from the more vigorous zones of the vineyard were generally characterised by lower levels of the chemical attributes considered in this study, emphasizing the importance of canopy size on wine quality. An interesting observation, although one which could not be tested robustly due to sample size limitation, is the apparent consistency of zonal segregation between vintages. If such vigour effects are temporally stable (as appears from this study) and spatial extents are large (not so in this case study), then it opens the possibility for zonal management to raise block-wide quality.

7. Outcomes/Conclusions

The project had multifaceted objectives most of which, except the impacts of spatial water deficits and/or irrigation strategy on financial returns and $^{13}CO_2$ isotope labelling study, were largely achieved. The project was carried out in a commercially operated property where production inputs were flexibly applied. Thus, a proper economic analysis of irrigation strategy and/or spatial variation in water deficits could not be performed under the operational management conditions of the study vineyard. A practical means of labelling under field conditions that provides useful data could not be devised.

Outcomes/conclusions related to completed project objectives are described below:

Utility of stable carbon isotope discrimination as a tool for identifying spatial water deficits

The $\delta^{13}C$ analysis showed that vine tissue samples that incorporate carbon from multiple seasons have potential for revealing inherent spatial patterns in soil water deficits. On the other hand, the effectiveness of $\delta^{13}C$ of berry soluble solids, whose carbon predominantly originates from current season carbon assimilation, can be variable particularly in blocks with variably irrigated parcels or when the berry-ripening period experiences moist conditions.

Leaf physiology during water deficit and recovery following irrigation

a. Gas exchange

Significant variations in leaf gas exchange rates were observed between vines from different vigour zones of the vineyard. Generally, photosynthesis and stomatal conductance rates were higher in high vigour than low vigour zone vines. This was largely so during water deficit periods and following an irrigation event.

Regardless of vine vigour, quick (within 24 h) recovery of gas exchange rates following small volume irrigation occurred when temperature and vapour pressure deficits were comparable before and after irrigation. Necessarily, however, the small volume irrigation events typically occurred just prior to hot and drier atmospheric conditions. Under these conditions, there was a generally limited, if any, increase in leaf gas exchange activity. However, even when no increase occurs, the role of the small volume strategic irrigation application appears to enable vines to tolerate an otherwise potentially damaging impact of extreme weather conditions. This underscores the fact that in predominantly rain-fed viticultural production systems as occurs in this region, irrigation is a tool for “risk” management since the volume applied is very small, typically 15 L/vine at a time. The role this plays in maintaining the functional state of the vines cannot be overemphasised.

b. Chlorophyll fluorescence analysis

Chlorophyll fluorescence measurements indicated that in summer midday conditions (full photon flux density, high VPD and moderate water stress) which tend to lower photosynthetic activity, Shiraz vines were able mitigate potential damaging impacts of high irradiance absorption by dissipating it via non-photochemical quenching processes. There was some evidence that the proportion of absorbed energy thermally dissipated was greater in low vigour vines. The decline of photochemical utilisation was matched by increased deployment of non-photochemical disposal mechanisms thus affording photoprotection when photosynthetic activity is reduced.

An outdoor water stress experiment using Shiraz and Sauvignon Blanc vines, also showed a tightly synchronised shift between photochemical and non-photochemical quenching of fluorescence. While the synchronicity was similar in water-replete and water-stressed vines, the amplitude was greater in water-stressed vines, providing further evidence that grapevines leaves have a fine-tuned mechanism of managing energy surfeit to avoid damage to the photosynthetic apparatus.

c. Vine water relations

At the study vineyard, soil moisture tension remains low (≤ 0.1 MPa) until November-December, depending on season. As a result, vine water status until the flowering period experiences no or only weak stress (typical predawn leaf water potential > -0.30 MPa). With the advancement of the growing season, however, there is a progressive decline in vine water status as indicated either by leaf and/or stem water potentials. In particular, post-flowering vines from the low vigour zones experienced lower water status than vines from the highest vigour zones. The water status of low vigour vines, however, showed a rapid recovery following small volume irrigation (15 L/vine) although the recovery lasts for only a short period (~ 2 days). In practical terms, this would mean frequent irrigation in the low vigour zones vines to maintain their water status. However, this needs to be balanced by a consideration of the return on the increased water investment.

d. Sap flow (transpiration)

Growing-season sapflow rate measurements revealed three (four) characteristic limitations to water use:

- During the first stage (late November to mid-December), soil moisture is generally adequate, and vine transpiration rates are limited by canopy development.
- In stage two, the canopy attains maximal size typical of a given vigour zone; water use is limited by a rapidly drying soil profile. Note that this stage does not exist in seasons when the irrigation cycle is initiated prior to the occurrence of significant drying of the soil profile.
- In stage three, canopy size is still stable, steady transpiration rates typical of a vigour zones are attained; water use is dictated by the frequency and quantum of irrigation.
- In stage four, starting from the latter phase of the berry ripening period, a slow and steady decline in vine transpiration is apparent perhaps reflecting an infrequent irrigation regimen and loss of functional leaf due to senescence.

Notwithstanding generic patterns described above, considerable variation (more than 5-fold) in individual vine transpiration rates were observed between the highest and lowest vigour vines. Clearly, all other things being equal, vine canopy size was the major rate limiting factor in water use. In a vineyard with a highly heterogeneous vigour, this has important implications in water resource utilisation. This was apparent, albeit to a lesser extent, from scaled up estimates of block-wide water use variations in the order of 1.7 to 2.0-fold between the highest and lowest vigour zones. The study site vineyard was split irrigated (high *vs* low-vigour zones); and interestingly, the low water use was generally from the low vigour zones despite the irrigation on average being twice as much as the high vigour zones application rates. The yields of the low vigour zones are also lower, pointing to lower water use efficiency.

e. Irrigation water utilisation

Irrigation water utilisation was continuously monitored in four of the six vigour zones of the vineyard. This revealed considerable variation in the acquisition of the applied water among the vigour zones. Vines from the lower vigour zones appeared to have limited capacity to utilise the applied irrigation water whereas the high vigour zones extracted it effectively. The seasonally integrated variation in soil water extraction was strongly and linearly related to vine size and/or yield. Were the irrigation applied uniformly across the vineyard block, the differential acquisition of the applied water would signify a spatially varied and inefficient utilisation of the water. The inefficiency in this case study was further magnified because the volume of water applied to the low vigour zones was double that of the high vigour zone. Consequently, the productivity of the applied water between the highest and lowest vigour zones varied by about a factor of three. The reason(s) for the reduced capacity of low vigour vines in utilising the applied water are not clear. However, nutritional augmentation, especially phosphorus, and timing of the early season irrigation are worth investigating.

f. Wine "quality"

Analyses of wines made from different vigour zones showed considerable variability between vintages in wine composition and sensory attributes. Generally, vintages which experienced wetter conditions during the grape ripening period produced wines with lower scores on sensory attributes as well as low values on all wine composition measures reported here. Perhaps more significantly, despite large between vintage variations, there was evidence of a temporally persistent zonal (vigour) effect particularly on wine composition. This effect was obvious between the extreme ends of the vigour spectrum. Where temporal consistency is coupled to a spatially significant area, it provides a platform for instituting a zonal management system to improve overall productivity.

8. Recommendations

Utility of carbon isotope discrimination for identifying soil water deficits patterns

The carbon isotope composition of a sample can provide an integrated picture of the environmental conditions (water availability and vapour pressure deficit) that prevailed during fixation of the carbon that constitute the sample. For a relatively small area, such as a vineyard block, the impact of VPD may be ignored, and any variation in $\delta^{13}C$ of samples can be largely attributed to spatial variation in soil water availability. While this idea forms the basis for evaluating the utility of $\delta^{13}C$ as a tool for identifying soil deficit patterns in this work, the results showed current season samples such as berry soluble solids are good for revealing current season water stress patterns. Such samples, however, are not suited for identifying inherent water deficit patterns that would be more pertinent for devising (irrigation) management zones. Natural patterns of soil water deficits are better identified from analyses of samples whose carbon originates from multiple seasons. Whereas bud samples appeared adequate in this study, it is suggested in future studies that ultrafine radial core samples from trunks or cordons may be more revealing as the life-histories of these organs are likely to be as old the vine itself. That said, on the bases of cost and analytical and technical skill requirements, this tool is more suited for a research context than for use in production systems.

Leaf physiology during water stress and recovery following small volume irrigation

Considerable differences between leaf photosynthesis rates of low and high vigour vines were observed during the drying and re-wetting phases of the soil profile following small volume irrigation, and generally over most of the growing season (flowering to harvest). Under mild weather conditions, application of even the typical small volume irrigation after a prolonged withholding, can raise water status and photosynthetic performance of both low and high vigour vines.

The crucial benefit of irrigation in this primarily rain-fed viticultural production system however appears to emanate from its application just prior to the advent of very hot and dry spells. Application of even the modest irrigation volumes (15-20 L/vine) the night before forecasted hot and dry spells, while not necessarily lifting gas exchange rates, nonetheless significantly increases leaf and/vine water status and appears to enable vines to tolerate the highly stressful and potentially damaging weather conditions. This irrigation enables vines to maintain a positive carbon balance during the hot and dry spells and when stressful conditions subside there is little or no lost time in restoring the canopy to a fully functional state.

It needs to be emphasised, however, that the point made above is based on observations from operational conditions under a commercial production system with no true control treatment. Thus further work with a replicated experiment that includes a control treatment is highly recommended. This is particularly important in the context of changing climate and potentially increased frequency of extreme weather events, and more so in regions where viticulture is primarily rain-fed. Clearer information will enable growers to use their limited water resources more strategically for managing risks.

Resource utilisation

Estimates of vine water use from monitoring under-vine soil moisture and sap-flow measurements indicated considerable zonal or spatial variation in water utilisation. One consequences of this variability was manifest as marked difference in productivity (utilisation efficiency) of the applied water across the vineyard block. As may be expected, this variation in water use was related to or driven by variation in vine vigour. It is reasonable to assume that capture of other resources such as nutrients or radiation varies similarly. Thus, it is recommended that in order to minimise variation in, and possibly to raise, resource use and efficiency, focus needs to be oriented to identifying and rectifying factors that give rise to vigour variation.

9. Appendix 1: Communication

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10. Appendix 2: Intellectual Property

N/A

11. Appendix 3: References

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12. Appendix 4: Staff

The following personnel worked on the project for various durations:

Ayalsew Zerihun – Chief investigator
Assoc. Prof. Mark Gibbered – Project supervisor
Brendan Evans – Technical assistant
Lisa Palmer – Technical assistant

13. Appendix 5: Acknowledgements

The provision of a monitoring site by Ferngrove Wines and their unreserved assistance during the monitoring period is gratefully acknowledged. Mr David Kelly kindly assisted with fruit harvesting processing. Dr Dean Lanyon, as the chief investigator of the linked project, contributed significantly with fruit harvesting and processing as well as availing data for the shared objectives of the co-located projects. Ms Verna Westwood kindly read and corrected the English.