Effect of site-specific irrigation management on grapevine yield and fruit quality attributes

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Abstract Spatial variation in yield and fruit composition has been observed in many vineyards leading to low productivity. In this study, site-specific irrigation was applied in a 6.4 ha commercial vineyard (*Vitis vinifera* L. cv. Shiraz) block in the Sunraysia region of Australia to improve production in low yielding areas of the block and decrease differences in yield and quality between zones. The block was divided into three irrigation management zones based on normalised difference vegetation index (NDVI). Data collected under uniform irrigation management during seasons prior to site-specific irrigation management showed that spatial variation in canopy cover, yield and fruit composition at the study site was substantial. Water use efficiency and yield improvements were achieved by implementing site-specific irrigation. Fruit composition results were varied; pH and titratable acidity showed increased similarity between zones but other parameters maintained differences between zones. These results lend support to the use of NDVI to determine irrigation management zones.

Keywords: management zones, normalized difference vegetation index, canopy temperature, Shiraz, water use efficiency

Introduction

Within-block spatial variation of various grapevine parameters, in particular yield, fruit composition and remotely-sensed vegetation indices, has been investigated by Bramley (2005), Bramley and Hamilton (2004) and Hall et al. (2003). The division of a vineyard block into homogenous zones is sometimes recommended, depending on the degree of spatial variation observed in the block, the spatial patterns and the persistence of these patterns over time. Zonal harvesting can be employed so that uniform batches of fruit are kept separate

(Bramley et al. 2003). This approach may be considered reactive, in that inputs remain the same and grape attributes are not manipulated. Alternatively, site-specific management of irrigation in each zone could be employed. Site-specific management of irrigation aims to maximise productivity. Such an approach will increase the efficient use of water and potentially reduce the variability in yield and fruit quality across the block. Arnó et al. (2009) provide a comprehensive summary of the numerous precision viticulture studies that primarily examine spatial variability of grapevine and vineyard parameters and the mapping and analysis of spatial data. However, few studies report the effects of site-specific crop management within vineyards.

Boshoff (2010) investigated canopy cover and plant water status interactions and their effects on yield, fruit composition and wine parameters and implemented three irrigation regimes (low, moderate and dryland) over plots classified by canopy cover (high, medium and low cover, indicated by the normalised difference vegetation index, NDVI, determined from multispectral aerial imagery). He suggested that site-specific management of irrigation could be used to manipulate yield and fruit quality within a block. However, it remains to be shown that yield and/or fruit quality could be sufficiently manipulated to make irrigation system modification a financially attractive option.

Simple, affordable and practical methods are needed to determine irrigation management zones. Yield monitors have been used in vineyards; however, they are expensive and difficult to use. Alternatively, significant correlations between NDVI and yield and quality parameters have previously been reported (Best et al. 2005; Hall et al. 2011; Lamb et al. 2004). In addition, Acevedo-Opazo et al. (2008) reported differences in plant water status between vineyard zones defined using NDVI. Recently, Taylor et al. (2010) provided further support of the use NDVI to define irrigation management zones by investigating grapevine cultivar, soil type and canopy cover as drivers of spatial variation in grapevine water status. Their analysis showed that cultivar had a dominant effect when vines were well watered while canopy cover (determined from historical mid-season measurements of NDVI) and soil type became more dominant as water restriction increased. It was concluded that canopy cover would be an effective parameter for guiding sub-block sampling of plant water status and irrigation management (Taylor et al. 2010).

The aim of this study was to evaluate the hypotheses that site-specific irrigation could increase grapevine production in a low yielding area of a block and decrease differences in yield and fruit composition between zones, thereby improving water use efficiency and reducing overall block variability.

Materials and Methods

Study site and sampling design

The study site was a 6.4 ha commercial drip-irrigated Shiraz (*Vitis vinifera* L.) block (34.42° S 142.28° E) planted in 1994 in the Sunraysia region of SE Australia. Vines were trained to two bilateral cordons (vertically separated) and minimally pruned. Vine and row spacings were 2.4 and 3 m, respectively, and rows were oriented east-west. Based on k-means cluster analysis of historical yield and soil electrical conductivity data, a sample of 100 irregularly spaced target vine locations was selected in a way so as to maximise the chance of adequately representing the entire range of variation in the block (Goodwin et al. 2009). The block was monitored using these 100 target vine locations over a five-year period for the seasons 2005/06 (YR-1), 2006/07 (YR-2), 2007/08 (YR-3), 2008/2009 (YR-4) and 2009/2010 (YR-5).

Yield and fruit composition

Yield was measured on each of the 100 target vines immediately prior to commercial harvest each season. A 50 cm (seasons YR-1, YR-2 and YR-3) or 100 cm (seasons YR-4 and YR-5) section of the target vine was harvested. The section was located to one side of the vine centred at the mid-point of the cordon.

A sample of berries was taken from harvested fruit of each vine to determine average berry weight and fruit composition. Firstly, a random sub-sample of 150 berries was weighed to determine average berry weight and then frozen and kept for analysis of tannins, anthocyanins, and iron-reactive phenolics. The remaining berry sample was kept in cool-storage and used, as soon as possible, for measurement of total soluble solids (TSS), pH and titratable acidity (TA).

Berry juice TSS (° Brix), pH and TA (g tartaric acid equivalents/l) were measured after crushing and centrifuging the fresh berry sample. TSS was measured using a refractometer. pH and TA were measured using an autotitrator (titration with NaOH to pH = 8.2).

Whole berries were homogenised and anthocyanin concentration (mg malvidin-3-glucoside equivalents/g berry fresh weight), tannin concentration (mg catechin equivalents/g berry fresh weight) and iron-reactive phenolic concentration (mg catechin equivalents/g berry fresh weight) determined by spectrophotometry after extraction with ethanol (Harbertson et al. 2003; Iland et al. 2000).

Water use efficiency

Water use efficiency was calculated in terms of fresh weight yield (t) produced per unit of water applied (ML), where water applied consisted of irrigation events and rainfall events greater than 10 mm during the growing season (September–April, Table 1). Rainfall was recorded by vineyard staff.

Normalised difference vegetation index

Aerial spectral imagery data were captured using a digital multispectral camera (High Resolution Airborne Multispectral System, SpecTerra Services Pty Ltd, Perth, WA, Australia) flown at 1800 m (above ground level) by a commercial company (SpecTerra Services Pty Ltd, Perth, WA, Australia) in seasons YR-1, YR-2 and YR-3. Spectra data were captured simultaneously at four spectral bands of 20 nm bandwidth centred at 450 (Blue), 550 (Green), 675 (Red) and 780 (NIR) nm at a spatial resolution of 0.5 m. Data pre-processing (including geo-referencing) was carried out by SpecTerra services. NDVI was calculated as (NIR – Red)/(NIR + Red). The pre-processed data were used to create maps (Fig. 1) with ArcView GIS version 3.3, ESRI, Redlands, California, USA). Individual vine data was extracted for the 100 target vine locations.

Canopy temperature

Spatial variation in Tc was measured using temperature sensors mounted on an all-terrain vehicle in YR-3 during veraison (7 January 2008 between 1300 and 1500 h, Australian Eastern Standard Time). . Measurements were taken by driving slowly past the target vines and continuously recording T_c at 10 Hz. T_c was measured with two infrared sensors (3600 ZLC, FoV 15°; Everest Interscience, Tucson, Arizona, USA) positioned no more than 30 cm directly above the canopy. T_a was measured at 0.1 Hz with a temperature/humidity sensor (HMP45A; Vaisala Oyj, Helsinki, Finland), positioned over well watered grass near the grapevine site. The measurements were taken on a day with moderate evaporative demand conditions (reference crop evapotranspiration = 7.4 mm, calculated as per Allen et al. 1998, for well watered grass) and the vines had been irrigated from 0645 to 1330 h. Tc - Ta data were mapped (Fig. 2) with ArcView GIS (version 3.3, ESRI, Redlands, California, USA)

Cluster analysis

Multivariate classification using fuzzy c-means clustering algorithm (Bezdek 1981; Bezdek et al. 1984) was undertaken to identify zones within the block with similar characteristics using Management Zone Analyst software (MZA; version 1.0.1, University of Missouri-Columbia and Agricultural Research Service, Columbia, MO, USA) as described in Fridgen et al. (2004). Fuzzy *c*-means clustering is an iterative process that classifies data, minimising within cluster variance and maximising between cluster differences for a given number of clusters. It recognises the continuous nature of natural data by determining degrees of membership of data points to different clusters ('fuzzy' cluster analysis) rather than assuming existence of sharp boundaries between clusters ('hard' cluster analysis).

NDVI and T_c-T_a data were used to generate two to six clusters within the block. The Mahalanobis distance metric was used to account for correlation between variates and to avoid effects of different scales of NDVI and temperature data (Bezdek 1981; McBratney and Moore 1985). Default values were used for the convergence criterion (0.0001) and maximum number of iterations (300). Three zones appeared to be an acceptable compromise between optimising clustering performance indices and minimising the number of clusters. Different combinations of variables were explored and clustering was generally similar regardless of the attributes included. However, clusters identified by using all variates (NDVI from YR-1, YR-2 and YR-3 and T_c-T_a from YR-3) did not differ from those identified using only the three seasons' NDVI data. Considering the practicalities of irrigation scheduling and the existing irrigation infrastructure, three irrigation zones were identified: West, East and South (Fig. 3), which had, respectively 36, 60 and four target vines. Clusters and irrigation management zones were mapped with ArcView GIS (version 3.3, ESRI, Redlands, California, USA; Fig. 3).

Irrigation management

The block was irrigated via two sub-mains aligned north-south, one located in the east and the second in the west, and single laterals within each row. Emitters were spaced at 0.6 m intervals and emitter rates were approximately 2 L/hr. The West irrigation management zone corresponded to the area irrigated by the central sub-main, while the East zone was irrigated by the eastern sub-main. The South zone was irrigated by the eastern sub-main and was created by installing taps in each drip-line of the rows within this zone prior to the YR-5 season.

Irrigation volumes were calculated from vineyard records (YR-1, YR-2 and YR-5) and flow meter readings (YR-2 and YR-3). In YR-1 to YR-4, irrigations were run simultaneously from both sub-mains with typical mid-season run-times of six to eight hours. Occasional additional irrigations were applied to the West zone in YR-1 to YR-4, but irrigation in the east and South zones did not differ during this time (Table 1).

In YR-5, the South management zone received two irrigations early in the season, the taps were then turned off and the South was not irrigated again until mid-December; from then the South zone was irrigated with the East zone. The East and West zones were irrigated uniformly until November. From November to late-February the frequency of irrigation was increased in the West management zone. Typically, the East zone would be irrigated once during each irrigation cycle for six hours while the West zone would be irrigated twice for three hours each irrigation. When fertigations or heat-related irrigations were scheduled the entire block was irrigated uniformly. From late-February, the block was irrigated uniformly. Consequently, East and West zones received similar irrigation volumes in YR-5 (4.5 ML/ha), while the South zone received less irrigation (3.7 ML/ha). Irrigation volumes applied to each zone in each season are summarised in Table 1.

Statistical analysis

Summary statistics (mean, median, range, CV, spread) were used as exploratory tools to examine the nature of data distribution, identify any extreme outliers and determine the gross variation. The ‘spread’ was estimated as [(max – min) /median)]*100 (Bramley 2005).

To evaluate if site-specific irrigation helped modify yield and fruit composition in different zones as we had hypothesized, a one-way analysis of variance (ANOVA) model, with zone as a (fixed effect) classification factor, was fitted to the data for each attribute in each season. The East zone was considered to be analogous to a control treatment, since the strategy for irrigation management of this zone was essentially unchanged throughout the study. Thus, comparisons were made between mean values of the East and West zones and the East and South zones for each attribute (yield and fruit composition measures) within seasons using Dunnett’s test (IBM SPSS Statistics, SPSS Inc., Chicago, USA). Statistical comparisons among the means of a particular zone under different irrigation managements were not made as these comparisons cannot be unequivocally claimed as arising from irrigation managements due to the confounding of irrigation management effects with the season effects.

A valid application of ANOVA requires random (independent) samples of observations. This assumption is unlikely to be satisfied in these types of studies. An alternative to get more accurate inferences would be the use of restricted maximum likelihood (ReML) which can explicitly account for the underlying spatial dependence. For our data, the inferences from ReML analysis (not shown) using a first order autoregressive spatial model were close to those from ANOVA. We therefore present here the results from only the ANOVA approach.

Results

Normalised difference vegetation index and canopy temperature

NDVI patterns across the block were consistent in YR-1, YR-2 and YR-3, with low NDVI in the west and high NDVI in the south of the block (Fig. 1). Correspondingly, Tc - Ta data indicated high canopy temperatures in the west and low canopy temperatures in the south.

Site yield and fruit composition

Mean yield and fruit composition values for the entire site in YR-5 were generally within the range of mean values seen in previous years, except that pH was higher and TA was lower than in YR-1, YR-2, YR-3 and YR-4 (Table 2). Mean yields were highest and berry weights were lowest in YR-3 (Table 2). Within-season variability was particularly high for yield and anthocyanins and was lowest for juice pH and TSS (Table 2). CV and spread values suggest that variability of yield and, to a lesser extent, berry fresh weight, TA and anthocyanins, tended to be smaller in YR-5, compared to previous seasons (Table 2).

Zone yield, water use efficiency and fruit composition - analysis of variance

In seasons YR-1 to YR-4, yield in the West zone was consistently lower than that in the East (and South) zone (Table 3). In YR-5, yield in the West was similar to that in the East zone and higher than in the previous four seasons. Yield in the South zone was similar to that in the East zone in all seasons. Berry fresh weight was lower in the West than the East in YR-2 and YR-4 but was similar in other seasons (Table 3). Berry fresh weight in the South zone was significantly higher than that in the East in YR-1 to YR-4, (Table 3). This difference was maintained in YR-5 even though berry weight was lower in the South than in previous seasons. By contrast, crop loads (i.e. berry number, calculated from yield and berry weight) were significantly lower in the West (765 – 2213 berries/m^2) than the East (2362 – 4234 berries/m^2) in YR-1 to YR-4, but were similar in YR-5 (2607 berries/m^2 in the West cf. 2905 berries/m^2 in the East). Crop loads were similar in East and South zones in all seasons except YR-3 when crop load in the South (2859 berries/m^2) was lower than that in the East (4234 berries/m^2).

Water use efficiency mirrored yield results in terms of differences between zones in YR-1 to YR-4 with water use efficiency in the East higher than that in the West and similar to that in the South (Table 3). In YR-5, water use efficiency was similar in the East and West zones but was higher in the South zone than the East.

In each season, juice TSS, pH, anthocyanins, iron-reactive phenolics and tannins were generally highest in the West zone and lowest in the South zone, while TA was highest in the South zone and lowest in the West (Table 3). Juice TSS, pH, TA and anthocyanins were significantly different between zones in seasons YR-1 to YR-4 (Table 3). By contrast, in YR-5, pH was not significantly different between zones and TA in the East and West zones was similar. Differences between zones in TSS and anthocyanins were maintained. Iron-reactive phenolics and tannins exhibited significant differences between zones in YR-2, YR-3 and YR-5 (Table 3) and the trends in each of these seasons was similar (i.e. highest in the West zone and lowest in the South zone).

Discussion

Observations of variable vine vigour and evidence of areas of water stress within a vineyard block led to implementation of site-specific irrigation management in an attempt to improve production in low yielding areas of the block and reduce variability of yield and fruit composition. Irrigation in the initial two seasons of the study was considered to be ‘uniform’ across the block. Water stress and low vine vigour and yield were common in the West zone. Excessive vine vigour existed within the South zone; yield and berry weight were high and quality parameters (iron-reactive phenolics, anthocyanins and tannins) within this area were generally poor compared to the East and West zones. The East zone produced moderate yields with intermediate quality parameters. Lateral water movement from neighbouring orange and avocado blocks planted on slopes north and south of the site may have provided additional water to the vigorous grapevines. It was also thought that the sandy soil and sloping aspect of the western side of the block limited water availability and contributed to water stress and subsequent low canopy cover.

Increases in irrigation applied to the West in YR-3 and YR-4 were modest (less than 8 % of total water applied to East and South zones). Differences in yield, berry weight and water use efficiency between East and West zones were maintained, suggesting that the small number of additional irrigations had little impact on productivity. Furthermore, canopy temperature data indicated that vines in the West zone continued to experience greater water deficits than vines in the South zone.

Analysis of NDVI and Tc - Ta data and consideration of practicalities of the irrigation infrastructure supported the establishment of a third irrigation management zone (South) and changes to the scheduling of irrigation in the West and South irrigation management zones in YR-5. NDVI is linearly related to canopy cover (Trout et al. 2008), and canopy cover has been shown to be a major determinant of grapevine water use (McClymont et al. 2009; Williams and Ayars 2005). Furthermore, Grant et al. (2007) and Möller et al. (2007) showed that grapevine T_c is inversely correlated with leaf conductance and plant water status and suggested that thermal imaging could be used to detect water stress and aid scheduling of irrigation. In this study, multivariate cluster analysis of NDVI data from three seasons was used to account for temporal variability and reveal areas with persistently high or low canopy cover and hence high or low water use. Although the inclusion of T_c-T_a in the cluster analysis did not alter the identified clusters, the data showed that T_c-T_a varied across the site despite measurements being taken immediately after an irrigation event. The spatial pattern of T_c-T_a supported the belief that large vines were accessing water in addition to irrigation and that water availability was limited for some vines due to soil type or root development. Initiation of irrigation was delayed for the South zone (historically characterised by vigorous vines with low T_c-T_a) and more frequent irrigations were applied to the West zone (characterised by small vines with higher T_c-T_a) to improve temporal water availability.

The aim of improving production and reducing yield variability was achieved by site-specific irrigation management. Site-specific irrigation helped increase yield and water use efficiency in the West zone relative to the East zone. This change appears to have been driven by increased crop load in the West zone and low berry weight in the East zone. With the understanding that the approach to irrigation management in the East zone was similar in all five seasons, these results suggest that an improvement in yield and water use efficiency was achieved by better irrigation management in the West zone.

The aim of the vineyard manager was to produce small berries. In this respect, the reduction of berry weight in the South zone (possibly related to irrigation cut-off during the initial berry development phase) under site-specific irrigation in YR-5 (1.44 g compared to 1.53 to 1.80 g in YR-1 to YR-4) was seen as positive. The ability to withhold irrigation throughout the initial berry development phase, as occurred in YR-5, provides the grower with greater control of berry size in the South zone.

Differences between zones in berry pH and TA lessened when site-specific irrigation was adopted and irrigation frequency increased in the West zone. The mechanisms for these changes are unclear and they may not be entirely attributable to site-specific irrigation. However, pH and TA are influenced by temperature, bunch exposure, leaf shading and crop load (Jackson and Lombard 1993). Measures of vegetative growth were not made in YR-4 and YR-5 but visual observations suggested that variability in canopy size was less pronounced in YR-5, when irrigation frequency increased in the West zone, than in previous years. This visually observed decrease in differences in canopy development between zones possibly contributed to decreased differences in exposure, shading and crop load and consequently greater similarity in pH and TA. Adjustment of canopy size in response to site-specific irrigation appeared, as yet, to be insufficient to reduce zonal differences and overall site variability in attributes such as TSS, anthocyanins, iron-reactive phenolics and tannins. Alternatively, factors other than water availability may exert a predominant influence on spatial patterns of these attributes.

Our analysis suggests that NDVI is a useful tool for delineation of irrigation management zones to increase overall productivity. Furthermore, identification of management zones by cluster analysis is a simple process using freeware such as MZA (Fridgen et al. 2004). Various commercial companies provide multi-spectral images and associated vegetation indices (e.g. NDVI and PCD) to the viticulture industry in Australia at reasonable cost. However some additional data handling is required to extract NDVI for individual vine locations.

While irrigation management zones were closely aligned with clusters identified by multivariate analysis, there was an imperfect agreement between the zones and clusters. Factors such as the position of existing sub-mains and valves, the fertigation system and irrigation requirements of other blocks influenced where the zones were located and how they were managed. This compromised the capacity to decrease site variability, however, such practical considerations, including the costs associated with modifying the irrigation infrastructure, are critical components in precision management.

Additional changes to irrigation scheduling practices could be implemented in future seasons to manipulate particular vine and berry attributes. For example, regulated deficit irrigation could now be imposed in the South zone to improve fruit quality without causing excessive water stress in the West zone. Determination of factors, other than water supply, influencing yield and fruit composition at this site could enable the development of additional management practices (for example, nutrition) that would further reduce variability or improve yield. Nevertheless, this study provides an assessment of the effect of site-specific irrigation and demonstrates that site-specific irrigation can help improve production and reduce variability of grape yield.

Conclusion

Modification of irrigation scheduling practices within three irrigation management zones of a vineyard block, increased yield of a previously low production area and enabled reduced water application in a high vigour area. Across site variability in yield, as indicated by the CV and spread, decreased under site-specific irrigation management. By contrast, little impact on variability of fruit composition parameters was observed. Continued monitoring is necessary to observe the long-term impact on fruit composition. We conclude that site-specific irrigation management at this vineyard helped improve resource use efficiency by increasing yield and decreasing irrigation volumes.

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Table 1 Irrigation and effective rainfall in YR-1 (2005/2006), YR-2 (2006/2007), YR-3 (2007/08), YR-4 (2008/2009) and YR-5 (2009/2010) growing seasons (September-April). Effective rainfall was defined as events greater than 10 mm. n = number of irrigation events.

Season	I (mm(n))			Rain
	West	East	South	(mm)
YR-1	420 (64)	414 (62)	414 (62)	134
YR-2	358 (52)	338 (48)	338 (48)	68
YR-3	494 (79)	458 (73)	458 (73)	88
YR-4	512 (81)	469 (74)	469 (74)	74
YR-5	455 (100)	447 (73)	373 (56)	136

Table 2 Summary statistics for yield and fruit quality attributes at a Shiraz vineyard in four seasons with uniform irrigation management (YR-1, YR-2, YR-3 and YR-4) and one season with site-specific irrigation management (YR-5). Units: titratable acidity (g tartaric acid equivalents/l); iron-reactive phenolics (mg catechin equivalents/g berry fresh weight); anthocyanins (mg malvidin-3-glucoside equivalents/g berry fresh weight); tannins (mg catechin equivalents/g berry fresh weight)

Attribute	Season	n	Mean	Median	Min	Max	CV (%)	Spread (%)
Yield (kg/m^2)	YR-1	99	3.21	2.85	0.79	7.46	43	234
	YR-2	100	2.32	2.17	0.17	6.89	64	310
	YR-3	100	3.61	3.37	0.91	8.66	46	230
	YR-4	100	3.39	3.27	1.33	8.36	39	215
	YR-5	100	2.95	2.81	1.09	5.54	30	159
Berry fresh weight (g)	YR-1	100	1.24	1.23	0.69	1.95	19	102
	YR-2	100	1.25	1.24	0.84	2.12	18	104
	YR-3	100	1.05	1.05	0.45	1.84	22	133
	YR-4	100	1.28	1.25	0.76	1.87	14	89
	YR-5	100	1.08	1.07	0.73	1.65	18	86
Total soluble solids (° brix)	YR-1	100	24.05	24.40	19.10	26.10	6	29
	YR-2	100	24.27	24.65	18.60	28.30	7	39
	YR-3	100	23.18	23.45	17.00	26.20	8	39
	YR-4	100	23.87	24.00	19.90	26.50	5	28
	YR-5	99	24.10	24.21	19.99	27.03	6	29
Juice pH	YR-1	100	3.89	3.91	3.50	4.18	4	17
	YR-2	100	3.69	3.72	3.30	4.01	5	19
	YR-3	100	3.82	3.82	3.33	4.25	5	24
	YR-4	100	3.90	3.90	3.68	4.12	3	11
	YR-5	100	3.99	3.99	3.72	4.31	3	15
Titratable acidity	YR-1	100	4.23	4.09	3.35	6.61	18	80

(g /l)	YR-2	100	4.73	4.30	3.37	8.54	25	120
	YR-3	99	4.90	4.71	3.52	8.79	19	112
	YR-4	99	5.35	5.20	4.03	8.56	14	87
	YR-5	100	3.98	3.91	2.77	5.90	13	80
Iron-reactive phenolics (mg/g)	YR-1	100	4.53	4.51	3.01	6.65	15	81
	YR-2	100	5.81	5.61	3.80	8.40	17	82
	YR-3	100	4.79	4.67	3.32	7.72	17	94
	YR-4	100	4.23	4.15	3.13	5.47	12	56
	YR-5	100	4.94	5.00	3.22	7.21	17	80
Anthocyanins (mg/g)	YR-1	100	1.31	1.39	0.32	1.82	24	107
	YR-2	100	1.54	1.54	0.62	2.44	28	118
	YR-3	100	1.39	1.42	0.41	2.13	31	121
	YR-4	100	1.38	1.43	0.54	2.29	23	122
	YR-5	100	1.37	1.41	0.65	2.06	26	100
Tannins (mg/g)	YR-1	100	1.64	1.64	1.10	2.31	16	74
	YR-2	100	2.79	2.69	1.27	4.60	22	124
	YR-3	100	2.41	2.35	1.40	3.94	19	108
	YR-4	100	1.99	2.02	1.16	2.80	17	81
	YR-5	100	2.55	2.64	1.24	3.94	24	102
Water use efficiency (t/ML)	YR-1	99	5.85	5.15	1.42	13.61	43	237
	YR-2	100	5.67	5.35	0.39	16.98	65	310
	YR-3	100	6.52	6.17	1.67	15.86	48	230
	YR-4	100	6.11	6.02	2.28	15.40	41	218
	YR-5	100	5.07	4.78	1.84	9.60	31	162

Table 3 Estimates of irrigation zone (East, West and South) means for yield and fruit quality attributes, based on one-way analysis of variance, at a Shiraz vineyard in four seasons with uniform irrigation management (YR-1, YR-2, YR-3 and YR-4) and one season with site-specific irrigation management (YR-5). Units: titratable acidity (g tartaric acid equivalents/l); iron-reactive phenolics (mg catechin equivalents/g berry fresh weight); anthocyanins (mg malvidin-3-glucoside equivalents/g berry fresh weight); tannins (mg catechin equivalents/g berry fresh weight). Means followed by a different letter (within a row) are significantly different from the control (East) at the 0.05 probability level according to Dunnett’s test

Attribute	Season	West	East	South	95 % CI of the differences from the control (East)	
					West - East	South - East
Yield (kg/m^2)	YR-1	2.43b	3.60a	4.44a	0.59, 1.75	-3.58, 1.90
	YR-2	0.86b	3.07a	4.09a	1.79, 2.63	-3.41, 1.37
	YR-3	2.33b	4.32a	4.61a	1.37, 2.61	-2.57, 1.99
	YR-4	2.62b	3.77a	4.50a	-1.72, -0.58	-0.67, 2.13
	YR-5	2.80a	2.96a	3.98a	-0.02, 0.01	-0.002, 0.07
Berry fresh weight (g)	YR-1	1.194b	1.237b	1.791a	-0.047, 0.133	-0.869, -0.240
	YR-2	1.101b	1.311a	1.759a	0.130, 0.289	-0.980, 0.084
	YR-3	1.040b	1.014b	1.601a	-0.119, 0.067	-0.931, -0.243
	YR-4	1.196c	1.314b	1.574a	-0.199, -0.038	0.062, 0.456
	YR-5	1.094b	1.040b	1.457a	-0.030, 0.137	0.212, 0.622
Total soluble solids (° brix)	YR-1	24.11a	24.21a	21.10b	-0.46, 0.65	2.10, 4.12
	YR-2	25.48a	23.74b	21.45b	-2.36, -1.13	-1.83, 6.41
	YR-3	24.52a	22.55b	20.40b	-2.66, -1.29	-2.95, 7.26
	YR-4	24.15a	23.80a	22.32a	-0.87, 0.16	-1.41, 4.35
	YR-5	24.90a	23.92b	21.74c	0.22, 1.74	-4.04, -0.31
Juice pH	YR-1	3.95a	3.87b	3.59c	-0.13, -0.03	0.14, 0.42
	YR-2	3.84a	3.63b	3.37c	-0.27, -0.16	0-12, 0.39
	YR-3	3.94a	3.77b	3.49c	-0.24, -0.10	0.03, 0.52

	YR-4	3.97a	3.86b	3.82b	0.06, 0.14	-0.14, 0.05
	YR-5	3.98a	4.00a	3.89a	-0.08, 0.03	-0.25, 0.03
Titratable acidity (g/L)	YR-1	3.781c	4.365b	5.998a	0.314, 0.853	-2.892, -0.375
	YR-2	3.852c	5.044b	7.563a	0.853, 1.531	-4.752, -0.286
	YR-3	4.261b	5.144a	7.048a	0.563, 1.203	-4.407, 0.598
	YR-4	4.966b	5.511a	6.374a	0.230, 0.861	-2.279, 0.553
	YR-5	3.939b	3.926b	5.192a	-0.211, 0.236	0.722, 1.811
Iron-reactive phenolics (mg/g)	YR-1	4.374a	4.614a	4.681a	-0.556, 0.076	-0.707, 0.841
	YR-2	6.747a	5.339b	4.367c	1.097, 1.719	-1.733, -0.211
	YR-3	5.206a	4.604b	3.781b	0.245, 0.959	-1.698, 0.051
	YR-4	4.278a	4.221a	3.837a	-0.191, 0.307	-0.993, 0.226
	YR-5	5.385a	4.764b	3.565c	0.260, 0.982	-2.083, -0.315
Anthocyanins (mg/g)	YR-1	1.481a	1.231b	0.852c	-0.379, -0.121	0.205, 0.553
	YR-2	1.966a	1.326b	0.848c	0.512, 0.768	-0.792, -0.165
	YR-3	1.772a	1.196b	0.760b	-0.713, -0.439	-0.135, 1.008
	YR-4	1.547a	1.312b	0.816b	-0.359, -0.111	-0.060, 1.051
	YR-5	1.541a	1.306b	0.725c	0.084, 0.385	-0.950, -0.213
Tannins (mg/g)	YR-1	1.646a	1.644a	1.564a	-0.124, 0.128	-0.389, 0.229
	YR-2	3.390a	2.490b	1.998b	0.694, 1.104	-0.996, 0.010
	YR-3	2.634a	2.299b	1.942b	0.133, 0.537	-0.852, 0.139
	YR-4	1.946a	2.037a	1.783a	-0.252, 0.071	-0.649, 0.141
	YR-5	2.896a	2.404b	1.583c	0.236, 0.748	-1.448, -0.195
Water use efficiency (t/ML)	YR-1	4.39b	6.58a	8.11a	-0.579, -0.223	-0.189, 0.679
	YR-2	2.02b	7.57a	10.09a	-1.076, -0.762	-0.084, 0.682
	YR-3	4.00b	7.91a	8.44a	-0.431, -0.244	-0.173, 0.283
	YR-4	4.47b	6.95a	8.29a	-0.070, -0.030	-0.023, 0.075
	YR-5	4.75b	5.08b	7.81a	-0.023, 0.009	0.014, 0.095

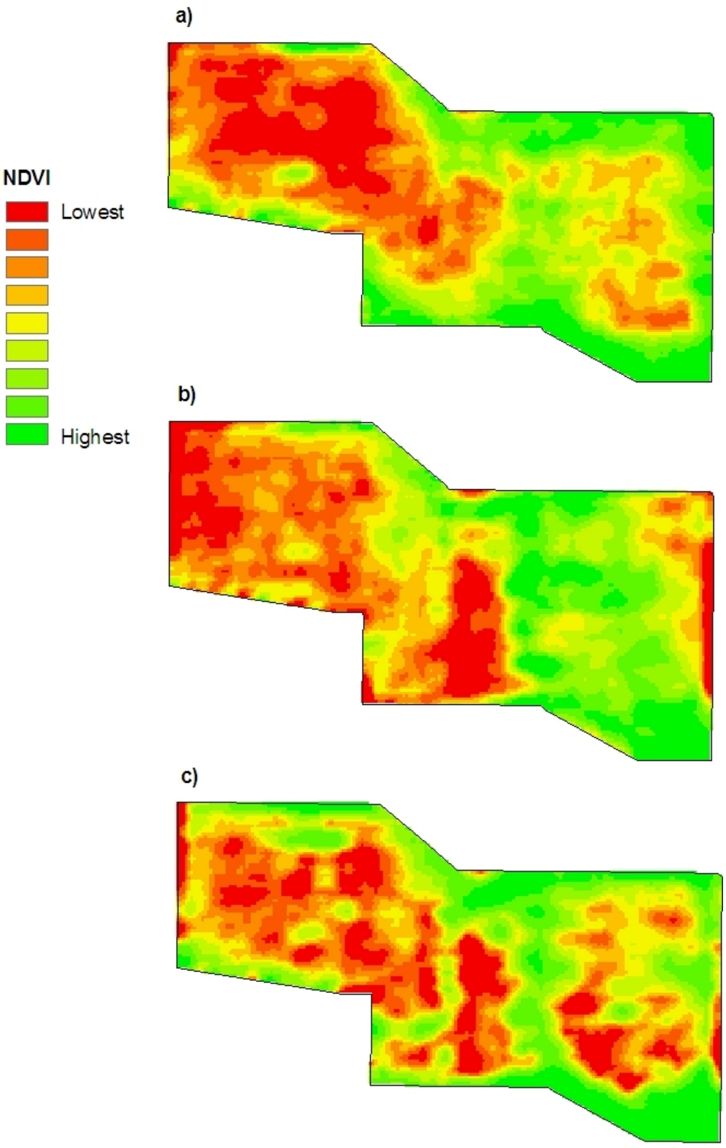

Fig. 1 Relative normalised difference vegetation index (NDVI) at the study site in three consecutive seasons **a)** YR-1, **b)** YR-2 and **c)** YR-3. NDVI was derived from aerial imagery data collected at veraison. A neighbourhood statistical procedure was used to derive these maps without the removal of non-vine data points

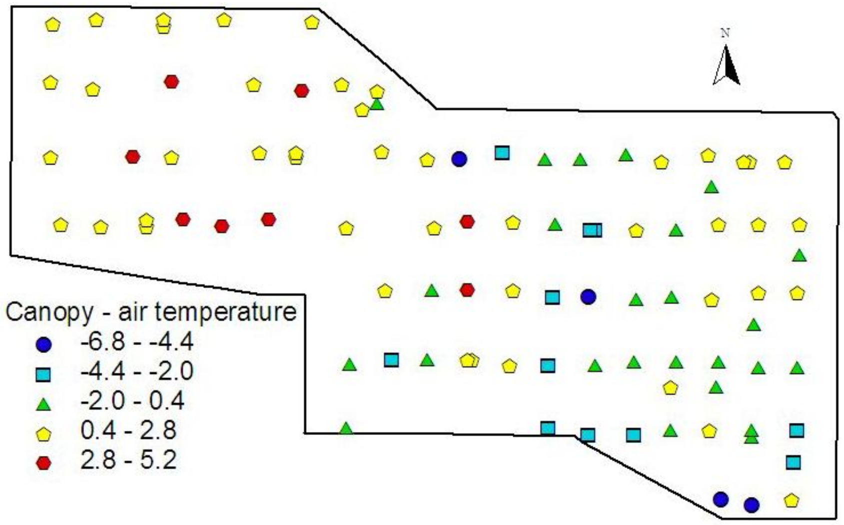

Fig. 2 Spatial variation in canopy – air temperature (°C) for 94 vines on 7 January 2008 (during veraison) in season YR-3. Canopy temperature measurements were taken in the mid-afternoon from directly above the canopy using infrared sensors mounted on an all-terrain vehicle. Air temperature was monitored over nearby, well watered grass

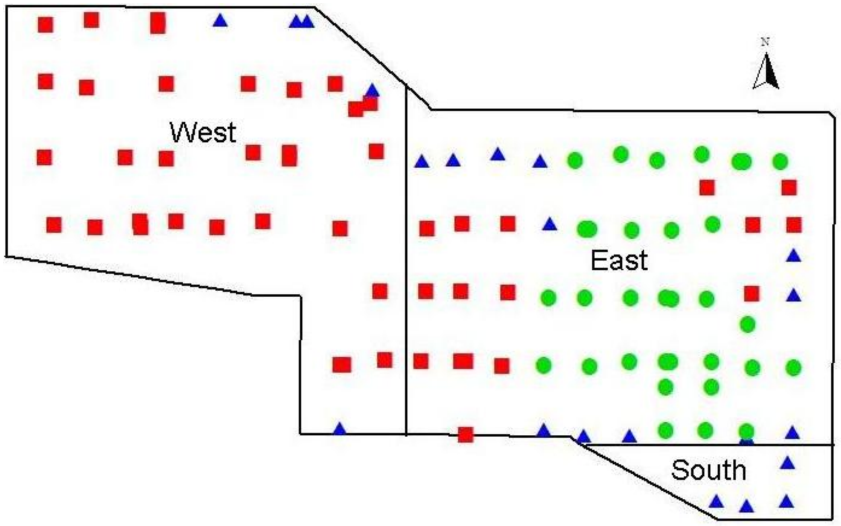

Fig. 3 Site-specific irrigation management zones (East, West and South) within the study block. Points indicate the target vines used for the measurement of yield and fruit composition. The results of the multivariate cluster analysis of normalized difference vegetation index (NDVI) are indicated by squares, circles and triangles showing classification to three clusters