Understanding variability in winegrape production systems 2. Within vineyard variation in quality over several vintages

R.G.V. BRAMLEY

CSIRO Land and Water PMB No. 2, Glen Osmond, SA 5064, Australia

Cooperative Research Centre for Viticulture, PO Box 154 Glen Osmond, SA 5064, Australia

Corresponding author: Dr Rob Bramley, facsimile +61 8 8303 8550, email rob.bramley@csiro.au

Abstract

Spatial variability in various indices of winegrape quality was studied over several vintages in blocks planted to Cabernet Sauvignon and Ruby Cabernet in the Coonawarra (1999–2002) and Sunraysia (2000–2002) regions of Australia. At both sites, inter-annual variation was marked whilst intra-annual variation was much greater for some indices (e.g. concentration of total phenolics) than others (e.g. Baumé). The magnitude of intra-annual variation was readily identified in terms of the 'spread', defined as the difference between the maximum and minimum values, expressed as a % of the median value. Typical values of the spread were 20% for Baumé, but could be as high as 117% for phenolics, and better indicated the extent of variation facing the winemaker than the coefficient of variation (CV; typically 3% for Baumé and 14% for phenolics). For all attributes, variation in any given year showed marked spatial structure, with the patterns of variation being broadly consistent for each attribute in each year of the study, and with many attributes following similar patterns. The results therefore strongly support the idea of zonal vineyard management. However, fruit quality zone identification is dependent on a large sampling effort. Therefore, given the current availability of yield monitors, the finding that between-zone differences in quality indices were generally significant ($P < 0.05$) for zones identified on the basis of yield alone, and, in the absence of an on-the-go sensing capability, it is suggested that zonal management should proceed on the basis of zones of characteristic yield productivity. Based on the present work, it is suggested that development of an on-the-go fruit quality sensing technology would enable the wine industry to maximise its opportunity to gain benefit from differential vineyard management such as selective harvesting. Indeed, the results of this work suggest that in the absence of zonal management, preferably supported by on-the-go quality sensing, winemaker demands for delivery of uniform parcels of fruit are unlikely to be satisfied.

Keywords: *Precision Viticulture, spatial variation, zonal management, Baumé, pH, titratable acidity, colour, phenolics*

Introduction

When asked what they most want from their grapegrowers, winemakers nearly always identify uniform batches of good quality fruit as their main priority. Very often, they further specify that this fruit should come from vines yielding below some threshold level. However, in the first paper of this series, Bramley and Hamilton (2004a) demonstrated that the range of within-vineyard variation in yield was typically 8 to 10-fold (i.e. 2–20 t/ha), and that low yield did not necessarily imply high quality. Furthermore, their maps of yield variation suggest that it is quite possible for the full range of variation in a block to be encompassed in a single row. These observations, together with the fact that it has been known in a general sense that vineyards are variable for as long as grapes have been grown, raise the question as to whether the winemaker's demand for uniform batches of fruit is reasonable?

Bramley and Hamilton (2004a) demonstrated that the patterns of within-vineyard spatial variation in yield were temporally stable. On this basis, they advocated adoption of a system of *zonal vineyard management* in which, rather than being managed uniformly, individual blocks are split into zones of characteristic performance and managed differentially. Thus, for example, different areas within a single block might be pruned to different bud numbers, fertilised at different rates, or selectively harvested; Bramley et al. (2003) and Bramley and Hamilton (2004b) have demonstrated the potential economic benefits of such a strategy. However, whilst Bramley and Hamilton (2004a) were able to show for a Coonawarra vineyard that the delineation of zones on the basis of yield alone was a useful basis for selective harvesting, they also demonstrated that the ranking of wines produced from different zones identified solely on the basis of yield was not necessarily consistent from year to year. This is impor-

tant, because if patterns of variation in yield are matched by patterns of variation in quality, then targeted management of vineyards becomes a much simpler problem than if they are not. On the other hand, in situations where these patterns do not match, it may be undesirable to focus on yield at the expense of quality, and possibly vice versa.

The purpose of this present paper is twofold. The first objective is to consider within-vineyard variation in fruit quality with a view to providing a more robust basis for zonal viticulture than that provided by consideration of yield variation alone. The second objective is to evaluate the extent to which it is possible for grapegrowers to deliver more uniform batches of fruit to the winery than they are currently able to do in the absence of a detailed knowledge of vineyard variability.

Materials and methods

Data collection

The work reported here was carried out in two contrasting vineyards. The first is a 7.3 ha vineyard in the cool-climate Coonawarra region in the south-east of South Australia. This vineyard was planted to Cabernet Sauvignon on its own roots in 1974; its production is focused on super-premium bottled table wine. The second is a 4.5 ha vineyard in the warm, irrigated, Sunraysia region of north western Victoria which was planted to Ruby Cabernet (own roots) in 1989. The fruit from this site is predominantly used for production of high colour bulk wines for blending into cask or lower-value bottled wines to enhance their colour. Data were collected in these vineyards over four vintages at the Coonawarra site (1999–2002) and three vintages (2000–2002) at the Sunraysia site. Both these sites were also used in the study of yield variation described in the first paper in this series (Bramley and Hamilton 2004a).

At each site, the sampling strategy used was based on a regular grid, the dimensions of which were determined by the vine and row spacing; the nodes of the sampling grid were defined by the locations of the trunks of target vines. Samples were collected at an intensity of approximately 26 samples/ha in Coonawarra in 1999 which was considered the maximum number possible given available resources. However, subsequent data processing (see below) suggested that this sampling intensity enabled production of robust maps of vine variation (as indicated by maps of kriging variances – see below) and it was therefore adopted for the remainder of the study. Thus, 190 target vines were sampled at the Coonawarra site and 130 vines in Sunraysia (120 in 2000). However, for the two sampling occasions after vintage 2000 in Coonawarra, rather than sampling at every grid node, approximately 15% of the grid nodes were left unsampled with the samples that would have been taken at these points reassigned to vines that were either adjacent to (along the row) or directly opposite (1 row away) other target vines (Figure 1a). This modification of the grid design was an attempt to satisfy the requirement of minimising the ratio of the smallest:largest sample separation distance (Bramley and White 1991), in order to maximise our opportunity to

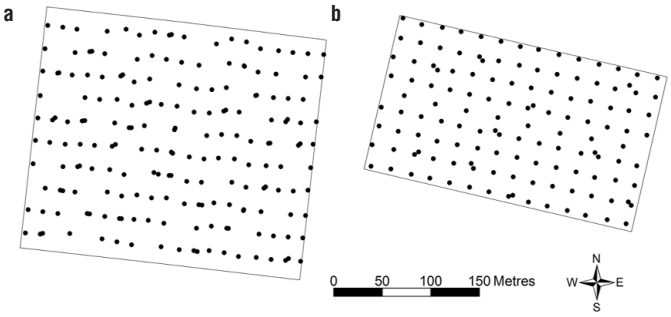

Figure 1. Sampling strategy used in (a) Coonawarra and (b) Sunraysia. Note that a regular grid forms the basis of (a), but with sampling points randomly removed from 30 of the grid nodes and reallocated to vines adjacent to other grid nodes; the latter were also randomly selected. See text for further explanation.

define the range of spatial dependence (e.g. Trangmar et al. 1985, Isaaks and Srivastava 1989, Webster and Oliver 2001) of vine variation. In Sunraysia, rather than deleting some of the sampling locations used in 2000, an additional 10 target vines (adjacent to, or opposite others) were added to the sampling strategy for 2001 and 2002. All sampling locations were geo-referenced using a differentially corrected global positioning system (dGPS), accurate to approximately ± 50 cm in the x and y planes.

At both sites, sample collection took place as close to harvest as possible. In some cases this meant that sampling occurred a few hours before harvest; in others, sampling was done a few days, but always less than 1 week, before harvest. Samples were taken from either whole vines (Coonawarra 1999–2001), a 1 m length of row centred on the trunk of the target vine (Coonawarra 2002), or a 0.5 m length of row measured from the trunk of the target vine (Sunraysia all years). All bunches were harvested by hand into a picking bucket. For each target vine, the number of bunches and their total mass were recorded; note that variation in the components of yield will be the subject of the next paper in this series. Harvested bunches were then mixed and randomly sampled such that approximately 1.5 kg fruit/vine was retained for further analysis.

Berries were randomly stripped from the retained bunches from the entire length of the bunch to give a representative sample of berries for each vine. Sampled berries were then mixed and triplicate samples, each of 50 berries, were counted into plastic vials which were subsequently weighed for determination of mean berry weight. These were then frozen (–30°C) for analysis of colour and phenolics at a later date. At Coonawarra, the juice was extracted from all of the fruit remaining from the initial 1.5 kg sample using a small bag press. At Sunraysia, juice was obtained from a sample of approximately 200 randomly selected berries by squeezing these in a large garlic crusher. In both cases, these fresh juice samples were analysed immediately for their pH, titratable acidity (TA) and Baumé/Brix using standard industry methods (Iland et al. 2000). The concentrations of colour and phenolics in homogenates of 50 berry samples (see above) were analysed at a later date using standard spectrophotometric methods (Iland et al. 2000). An exception to the latter occurred in 2002 when the near infrared

(NIR) method (Dambergs et al. 2003) was used for determination of colour and phenolics. Equivalent 'wet chemistry' values were estimated based on regression relationships derived from 10% of the sample set which was analysed by both methods (R^2 = 0.90 and 0.89 for colour and phenolics, respectively), thus enabling comparison of analytical data for these analytes between different years of the study.

Mapping and spatial analysis

For each year, and for each analyte, maps were interpolated onto a 2 m grid (pixels of 4 m^2) by global point kriging of the vine data using VESPER (Minasny et al. 1999). It is not within the scope of this paper to provide a detailed discussion of kriging or other geostatistical methods and readers interested in fuller accounts of these are referred to Trangmar et al. (1985), Isaaks and Srivastava (1989) and Webster and Oliver (2001). Suffice to say here that kriging is an interpolation procedure in which estimates of values at unsampled sites are interpolated on the basis of known values at georeferenced locations, weighted according to the parameters of the *variogram* – a model that describes variation within a dataset as a function of the distance or *lag* separating the samples comprising it. Its important parameters are the *sill* (equivalent to the sample variance), the *nugget variance*, which is equivalent to the true sampling and measurement error, and which is independent of location, and the *range* of spatial dependence. Samples that are closer together than the range are said to be spatially dependent; that is, their values are similar. Conversely, samples separated by distances greater than the range are independent of each other and therefore differ as a function of random, rather than spatial, effects. The ratio of the nugget variance to the sill provides an indication of the strength of spatial dependence (Trangmar et al. 1985, Cambardella et al. 1994). In order to provide a comparative assessment of the degree of spatial variation amongst the various fruit attributes measured, the variograms for all fruit attributes were fitted with an exponential model only, and with a common set of input parameters and boundary conditions (maximum distance, number of lags) when running VESPER (Minasny et al. 1999; maximum distance = 150 m; 30 lags; 50% lag tolerance).

As discussed in the first paper of this series (Bramley and Hamilton 2004a), knowing about spatial variation in vineyards is all very well, but in the absence of knowledge as to the temporal stability of the patterns of variation, it is of questionable value. On the other hand, if the patterns of spatial variation are temporally stable, then the data take on a significant predictive value. It is also of interest to know to what extent the various indices of fruit quality are spatially correlated given that winemakers use a variety of these rather than a single index or attribute. *k*-means clustering lends itself to investigation of both of these issues.

k-means clustering is a non-hierarchical method of data aggregation that maximises the Euclidean distance between cluster means and minimises the distances within the clusters. It was successfully used to demonstrate temporal stability in the patterns of yield variation (1999–2001) at the Coonawarra site (Bramley and Hamilton 2004a). As was the case in the first paper in this series, the cluster analysis was carried out using the kriged map surfaces (i.e. the output from VESPER) rather than the raw vine data.

Analysis and presentation of the outputs from VESPER (Minasny et al. 1999) was carried out in ARCVIEW (version 8.3; ESRI 2003) using the SPATIAL ANALYST extension. All other statistical analysis was carried out using JMP (version 5.0.1; SAS 2002).

Results and discussion

Gross variation

At both sites, there was considerable inter-annual variation in all indices of fruit quality (Table 1). In terms of intra-annual variation however, some indices (e.g. phenolics) tended to be more variable than others (e.g. Baumé), when expressed in terms of their coefficients of variation (CV). On this basis, it might be concluded that variation in fruit quality at harvest is considerably less than variation in yield (Bramley and Hamilton 2004a). Indeed, Bramley and Hamilton (2004a) reported within-vineyard yield variation at these sites to be of the order of 8 to 10-fold which, in the case of their yield monitor data, translates to a CV of around 40%.

The fact that the values reported in Table 1 are consistent with those reported by Krstic et al. (2002) suggests that in terms of the magnitude of the variation, the two study sites are broadly typical of other Australian vineyards. However, whilst CV provides an index of gross variation that is meaningful to biometricians and scientists, it can easily disguise the actual amount of variation which, in this case, the winemaker has to accommodate. Thus, the range (difference between maximum and minimum) may be a more useful indicator of gross variation; Table 1 indicates a 3-fold range of within-vineyard variation in some indices of quality. However, for the purpose of better comparing the magnitude of variation amongst quality indices and between years, an additional index, here referred to as the 'spread', is proposed (Table 1), where 'spread' is the range (max–min) expressed as a percentage of the median. In essence, 'spread' provides part of the information conveyed in a standard 'box plot' as a single number. I suggest that this index provides winemakers with a more informative indication of how much variability there is in the fruit that they are faced with processing. Thus, there is only a 15% spread (CV of approximately 3%) in within-vineyard variation in maturity (Baumé) at harvest, whereas the concentrations of colour (anthocyanins) and total phenolics (CVs of approximately 14%) have an average spread of around 85% (Table 1). Given the importance of colour as a quality index, and the acknowledged relationship between juice colour and wine quality (Francis et al. 1999, Gishen et al. 2002), it is suggested that the knowledge that within-vineyard variation in fruit quality (and therefore of wine quality) is of the order of two-fold is more valuable with respect to the tasks facing the winemaker, particularly in terms of fruit parcelling, than knowing that the CV is

Table 1. Summary statistics for selected indices of fruit quality at harvest.[1]

		Coonawarra Cabernet Sauvignon				Sunraysia Ruby Cabernet			
Attribute	**Year**	**Median**	**Range**	**CV%**	**Spread[2]**	**Median**	**Range**	**CV%**	**Spread[2]**
Baumé (°)	1999	14.6	13.4–15.6	2.8	15.1				
	2000	13.2	12.1–14.0	2.6	14.4	13.2	10.9–15.7	5.5	36.6
	2001	13.3	11.4–14.7	3.9	24.8	13.7	12.2–14.5	2.8	16.7
	2002	14.3	12.9–15.8	4.0	20.7	14.8	12.0–17.3	6.8	35.7
Juice pH	1999	3.65	3.29–4.22	5.2	25.5				
	2000	3.66	3.35–4.39	4.7	28.4	3.91	3.63–4.27	3.2	16.4
	2001	3.51	3.25–3.93	4.3	19.4	3.90	3.64–4.22	2.8	14.9
	2002	3.84	3.44–4.31	4.4	22.7	4.17	3.89–4.48	2.7	14.2
TA (g/L)	1999	5.10	3.30–7.90	15.4	90.2				
	2000	4.90	4.00–6.60	9.8	53.1	4.64	3.36–5.90	10.6	54.8
	2001	5.00	3.70–7.80	13.4	82.0	4.13	3.20–5.01	9.4	43.8
	2002	4.80	3.80–6.10	10.7	47.9	5.41	4.18–7.25	9.4	56.8
Anthocyanins	1999	1.80	1.13–2.89	13.7	97.4				
(mg/g)	2000	1.93	1.23–2.83	15.7	82.6	2.33	1.23–3.07	12.7	78.9
	2001	1.00	0.58–1.73	18.1	115.0	2.32	1.69–3.34	14.7	71.1
	2002	2.61	1.06–3.71	21.6	101.3	2.25	1.57–3.45	11.7	83.4
Phenolics	1999	1.51	1.04–2.32	11.0	85.4				
(a.u./g)	2000	1.66	1.17–2.37	13.5	72.5	1.87	1.30–2.43	11.5	60.8
	2001	0.89	0.45–1.50	19.0	117.6	1.82	1.52–2.48	10.4	52.6
	2002	1.67	0.88–2.43	13.9	92.4	1.56	1.07–2.20	13.5	72.5
Berry weight	1999	0.77	0.44–1.27	14.5	109.7				
(g)	2000	0.91	0.35–1.19	15.4	91.8	0.87	0.34–1.24	21.8	103.5
	2001	0.95	0.25–1.35	18.4	116.9	0.80	0.36–1.21	22.3	107.3
	2002	0.68	0.30–0.88	15.7	86.0	0.91	0.43–1.52	22.8	119.5

[1] Note that at Coonawarra, the number of samples (*n*) was 190 for the majority of years/attributes and was never less than 182; in Sunraysia, *n* was not less than 118 in 2000 and not less than 129 in 2001–2002.
[2] Spread is defined as the range divided by the median, expressed as a percentage.

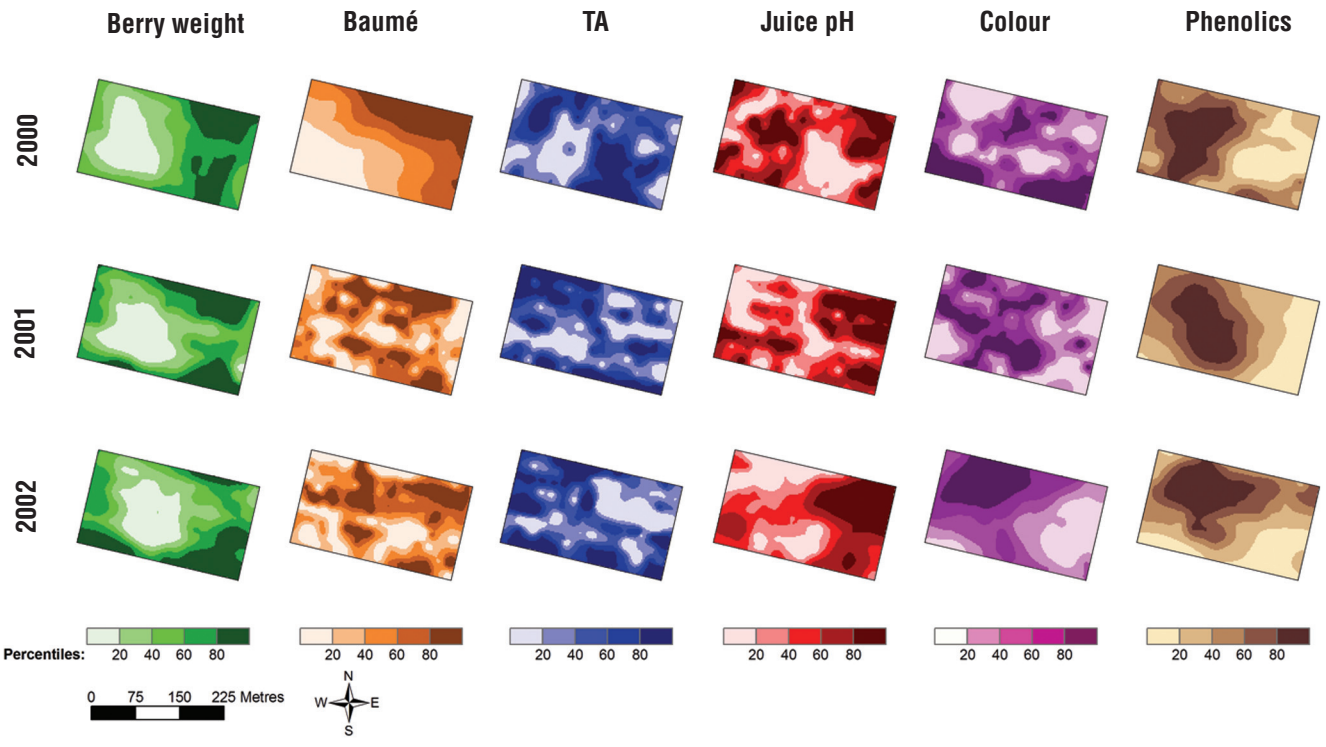

Figure 2. Spatial variation in some common indices of fruit quality in a 4.5 ha Sunraysia vineyard planted to Ruby Cabernet in 1989. Note that for each index in each year, the figure legends reflect a classification of the data based on 20th percentiles.

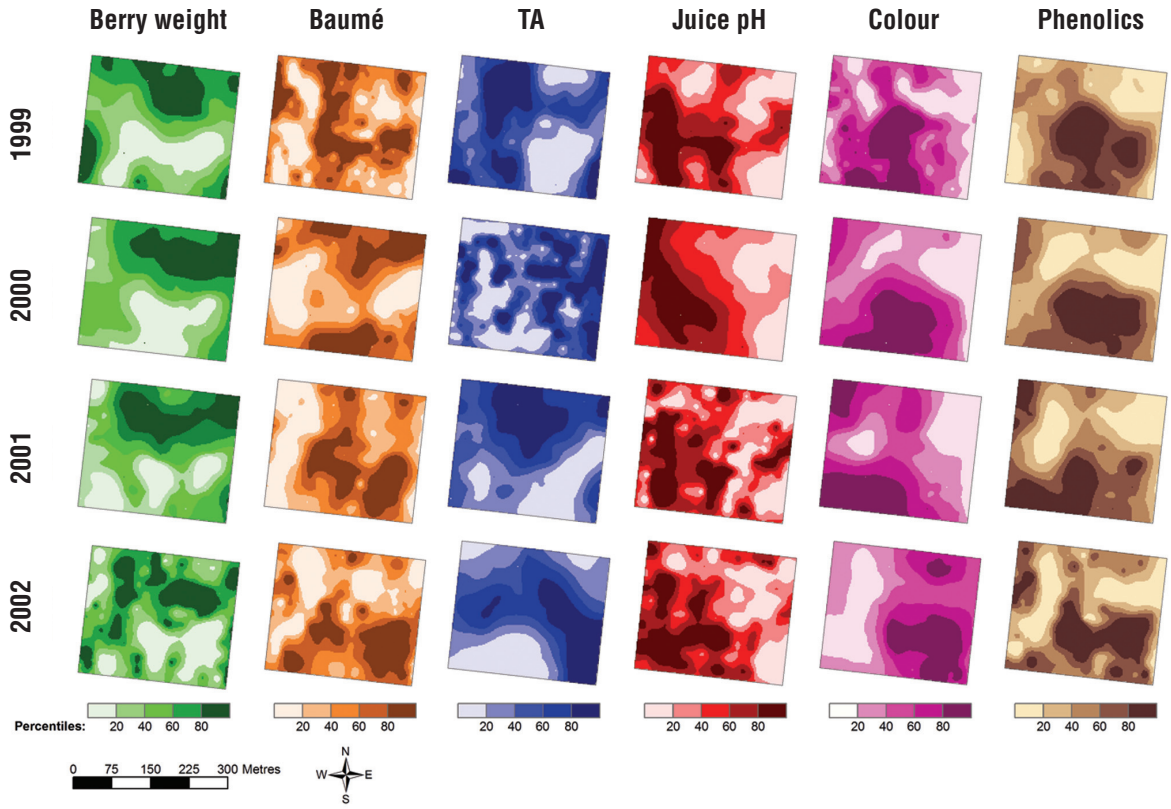

Figure 3. Spatial variation in some common indices of fruit quality in a 7.3 ha Coonawarra vineyard planted to Cabernet Sauvignon in 1974. Note that for each index in each year, the figure legends reflect a classification of the data based on 20th percentiles.

14%. It is conceivable that, in the future, such knowledge may also impact on the price of both the grapes delivered to the winery, and also the finished wines and the manner in which they are marketed.

Spatial variation

Neither the CV nor the 'spread' provide information about the spatial structure (if any) of the variation; indeed, both are simple indices of gross variation and tell us nothing about possible differences between different parts of a vineyard. Given that both the Coonawarra and Sunraysia datasets derive from single vineyards which, hitherto, have been harvested as single parcels, both indices are still potentially useful, especially the spread, as indicated above. However, as Bramley and Hamilton (2004a) have pointed out, knowing about the spatial component of the variation promotes a capacity for targeted, or *zonal* management, and with respect to fruit and wine quality, may provide a basis for reducing the variability within individual parcels of fruit delivered to the winery.

Variation in all the indices measured appeared to show marked spatial structure at both the Sunraysia (Figure 2) and Coonawarra (Figure 3) sites. However, when the magnitude of these spatial effects was assessed using the index of Cambardella et al. (1994), most of the fruit attributes measured exhibited a 'moderate' degree of spatial dependence; that is, the ratio of nugget:sill variance was between 26 and 75 when expressed as a percentage. Note that this classification of nugget:sill variance (Cambardella et al. 1994) is entirely qualitative. Nevertheless, it highlights a relatively large *nugget effect* in the fruit quality data from both the Coonawarra and Sunraysia sites. Because of this, together with the maximum distance constraint placed on variogram fitting (150 m), many of the variograms were fairly flat with a large range of spatial dependence relative to the dimensions of each block; the mean range of spatial dependence was 85 ± 2 m in Sunraysia and 133 ± 5 m in Coonawarra. The lack of strong spatial structure in the variograms might also be a reflection of the sampling design used here being less than optimal for defining short-range variation, in spite of some samples being only one vine spacing or row width apart. This result could also be a consequence of a high degree of within-vine, and vine to vine variation (Johnstone 1999, Trought et al. 1997).

One consequence of flatish variograms is that the kriging process results in a lot of smoothing. Hence, the distribution of interpolated values is 'tighter' than that for the raw data. It is partly for this reason that the legends to Figures 2 and 3 are expressed in terms of 20th percentiles, although this was also done to facilitate comparison of maps between years and identification of areas within each block where an attribute had consistently relatively low or high values. Clearly, both Figures 2 and 3 suggest that, just as yield exhibits marked spatial structure (Bramley and Hamilton 2004a), so too do these various indices of fruit quality, albeit with a less strong delineation between high and low values. In other words, within-vineyard variation in fruit quality is not random, as is implicit in the work of Krstic et al. (2002). The present results therefore support the view that grape sampling for quality assessment would be improved if carried out with some knowledge of the likely spatial structure of the variation.

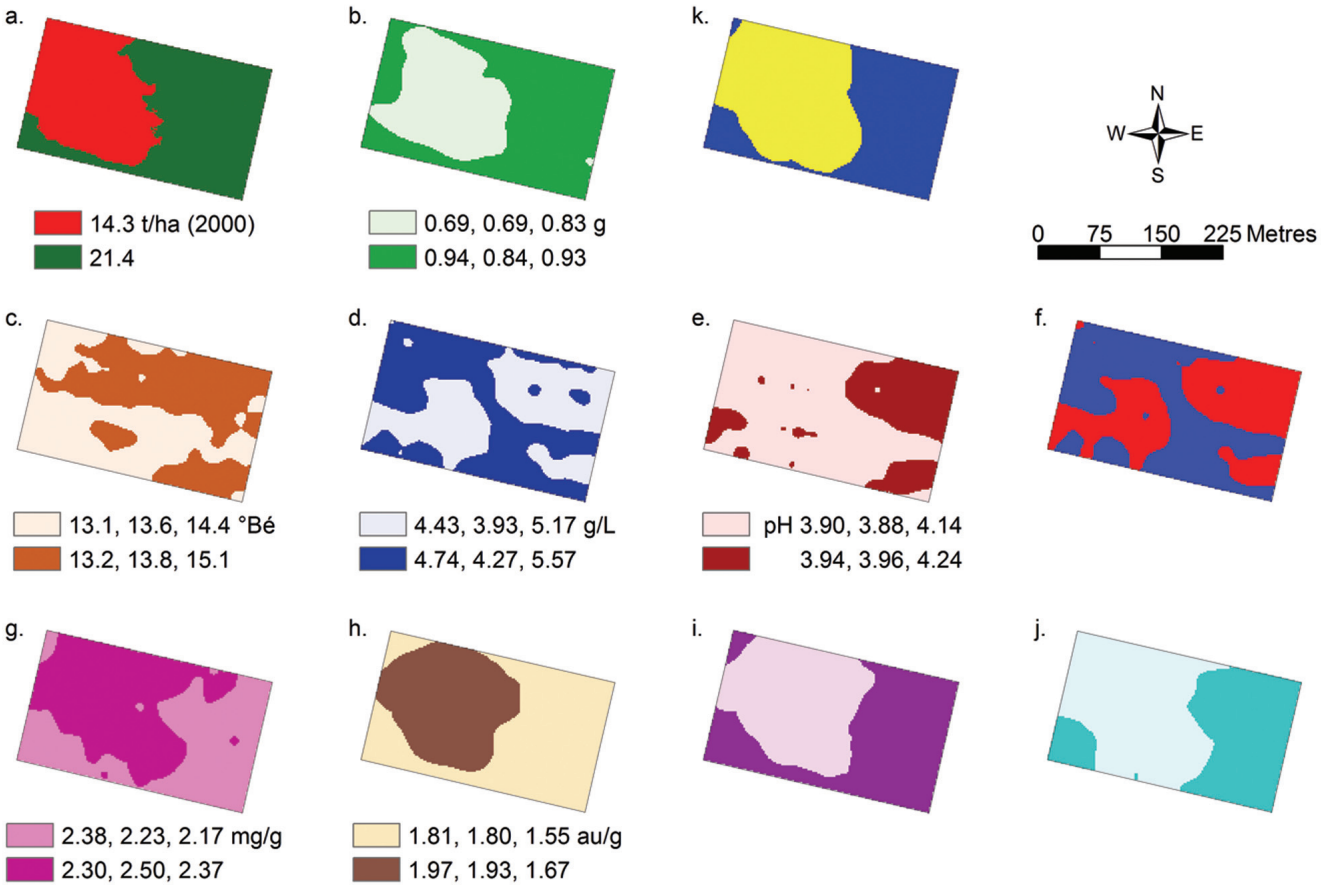

Figure 4. Results of *k*-means clustering (Sunraysia site – two cluster solutions) of interpolated estimates of (a) yield as measured using a yield monitor (vintage 2000; Bramley and Hamilton 2004a) and bulk electrical soil conductivity as measured using EM38 sensing (Bramley 2001), and of field/laboratory measurements of (b) berry weight, (c) Baumé, (d) titratable acidity (TA, (e) juice pH, (f) pH and TA, (g) colour (anthocyanins), (h) phenolics, (i) colour and phenolics, (j) all chemical attributes and (k) all chemical attributes plus berry weight. The legends to the single attribute maps indicate (left to right) the cluster means in 2000, 2001 and 2002. For each map, the different colours indicate the locations of the two clusters.

Cluster analysis

Figures 4 and 5 show the results of cluster analyses for the Sunraysia and Coonawarra sites. For Coonawarra, 3 cluster solutions were pursued initially given the finding (Bramley and Hamilton 2004a) that this vineyard could sensibly be split into 3 significantly differently ($P < 0.05$) yielding zones based on the yield maps obtained in 1999–2001 (Figure 5a). For Sunraysia, two-cluster solutions were chosen. This was done for the following reasons. First, Bramley (2001) has previously observed that patterns of yield variation in this vineyard closely match variation in soil properties (the amount and/or position of clay in the soil profile). Second, the vineyard owner was of the view that the western half performed less well than the eastern half, possibly due to it being prone to waterlogging in winter and spring. Third, the results of a *k*-means cluster analysis of yield, as measured using a yield monitor (vintage 2000), and bulk electrical soil conductivity, as measured using inductively coupled electromagnetic induction (EM38) soil survey (e.g. Bramley et al. 2002) suggest strong similarities between variation in both yield and soil properties (Bramley 2001). Thus, the results of clustering the yield map and EM38 map (Figure 4a) suggest that the block can be split into two zones. Using a test of significance based on the kriging variance (Cuppitt and Whelan 2001, Bramley and Hamilton 2004a), these zones can be seen to be significantly different ($P < 0.05$) with respect to both yield (Figure 4a) and bulk electrical soil conductivity.

k-means clustering of Sunraysia berry weight measurements over 3 vintages (Figure 4b) suggested a pattern of variation very similar to that for yield (Figure 4a). Similarly, variation in colour (Figure 4g) and phenolics (Figure 4h), and thus, colour and phenolics combined (Figure 4i), matches the zonation identified from yield and soil data. In contrast, variation in Baumé (Figure 4c), TA (Figure 4d) and pH (Figure 4e) suggests a somewhat different zonation to the other attributes; as expected, TA and pH exhibit similar spatial structure (Figures 4d–f). However, when all these chemical attributes are clustered together, either with (Figure 4k) or without (Figure 4j) berry weight, it appears that whilst the western zone may be characterised as performing poorly with respect to yield, it can also be characterised as producing more desirable fruit – smaller berries with higher concentrations of colour (except vintage 2000) and phenolics.

In Coonawarra the picture was less clear. Areas of low berry weight (Figure 5b) tend to correspond to areas of

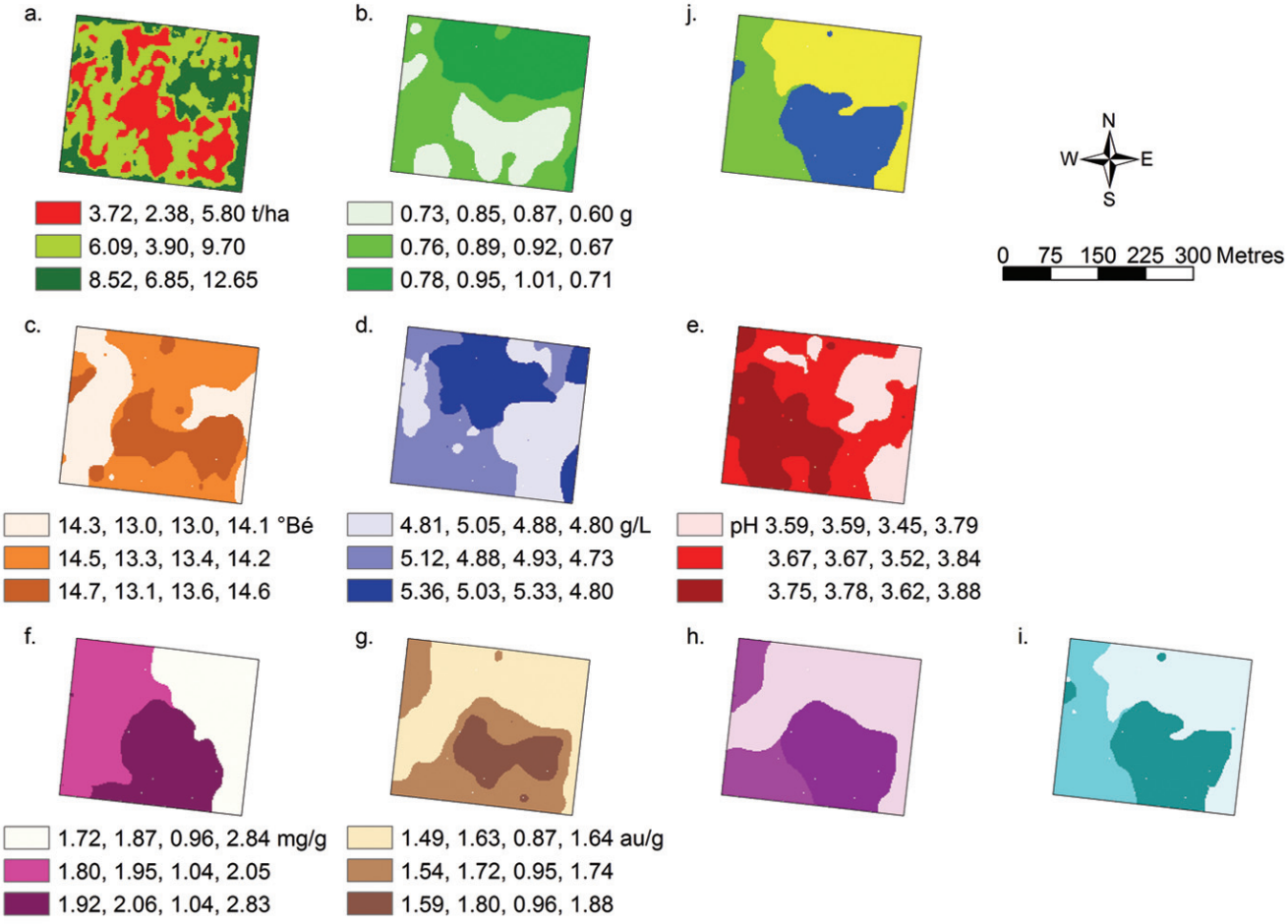

Figure 5. Results of *k*-means clustering (Coonawarra site – three cluster solutions) of interpolated estimates of (a) yield as measured using a yield monitor (1999–2001; Bramley and Hamilton 2004a), and of (b) berry weight, (c) Baumé, (d) titratable acidity, (e) juice pH, (f) colour (anthocyanins), (g) phenolics, (h) colour and phenolics, (i) all chemical attributes and (j) all chemical attributes plus berry weight as measured following field sampling and laboratory analysis. Note that the apparent difference in the resolution of map (a) compared to maps (b–j) is due to the latter being derived from the interpolated surfaces shown in Figure 3 (i.e. up to 190 field measurements) which have a smaller *support* (e.g. Webster and Oliver 2001) than map (a) which is based on surfaces interpolated from over 10,000 data points. The legends to the single attribute maps indicate (left to right) the cluster means in each year (1999–2002). For each map, the three colours indicate the locations of the different clusters.

low yield (Figure 5a) and these also tend to have higher colour (Figure 5f) and phenolics (Figure 5g) than the higher yielding parts of the block. As in Sunraysia, the patterns of colour and phenolics are similar (Figure 5f–h), but those of pH (Figure 5e) and TA (Figure 5d) are much less so. Further, variation in Baumé (Figure 5c) appears to be being driven by different factors to the other attributes as evidenced by the fact that whilst the zone of highest Baumé corresponds broadly to the area of low yield in the southern part of the block, regions of low Baumé occur in both the high yielding area towards the north-east and the low yielding strip on the western side. The drivers of this variation, and in particular, a possible effect of vine nutrient status on yield and fruit quality variation are explored in a later paper in this series. Simplification of the Coonawarra zonation through the use of a two-cluster solution did not assist in understanding the inter-relationships between the various attributes or in interpreting their spatial structure (data not shown).

Notwithstanding the less obvious zonation for selected attributes in Coonawarra compared to Sunraysia, when all the attributes are clustered together, either with (Figure 5j) or without (Figure 5i) berry weight, a similar result is obtained to that for Sunraysia. That is, a zonation similar to that identified for berry weight alone is apparent; the low yield / low berry weight zone in the southern part of the block stands out as one zone, another is centred around the higher yielding area in the north-east, whilst the third broadly corresponds to the lower yielding, low Baumé western portion. This result highlights the utility and uniquenes of berry weight as an index of both yield (high yield tends to imply large berries) and quality (high quality tends to result from small berries).

The legends to the single-attribute maps shown in Figures 4 and 5 suggest that the differences between cluster means are small. Indeed, most practitioners would probably dismiss them as being too small to impact on management. Note however, that the *k*-means clustering analysis shown in Figures 4 and 5 was done using the interpolated data shown in Figures 2 and 3. As indicated above, the kriging process has tightened the distributions of the data due to the smoothing that occurs when using

Table 2. Year and zone based means (2000–2002) for selected fruit attributes in low (L) and high (H) yielding zones within a 4.5 ha Sunraysia vineyard planted to Ruby Cabernet in 1989.[1]

Year	Zone	Berry wt (g)	Baumé (°)	pH	TA (g/L)	Colour conc. (mg/g)[2]	Phenolics conc. (au/g)[2]
2000	L	0.70a	13.1a	3.92a	4.48a	2.28a	1.96b
	H	0.96b	13.2a	3.91a	4.67b	2.39b	1.81a
2001	L	0.70a	13.6a	3.87a	4.12a	2.44b	1.93b
	H	0.86b	13.7a	3.93b	4.11a	2.30a	1.79a
2002	L	0.83a	14.7a	4.13a	5.45a	2.39b	1.66b
	H	0.96b	14.7a	4.20b	5.36a	2.19a	1.55a

[1] Data reported are the means of samples collected immediately prior to vintage from a 0.5 m length of row measured from the trunk of target vines. For any given vine property and year, zone means that are not connected by the same letter are significantly different ($P < 0.05$). 120 vines were sampled in 2000; 130 vines were sampled subsequently. In 2000, the number of samples (n) contributing to the means was not less than 118; in 2001 and 2002, n was not less than 129. The distribution of the sampled vines between the low and high yielding zones was 52 and 68 in 2000, and 57 and 73 in 2001 and 2002. The differences in these numbers between 2000 and subsequently reflects a change made to our sampling strategy to improve characterisation of spatial variation. 120 of the sampled vines were common to all years.
[2] Colour and phenolics are expressed as the concentrations of total anthocyanins and phenolics (Iland et al. 2000).

Table 3. Year and zone based means (1999–2002) for selected fruit attributes in low (L), medium (M) and high (H) yielding zones within a 7.3 ha Coonawarra vineyard planted to Cabernet Sauvignon in 1974.[1]

Year	Zone	Berry wt (g)	Baumé (°)	pH	TA (g/L)	Colour conc. (mg/g)[2]	Phenolics conc. (au/g)[2]
1999	L	0.71a	14.7c	3.77c	4.78a	1.91c	1.60c
	M	0.77b	14.5b	3.66b	5.14b	1.81b	1.52b
	H	0.81b	14.3a	3.56a	5.46c	1.65a	1.41a
2000	L	0.81a	13.1a	3.77c	4.91a	2.13c	1.82c
	M	0.92b	13.1a	3.68b	4.89a	1.90b	1.64b
	H	0.98c	13.2a	3.57a	5.27b	1.77a	1.56a
2001	L	0.82a	13.6c	3.64c	4.77a	1.09c	1.01c
	M	0.98b	13.3b	3.49b	5.07b	1.00b	0.88b
	H	1.03b	13.0a	3.45a	5.31c	0.90a	0.81a
2002	L	0.60a	14.6c	3.93c	4.65a	2.62a	1.85c
	M	0.68b	14.2b	3.82b	4.82ab	2.51a	1.69b
	H	0.74c	14.0a	3.75a	4.90b	2.54a	1.55a

[1] Data reported are the means of samples collected immediately prior to vintage. For 1999–2001, these samples were from whole vines. In 2002, they were taken from a metre of vine row centred on the trunk of target vines. For any given vine property and year, zone means that are not connected by the same letter are significantly different ($P < 0.05$). In each year, 190 vines were sampled. In 1999 and 2000, n was 190 for all properties reported; in 2001 n was not less than 186; and in 2002, n was not less than 182. The distribution of the 190 sampled vines amongst the low, medium and high zones was 66, 79 and 45 in 1999 and 2000, and 63, 83 and 44 in 2001 and 2002. The differences in these numbers between 2000 and 2001 reflects a change made to our sampling strategy to improve characterisation of spatial variation. 160 of the sampled vines were common to all years.
[2] Colour and phenolics are expressed as the concentrations of total anthocyanins and phenolics (Iland et al. 2000).

variograms with a relatively large nugget variance. Further, the test for the significance of differences between cluster means using the method of Cuppitt and Whelan (2001) does not work here, as it did for maps derived from a yield monitor or high intensity soil survey (e.g. Figure 4a), because the latter were produced using *local* kriging and a *support* (e.g. Webster and Oliver 2001) of several thousand data points, whereas the maps of these fruit attributes (Figure 2), were produced using *global* kriging and no more than 130 data points. Consequently, the interpolation distances in the present study are larger than for yield maps, as is the total amount of variation encompassed in a single variogram, and the kriging variances which, as a result, do not offer a useful basis for a test of significance between cluster means. Note that a standard *t*-test cannot be used on this kind of data because of the large number of pixels (i.e. data points) in each cluster map, which means that the degrees of freedom for the test are so large that even very small differences are statistically significant (as is the case here using a standard test). Nevertheless, Figure 4 is striking in that it suggests strong similarity in the spatial structure of attributes that one might expect to vary similarly (e.g. colour and phenolics, or pH and TA), and also indicates that in this vineyard the patterns of variation in fruit quality follow similar patterns to variation in yield. It is therefore suggested that notwithstanding the smaller differences between cluster means, both the kriging and *k*-means clustering analyses undertaken for Sunraysia have provided useful information about spatial variation in fruit quality.

This last point is further demonstrated by Table 2 which shows zone-based means for the various fruit indices in Sunraysia. These were calculated from the raw vine data when the target vines (Figure 1b) were divided into those which lie in either the western, or low yielding zone (L; Figure 4a), and those from the eastern, or higher yielding zone (H). Table 3 presents a similar analysis for Coonawarra based on the allocation of target vines (Figure 1a) to the yield zones identified by Bramley and Hamilton (2004a; Figure 5a). Both Table 2 and Table 3 clearly indicate, in the absence of any confounding effects attributable to kriging sparse data, that at both sites, the zones identified on the basis of yield differ significantly ($P < 0.05$) in each year of the study with respect to many of the fruit attributes measured. In Sunraysia, the yield-based zones differ each year with respect to berry weight, colour and phenolics. In contrast, Baumé shows no significant difference ($P > 0.05$) between the zones, whilst the results for pH and TA show significant differences in only 1 or 2 years – a result which is perhaps reflective of the different patterns shown in Figure 4. In Coonawarra, consistent and significant ($P < 0.05$) differences between the zones are seen with respect to pH and phenolics, whilst similar significant differences exist for most of the attributes in most years. The exceptions are Baumé (vintage 2000), TA (vintage 2000 and 2002), colour (2002) and berry weight (1999 and 2001). Note that both 2000, and in particular 2002, were low yielding years, whilst 2001 was a high yielding year; 1999 was an average year. Thus, Table 3

suggests that in low yielding years, there may be little to be gained from zonal management in terms of fruit quality, whilst in higher yielding years, there may be compelling fruit quality reasons for considering targeted management, even though inter-zonal differences in berry weight suggest little difference between the medium and higher yielding areas.

As indicated above, whether these differences are large enough to impact on the decision-making of winemakers is open to debate, especially given that many winemakers do not currently analyse for colour and phenolics. However, the present results strongly suggest that zonal management (Bramley and Hamilton 2004a) may offer opportunities (e.g. Bramley and Hamilton 2004b, Bramley et al. 2003) that are not available when vineyards are managed uniformly. This is especially the case for the Sunraysia vineyard, given that the yield and quality zones (Figure 4) appear to be the same.

Taken overall, the present results also lend weight to the idea that for zonal management to be most effective, zone-based monitoring of fruit quality, as opposed to whole-block monitoring, will be essential (Bramley and Hamilton 2004b). This is important because whilst the location of the yield-derived zones is temporally stable (Bramley and Hamilton 2004a), their relative ranking with respect to selected quality indices may not be. Thus, had a sensory evaluation of fruit and final wines been included in the present study, the opportunities of zonal management might have been as obvious as was the case in other vineyards in Padthaway (Bramley and Hamilton 2004b) and Margaret River (Bramley et al. 2003).

Finally, it should be emphasised that the work presented here was based on hand sampling vines and fruit at sampling rates that would be considered impractical in commercial vineyards. In light of this, and also possible misgivings as to whether sufficient samples were taken in this study, and the extent to which short range spatial variation has been adequately characterised by the sampling strategies used (Figure 1), this work points to the desirability of the wine industry having access to an on-the-go fruit sensing capacity, analogous to existing yield monitoring technology. Given the apparent temporal stability in the patterns of spatial variation shown in Figures 2–5, the predictive utility of the data that would derive from such an instrument would clearly be at least as great as is the case for the data provided by yield monitors, especially if coupled to a program of zone-based sampling as an aid to seasonal decision making (Bramley and Hamilton 2004a).

No technology for on-the-go fruit quality sensing is currently commercially available. Whether such technology develops from the laboratory-based NIR methods of Dambergs et al. (2003) or from a remote sensing basis (Lamb et al. 2004) remains to be seen, although at the time of writing, at least two on-the-go winegrape quality assessment systems are known to be under development including that reported by Tisseyre et al. (2001). The work of Dambergs et al. (2003) suggests that, with the exception of TA, an on-the-go NIR-based sensor could potentially assess all of the analytes discussed here.

Conclusions

Just as the within-vineyard yield of winegrapes is spatially variable, so too is their quality at harvest, albeit with a smaller range (max–min) of values in any given year. Whilst this variation appears to be sufficiently temporally stable to justify the identification of 'quality zones' within vineyards, in the absence of an on-the-go quality sensing technology, the use of a zonation based on yield monitoring, rather than fruit analysis, seems justified. This is especially so, given the large sampling and analytical requirement for characterisation of spatial variation in fruit quality, and the finding that fruit quality indices differ significantly between zones identified on the basis of yield alone. It is further suggested that until zonal management is adopted by the wine industry, winemaker demands for delivery of uniform parcels of fruit are unlikely to be satisfied.

Acknowledgements

This work was funded by CSIRO Land and Water (CLW), Southcorp Wines Pty Ltd (SCW), the Commonwealth Cooperative Research Centres Program under the aegis of the Cooperative Research Centre for Viticulture (CRCV) and Australia's grapegrowers and winemakers through their investment body the Grape and Wine Research and Development Corporation. Support from the latter was matched by the Federal Government. In addition to these organisations, I am most grateful to Susie Williams (CLW/CRCV) for her excellent technical assistance, to Angela Reid (CLW/CRCV) for statistical advice, and to Peter Walmsley (Sunraysia) and many of the staff and management of Southcorp Wines (Coonawarra) without whose support, the work would not have been possible. In particular, the input of Drs Richard Hamilton and Tony Proffitt (now with Albert Haak and Associates) has been valued greatly. I am also grateful to Mark Gishen and Bob Dambergs and their staff at the Australian Wine Research Institute for their assistance with the NIR analysis in 2002.

References

Bramley, R.G.V. (2001) Progress in the development of precision viticulture – Variation in yield, quality and soil properties in contrasting Australian vineyards. In: Precision tools for improving land management. Occasional report No. 14. (Fertilizer and Lime Research Centre, Massey University: Palmerston North) pp. 25–43.

Bramley, R.G.V. and Hamilton, R.P. (2004a) Understanding variability in winegrape production systems. 1. Within vineyard variation in yield over several vintages. Australian Journal of Grape and Wine Research **10**, 32–45.

Bramley, R.G.V. and Hamilton, R.P. (2004b). Hitting the zone – Making viticulture more precise. Proceedings of the 12th Australian Wine Industry Technical Conference. (Winetitles, Adelaide) In press.

Bramley, R.G.V. and White, R.E. (1991) An analysis of variability in the activity of nitrifiers in a soil under pasture. II. Some problems encountered in the geostatistical analysis of biological soil properties. Australian Journal of Soil Research **29**, 109–122.

Bramley, R.G.V., Evans, T.E and Proffitt, A.P.B. (2002) Digital elevation models and EM38 survey – Useful tools in the assessment of constraints to vineyard productivity. Proceedings of the 11th Australian Wine Industry Technical Conference. (Winetitles, Adelaide) p. 216.

Bramley, R., Pearse, B. and Chamberlain, P. (2003) Being Profitable Precisely – A case study of Precision Viticulture from Margaret River. Australian and New Zealand Grapegrower and Winemaker – Annual Technical Issue, 84–87.

Cambardella, C.A., Moorman, T.B., Novak, J.M., Parkin, T.B., Karlen, D.L., Turco, R.F. and Konopka, A.E. (1994) Field-scale variability of soil properties in central Iowa soils. Soil Science Society of America, Journal **58**, 1501–1511.

Cuppitt, J. and Whelan, B.M. (2001) Determining potential within-field crop management zones. In: ECPA 2001 – 3rd European Conference on Precision Agriculture. (agro Montpellier, Ecole Nationale Supérieure Agronomique de Montpellier, France). Volume 1. pp. 7–12.

Dambergs, R.G., Cozzolino, D., Esler, M.B. Cynkar, W.U., Kambouris, A., Francis, I.L. Høj, P.B. and Gishen, M. (2003) The use of near infrared spectroscopy for grape quality measurement. Australian and New Zealand Grapegrower and Winemaker 473a, 69–76.

ESRI (2003) Arcview GIS 8.3. (Environmental Systems Research Institute: Redlands, CA, USA).

Francis, I.L., Iland, P.G., Cynkar, W.U., Kwiatkowski, M., Williams, P.J., Armstrong, H., Botting, D.C., Gawel, R. and Ryan, C. (1999) Assessing wine quality with the G-G assay. In: 2025 – Meeting the Technical Challenge. Proceedings of the 10th Australian Wine Industry Technical Conference. (Australian Wine Industry Technical Conference, Inc.: Adelaide) pp. 104–108.

Gishen, M., Iland, P.G., Dambergs, R.G., Esler, M.B., Francis, I.L., Kambouris, A., Johnstone, R.S. and Høj, P.B. (2002) Objective measures of grape and wine quality. In: Proceedings of the 11th Australian Wine Industry Technical Conference. (Australian Wine Industry Technical Conference, Inc.: Adelaide). pp. 188–194.

Iland, P., Ewart, A., Sitters, J., Markides, A. and Bruer, N. (2000) Techniques for Chemical Analysis and Quality Monitoring During Winemaking. (Patrick Iland Wine Promotions: Campbelltown, South Australia)

Isaaks, E.H. and Srivastava, R.M. (1989) Applied Geostatistics. (Oxford University Press: New York)

Johnstone, R.S. (1999) Vineyard variability – is it important? In: 2025 – Meeting the Technical Challenge. Proceedings of the 10th Australian Wine Industry Technical Conference. (Australian Wine Industry Technical Conference, Inc.: Adelaide). pp. 113–115.

Krstic, M.P., Leamon, K., DeGaris, K., Whiting, J., McCarthy, M., and Clingeleffer, P. (2002) Sampling for wine grape quality parameters in the vineyard: Variability and post-harvest issues. In: Proceedings of the 11th Australian Wine Industry Technical Conference. (Australian Wine Industry Technical Conference, Inc.: Adelaide). pp. 87–90.

Lamb, D.W., Weedon, M.M. and Bramley, R.G.V. (2004) Using remote sensing to map grape phenolics and colour in a Cabernet Sauvignon vineyard – The impact of image resolution and vine phenology. Australian Journal of Grape and Wine Research **10**, 46–54.

Minasny, B., McBratney, A.B. and Whelan, B.M. (1999) VESPER version 1.2. Australian Centre for Precision Agriculture, The University of Sydney. (www.usyd.edu.au/su/agric/acpa).

SAS (2002) JMP Version 5. (SAS Institute Inc. Cary, NC, USA).

Tisseyre, B., Mazzoni, C., Ardoin, N. and Clipet, C. (2001) Yield and harvest quality measurement in precision viticulture – Application for a selective vintage. In: ECPA 2001 – 3rd European Conference on Precision Agriculture.' (agro Montpellier, Ecole Nationale Supérieure Agronomique de Montpellier: France). Volume 1. pp. 133–138.

Trangmar, B.B., Yost, R.S. and Uehara, G. (1985) Application of geostatistics to spatial studies of soil properties. Advances in Agronomy **38**, 45–94.

Trought, M.C.T. (1997) The New Zealand Terroir: Sources of variation in fruit composition in New Zealand vineyards. In: Proceedings of the 4th International Symposium on Cool Climate Enology and Viticulture. (New York State Agricultural Experiment Station: Geneva, New York). pp. 23–27.

Webster, R. and Oliver, M.A. (2001) Geostatistics for Environmental Scientists. (John Wiley & Sons: Chichester, England)

Manuscript received: 2 February 2005