

Making sense of vineyard variability in Australia

RGV Bramley^{1,3,4} and DW Lamb^{2,3}

¹*CSIRO Land and Water and* ³*Cooperative Research Centre for Viticulture
PMB No. 2 Glen Osmond, SA 5064, Australia.*

²*School of Biological, Biomedical & Molecular Sciences, University of New England
Armidale, NSW 2351, Australia*

⁴*Corresponding author - Email: Rob.Bramley@csiro.au*

Abstract

Vineyards are variable. Grapegrowers and winemakers have known this for as long as they have been growing grapes and making wine, 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.

Since vintage 1999, when the first winegrape yield monitor became commercially available in Australia, a major program of research has focussed on understanding the nature, extent and key drivers of variability in the winegrape production process, and on the opportunities to apply a precision agriculture approach to both viticultural management and winemaking. The results obtained to date support the introduction of a system of zonal vineyard management. Under this approach, rather than being managed uniformly, individual blocks can be split into zones in which the management of inputs to the production system can be applied differentially, and the outputs harvested selectively. A number of cost-effective supporting tools and technologies are available to support this approach including yield mapping, remote sensing and high resolution soil and topographic survey. This paper provides an overview of the development of precision viticulture in Australia.

Las viñas son variables. Este es un hecho conocido por productores de uvas y vino desde tiempos ancestrales, pero dada la carencia de métodos para medir esta variación, la variabilidad ha sido aceptada como un hecho y la mayoría de las viñas han sido conducidas como si éstas fuesen uniformes.

Desde la cosecha de 1999, cuando los primeros equipos comerciales para medir las variación espacial del rendimiento de las viñas estuvieron disponibles en Australia, un programa de investigación fue establecido con los objetivos de entender la naturaleza, extensión y factores determinantes de la variabilidad espacial en el proceso de producción de uvas y de identificar las posibilidades de aplicar conceptos de agricultura de precisión en el manejo de viñas y la producción de vino. Los resultados obtenidos hasta este momento, subrayan los beneficios de implementar un sistema de manejo zonal en las viñas. Con este método, en contraste con un manejo basado en el supuesto de uniformidad, las viñas pueden ser divididas en zonas, cada una de las cuales es tratada diferencialmente en términos de insumos y cosecha. Herramientas para implementar estas prácticas en forma redituable incluyen mapas de rendimiento, sensores

remotos y evaluaciones topográficas y edáficas de alta resolución. Este trabajo resume los desarrollos de viticultura de precisión en Australia.

Keywords: Precision Viticulture, zonal management, spatial variation, Australia

Introduction

Precision Agriculture (PA; Cook & Bramley 1998; Pierce & 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. These include the global positioning system (GPS), geographical information systems (GIS), yield monitors and a number of technologies for remote and proximal sensing which, when used in conjunction with the GPS, enable georeferenced records of crop performance to be collected, both mid-season and also '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.

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 & Proffitt 1999; Bramley 2001b; 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 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 & Proffitt 1999).

The implementation of a PV approach to vineyard management is a continual cyclical process (Bramley 2001b; 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 during the season and/or selective harvesting at vintage. Here, 'targeted management' can mean the timing and rate of application of water, fertilizer 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 & 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 (Bramley & Hamilton, 2003). 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 & Bramley 1998; Bramley & 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.

These questions are being addressed in a number of Australian research projects focussed on understanding vineyard variability and the associated development of PV and tools to facilitate its implementation. This paper provides an overview of much of this work.

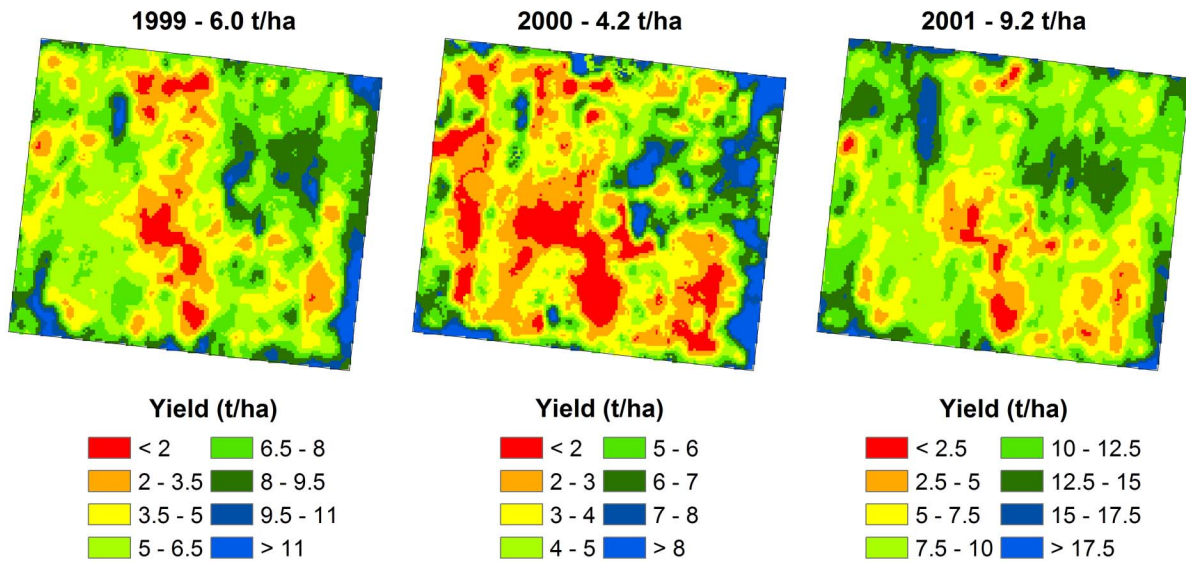
The nature and extent of vineyard variation

Figure 1a shows yield variation over three years in a 7.3 ha vineyard in the premium Coonawarra winegrape-growing region in the south-east of South Australia. This block was planted to Cabernet Sauvignon on its own roots in 1974. The yield maps were produced following the protocol of Bramley and Williams (2001) after harvesting the block with a Gregoire G120 mechanical harvester fitted with a yield monitor and a differentially corrected GPS logging yield and position at intervals of approximately 3 m along the row. In any given year, the yield variation shown in Figure 1 is typical of that seen in vineyards planted to a range of varieties at a range of locations in both the warmer and cooler grapegrowing regions of Australia, in that the range of variation is of the order of 8 to 10-fold (eg 2-20 t/ha; Bramley, 2001a,b).

Notwithstanding the differences in the annual mean yields for the block, the patterns of variation appear to be stable in that there is a consistently low-yielding 'strip' in the central part of the block and a characteristically higher yielding area in the north eastern quarter. This similarity in the pattern of spatial variation in yield, for years in which the mean yield for the block differed markedly, is emphasised when the data are normalised ($\mu=0$, $\sigma=1$) to remove the effects of what are assumed to be climate driven differences in yield potential from year to year (Figure 1b).

Using 'hard' multivariate k-means clustering, and a technique based on a modification of the frequency analysis method of Diker *et al.* (2003), Bramley and Hamilton (2003) have recently demonstrated that the patterns of yield variation shown in Figure 1 are temporally stable, and that as a consequence of this, different areas or 'zones' can be identified for this block, in which yield is typically low, medium or high, relative to the mean in any given year (Figure 2). They obtained similar results for a block of Merlot in the Clare Valley. Bramley and Hamilton (2003) further showed that by assessing yield variation with respect to a range of yield targets, and incorporating expert knowledge into the analysis of zones, it was possible for vineyard managers to incorporate considerations of risk, and / or the benefit:cost of applying differential management to different areas within vineyards that had previously been considered as single management units. In the Clare Valley example, whether or not the period around flowering was

a



b

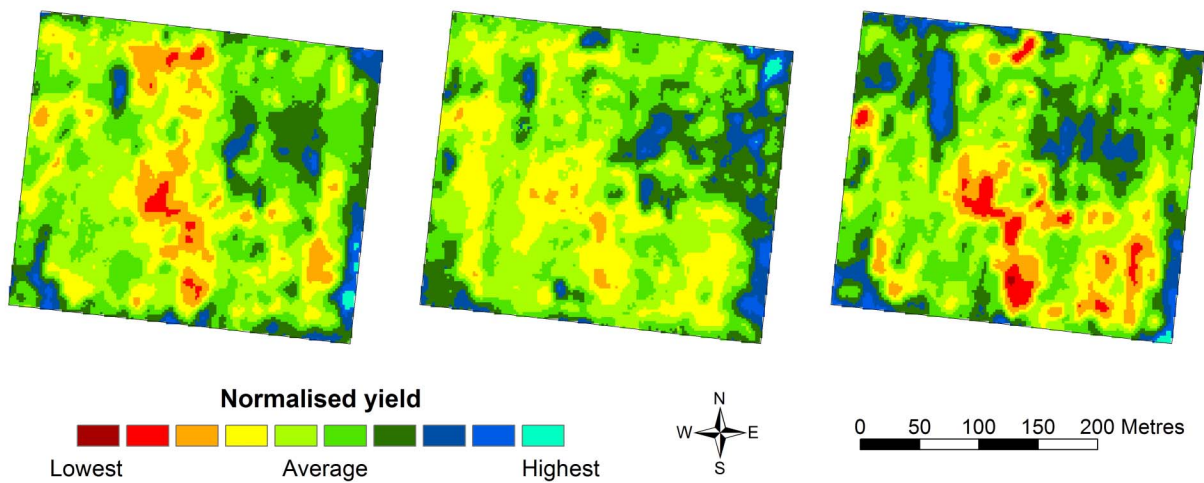
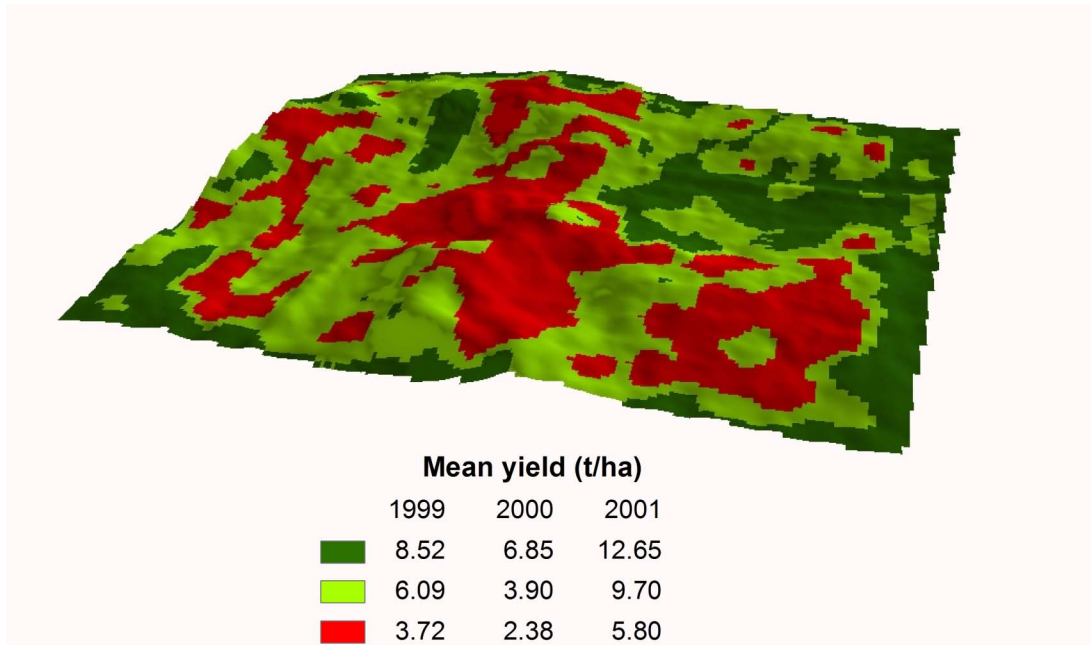


Figure 1

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. Data of Bramley and Hamilton (2003).

a.



b.

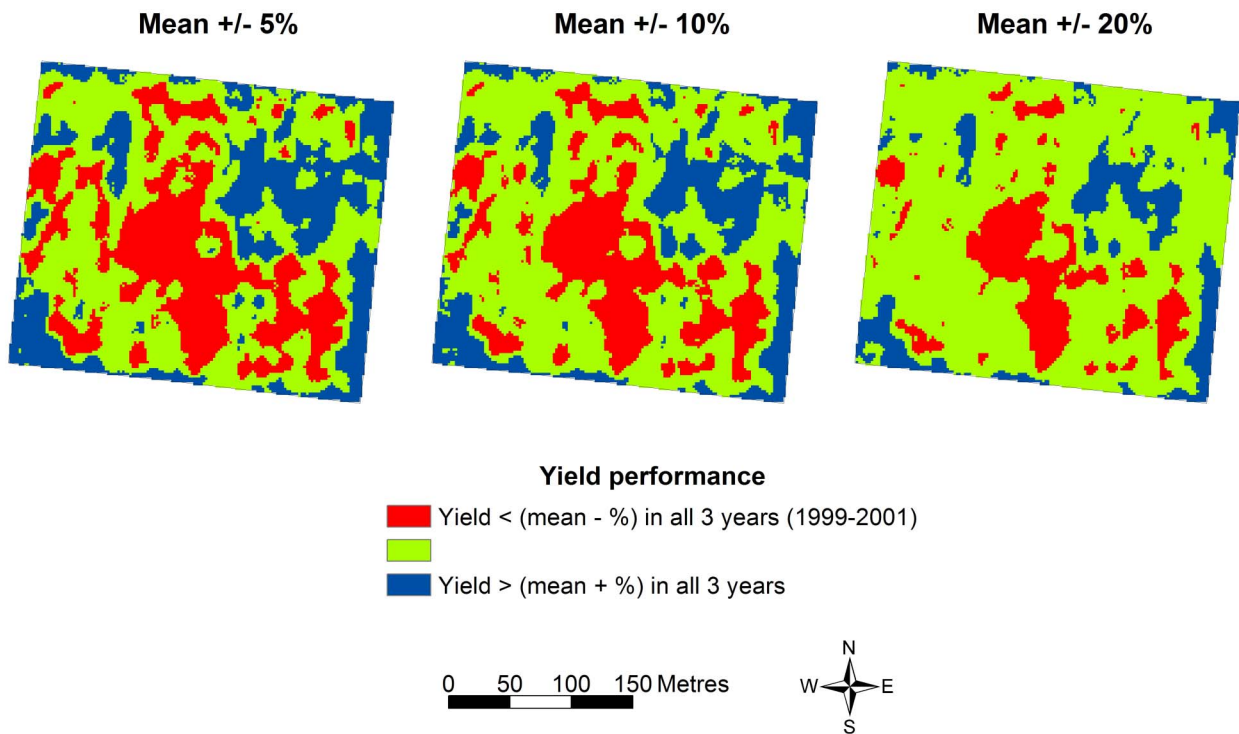


Figure 2

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. This was also the case for the mean zone yields in (b), irrespective of the yield target. Data of Bramley and Hamilton (2003).

Table 1 Variation in selected fruit and vine indices at vintage over 3 years in two contrasting Australian vineyards^A

	Baumé (°)			Titratable Acidity(g/L)			Anthocyanins (mg/L)			Phenolics (AU/g)			Berry weight (g)			Yield (kg/m row)		
Cabernet Sauvignon – Coonawarra. Cool climate. Grapes intended for premium bottled table wine.																		
Year	'99	'00	'01	'99	'00	'01	'99	'00	'01	'99	'00	'01	'99	'00	'01	'99	'00	'01
Max	15.6	14.0	14.7	7.9	6.6	7.8	2.89	2.83	1.73	2.32	2.37	1.50	1.27	1.19	1.35	15.9	7.04	16.3
Min	13.4	12.1	11.4	3.3	4.0	3.7	1.13	1.24	0.58	1.04	1.17	0.45	0.44	0.35	0.25	0.50	0.14	0.21
Median	14.6	13.2	13.3	5.1	4.9	5.0	1.80	1.93	0.89	1.51	1.66	0.89	0.77	0.91	0.95	4.49	2.17	6.42
CV %	2.8	2.6	3.9	15.4	9.8	13.4	13.7	15.7	18.1	11.0	13.5	19.0	14.5	15.4	18.4	49.3	64.9	51.6
N	190	190	190	190	190	190	190	190	189	190	190	189	190	190	190	190	190	190
Ruby Cabernet – Sunraysia. Warm climate. Grapes intended for blending into low-mid priced products																		
Year	'00	'01	'02	'00	'01	'02	'00	'01	'02	'00	'01	'02	'00	'01	'02	'00	'01	'02
Max	15.7	14.5	17.3	5.9	5.0	7.3	3.07	3.33	3.45	2.43	2.48	2.20	1.24	1.21	1.52	13.9	14.8	18.5
Min	10.9	12.2	12.0	3.4	3.2	4.2	0.75	1.69	1.57	1.22	1.52	1.07	0.34	0.36	0.43	1.37	0.92	0.38
Median	13.2	13.7	14.8	4.6	4.1	5.4	2.33	2.32	2.25	1.86	1.82	1.56	0.87	0.80	0.91	7.48	6.72	7.5
CV %	5.6	2.8	6.8	10.7	9.4	9.4	14.2	14.7	11.7	11.9	10.4	13.5	21.9	22.3	22.8	36.5	38.8	46.6
N	119	130	130	119	129	130	119	129	130	119	129	130	119	129	130	120	129	130

^AFurther details of these sites are provided in Bramley (2001a,b)

colder than normal impacted on the extent to which differentiation between the zones was merited, either in terms of vineyard management during the remainder of the season or the use of a selective harvesting strategy.

Variation in fruit and wine quality is the focus of much of the work being currently undertaken, especially in terms of trying to gain greater control over wine flavour and aroma through careful management in the vineyard. Various studies, based on hand sampling at vintage followed by laboratory analysis of a range of indices of fruit quality, have shown that variation in fruit quality exhibits marked spatial structure (eg Bramley 2001a,b; Lamb *et al.*, 2003), but that the patterns of variation are not necessarily the same as those for variation in yield. However, the range of values and their associated coefficients of variation (eg. Table 1) tend to be much less than for yield (eg Figure 1), irrespective of either the variety grown, the inherent vineyard characteristics (climate, soil type, etc.), or the type of viticulture practiced. Thus, whilst Bramley and Hamilton (2003) noted that there were differences in the final wines produced from different 'zones' within the Coonawarra study site (Figure 2), and that these differences were sufficiently large to be of interest to winemakers faced with blending decisions, they were not sufficiently large to warrant allocation of the wines to final products at different commercial price points. In contrast, as is discussed below, Bramley *et al.* (2003) have reported a commercial example of the implementation of PV in which selective harvesting based on canopy variation (which was closely correlated with variation in final yield), followed by differentiation of final products, led to a very significant increase in the total value of production. These two examples (Bramley &

Hamilton, 2003; Bramley *et al.*, 2003) both point to the viability of a system of *zonal management* in which yield data, possibly supplemented by soil and topographical information and remotely sensed imagery (see below), are used to segregate vineyards into *zones* for which differential management is warranted. As Bramley and Hamilton (2003) have highlighted, the relative performance of these zones with respect to wine quality may vary from year to year, but provided mid-season and pre-vintage assessments of vineyard performance (yield and fruit quality) are made on a per-zone basis, the opportunity exists for much better viticultural and oenological management decisions to be made than would be the case if the whole vineyard was managed on the assumption that it is homogenous – which is what happens under current conventional management.

Vineyard variation is driven by variation in soil properties and topography

Variation in soil properties, often associated with variation in topography, appears to be a key driver of vineyard variability. In general, the Coonawarra region is regarded as being flat and our study site (Figures 1-2) has a range of elevation of only 1.2 m between the lowest and highest points – less than the range of elevation at the Lords cricket ground in London, the home of international test cricket ! However, as Figure 2a shows, the low yielding zones at our Coonawarra study site occur on ‘ridges’, whilst the higher yielding areas occur in ‘hollows’. Through a study of soil depth and particle size at 190 locations (approximately 26 samples/ha; Bramley 2003b; Bramley & Janik, 2003), Bramley and Lanyon (2002) demonstrated that in this vineyard, which is characterised by shallow *terra rossa* soils (light red clays) over limestone, yield variation is driven by variation in plant available water in the root zone, which in turn is controlled by variation in soil depth, which in turn is controlled by variation in topography. Similarly, Bramley (2003a) demonstrated the importance of elevation in controlling yield variation in a Clare Valley vineyard which was variably affected by soil salinity (Figure 3). In this case, the low lying parts of the landscape, and an area to the west of the block which is adjacent to a surface water dam used for irrigation, were shown to be those in which yield was depressed, because these areas are those in which soil salinity is greatest; the range of elevation in this example was approximately 13 m.

In a further example from the Sunraysia region, Bramley (2001a,b) demonstrated the dependence of yield variation on the amount and position of clay in the soil profile. At this site, which is prone to waterlogging in winter and spring, rather than yield being restricted by limited availability of water, the low yielding area at the western side of the block (Figure 4a) corresponds to areas where the clay subsoil occurs closest to the surface and where, in wet years, waterlogging is more pronounced. As in the other examples, access to an elevation model was invaluable in understanding the cause of the variation (Figure 4b). Such a model may be readily created following field survey with real-time kinematic GPS (accurate to approximately 2 cm in the x, y and z planes).

All the above examples relate predominantly to soil physical properties. In addition, there is good evidence to suggest that crop nutrition, as affected by soil chemistry may impact on aspects of wine quality. For example, Bramley (2001b) and Bramley and Janik (2003) have drawn attention to a possible association between manganese nutrition and grape phenolics, which is further supported by anecdotal evidence from Chile (Prof. Rodrigo Ortega – pers.comm.). Given the

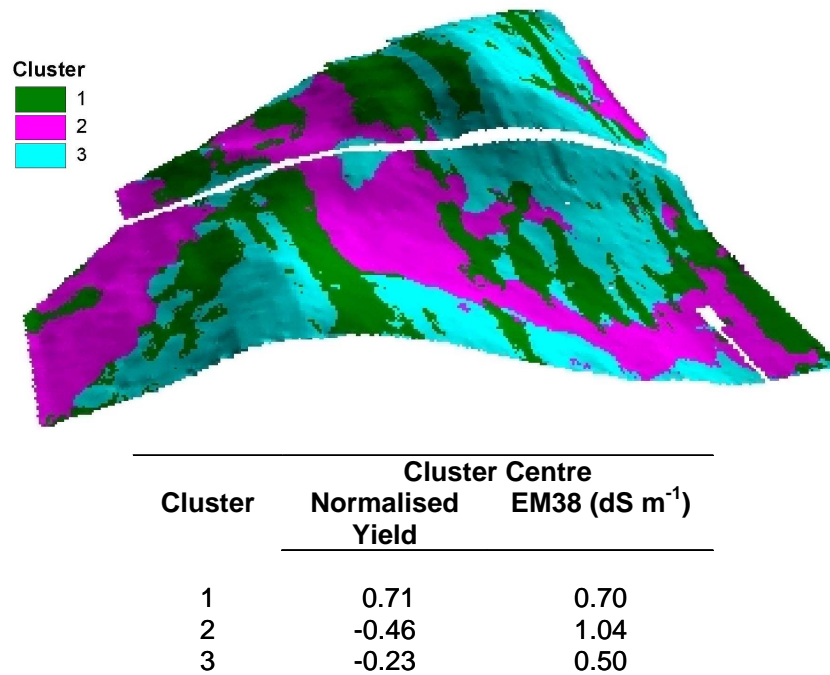


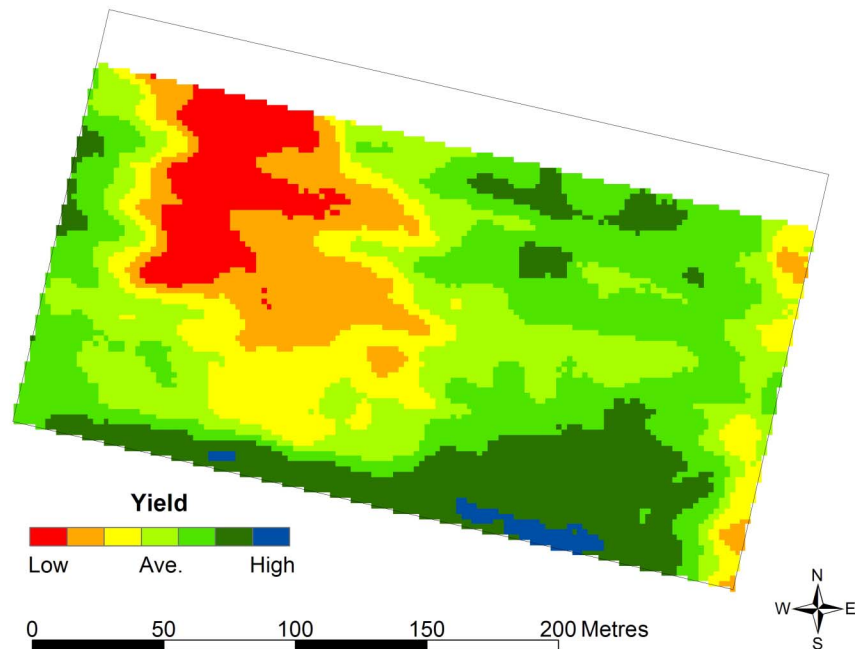
Figure 3. Variation in elevation, yield and soil salinity as assessed by EM38 soil survey, in a 22 ha vineyard in the Clare Valley, Australia. Data of Bramley (2003a).

requirement of grapevines for 16 essential nutrients (White, 2003), and the likely role of many of these as precursors for the synthesis of a myriad of flavour and aroma compounds in leaves and berries, it would be surprising if soil fertility had little impact on fruit quality. This issue, and the associated possibility of using targeted management of nutrients to control crop quality, is a subject which warrants substantial further research.

Soil survey and mid-season sampling of fruit and vines

The importance of soil as a major driver of vineyard variability raises questions as to how vineyard soils should be surveyed – both prior to vineyard establishment and also for the purposes of assisting with the ongoing management of established vineyards. In Australia, the wine industry has adopted a standard method for vineyard soil survey based on the digging of inspection pits located at the nodes of a 75 m grid. Indeed in some regions, it is a statutory requirement that, prior to the granting of an irrigation licence, such a soil survey should be carried out. However, our research has highlighted some major shortcomings of this method, and also pointed towards the merits of a more targeted approach to vineyard sampling (Bramley, 2001b, 2003b; Bramley & Janik, 2003). In particular, the 75 m grid ignores topography, and also the expert knowledge of both the land manager and the soil surveyor, and results in the production of soil map at resolutions that are inconsistent with the objectives of viticultural production. In the case of the manager adopting PV, the 75 m grid is very likely to result in an inadequate level of detail of soil variation for the development of targeted management strategies

a.



b.

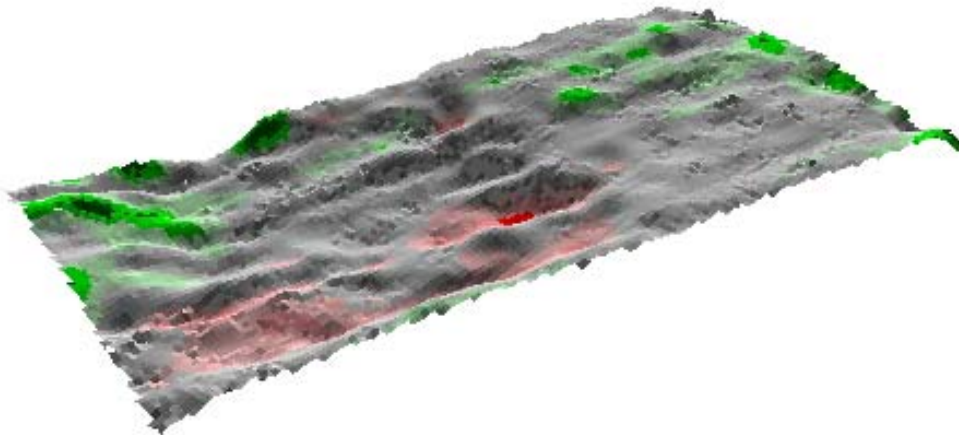


Figure 4. Variation in yield and elevation in a 4.5 ha vineyard in the Sunraysia region of north-west Victoria, Australia. The map shown in (a) was constructed by *adding* maps of normalised ($\mu = 0$, $\sigma = 1$) yield of Ruby Cabernet for vintage 1999 ($\mu=27.9$ t/ha) and 2000 ($\mu=17.3$ t/ha). As such, it identifies the poorly performing western portion of the block where waterlogging in winter and spring, due to poor soil drainage, was thought to be limiting vine growth and grape yield (Bramley, 2001a,b); such waterlogging was particularly severe in season 2000. The map shown in (b) was constructed by subtracting the normalised map for 2000 from that for 1999 and draping the result over an elevation model. Thus, the pink areas in (b) are those in which, relative to the mean for the year, yield in 2000 was substantially worse than in 1999. These areas tend to occur in hollows where the effects and duration of the waterlogging would have been exaggerated in 2000, compared to those experienced in a more ‘normal’ year such as 1999.

or informed vineyard designs (Bramley, 2003b). In the case of the manager who intends to persist with an approach based on the assumption of vineyard homogeneity, the 75 m grid almost certainly results in over-sampling and therefore unnecessary cost. Bramley (2003b) has recently drawn attention to the opportunity to deliver powerful improvements to vineyard soil survey over the existing industry standard, through the use of high resolution proximal soil sensing (for example using EM38 electromagnetic induction) and elevation modelling, accompanied by appropriately targeted ground truthing, based in part, on the expert knowledge of both the vineyard manager and soil surveyor. A key aspect of this strategy is that the locations sampled for ground truthing the proximal sensor are chosen to cover the full range of expected variation in soil properties. Note that Bramley (2003b) has demonstrated that the ground truthing involved in such a strategy need be at no greater sampling intensity than that implied by the 75 m grid. Thus, the additional cost of this strategy is confined to the high resolution proximal sensing and elevation modelling. This cost is equivalent to about A\$1/tonne fruit produced (Table 2) and is therefore fairly trivial.

A somewhat similar situation exists with respect to the sampling of vines for the purpose of managing crop nutrition. As Bramley and Janik (2003) have highlighted, the standard approach for collection of petioles for assessment of nutrient status results in a single piece of information (the block-average nutrient status), the only spatial component of which is that provided by the block boundary (Figure 5a). If however, petioles are collected using a method involving geo-

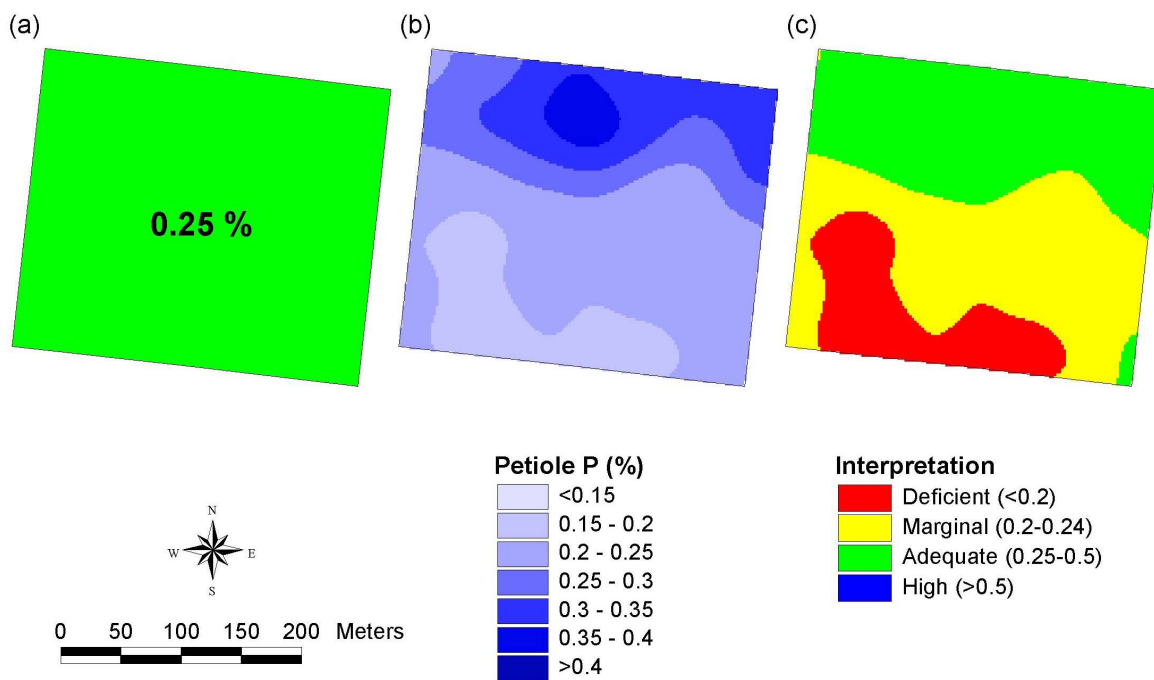


Figure 5. Petiole phosphorus at flowering at the Coonawarra study site, 2001, assessed using either (a) an ‘industry standard’ approach, or (b) an approach based on intensive sampling of georeferenced vines. In both cases, the results were interpreted against the same criteria (c; Robinson *et al.*, 1997). Data of Bramley and Janik (2003).

referencing of sampling points using a GPS, followed by separate, as opposed to bulked, analysis of the collected material, the vineyard manager has the opportunity to provide the nutrients that the vines actually need – in the locations where they are needed – rather than assuming that responding to the average need delivers what is required to the whole vineyard (Figure 5b,c; Bramley & Janik, 2003). Of course, the cost of employing such a strategy may be considerably larger than the standard method, but this additional cost is arguably offset by the increased value of the information obtained (Cook & Bramley, 2000) and falls within a readily affordable PV adoption budget (Table 2). The high requirement that PA / PV potentially has for soil and plant analysis, and the pressure this places on both laboratories and the users of such services, is discussed at some length by Bramley and Janik (2003) who also highlight the potential of a new method of soil analysis based on mid-infrared reflectance spectroscopy. This, and other surrogate analytical tools, have the dual benefits of being both quick and cheap, thereby satisfying the requirements of both the laboratory manager and his / her client.

Remote sensing

As discussed by Hall *et al.* (2002), remote sensing is a potentially valuable tool for assessment of vineyard variability, and has particular application for mid-season monitoring. Commercial remote sensing services are now fairly widely available in Australia at low cost (Table 2).

Recent research has focussed on centimetre- and metre-resolution multispectral remote sensing in the blue (B), green (G), red (R) and infra-red (IR) bands of the visible electromagnetic spectrum. Collection of reflectance data at wavelengths corresponding to these parts of the spectrum allows calculation of a number of indices of canopy condition, of which the normalised difference vegetation index (NDVI; $(IR-R)/(IR+R)$) is the most commonly used (Hall *et al.*, 2002). However, other indices, such as the so-called plant cell density (PCD; IR/R) and vigour index (G/R), are also used by some commercial providers in Australia. In essence, all of these provide information about the amount of photosynthetically active biomass (PAB). With further research, hyperspectral instruments collecting data from other parts of the spectrum may also prove useful.

From an operational point of view, image acquisition based on airborne platforms offers an advantage over satellite based platforms in terms of the timeliness of image acquisition. Whilst some new satellite based sensors offer on-ground image resolutions comparable to airborne sensors, they currently are significantly more expensive to individual growers than airborne derived imagery because the commercial providers of this data do not release small-area (ie vineyard sized) coverage images. This is regrettable because when the cost of satellite imagery is calculated on a per-hectare basis from the cost of an entire scene, it is an order of magnitude cheaper to purchase than the airborne imagery.

Lamb *et al.* (2003) have recently demonstrated that the utility of airborne imagery collected at a range of times during the season for prediction of characteristics at harvest was found to depend on grapevine phenology. Veraison +/- 2 weeks was shown to be the best time for vineyard image acquisition (Figure 6), and the variation observed in imagery collected at this time was shown to predict variation in fruit colour and phenolics at vintage. In other work conducted by Hall (2003), similar imagery of red winegrape vines acquired at flowering was also shown to predict yield variation in the following season. Lamb *et al.* (2003) observed that the highest correlations

between PAB and fruit colour and phenolics at vintage were obtained from imagery with a resolution comparable to the row spacing (typically either 2.5 or 3 m). However, using ultra-high-resolution imagery (10 cm), Hall (2003) was able to separate out descriptors of vine size from those related to leaf-only spectra. The image-derived descriptors of canopy size were found to explain the greatest amount of variance observed in the canopy, but not significantly more than that observed by Lamb *et al.* (2003) using resolution of the order of the vine-row spacing. Clearly the coarser, 2-3 m resolution imagery of Lamb *et al.* (2003) integrates the attributes of vine-size and leaf-only spectral signature, but it is the former attribute which is the dominant contributor to the ability of the remotely-sensed data to explain the variance in fruit yield and/or quality. This has practical implications for the use of remote sensing as a means of discriminating between regions of differing fruit quality. Higher-resolution (and often more expensive) imagery, could be used to extract information from vine-only pixels thereby providing information such as leaf-only spectra. However, the extraction of such information may be introducing an unnecessary additional level of complexity to the data analysis – of course, at a cost to the user.

Bramley *et al.* (2003) recently provided a striking commercial example of the benefits of using remotely sensed imagery in a selective harvesting trial in a 3.3 ha area in the Margaret River region of Western Australia. In brief, a PCD image acquired at veraison was used as the basis for targeted sampling of fruit from areas of perceived high and low vigour two weeks prior to vintage. Analysis of this fruit suggested that significant differences in quality existed between the apparently low and high vigour regions. Accordingly, at harvest, the trial area was split into two and the fruit harvested into two batches by running two chaser bins next to the harvester. Just as the yield map produced bore a strong resemblance to the PCD image, so too did the analysis of harvested fruit match the analyses conducted two weeks earlier. Thus, the fruit from the low

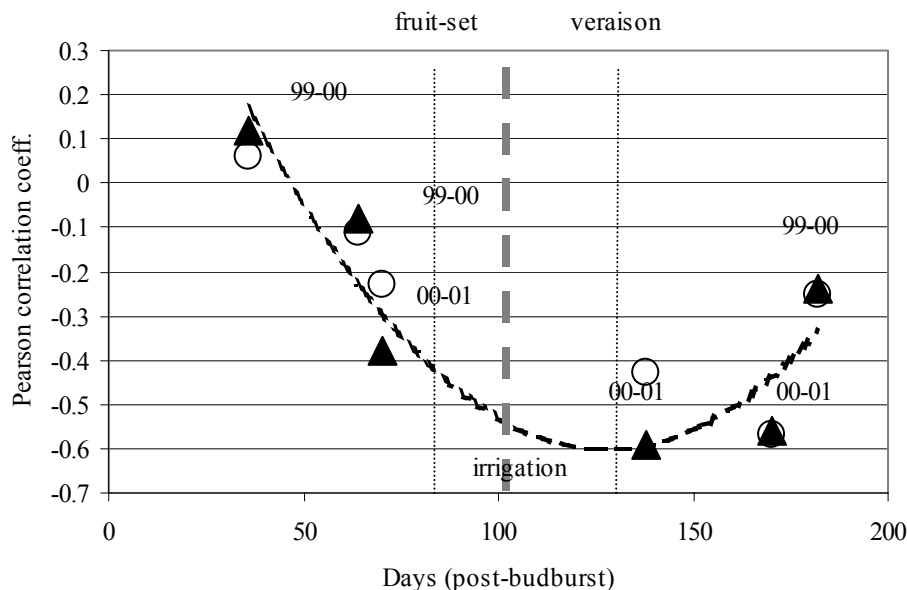


Figure 6. Pearson correlation coefficients for NDVI against colour (○) and total phenolics (▲) as a function of days post-budburst; 99-00 and 00-01 indicate the growing season of the corresponding data. Data of Lamb *et al.* (2003).

Table 2. Estimated budget for implementing a Precision Viticulture approach to vineyard management in Australia^A.

Assumptions:	Average grape yield = 10 t/ha Harvester operates at 0.4 ha/h for 450 h/yr = 180 ha/yr ^B Grape price = \$1500/t (premium fruit); \$400/t (non premium fruit) ^C
Yield monitoring:	Yield monitor costs \$10,000 GPS costs \$10,000 Subscription to differential signal costs \$2,500/yr Costs are spread over 5 years <p style="text-align: right;"><u>Total cost of yield monitoring = \$3.60/t</u></p>
Supplementary information:	EM38 soil survey (one-off cost, spread over 5 years) = \$1/t Airborne remote sensing @ \$25/ha = \$2.50/t <p style="text-align: right;"><u>Total cost of remote/proximal sensing = \$3.50/t</u></p> <p style="text-align: right;"><u>Total cost of basic data acquisition = \$7.10/t</u> (ie. 0.5 - 2 % of the price received for fruit)</p>
Soil and plant analysis:	If we are prepared to spend \$15/t on PV, we are left with \$7.90/t (ie \$79/ha/yr) for soil/plant analysis, plus whatever is spent currently on such analysis; this is unlikely to be an annual cost.

^AAll costs are in A\$

^BThis rate of harvester usage is that employed by one of Australia's major wine companies in their company-owned vineyards. A commercial harvesting contractor would operate a machine at up to double this rate, thus reducing the overall cost of operation in \$/t.

^CThe difference between these estimated prices reflect differences between premium cool-climate fruit and non-premium fruit from a warm irrigated region.

vigour area was assigned to a product with a retail value of approximately A\$30/bottle, whilst that from the higher yielding, high vigour area, was assigned to a product with a retail value of approximately A\$19/bottle. As a result of harvesting on a zonal basis, the retail value of production from the 3.3 ha trial area was increased by almost A\$102,000 (Bramley *et al.*, 2003).

Towards optimal management of grape and wine production

The null hypothesis of precision agriculture (Whelan & McBratney, 2000) 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." Recent Australian research into vineyard variability and the associated development of PV, as discussed above, has clearly demonstrated

that: vineyards are highly variable with this variability being characterised by a strong spatial structure; the patterns of vineyard variability are broadly temporally stable; a precision viticulture approach to winegrape production is potentially highly profitable; and the costs of data acquisition implied by the adoption of precision viticulture (Table 2) are small in relation to their value. Thus, we are confident that, with respect to winegrape production systems, the null hypothesis of Whelan and McBratney (2000) can be rejected. Furthermore, whilst it is undoubtedly true that it takes much longer to learn how to use a new technology than it does to develop it in the first place, the level of understanding of how to use the technologies which collectively encompass PV is sufficient to warrant adoption of at least some elements. However, further research will improve this understanding and thus facilitate further adoption and access to the benefits that such adoption will deliver.

Acknowledgments

The majority of the work referred to here was funded by CSIRO Land and Water (CLW), Southcorp Wines Pty Ltd (SCW), the Commonwealth Cooperative Research Centres Program under the aegis of the 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, 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 Richard Hamilton, John Matz, Colin Hinze and Tony Proffitt (now with Albert Haak and Associates) has been valued greatly. We also wish to acknowledge the support of staff of the Charles Sturt University Vineyard and the National Wine and Grape Industry Centre (NWGIC), as well as the ongoing technical support of staff of Charles Sturt University's Spatial Analysis Unit (CSU-SPAN).

References

- Bramley, R.G.V. 2001a. Variation in the yield and quality of winegrapes and the effect of soil property variation in two contrasting Australian vineyards. *In: ECPA 2001 - 3rd European Conference on Precision Agriculture* 2 767-772 (Eds Blackmore, S. and Grenier, G.) agro Montpellier, Ecole Nationale Supérieure Agronomique de Montpellier, France.
- Bramley, R.G.V. 2001b. 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. Also available at www.crcv.com.au/research/programs/one/bramley1.pdf*
- Bramley, R.G.V. 2003a. Precision viticulture – Tools to optimize winegrape production in a difficult landscape *In: Proceedings of the 6th International Conference on Precision Agriculture and Other Precision Resources Management, July 14-17, 2002, Minneapolis. (Ed. P. Robert). ASA-CSSA-SSSA, Madison, WI.*
- Bramley, R. 2003b. Smarter thinking on soil survey. *Australian and New Zealand Wine Industry Journal* 18 (3) 88-94.

- Bramley, R.G.V. and Hamilton, R.P. 2003. Understanding variability in winegrape production systems. 1. Within vineyard variation in yield over several vintages. *Australian Journal of Grape and Wine Research*. In press.
- Bramley, R.G.V. and Janik, L.J. 2003. Precision agriculture demands a new approach to soil and plant sampling and analysis – Examples from Australia. *Communications in Soil Science and Plant Analysis*. In press.
- Bramley, R.G.V. and Lanyon, D.M. 2002. Evidence in support of the view that vineyards are leaky – Indirect evidence and food for thought from precision viticulture research. In: *Vineyard 'leakiness'* (Eds Bramley, R.G.V. and Lanyon, D.M.) Proceedings of a workshop held at the Waite Campus, Adelaide, January 24-25, 2002, to scope the potential threat to the sustainability of Australian viticulture through excessive drainage below the root zone. Final Report on GWRDC Project No. GWR01/04. CSIRO Land and Water / Grape and Wine Research and Development Corporation, Adelaide.
www.clw.csiro.au/publications/consultancy/2002/Vineyard_leakiness_high_res.pdf
- 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*. **473a**, 84-87.
- 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.
- 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. and Bramley, R.G.V. 2000. Coping with Variability in Agricultural Production – Implications for Soil Testing and Fertiliser Management. *Communications in Soil Science and Plant Analysis* **31** 1531-1551.
- 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. (Ed. P. Robert). ASA-CSSA-SSSA, Madison, WI.
- Hall, A. 2003. Defining grapevine and vineyard characteristics from high-spatial-resolution remotely-sensed optical imagery. PhD thesis, Charles Sturt University, 144 pp.
- 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.
- Lamb, D.W., Weedon, M.M. and Bramley, R.G.V. 2003. 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*. In press.
- Pierce, F.J. and Nowak, P. 1999. Aspects of Precision Agriculture. *Advances in Agronomy* **67** 1-85.
- Robinson, J.B., Treeby, M.T. and Stephenson, R.A. 1997. Fruits, Vines and Nuts. In: *Plant Analysis: An Interpretation Manual*; (Eds Reuter, D.J. and Robinson, J.B.). CSIRO Publishing: Collingwood, Australia, 349-382.
- Whelan, B.M. and McBratney, A.B. (2000) The “null hypothesis” of precision agriculture management. *Precision Agriculture* **2**, 265-279.
- White, R.E. 2003. *Soils for Fine Wines*. Oxford University Press, New York.