32 **Variability in winegrape production systems: I** ***Australian Journal of Grape and Wine Research*** **10**, 32–45, 2004

Understanding variability in winegrape production systems

1. Within vineyard variation in yield over several vintages

R.G.V. BRAMLEY[1,3,4] and R.P. HAMILTON[2,3]

[1] CSIRO Land and Water and [3]Cooperative Research Centre for Viticulture, PMB No. 2, Glen Osmond, SA 5064, Australia
[2] Southcorp Wines Pty Ltd, PO Box 96, Magill, SA 5072, Australia
[4] Corresponding author: Dr Rob Bramley, facsimile +61 8 8303 8550, email rob.bramley@csiro.au

Abstract

Spatial variability in winegrape yield was studied over several vintages in blocks planted to Cabernet Sauvignon, Merlot and Ruby Cabernet in the Coonawarra, Clare Valley and Sunraysia regions of Australia using new yield monitoring technology, a differentially corrected global positioning system (GPS), a geographical information system and some simple methods of spatial analysis. In any given year, yield was highly variable and typically of the order of 10 fold (i.e. 2 to 20 t/ha). However, through the use of *k*-means clustering and a method based on assessment of the probability of achieving yield targets relative to the mean annual block yield, temporal stability in the patterns of yield variation was demonstrated, even though there were substantial year to year differences in mean annual yield in these blocks.

The methods used to demonstrate temporal stability in the patterns of yield variation also promote identification of zones of characteristic performance within variable vineyard blocks. Of significance in this work was the finding that, whilst *k*-means clustering is the more statistically robust of the two methods used, the ability to incorporate expert knowledge into the yield target method enhances the ability of the manager to accommodate the effects of abnormal events (e.g. an unusually cold flowering period) in the zone identification process. Targeted harvesting of different zones, followed by comparison between commercial lots of wine, provided indication that wine characteristics vary from zone to zone. However, the ranking of wine scores for the various zones changed between seasons.

Our results have important implications for the adoption of Precision Viticulture. In particular, they support the introduction of a system of zonal vineyard management. Thus, rather than being managed uniformly, individual blocks can be split into zones in which the management of both inputs to, and outputs from the production system can be applied differentially.

Keywords: *Precision Viticulture, zonal management, spatial variation, yield monitor*

Introduction

Vineyards are variable. Growers have known this for as long as they have been growing grapes, but in the absence of tools or methods to accurately observe and measure the variation, variability has been accepted as a fact of life and the majority of vineyards have been managed on the assumption that they are homogenous.

Precision Agriculture (PA, Cook and Bramley 1998, Pierce and Nowak 1999) involves the collection and use of large amounts of data relating to crop performance and the attributes of individual production areas (fields, paddocks, blocks, etc.) at a high spatial resolution. Its purpose is to enable crop management to be targeted in a way that recognises that, far from being homogenous, the productivity of agricultural land is inherently variable. Critical to this new approach to farming are a number of enabling technologies, including the global positioning system (GPS), geographical information systems (GIS) and yield monitors which, when used in conjunction with the GPS, enable geo-referenced records of yield to be collected ‘on-the-go’ during harvest. Thus, growers are able to better observe and develop understanding of the variability in their production systems, and to use this to better match the inputs to production to desired or expected outputs.

Conceptually, PA is neither new nor complicated (Rawlins 1997) and has been practised in the dairy industry for many years. Cows producing a full bucket of milk are given a full scoop of grain at milking whilst those producing half a bucket might only get half a scoop. The management focus is therefore the individual rather than the herd (Cook and Bramley 1998). With respect to broadacre cereal production, PA is a more recent innovation, although some Australian grain growers have now been yield-mapping for around 10 years (Cook et al. 2003).

Since vintage 1999, when the first commercially available grape yield monitor came onto the market, it has been possible for grapegrowers and winemakers to practice Precision Viticulture (PV, Bramley and Proffitt 1999, Bramley 2001, Bramley et al. 2003). Thus, the potential has existed for grape and wine producers to acquire detailed geo-referenced information about vineyard performance and to use this information to tailor production of both grapes and the resultant wines according to expectations of vineyard performance, and desired goals in terms of both yield and quality (Bramley and Proffitt 1999).

Implementation of a PV approach to vineyard management is a continual cyclical process (Bramley 2001, Bramley et al. 2003) which begins with *observation* of vineyard performance and associated vineyard attributes, followed by *interpretation* and *evaluation* of the collected data, leading to *implementation* of either targeted management of inputs and/or selective harvesting at vintage. Here, 'targeted management' can mean the timing and rate of application of water, fertiliser or spray, or the use of machinery and labour for operations such as harvesting, pruning or just about any aspect of vineyard management. Of particular interest to both grapegrowers and winemakers is the opportunity to use PV as a means of ensuring that parcels of fruit delivered to the winery are as uniform as possible, as well as meeting specifications for their intended end product (Bramley and Proffitt 1999, Bramley et al. 2003). Thus, 'selective harvesting' means split picking of fruit at harvest according to different yield/quality criteria in order to exploit the observed variation.

Before embarking on PV and investing in the capital or contracted services that this new approach to viticultural production implies, grapegrowers and winemakers have wanted the answers to a number of key questions. First, they need to know whether the patterns of within-vineyard variation are constant from year to year. If they are not, then clearly the idea that PV increases the certainty that a given management decision will deliver a desired or expected outcome (Cook and Bramley 1998, Bramley and Proffitt 1999) may not be correct. Second, they need to know whether patterns of variation in yield are matched by patterns of variation in quality. If they are, then targeted management of vineyards becomes a much simpler problem than if they are not, given for example, that it would be undesirable to focus on yield at the expense of quality, and possibly vice versa. Third, they want to know what the key drivers of vineyard variation are and whether these may be managed. Clearly, if these are either unknown or unmanageable, then the opportunities for targeting inputs are probably limited, even if the opportunity remains to segregate outputs. Finally, they want to know whether targeting management delivers an economic benefit over conventional uniform management, a practice which effectively assumes that vineyards are homogenous in so far as their potential productivity is concerned.

The first and last of these questions are specifically addressed by the 'null hypothesis of precision agriculture' (Whelan and McBratney 2000) which states that 'given the large temporal variation evident in crop yield relative to the scale of a single field, then the optimal risk aversion strategy is uniform management.' Bramley and Proffitt (1999) made some simple assumptions about crop quality variation and used a yield map and gross margin analysis to suggest that adoption of PV was potentially highly profitable. More recently, Bramley et al. (2003) provided a real commercial demonstration that this is indeed the case, when, by selectively harvesting 3.3 ha of Cabernet Sauvignon in a Margaret River vineyard, they increased the retail value of production by over $30,000/ha. The purpose of this present paper therefore, is to complete the testing of Whelan and McBratney's null hypothesis by examining within-vineyard yield variability and the extent to which its patterns are temporally stable. Subsequent papers in this series will examine variation in the components of yield, grape quality and the drivers of variation.

Materials and methods

Data collection

The bulk of the work reported here was carried out in a 7.3 ha vineyard in the Coonawarra region in the south-east of South Australia. This vineyard was planted to Cabernet Sauvignon on its own roots in 1974. At vintage, in each of 1999, 2000, 2001 and 2002, the vineyard was harvested using a Gregoire G120 self-propelled mechanical harvester fitted with a HarvestMaster grape yield monitor and differentially corrected GPS (dGPS; accurate to about 50 cm in the x and y planes). The HarvestMaster yield monitor employs an array of sonic beam sensors mounted over the grape discharge chute to estimate the volume, and hence tonnage, of fruit harvested. The yield monitor was configured to log instantaneous yield and position at intervals of 3 m along the row. Unfortunately, yields were too low at vintage 2002 for this system to work effectively. Accordingly, for vintage 2003, a Farmscan yield monitor was used. This more recently-developed system uses load cells installed under the grape discharge belt to provide instantaneous measurements of the weight of fruit being harvested and was configured to log yield and position at 3 second intervals. For both yield monitoring systems, instantaneous measures of yield are converted to units of t/ha on the basis of the row spacing and the distance travelled between consecutive points at which data were logged. Other aspects of the harvesting system in 2003 were the same as in the previous 4 years, although for operational reasons unrelated to the equipment, we were only able to yield-monitor every third row in 2003.

In addition to the Coonawarra site, yield data were also collected during the 2000 and 2001 vintages from a 4.5 ha vineyard in the Sunraysia region of north-east Victoria which was planted to Ruby Cabernet (own roots) in 1989. The harvesting/yield monitoring system used at this site was the same as that used in Coonawarra (1999-2002). Data were also collected in 2000, 2001, 2002 and 2003 in a 3.6 ha vineyard in the Clare Valley of South Australia which was planted to Merlot in 1981, again on its own roots. At this site, a HarvestMaster yield monitor was also used, but mounted on a Gregoire G60 tow-behind harvester rather than a self-propelled machine as at the other sites.

Yield mapping

For each year, yield maps were produced following the protocol of Bramley and Williams (2001) with a data pre-treatment to remove aberrant values; that is, yield surfaces were interpolated onto a 2 m grid (pixels of 4 m^2) by local block kriging (10 m × 10 m blocks) of the yield monitor data using VESPER (Minasny et al. 1999). The data pre-treatment involved normalising the data ($\mu = 0$, $\sigma = 1$) after removal of data records with zero yield or GPS errors (Bramley and Williams 2001), and then removing records for which the normalised yield was either greater than +3 or less than –3; that is, data with yield values more than 3 standard deviations from the mean. This is a common pre-treatment for yield monitor data (e.g. Pringle et al. 2003), and in our experience is effective at removing aberrant values that are artefacts of the harvesting process (e.g. occasional blockages of the discharge belt and high values at row ends when the discharge belt is switched on or off).

An important aspect of the kriging method of interpolation is that, in addition to interpolating estimates of values at unsampled sites on the basis of known values at georeferenced locations, estimates of the variance of the kriged values are also produced. As such, a map of kriging variances provides an indication of the quality of the interpolated surface of interest; other interpolation methods, such as inverse distance weighing, do not do this. Of particular relevance to the present work is that kriging variances can also be used as a basis for tests of significance between different areas, or zones, within a map interpolated by kriging (Cuppitt and Whelan 2001).

In addition to maps of yield (t/ha) obtained in each year, maps of normalised yield were also interpolated. In the context of analysis of multi-year data, the purpose of mapping normalised yield for individual years is to promote examination of variability that is independent of any seasonal effects due, for example, to differences in annual rainfall or the number of growing season degree days. Normalised maps are also of value when data are not available for calibration of the yield monitor against winery tonnages – as was the case at Sunraysia in 1999. For the normalised maps, following the initial trimming that was used for production of maps of actual yield, an iterative procedure was used in which the data were re-normalised based on new values of the mean and standard deviation for the trimmed data sets. The data were then re-trimmed until all normalised values (N_i) conformed to the rule: $-3 < N_i < +3$. Note that for a normally distributed data set, 99% of the data lie within 3 standard deviations of the mean. Thus, for maps of actual yield, approximately 1% of the data were discarded in the trimming process, whilst for the production of maps of normalised yield, between 2 and 5% of the data were trimmed in order to ensure that they followed similar distributions. Given that at the Coonawarra site, for example, a yield monitor data file typically contains more than 11,000 geo-referenced yield records, the need to 'de-spike' the data posed no threat to the viability of the kriging process in terms of its data requirements.

Analysis of persistence in the patterns of yield variation

Two methods were used to investigate persistence in the pattern of yield variation. Both were centred around the interpolated yield values rather than the raw data. This distinction is important because one consequence of the map production process is that, for any given site, every pixel (i.e. grid cell) within the grid used for interpolation contains a yield value for each year in which a map was produced. Note that it would be most unlikely for the yield monitor to record yield at exactly the same locations each year.

The first method used was based on the procedure described by Diker et al. (2003) for analysis of maize yield data grown under centre pivot irrigation in north-east Colorado. For each year for which yield data were available, Diker et al. (2003) assigned a value of 1 to all grid cells corresponding to yields greater than the mean for that year; all other grid cells were assigned a value of 0. Summation of the resulting maps for 3 years therefore produced a map in which every grid cell had a value between 0 and 3. Grid cells with a value of 0 were those in which yield was below average in all three years – that is, yield was consistently below average – whilst those with a value of 3 consistently yielded above average. In their particular study, Diker et al. (2003) were able to show that the distributions of yield in grid cells with values of 1 or 2 were not statistically significantly different and so were able to divide their centre pivots into two 'zones' of typically above and below average yield and a third 'zone' in which yield tended to be intermittent between these two.

One problem with the analysis of Diker et al. (2003), henceforth referred to as the 'target yield method', is that it assumes that the average yield in any given year is satisfactory. Furthermore, Diker et al. (2003) were effectively dealing with a 'controlled environment' system, given the absolute necessity for irrigation for production of maize in north east Colorado. Thus, inter-annual variation was not expected to be large. This is presumably one reason why Diker et al. (2003) found that the distributions of yield in grid cells with values of 1 or 2 were not statistically significantly different. However, in view of the large inter-annual variation in grape yield experienced in most Australian viticultural areas, and also in light of the strong commercial focus of the Australian wine industry, we thought it more realistic to use target yields based on some value above the mean for this analysis. Thus, for any given year, we assigned values of 1 to grid cells in which yield was greater than the target and 0 to cells in which it was not. We considered this to be an improvement over the method of Diker et al. (2003) because it allows comparison of a number of different targets and could promote analysis of the probability of reaching a particular level of performance. Thus, our analysis was carried out for yield targets equivalent to: mean + 5%, mean + 10% and mean +20 %. Importantly, we also 'inverted' this analysis to consider the likelihood of substandard performance. Accordingly, we also conducted analyses with yield targets equivalent to: mean –5%, mean –10% and mean –20%. These

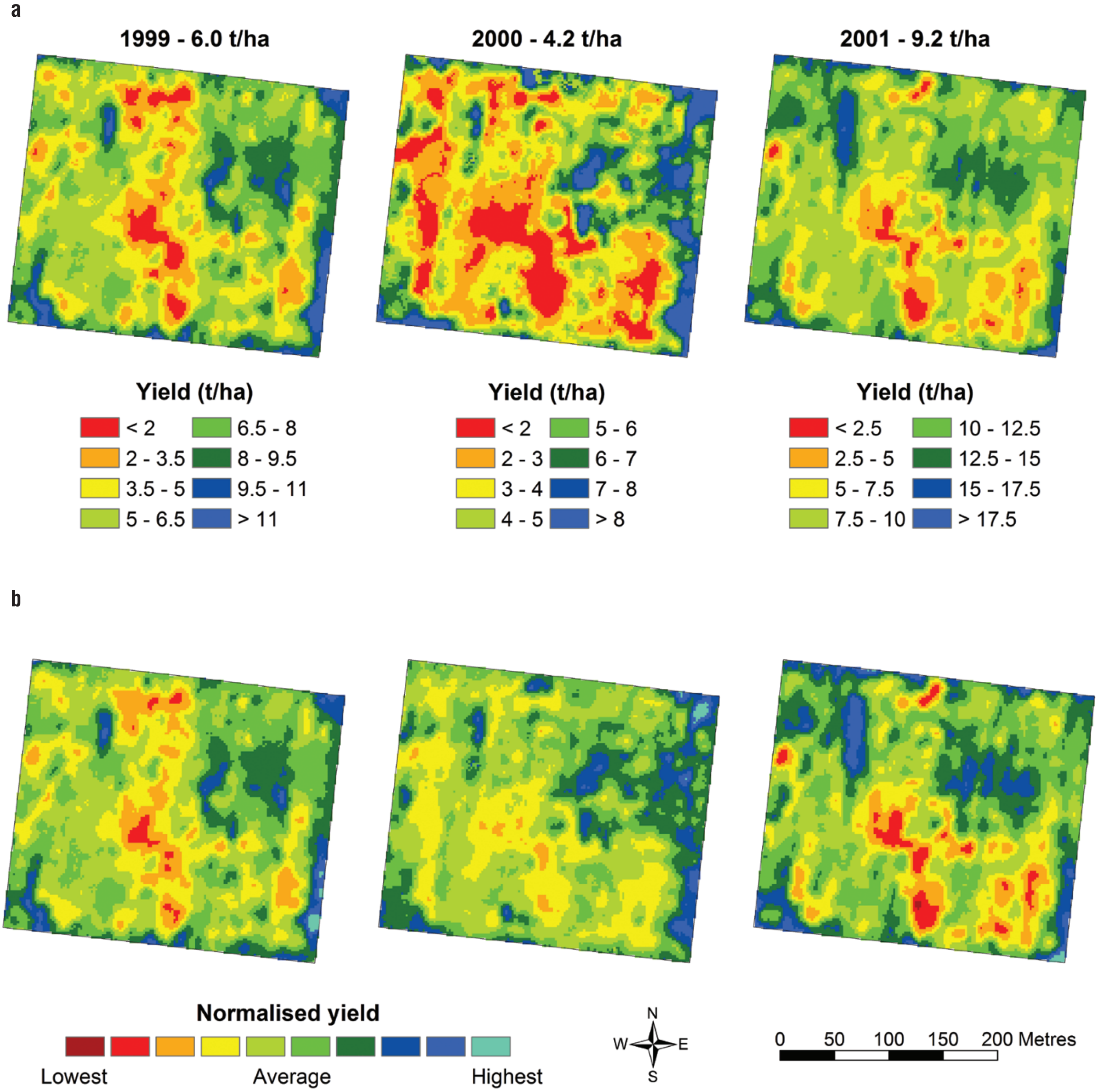


Figure 1. Yield of Cabernet Sauvignon in a 7.3 ha Coonawarra vineyard (1999–2001). The yields indicated above each map in (a) are the means for the block for that year. Because of the differences between these annual mean yields, different legends were appropriate for the three maps. However normalisation of the data ($\mu = 0$, $\sigma = 1$) in each year (b) allows the patterns of variation to be inspected independently of the seasonal effects driving the differences in annual mean yield.

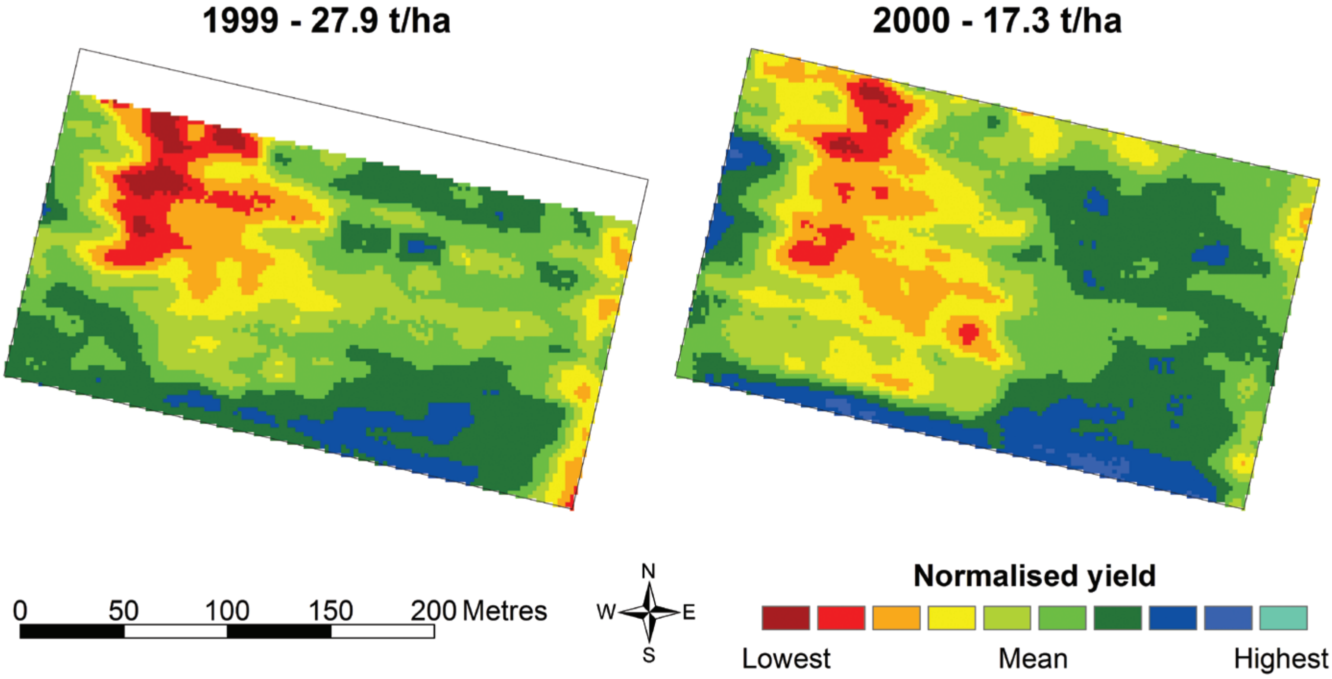


Figure 2. Normalised ($\mu = 0$, $\sigma = 1$) yield of Ruby Cabernet in a 4.5 ha Sunraysia vineyard. The yields indicated above each map are the means for the block for that year.

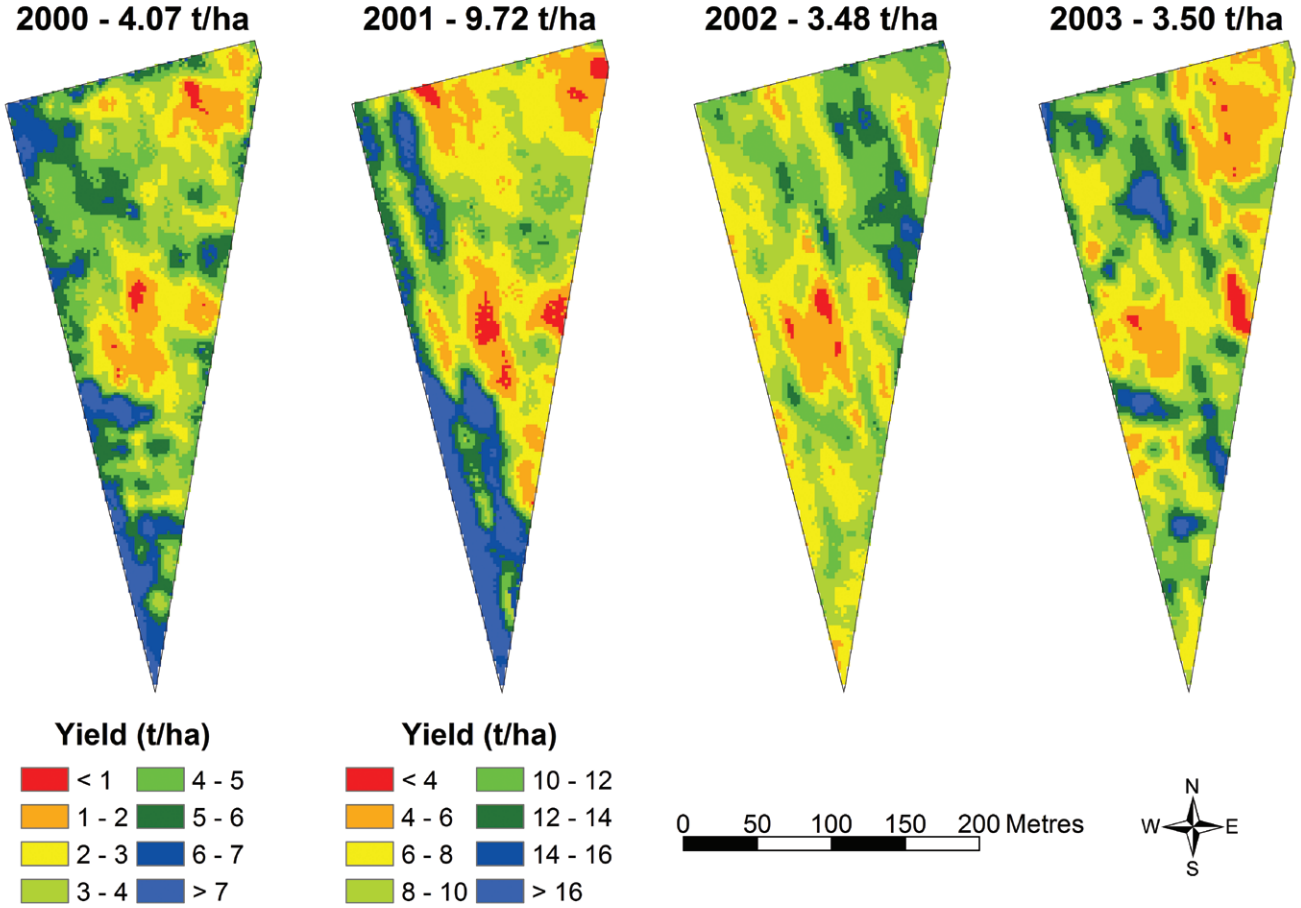


Figure 3. Yield of Merlot in a 3.6 ha Clare Valley vineyard (2000–2003). The yields indicated above each map are the means for the block for that year. The legend for 2002 and 2003 is the same as that shown for 2000.

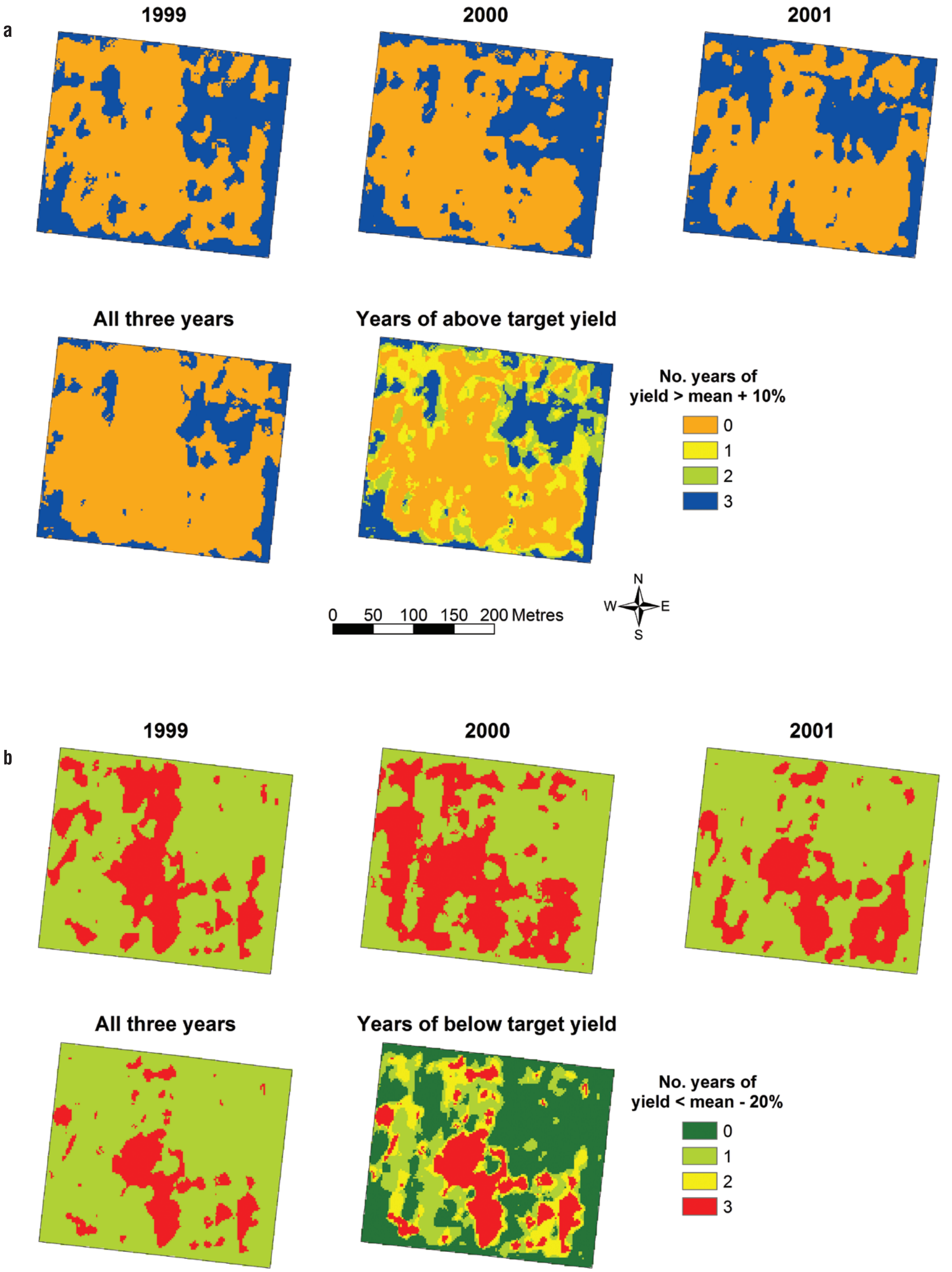


Figure 4. Yield performance at the Coonawarra site. Areas shaded blue in (a) are those which yielded more than a yield target of 10% higher than the annual mean; areas shaded orange yielded below this target. Areas shaded red in (b) are those which failed to reach a yield of 20% below the annual mean, whilst those shaded light green yielded above this target.

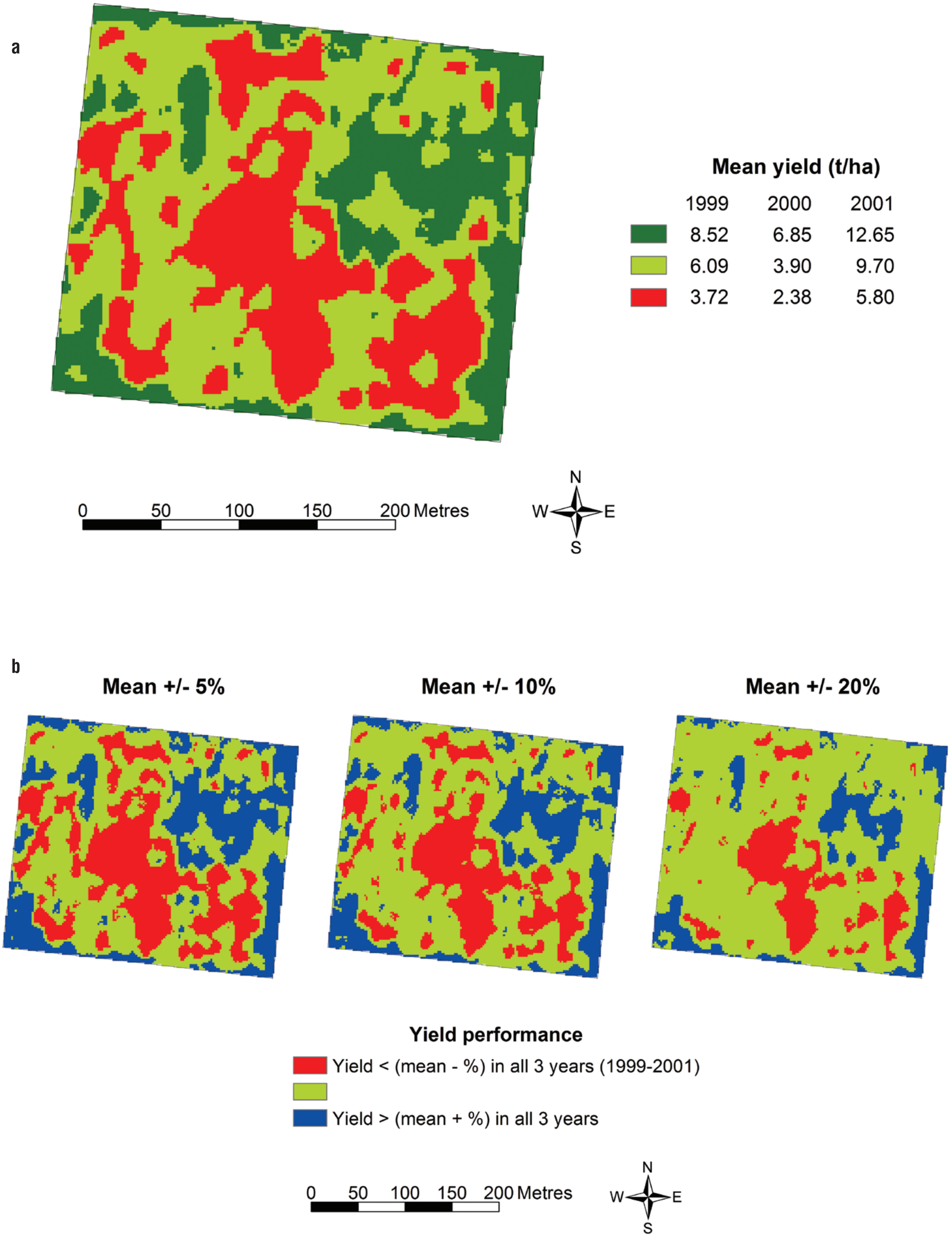
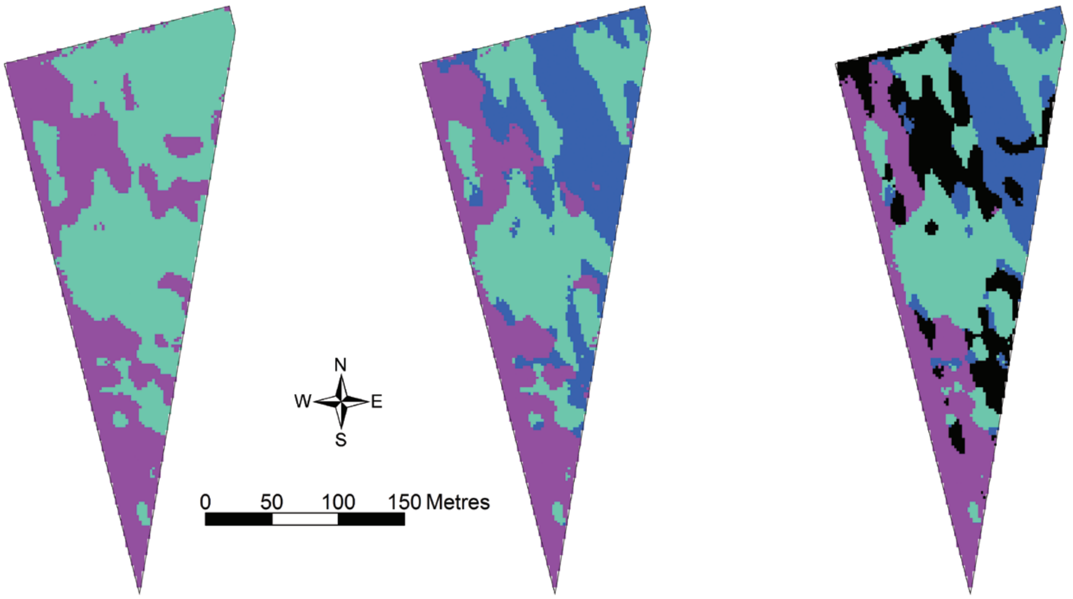


Figure 5. Analysis of persistence in the patterns of yield variability at the Coonawarra site using either (a) *k*-means clustering or (b) yield targets. The mean yields reported for each cluster in (a) were all significantly different ($P < 0.05$) in all years of the study.



	2000	2001	2002	2003	2000	2001	2002	2003	2000	2001	2002	2003
🟪	5.51^a	13.17^a	3.66^a	4.47^a	5.74^a	14.13^a	3.35^a	4.44^a	5.68^a	15.47^a	3.11^a	3.89^a
🟩	3.07^b	7.33^b	3.36^a	2.82^b	2.91^b	7.06^b	2.65^a	2.83^b	2.80^b	6.86^b	2.59^a	2.71^b
🟦					3.79^b	8.67^b	4.66^b	3.36^b	3.38^b	8.08^b	4.86^b	2.47^b
⬛									4.77^a	8.86^b	3.99^c	5.17^c

Figure 6. Results of *k*-means clustering of yield data (4 vintages) from a 3.6 ha vineyard in the Clare Valley – 2, 3 and 4 cluster solutions. The data shown are the mean cluster yields for each year. For any given year and clustering solution, different letters indicate that the mean cluster yields are significantly different ($P < 0.05$).

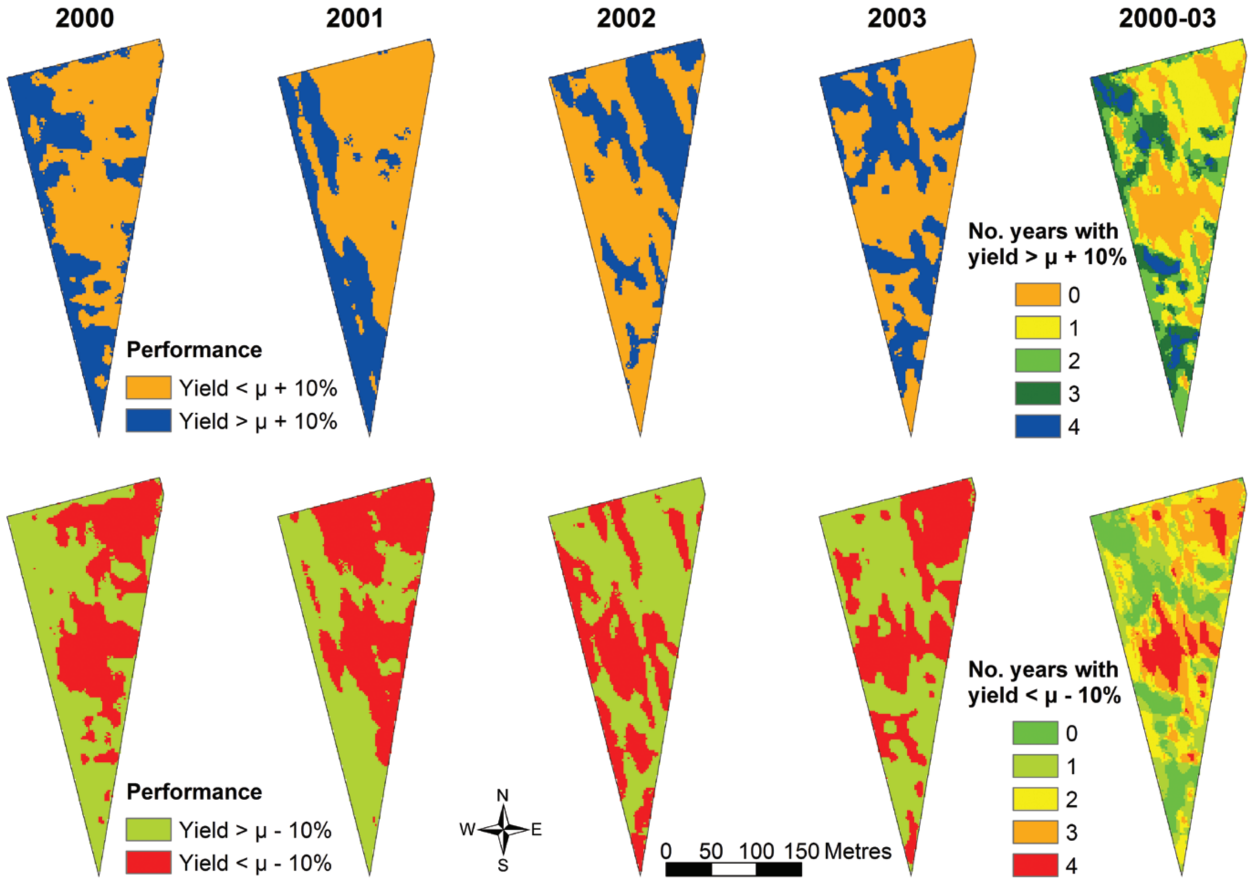


Figure 7. Yield performance at the Clare site 2000–2003 assessed using the 'target yield' method.

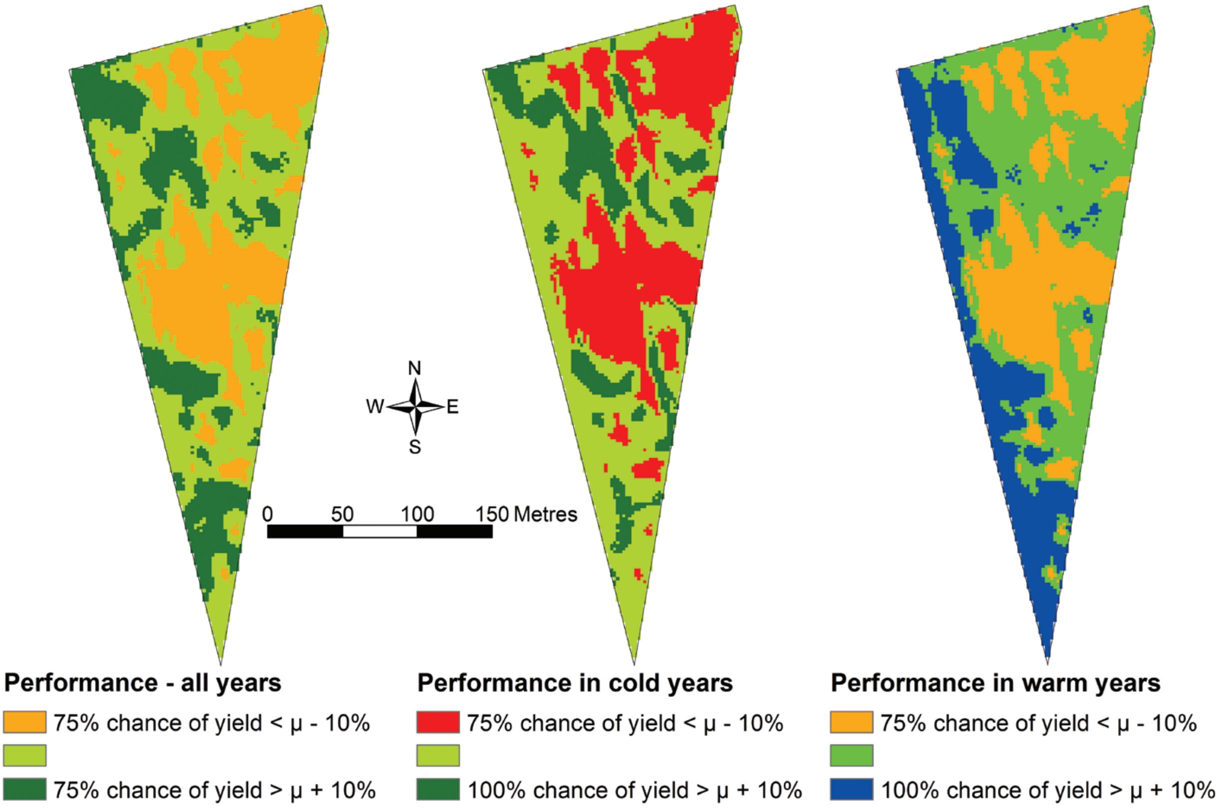
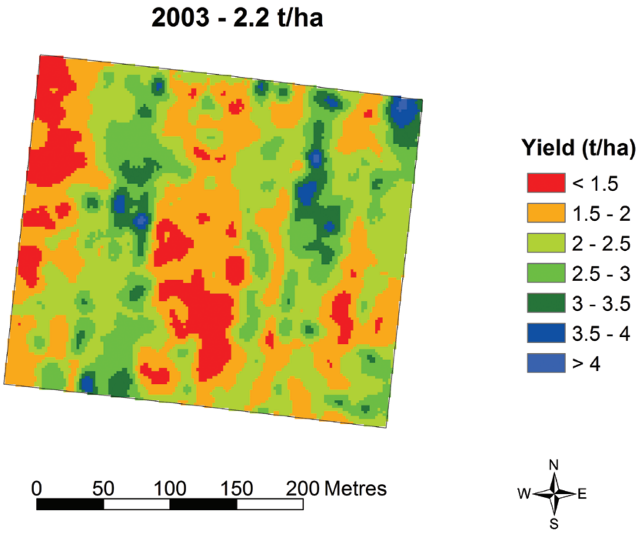


Figure 8. The influence of inter-annual climatic variation on zone identification at the Clare site, 2000–2003. Note that 'warm' and 'cold' are used here simply as relative terms; the seasons leading to vintage 2000 and 2001 were considered 'warm', whilst those leading to 2002 and 2003 were deemed to be cold. See text for further explanation.



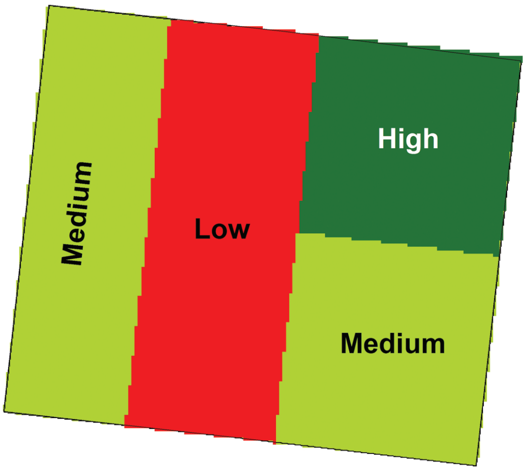


Figure 9. Yield of Cabernet Sauvignon at the Coonawarra site, vintage 2003. Note that this map was produced from yield monitor data collected on every third row, unlike the previous years (Figure 1) when every row was yield monitored. The process of map interpolation was otherwise the same for all years.

Figure 10. Simple zonation of the Coonawarra site based solely on inspection of the 1999 yield map (Figure 1). Separate wines were made from fruit collected from these zones in 2000 and 2001 (Table 3).

analyses were carried out in ARCVIEW (version 8.3; ESRI 2003) using the SPATIAL ANALYST extension.

The second method used to investigate persistence in the patterns of yield variation involved the use of multivariate *k*-means clustering; the statistical package, JMP (SAS 2002), was used for this analysis. *k*-means clustering is a non-hierarchical method of data aggregation in which the variance within clusters is minimised whilst the variance between clusters (i.e. distance between cluster centres) is maximised. It has been successfully used in PA for the delineation of management zones using, for example, data layers such as yield, elevation and soil electrical conductivity (e.g. Cuppitt and Whelan 2001). In the present analysis, all the data layers used were yield (several vintages), but since the input data were all geo-coded to the same grid, it was thought likely that consistently high yielding and consistently low yielding areas would be clustered separately. The effects of soil and topographic variation on yield variability will be discussed in a later paper in this series.

Results

At all three sites, yield variation was marked, both in time and space (Figures 1–3); temporal variation was the reason why we found production of the normalised maps (Figures 1b and 2) to be valuable.

In spite of the inter-annual variation in mean yield, Figures 1–3 suggest that the patterns of within-vineyard variation in yield are fairly stable from one year to the next, as is the magnitude of the variation seen in any given year, which is typically of the order of 8 to 10-fold (i.e. 2–20 t/ha). This is arguably the expected result given the perennial nature of grapevines. Nevertheless, it was still considered desirable for a more robust examination of the persistence of patterns of yield variability to be conducted.

Coonawarra

The results of the analysis based on the target yield method are shown in Figures 4 and 5b. Figure 5a shows the results of *k*-means clustering.

As Figure 4a shows, the areas within the Coonawarra study site which consistently exceeded a yield target (mean + 10 % in this example) are almost identical from year to year (1999–2001); the north–eastern part of the block is always the highest yielding. Similarly, those areas which underperform (Figure 4b) do so consistently. Note, however, that in 2000, the lowest yielding year for which data are available for the whole block, underperformance was seen over wider areas of the block than in other years. This underperformance was presumably attributable to the abnormal stresses the vines experienced in the 1999/00 season, and in particular, the cool, wet and windy conditions experienced at flowering which impacted substantially on subsequent fruit set. Nevertheless, when considered alongside Figure 1, Figure 4 strongly suggests that this Coonawarra vineyard is characterised by areas which consistently yield above or below the annual block average.

These results are supported by those obtained from the *k*-means clustering of the yield data obtained in 1999, 2000 and 2001 (Figure 5a), which again suggests that the north-eastern part of the block is consistently higher yielding than the remainder, whilst a central strip running north-south consistently yields below the rest of the block. Note that the number of clusters identified in this kind of analysis is principally a matter of user choice. In this case, we chose a three cluster solution (Figure 5a) given that the analysis based on the target yield method (Figure 5b) strongly supported the view that this block could be divided into areas that typically yield above, below and close to the average yield obtained for the whole block in any given year. Through the use of a significance test based on the kriging variance and mean cluster yield (Cuppitt and Whelan 2001), the mean yields for each of the 3 clusters were shown to be statistically significantly different ($P < 0.05$) in each year of the study, and to follow a consistent ranking with cluster 1 always being the highest yielding, cluster 2 the lowest, and cluster 3 in between these two (Figure 5a). The results presented in Figure 5a therefore strongly support the view that the pattern of yield variability in this vineyard is temporally stable.

In spite of the finding that the pattern of yield variation in the Coonawarra block is constant from year to year, Figures 1, 4 and 5a provide little guidance to the vineyard manager of the risk associated with either ignoring the variation and persisting with the current strategy of uniform management of the block, or of targeting different management strategies in different areas. Thus, Figure 5b, which is a summary of the results of the target yield analysis, is useful since it indicates the probability of a target being exceeded (or not being met) over the whole management unit when managed uniformly. This type of information could therefore be valuable in assessing the extent to which any additional effort should be expended in implementing differential management, given expectations of the financial return that such additional effort might realise.

Clare

At the Clare site, yield in 2001 was considerably higher than in the other years (Figure 3), as was the case at Coonawarra (Figure 1). However, whilst the mean yields in the other years of the study were similar, the patterns of yield variation were much less so. Indeed, Figure 3 suggests that the patterns of variation in 2000 and 2001 were different to those in 2002 and 2003, even though there are areas in the central and north eastern parts of the block which appear to be consistently low- yielding. Yield performance on the western side of the block, in particular, was apparently quite inconsistent (Figure 3). This is presumably the reason why the results of the *k*-means clustering of the Clare data (Figure 6) were less conclusive than in Coonawarra. As Figure 6 shows, whether the data are grouped into 2, 3 or 4 clusters, the differences between mean cluster yields are not always statistically significant ($P < 0.05$). Furthermore, the cluster rankings (i.e. from highest to lowest yield) are not always consistent either. The least ambiguous result is the

Table 1. Actual (2001) and long term average maximum and minimum daily temperatures for the months of November and December, and during the flowering period (27/11–18/12/01) at the Clare site[1].

Period	**22 year average maximum (°C)**	**Actual average maximum (°C)**	**22 year average minimum (°C)**	**Actual average minimum (°C)**
November	23.2	20.7	10.1	8.4
December	26.1	22.6	11.7	8.7
Flowering		21.3		8.2

[1] Data kindly supplied by John Matz (Southcorp Wines, Clare Valley).

Table 2. Mean zone yields for the Clare site (Merlot) when zones are identified on the basis of the 'target yield' method with and without incorporation of expert knowledge of climate variation into the analysis of persistence in patterns of yield variation (Figure 8)[1, 2].

	Mean zone yield (t/ha)			
Zone	**2000**	**2001**	**2002**	**2003**
		All years – Figure 8a		
Low	2.50^{a}	6.63^{a}	2.97^{a}	2.47^{a}
Medium	4.31^{b}	$10.11^{a,b}$	$3.64^{a,b}$	3.46^{b}
High	5.94^{c}	13.60^{b}	3.91^{b}	5.12^{c}
		Cold years – Figure 8b		
Medium			3.49^{a}	3.61^{b}
High			4.49^{b}	5.25^{c}
		Warm years – Figure 8c		
Medium	4.85b	11.26b		
High	5.98c	15.15c		

[1] For any given year and zoning solution, yields marked with different letters are significantly different ($P < 0.05$).

[2] Note that in the warm and cold years, the lowest yielding zone was the same as that identified for all years, independent of consideration of any climatic effect.

2 cluster solution, although even this fails to make a significant ($P < 0.05$) delineation between clusters in 2002 (Figure 6). Since the higher-yielding cluster occurs predominantly on the western side of the block (Figure 6), and Figure 3 shows this to be the area of greatest contrast between 2002 and the preceding years, the lack of significance between some of the clusters is perhaps not surprising. Indeed, the apparent consistency between the yield maps obtained in 2000 and 2001 and their contrast with those for 2003 and in particular, 2002, is highlighted in Figure 7 which presents the results of an analysis of block performance with respect to target yields of 10% above and below the annual block mean. Figure 7 clearly identifies the low-yielding areas in the central and north-eastern parts of the block and shows these to be consistently low-yielding. In contrast, the higher-yielding areas are much less consistent in their location.

The season leading up to vintage 2002 was unusually cold during the flowering period which, at least partly as a consequence, lasted for considerably longer than the normal 3–7 days (Table 1; John Matz, Southcorp Wines – pers. comm.). In addition to affecting flowering and fruit set at this time, the extended cool spring period is likely to have led to limited bud initiation, and thus yield in the subsequent year. Further, whilst the season leading to vintage 2003 was not climatically abnormal, there was nevertheless some frost damage in the western part of the block early in the season. Overall therefore, it seemed reasonable to classify 2000 and 2001 as 'warm' or 'normal' years and 2002 and 2003 as 'cold' years. Figure 8 illustrates the benefit of this classification.

Given the consistency of location of low-yielding areas in the central and north eastern parts of the block, the areas which yielded less than 10% below the mean in 3 or 4 out of the 4 years of the study were grouped together. Thus, in this case, we have defined underperformance as yielding less than 10% below the mean, and identified areas in which the probability of underperformance is 75%. Using a similar approach, areas with a 75% probability of yield being greater than 10% higher than the annual mean were identified. The result is Figure 8a which appears to suffer the same shortcomings as the *k*-means clustering (Figure 6). Indeed, based on the test of Cuppitt and Whelan (2001), there were no significant differences ($P < 0.05$) between the mean yields of the 'zones' identified in Figure 8a in either 2001 or 2002 other than those between the highest- and lowest-yielding areas (Table 2). More useful to the vineyard manager, we suggest, are the maps shown in Figures 8b and c. In these, the areas of underperformance are the same as those in Figure 8a. However, the higher-yielding areas have been defined on the basis of the information presented in Figure 7 such that for 'warm' years (Figure 8c), areas identified as having a 100% chance of the yield target being exceeded are those in which it was exceeded in both 2000 and 2001, whilst for 'cold' years (Figure 8b), the higher-yielding areas are defined on the basis of the data presented in Figure 7 for 2002 and 2003.

As Table 2 shows, the mean 'zone' yields were significantly different ($P < 0.05$) from each other in all years except in 2002 when there was no significant difference ($P < 0.05$) between the mean yield of the lowest and medium yielding zones. Overall however, the results presented in Figure 8 and Table 2 suggest that the vineyard manager can be confident in using these data to identify zones that perform poorly in most years. In contrast, decisions as to the targeting of management in zones which are expected to yield well, need to be made in light of the prevailing mid-season climatic conditions, and also possibly those of the previous year.

Sunraysia

Insufficient data were available for analysis of persistence in patterns of variation at the Sunraysia site using either the target yield or *k*-means clustering methods. This was due to fact that data were only successfully collected during the 1999 and 2000 vintages, whilst in 1999, the harvesting contractor did not have access to information about the actual tonnage delivered to the winery. In any case, GPS errors in the northern part of the block left us without data in that area. Calibration of the yield monitor against the tonnage delivered to the winery was therefore impossible. Nevertheless, inspection of Figure 2 suggests that, albeit based on only 2 years of data, the broad pattern of yield variation at this site is, like the others, temporally stable.

Discussion

Vineyard variability is not a new phenomenon; growers are generally well aware that vine performance varies within their vineyards and have known this for as long as grapes have been grown. However, in the absence of access to the tools of PV, they have been uncertain as to the precise location of areas of differing performance. Moreover, they have had inadequate knowledge of the magnitude of the variation within the vineyard, and an inability to adjust their management to account for it. Consequently, they have generally managed individual blocks as though they were uniform and within vineyard variation has been treated as 'noise'. It is perhaps not surprising therefore, that almost without exception, when presented with a yield map, growers are amazed at the extent to which yield varies within blocks managed as single units. The lack of a means to measure and monitor vineyard variability prior to 1999 presumably also explains the paucity of published research on this topic. However, the fact that we saw similar results with different varieties grown at sites in regions as diverse as the Coonawarra, Clare Valley and Sunraysia suggests that our results are likely to have broad implications for the whole industry. In particular, they demonstrate that vineyard variability is of sufficient magnitude in any given year, while its patterns remain sufficiently stable between years, to warrant consideration of the implementation of 'zonal management' strategies in vineyards. In other words, in the case of winegrape production, we feel confident in rejecting the null hypothesis of precision agriculture (Whelan and McBratney 2000); that is, uniform management is *not* the optimal risk aversion strategy.

The methods employed here to assess persistence in the patterns of spatial variation are simple and easy to use; the target yield method can be easily implemented in GIS, and with simple arithmetic underpinning target yield this method can also be implemented using a standard spreadsheet, although a GIS or other appropriate viewing software would still be needed for display of results. It is therefore something that a vineyard manager and/or their consultant could implement. Similarly, *k*-means clustering is accessible. This is important because our results, and especially those from Clare, suggest that the greatest benefit from using these methods may accrue through the use of both, rather than just one or the other. In simple situations such as that at Coonawarra (Figures 4 and 5), *k*-means clustering alone may provide all that is needed for identification of zones. However, the Clare study (Figures 6–8) provides an important lesson for those interested in pursuing 'zonal management': the target yield method of zone identification allows the user to incorporate some expert knowledge into the analysis (in this case, knowledge of the occurrence and effects of an abnormally cold flowering season in 2001), and to also incorporate some consideration of risk by using maps such as those shown in Figures 4, 5b, 7 and 8. Furthermore, there is no reason why the test of the significance of differences between cluster means (Cuppitt and Whelan 2001) should not also be used to test for differences between zones identified using the target yield method (Table 2). In the case of our Coonawarra site, the zones identified in Figure 5b were all statistically significantly different ($P < 0.05$) with respect to the mean yields for each zone in 1999, 2000 and 2001, irrespective of whether the target yield was 5, 10 or 20% above or below the annual block mean. We did not include data from 2003 in our analysis of persistence of variability in Coonawarra because the harvester equipped with our yield monitor only harvested every third row, and the 'support' of the yield map is therefore somewhat different than in the other years, given that it was interpolated from far fewer data. Nevertheless, the 2003 map (Figure 9) bears a strong resemblance to those shown in Figure 1, although there were no significant differences between the mean cluster yields when means were calculated for 2003 for the clusters identified in 1999–2001 using *k*-means clustering. Since the Coonawarra vintage in 2002 was similarly affected to that in Clare in the same year, and carry-over effects into 2003 appeared to have occurred (based on the block average being substantially lower than the long term average), we suggest that the analysis of persistence in yield variability at Coonawarra may have benefited from a combination of the *k*-means and target yield approaches and incorporation of appropriate expert knowledge. Clearly, at all our sites, on-going data collection will both promote improved zone delineation and provide insights as to how management should be targeted in different zones.

The work reported here has focused on variation in grape yield. However, to many winemakers, variation in fruit composition and quality are arguably of greater concern (Johnstone 1999, Trought 1997). To date, there is no commercially available on-the-go sensor for any grape quality index that could be used in conjunction with the yield monitor, although sensors for Brix, TA and juice pH are under development (Tisseyre et al. 2001). Our understanding of crop quality variation is therefore currently dependent on hand sampling, although as Bramley et al. (2003) and Lamb et al. (2003) have demonstrated, remote sensing methods (e.g. Hall et al. 2002, Lamb and Bramley 2002) may assist in this task.

A discussion of variation in indices of berry quality at the Coonawarra and Sunraysia sites, assessed using such hand sampling, will be the subject of a later paper in this series. However, following the 1999 vintage, the winemaker at Coonawarra was interested to see whether different zones within the block would produce wines with different characteristics. Notwithstanding the conventional wisdom amongst broadacre PA researchers and practitioners, that several years of data are needed for zone delineation, some crude zones (Figure 10) were delineated on the basis of the 1999 yield map (Figure 1).

Table 3. Selected chemical attributes of wines made from low-, medium- and high-yielding zones at the Coonawarra site[1,2]

Zone:	**Low-yielding**	**Medium**	**High-yielding**
	Vintage 2000		
Total anthocyanins (mg/g)	980	868	931
Total phenolics (abs. units)	67	59	60
Colour density (-SO2)	23	20	21
Colour density (SO2)	19	16	16
Sensory	Low and medium – same score, but high yielding was slightly lower in winemaker preferences.		
	Vintage 2001		
Baumé (°Bé)	13.1	12.7	13.6
pH	3.82	3.74	3.67
TA (g/L)	5.1	5.0	5.0
Sensory score	14	17	15

[1] Note that in 2000, the wines were made in the laboratory (in triplicate) from small (approx. 5 kg) samples; in 2001, commercial quantities (25 t lots) were made in the winery.

[2] In 2000, wines made from fruit harvested from the low yielding zone were significantly different ($P < 0.05$) from those made from fruit harvested from the medium and high zones with respect to all the listed analytes. However, wines made from fruit harvested from the medium- and high-yielding zones were not significantly different except in the case of total anthocyanin concentrations (Dr Tony Proffitt, formerly of Southcorp Wines – pers. comm.). Tests of significant differences were not made in 2001 as the wines were not made in replicate.

The three zones identified were the low-yielding strip in the centre of the block, the high-yielding area in the north east and the remainder of the block. At vintage 2000, small samples (approx. 5 kg) of fruit were taken from these zones and wines made from each in the laboratory using methodology developed at the University of Adelaide (Dr Patrick Iland – pers. comm.). The following year, wines were made in commercial quantities (25 t tanks) as part of the normal commercial production run, from fruit that was mechanically harvested into separate bins from each zone. Table 3 presents the results of some standard chemical analyses (Iland et al. 2000) done on the resulting wines. In both 2000 and 2001, wines made from these crudely delineated zones had different chemical and sensory characteristics, but the best zone in one year was not deemed to be so in the other (Table 3). This reinforces the notion that for zonal management of vineyards to be successful, consideration needs to be given to crop attributes other than yield alone.

When coupled with the data presented in Figure 5a, the results presented in Table 3 can be seen to be important to both vineyard and winery managers. If the mean cluster yields (Figure 5a) are expressed as ratios of the yield in the lowest yielding cluster in each year, the ratio of lowest:medium:highest mean cluster yield is 1:1.6:2.3 in 1999, 1:1.6:2.9 in 2000 and 1:1.7:2.2 in 2001. In other words, with the exception of the highest-yielding zone in the lowest yielding year (2000), the pattern is constant – which is what might be expected given that the patterns of variability are persistent. The fact that the ratio of the mean yield in the highest-yielding zone in 2000 was *higher* than the norm for the other years suggests that the capacity of the vines to develop fruit was greater than the level naturally set in a low-yielding year. It is therefore of interest that in terms of ranking wines produced from zones which correspond broadly with those shown in Figure 5a (the major difference is in the south-eastern corner which *k*-means clustering places in the 'low' zone whilst the crude delineation used for the winemaking trial included this area in the 'medium' zone), in 2000 there was only a slight difference between the 'high' zone and the others, whilst in 2001, wines made from the 'high' zone were much less preferred than those from the best (i.e. 'medium') zone. Clearly such differences could be important in allocating fruit to final products and in making blending decisions when winemaking at commercial scales.

Following on from this, it is often asserted by grapegrowers and winemakers, both in Australia and from around the world, that there is a yield:quality trade-off operating in winegrape production systems. If, for example, we were to assume (e.g. Bramley and Proffitt 1999) that wine quality is optimised in this vineyard when yields are about 6 t/ha, then on the basis of Figure 5a, the best wine should have come from the medium-yielding zones in 1999, the highest-yielding zone in 2000 and the lowest-yielding zone in 2001. Whilst the limited data presented in Table 3 support the view that higher yields do not necessarily produce the best wines, they provide no evidence in support of the view that lower yields do produce such wines. Clearly therefore, in order to make the most of zonal management, we need to improve our understanding of the physiology of grape and wine production and the vineyard factors that control it; some of these factors will be the subject of a subsequent paper in this series. Nevertheless, our new ability to identify characteristic zones within vineyards that, hitherto, have been managed on the basis that they were essentially homogenous, provides a framework against which such understanding can be sought. Thus, in addition to providing vineyard managers and winemakers with the concept of zonal management, this work provides these practitioners with the challenge to realise the opportunity of focusing their assessment of 'seasonal performance' within zones rather than whole blocks, and the ability to better define premium fruit parcels and thereby maximise commercial returns.

Finally, it is worth pointing out that the work presented here was inspired by developments that were initiated in broadacre agriculture, both in Australia and overseas, rather than within the wine industry. We therefore suggest that rather than seeking answers to all its research and production questions from within, the broader wine industry would do well to follow the advice of Scholefield and Robinson (1999) and 'improve their production systems by looking over the fence at what other industries are doing.'

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. The Clare data were derived during a separate study funded by CLW and SCW. In addition to these organisations, we are most grateful to Susie Williams (CLW / CRCV) for her excellent technical assistance, and to Mr Peter Walmsley (Sunraysia) and many of the staff and management of Southcorp Wines (Coonawarra, Clare) without whose support, the work would not have been possible. In particular, the input of John Matz, Colin Hinze and Tony Proffitt (now with Albert Haak and Associates) has been valued greatly.

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. Eds. L.D. Currie and P. Loganathan. Occasional report No. 14. Fertilizer and Lime Research Centre, Massey University, Palmerston North. pp 25–43.

Bramley, R.G.V. and Proffitt, A.P.B. (1999) Managing variability in viticultural production. Grapegrower and Winemaker 427, 11–16.

Bramley, R.G.V and Williams, S.K. (2001) A protocol for the construction of yield maps from data collected using commercially available grape yield monitors. www.crcv.com.au/CRCVProtocolBkfinal.pdf Cooperative Research Centre for Viticulture, Adelaide.

Bramley, R., Pearse, B. and Chamberlain, P. (2003) Being Profitable Precisely – A case study of Precision Viticulture from Margaret River. Australian Grapegrower and Winemaker 473a, 84–87.

Cook, S.E. and Bramley, R.G.V. (1998) Precision Agriculture – Opportunities, Benefits and Pitfalls. Australian Journal of Experimental Agriculture **38**, 753–763.

Cook, S.E., Adams, M.L., Bramley, R.G.V. and Whelan, B.R. (2003) State of Precision Agriculture in Australia. In: 'Precision Farming – A Global Perspective'. Ed. A. Srinivasan (The Haworth Press Inc.: Binghamton, New York). In press.

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.

Diker, K., Buchleiter, G.W., Farahani, H.J., Heerman, D.F. and Brodahl, M.K. (2003) Frequency analysis of yield for delineating management zones. In: Proceedings of the 6th International Conference on Precision Agriculture and Other Precision Resources Management, July 14–17, 2002, Minneapolis. ASA-CSSA-SSSA, Madison, WI.

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

Hall, A., Lamb, D.W., Holzapfel, B. and Louis, J. (2002) Optical remote sensing applications in viticulture – a review. Australian Journal of Grape and Wine Research **8**, 36–47.

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.

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.

Lamb, D.W. and Bramley, R.G.V. (2002) Precision viticulture – tools, techniques and benefits. In: Proceedings of the 11th Australian Wine Industry Technical Conference. (Australian Wine Industry Technical Conference, Inc., Adelaide). pp. 91–97.

Lamb, D.W., Weedon, M.M., and Bramley, R.G.V. (2003). Using remote sensing to map grape phenolics and colour at harvest in a Cabernet Sauvignon vineyard: timing observations against vine phenology and optimising image resolution. 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, University of Sydney. (www.usyd.edu.au/su/agric/acpa).

Pierce, F.J. and Nowak, P. (1999) Aspects of Precision Agriculture. Advances in Agronomy **67**, 1–85.

Pringle, M.J., McBratney, A.B., Whelan, B.M. and Taylor, J.A. (2003) A preliminary approach to assessing the opportunity for site-specific crop management in a field, using yield monitor data. Agricultural Systems **76**, 273–292.

Rawlins, S.L. (1997) Precision agriculture: The state of the art and lessons from overseas for the Australian sugar industry. In: 'Precision Agriculture – What Can It Offer The Australian Sugar Industry ?' Proceedings of a workshop held at the Mercure Inn, Townsville, 10–12 June. CSIRO Land and Water, Townsville.

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

Scholefield, P.B. and Robinson, J.B. (1999) Vineyard technologies – what can we learn from other industries ? In: '2025 – Meeting the Technical Challenge.' Proceedings of the 10th Australian Wine Industry Technical Conference. (Australian Wine Industry Technical Conference, Inc., Adelaide). pp. 220–223.

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 Superieure Agronomique de Montpellier, France). Volume 1. pp. 133–138.

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.

Whelan, B.M. and McBratney, A.B. (2000) The 'null hypothesis' of precision agriculture management. Precision Agriculture **2**, 265–279.

Manuscript received: 22 August 2003