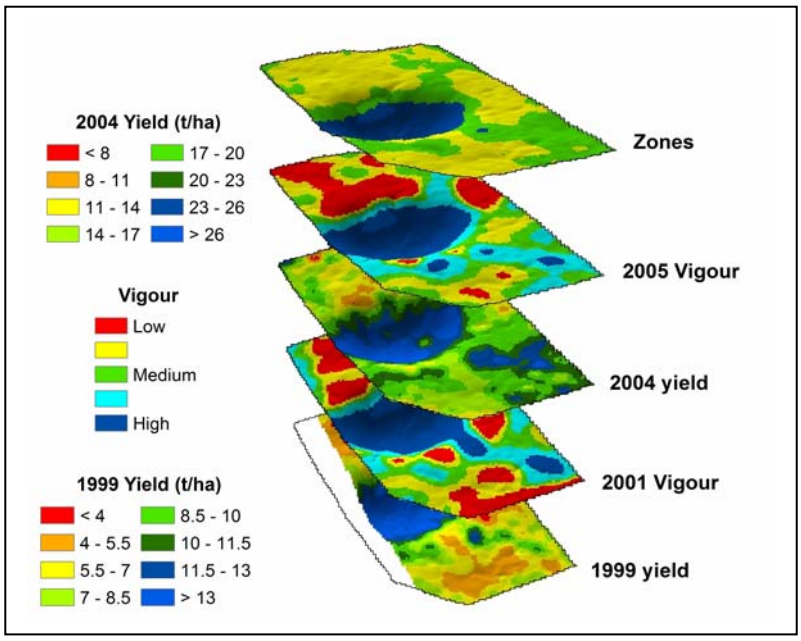
Cooperative Research Centre for Viticulture

Australian Government
Grape and Wine Research and Development Corporation

Precision Viticulture – Making sense of vineyard variability



FINAL REPORT to

GRAPE AND WINE RESEARCH & DEVELOPMENT CORPORATION

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Abstract

This project focussed on understanding the nature, extent and key drivers of vineyard variability and on the opportunities for tailoring the management of winegrape production using a range of technologies which promote the collection and analysis of information about vineyard performance at a high spatial resolution – an approach which has become known as Precision Viticulture.

Within vineyard variation in yield is typically of the order of 8 to 10-fold (ie 2-20 t ha^{-1}). Fruit quality is also variable with its patterns of spatial variation tending to follow those for yield. This variation is predominantly driven by variation in the land underlying the vineyard (soil hydrology, soil fertility and topography). As a consequence, high resolution spatial information about variation in soil properties and topography are invaluable in assisting with understanding variation in vineyard performance and thus, how management might be tailored in response to it. Similarly, remotely sensed imagery provides a valuable indication of vine vigour, whilst a new mode of experimentation involving whole management units rather than small plots offers growers a means of understanding the variable response to treatments and/or management strategies.

Use of these technologies, and the associated implementation of zonal management, offers significant benefits over the traditional (uniform) approach to vineyard management, particularly in terms of selective harvesting and product streaming.

Executive Summary

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 in both yield and quality has been accepted as a fact of life and the majority of vineyards have been managed on the assumption that they are homogenous.

Three consequences of vineyard variability are inefficiencies in the management of inputs to the production system, uncertainty in the prediction of yield, and perhaps of greatest concern, delivery of grapes of inconsistent quality to the winery. Inefficient use of inputs to the production system, whether these be water, sprays, fertilizers or the use of labour and machinery, compromises the profitability of the production system and may also lead to detrimental environmental impacts both on and off site. Uncertainty in yield prediction obstructs precise scheduling by winemakers faced with an increasing mismatch between the tonnage of grapes to be crushed and the crushing and storage capacity of the winery. Meanwhile, variation in fruit quality, and the resultant acceptance of 'average' quality from whole vineyards limits the opportunity to maximise the production of premium quality wines and to tailor production to market demand and opportunity.

This project has focussed on vineyard variability; its nature, extent, key drivers, the opportunities for targeting management in response to it, and the potential utility of a range of tools that may assist with this, remote sensing being a particular area of focus. The key findings of the project include:

- Within-vineyard yield variation has been shown to be typically of the order of 8 to 10-fold (eg 2-20 t/ha);
- Fruit quality is also variable and tends to follow the same patterns of variation as yield (t/ha), although not necessarily in the same rank order. As a consequence, segregation of vineyards into 'zones' on the basis of yield maps and or remotely sensed imagery, very often results in differences in the final wines produced from fruit harvested from these zones. Whether the end use of these wines warrants them being priced differently is something that will need to be judged on a case by case basis. Nevertheless a number of commercial examples already exist in which selective harvesting has been proven to be highly profitable.
- Variation in soil properties and/or topography, appears to be a key driver of vineyard variability. Indeed, even in apparently flat landscapes, we have found an elevation model to be invaluable in helping understand vineyard variation.
- In much more steeply sloping landscapes, an elevation model is also highly valuable, especially if used to generate maps of explanatory variables such as the topographic wetness index or maps showing variation in temperature or incident radiation.
- Air-borne remote sensing is a potentially valuable tool for assessment of vineyard variability, and has particular application for mid-season monitoring for both red and white winegrape varieties. It also offers a cheap entry point to Precision Viticulture. Veraison is clearly the best time for sensing red varieties, although time of sensing appears to be less critical in the case of white varieties.
- Sideways-looking proximal canopy sensors also appear to offer considerable potential utility for mid-season vineyard reconnaissance and, in the case of constrained VSP canopies, may offer a better indication of canopy size than airborne sensing.
- Through a PhD study conducted as a part of the project, a methodology for processing very high (~10-cm) spatial resolution imagery to acquire values that describe the canopies of individual grapevines was developed. Correlations were found to exist between image derived descriptors of grapevine canopy architecture (size and density) and fruit quality variables, particularly the anthocyanin and phenolic contents of fruit, total soluble solids and berry size.

- Importantly, image-derived descriptors of canopy size obtained from the 10 cm resolution imagery were found to explain the greatest amount of variance observed in the canopy, but this was not significantly greater than those observed using resolution of the order of the vine-row spacing.
- The industry standard method for vineyard soil survey based on the digging of inspection pits located in a 75 m grid is very likely to result in an inadequate level of detail of soil variation for the development of targeted management strategies or informed vineyard designs. 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.
- Vineyard soil survey based on high resolution proximal soil sensing (for example using EM38 sensing), elevation modelling, the expert knowledge of both the vineyard manager and soil surveyor, and appropriately targeted ground truthing delivers powerful improvements to vineyard soil survey compared to the existing industry standard. However, caution is needed in using this equipment in vineyards containing steel posts.
- Irrespective of the key data layers (remotely sensed imagery, yield maps, high resolution soil maps, elevation models, etc…) used to identify 'zones' within vineyards, key differences between fruit and/or wine quality attributes between the zones are likely to exist. Thus, targeted sampling based on these data is likely to deliver much improved information than random vineyard sampling.
- A new method of conducting viticultural experiments, in which treatments are imposed in highly replicated designs over whole blocks rather than small plots, and employing spatial methods for analysis of results with or without classical statistics, offers considerable advantages over more classical approaches since it allows the variable response to treatments (ie management strategies) to be understood. Management can therefore be better targeted to promote an enhanced likelihood of delivering the desired outcome.

All of the above notwithstanding, it needs to be clearly understood that:

- PV is difficult and requires skills in viticulture, soil science, spatial statistics and GIS that are unlikely to commonly reside in the same individual. Thus, successful adoption of PV will be dependent on appropriate education and extension, and access to appropriate consultant support. Of necessity, any given vineyard operation may need to acquire this support from more than one consultant with appropriate skills specific to a particular aspect (eg image analysis, spatial statistics, pest and disease management, etc). Nevertheless, evidence to date (including real commercial examples of adoption), suggests that the effort put into PV will be more than offset by the benefits subsequently accrued.

It is therefore recommended that a significant investment be made in Precision Viticulture extension and education of both consultants and growers/vineyard managers. Of necessity, this will need to be supported by an on-going PV research effort to ensure 'supply' of expertise to extension and consultant personnel.

What is also now needed is a rethink of the logistics of grape supply to facilitate accrual of the benefits of selective harvesting. Indeed, integration of zonal management into supply chain / demand chain research will be essential if the 'consumer to vineyard' demand chain paradigm is to form a major part of the platform underpinning the Australian wine industry going forward. Sensibly, and in view of the apparent importance of soil and topographic variation, such work would also be linked closely to studies of *terroir*.

Furthermore, zonal management has, to date, focused on the differential collection of outputs from the production system rather than differential application of inputs to it (water, fertilizer, sprays, labour, etc…), and the associated economic analysis has been rudimentary at best. A more robust analysis of the economics of Precision Viticulture is warranted, as is examination of variable rate

management of inputs to winegrape production. A study along these lines would sensibly draw on research outputs from the GWRDC Soil and Water Initiative.

Finally, as this project team has indicated before, it is recommended that research managers give careful consideration to the fact that on the one hand, they have demonstrated through funding provided to this project, that they consider spatial variability to be important – this project has shown that they were right ! - whilst on the other, they provide a much larger amount of funding in support of viticultural/oenological research which is conducted using approaches that quite explicitly ignore spatial variation. There is a risk that without appropriate on-going support, the skills embodied in the CRCV project team will be lost to other industries or other research endeavours and thus be rendered effectively unavailable to the more traditional areas of viticultural and oenological research; many fewer examples currently exist in the research community of the findings of this project being adopted than are evident in the commercial sector.

Background

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 in both yield and quality has been accepted as a fact of life and the majority of vineyards have been managed on the assumption that they are homogenous.

Three consequences of vineyard variability are inefficiencies in the management of inputs to the production system, uncertainty in the prediction of yield, and perhaps of greatest concern, delivery of grapes of inconsistent quality to the winery. Inefficient use of inputs to the production system, whether these be water, sprays, fertilizers or the use of labour and machinery, compromises the profitability of the production system and may also lead to detrimental environmental impacts both on and off site. Uncertainty in yield prediction obstructs precise scheduling by winemakers faced with an increasing mismatch between the tonnage of grapes to be crushed and the crushing and storage capacity of the winery. Meanwhile, variation in fruit quality, and the resultant acceptance of 'average' quality from whole vineyards limits the opportunity to maximise the production of premium quality wines and to tailor production to market demand and opportunity.

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), yield monitors and a number of platforms 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 Australian market, it has been possible for grapegrowers and winemakers to practice Precision Viticulture (PV; Bramley and Proffitt 1999; Bramley and Lamb, 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 and Proffitt 1999). In the context of observing, quantifying and mapping spatial variability in agricultural crops, technologies such as satellite and airborne remote sensing were being more widely used in other cropping systems at the commencement of the project (Lamb, 2000), and very little was known of the potential, or otherwise of remote sensing as a viticultural management tool, even though these technologies were effectively already available to the wine industry. The primary purpose of this project, therefore, was to see to what extent these new technologies offered grapegrowers and winemakers an improvement over more conventional approaches to production.

Project Aims and Performance Targets

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 may not be correct

(Cook and Bramley 1998; Bramley and Proffitt 1999). 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. With these issues in mind, this project was established with a number of key objectives for years 1 to 4 (as listed in the year 1 project application to GWRDC):

1. To quantify the nature and extent of within-vineyard variation in grape yield and associated fruit and vine characteristics in two vineyard sites;
2. To analyse soil and associated vineyard properties to identify possible causes of such variation with a view to assessing the feasibility of crop response to targeted management;
3. To investigate the utility of high-resolution remote sensing as a means of directing timely in-field sampling to ascertain causes of detected variability in soil properties (pre-establishment) and vine vigour (pests, diseases, available moisture);
4. To develop methods for targeted in-field sampling and experimentation for assessing response to management;
5. To scope the opportunity for adoption of precision agriculture technologies in the wider Australian grape and wine industry.

The outcomes foreshadowed through satisfaction of the objectives were:

- New methods of monitoring and measuring within vineyard variability in grapevine yield and quality attributes;
- New methods of monitoring and measuring within vineyard variability in site factors that influence grapevine yield and quality attributes;
- A recommended sampling and analysis strategy for quantifying soil variations in vineyards;
- An assessment of vine management practices suitable for the employment of airborne remote sensing as a means of monitoring variability in vine canopies; and
- An order of priority of those vineyard parameters observed to contribute to spatial variability in yield and quality specifications, and a recommended sampling and analysis strategy for growers wishing to measure those observed parameters.

Subsequently, a follow-on 3 year project (years 5-7) was approved which had the following objectives (as listed in the continuing application to GWRDC):

6. To identify and improve understanding of the key drivers of vineyard variability;
7. To evaluate the On-Farm Experimentation (OFE) approach to providing growers with tools that assist them in understanding the variable response of their production systems to management inputs and identify appropriate designs and analysis tools for such experiments; and
8. Through the use of 2-D data derived from remote sensing and on-ground measurements, gain an improved understanding of the environmental processes which determine the anthocyanin levels in red winegrapes.

Associated with these last three objectives, the following performance targets were identified:

Output	Performance Targets	Date
1.1. A knowledge base for the support of targeted within vineyard fertilizer use for fruit quality management.	Data sets describing the nutrient status of petioles at flowering, veraison and in whole berries for the Coonawarra and Sunraysia sites available for spatial analysis and construction of preliminary nutrient budgets and comparison to yield and quality maps.	Sept. 2003
	PhD program established to explore manganese nutrition / fruit quality relationships, literature review and probation period of student successfully completed	December 2003
	PhD thesis submitted	June 2006
1.2. An evaluation of the feasibility of a PV approach to viticultural management in sloping country	Establishment of PV research site to examine the effects of slope on variability. Site selected in Barossa/Eden Hills, baseline data (block boundaries etc) and target vines georeferenced and petioles sampled at flowering and veraison	March 2004
1.3. An evaluation of utility of remote sensing technologies as aids to vineyard management for white winegrape production.	Remotely sensed imagery processed and available and yield maps for all research sites produced along with maps of measured fruit / vine.	June 2004, 05 and 06
1.4. Information on the key drivers of vineyard variation in contrasting sites.	Web-accessible report summarising the above outputs available	June 2006
2.1. Information on the value of the On-Farm Experimentation (OFE) approach to provide growers with tools that assist them in understanding the variable response of their production systems to management inputs	Postdoctoral fellow appointed and desktop study completed of potential experimental designs and minimum data requirements for whole of block experiments established and report available to industry.	Feb 2004
	At least 3 sites for OFE established and experimental objectives / designs agreed with vineyard managers.	May 2004
2.2. Appropriate (geo)statistical and GIS-based methodologies for the analysis of experimental results packaged into easy-to-use tools for growers and their consultants	Protocol for OFE in vineyards published in web-accessible format	June 2006
3.1 Evaluation of the use of a spectro-optical method of determining anthocyanin content of grapevine leaves	Spectral data acquired and laboratory chemical analysis of vine leaves commenced	February 2004

As advised in annual progress reports, output 1.1 was substantially reduced in view of funding restrictions and the difficulty of appointing an appropriate PhD student with access to an APA scholarship. Similarly, due to the delay in appointing a suitable postdoctoral fellow to the project, progress against outputs 2.1 and 2.2 has been delayed; nevertheless, this part of the project is now progressing well and will be completed via a new 18 month project, funding for which will commence in July 2006 (GWRDC Project No. CX2275).

Methods – the structure and nature of this report

In view of the number of components to this project, the wide range of tasks undertaken and the extensive reporting of these in industry media, conference proceedings and peer reviewed journals (see Appendix 1), this report is structured in such a way as to draw heavily on material that is already published. Indeed, almost all of the papers listed in Appendix 1 are incorporated into the CD version of this report as linked pdf files. Thus, instead of following a traditional approach to project reporting (methods, results, discussion), the approach used here has been to provide a brief description of the work done in order to address the various project objectives, with close reference to the linked publications which provide more substantial details of both methodology, results and conclusions. In view of this report structure, those with a particular interest in specific aspects of this work are strongly encouraged to read the CD version of the report rather than a hard copy, and to access details of the methodologies used from the linked pdf files.

Exceptions to the above are those parts of the work which are yet to be substantially published (for example, the work conducted in a steeply sloping Eden Valley vineyard, and the development of whole-of block experimentation) and these are discussed in more substantial detail, albeit on a project component basis.

Years 1 to 4

During this period, the project was organised into two components:

A. **On-ground sampling and proximal sensing:** Work in this area was conducted by a CSIRO-based team (Rob Bramley and Susie Williams – then of CSIRO Land and Water, Adelaide) with some additional input from Peter Clingeleffer (CSIRO Plant Industry, Merbein). Work conducted in this component was focussed on objectives 1, 2 and 4;

B. **Remote sensing:** Work in this area was conducted by a team initially based at Charles Sturt University in Wagga Wagga (David Lamb, Andrew Hall – PhD student, John Louis, Paul Frazier, Bruno Holzapfel, Mark Weedon). Approximately 2 years after the start of the project, David Lamb and Paul Frazier moved to the University of New England in Armidale but the work otherwise continued normally. Work conducted in this component was focussed on objective 3.

Objective 5 was addressed by both components collectively.

Two key sites common to both components were used during this phase of the project; a 7.3 ha vineyard in Coonawarra that was planted to Cabernet Sauvignon in 1974 and a 4.5 ha vineyard at Nangiloc in the Sunraysia region which was planted to Ruby Cabernet in 1989. The Coonawarra site is owned and managed by Fosters Wine Estates (formerly Southcorp Wines) and supplies fruit for production of premium wine at the Wynns winery, whilst the Sunraysia site is owned by Mr Peter Walmsley, a private grower supplying fruit to the Karadoc winery; harvesting of Mr Walmsley's vineyard was carried out by a contractor. A third site, located at Charles Sturt University in the Riverina region, and managed by the Charles Sturt University Winery, was dedicated to the high-resolution remote sensing component of the project and formed the key focus for the PhD study conducted as part of this project by Andrew Hall.

Years 5 to 7

During this period, the project was organised into four main components:

A. **On going analysis of data collected in years 1 to 4:** Work in this area was conducted by the CSIRO team (Rob Bramley, Susie Williams, David Gobbett and Angela Reid – CSIRO) and sought to address objective 6;

B. **Terrain analysis and evaluation of the application of Precision Viticulture in steeply sloping vineyards:** Work in this area was conducted by the CSIRO team (Rob Bramley, Susie Williams and David Gobbett) and also sought to address objective 6;

C. **Whole of block experimentation:** Work in this area was conducted by the CSIRO Team (Kerstin Panten, Rob Bramley, Susie Williams) and was targeted at objective 7;

D. **Remote and Proximal Sensing:** Work in this area was the focus of the UNE (David Lamb, Allan Mitchell, Paul Frazier and Graham Hyde) and CSU (John Louis, Andrew Hall, Michael Kemp and Mark Wilson) teams and sought to address objective 8, and also to revisit objectives 3 and 4 given (a) that the remote sensing work conducted in years 1 to 4 focussed on red wine varieties only and for a specific set of vineyard conditions not wholly representative of the industry, and (b) concerns expressed in some quarters as to the ubiquitous application and adoption of EM38 sensing technology.

These major components tackled in years 5-7 also contributed to building our understanding of the issues embodied in addressing objective 5 from the earlier phase of the project. This work was supplemented by the participation of the two senior researchers in the production of a book on Precision Viticulture (Proffitt et al., 2006) via a CRCV Supplementary Bid Project (GWRDC Project No. CRV 04/06S).

Component A continued to rely on data collected from our initial Coonawarra and Sunraysia sites. Component B and the white wine part of Component D was dependent on a 12 ha sub-section of a 22 ha block of Riesling in the Eden Valley. This is owned by Fosters Wine Estates and was planted in 1971. Component C was focussed at two sites. The first is a block of Merlot in the Clare Valley, once again owned by Fosters Wine Estates, planted in 1998, whilst the second is a block of Shiraz in the Coonawarra owned by the Wingara Wine Group. The latter was planted in 1995. A subset of Component D, an extension of the red wine grape work conducted in years 1 – 4, was focussed on a 1.35 ha block of Merlot (planted 1997) and a 1.71 ha block of Shiraz (planted 1997) in Petersons Armidale Vineyard (Armidale, New England Region, NSW). These blocks were particularly desirable for the intended work as they consist of tightly-confined VSP-trellised canopies with a cover crop/sward that remains vigorous throughout the entire grape growing season and a wide (3 m) row spacing.

Both components of years 1 to 4, and Component D in years 5 to 7 have drawn on a number of other special purpose sites for particular aspects of the work (for example the EM38 trials). In all cases, collaboration with, and the participation of, a large number of people / organisations with an involvement in the wine industry was essential. These included vineyard owners, managers, contractors and other service providers (see Acknowledgments).

Results and Discussion

Objective 1: To quantify the nature and extent of within-vineyard variation in grape yield and associated fruit and vine characteristics in two vineyard sites

Our research has shown that within a single vineyard block under conventional (ie uniform) management:

- Yield can be expected to vary by approximately 10-fold (ie 2-20 t ha^{-1}), with this variation showing a marked spatial structure (Bramley and Hamilton, 2004; Taylor et al., 2005).

- Fruit quality is also variable and shows patterns of spatial variation which tend to follow those for yield (Bramley, 2005a), although not necessarily in the same rank order (Bramley and Hamilton, 2005).

- Patterns of variation in yield closely match those for vine vigour as assessed using remotely sensed imagery (Objective 3; Bramley et al., 2005b; Bramley and Hamilton, 2006).

This work, and the associated development of Precision Viticulture (Bramley and Proffitt, 1999; Bramley and Lamb, 2003a; Lamb and Bramley, 2002; Lamb et al., 2004), strongly suggests that, not only is uniform management a sub-optimal strategy, but that targeting management in recognition of underlying variability may deliver significant benefits with respect to both profitability and natural resource management (Bramley, 2005c; Bramley and Hamilton, 2005, 2006; Bramley et al., 2005b).

Objective 2: To analyse soil and associated vineyard properties to identify possible causes of such variation with a view to assessing the feasibility of crop response to targeted management

Discussion with early adopters of Precision Viticulture strongly suggests that selective harvesting is of greater initial interest than targeted management of inputs (Bramley, 2005c; Bramley et al., 2005b). At least a part of the reason for this is uncertainty as to how input management should be fine-tuned in response to environmental variables – a key reason for the development of whole-of-block experimentation (Objective 7), and more broadly, GWRDC's Soil and Water Initiative. Nevertheless, work conducted in this project clearly indicates that much scope exists for increasing the efficiency of use of inputs to vineyard production systems through an improved understanding of the land supporting the vineyard. Thus, we have demonstrated that:

- Variation in soil properties, often associated with variation in topography, appears to be a key driver of vineyard variability (Bramley, 2001b, 2001d, 2003c; Bramley and Hamilton, 2005, 2006; Bramley and Lanyon, 2002; Bramley et al., 2000, 2004).

- At the Coonawarra site, yield variation has been clearly shown to be caused by variation in plant available water in the root zone (Bramley and Lanyon, 2002; Bramley 2003c). In turn, this has been shown to be controlled by variation in soil depth, which is itself controlled by variation in topography – note that the range in elevation in this vineyard was only 1.2 m.

- At the Sunraysia site, a less exhaustive study was conducted than at Coonawarra. Nevertheless, yield variation is clearly associated with variation in plant available water, and in particular, and in contrast to the Coonawarra site, an excess of water in spring due to waterlogging of poorly drained areas (Bramley, 2001b, 2001d). These are in turn associated with the occurrence of the clayey B horizon occurring much closer to the surface than in the higher yielding areas which are characterised by a much greater depth of sandy topsoil.

- These findings are consistent with those obtained for other cropping systems from around the world (eg. Shatar and McBratney, 1999; Machado et al., 2002; Delfin and Berglund, 2005), and for other vineyard work conducted in other projects outside CRCV (eg. Bramley, 2003).

Objective 3: ***To investigate the utility of high-resolution remote sensing as a means of directing timely in-field sampling to ascertain causes of detected variability in soil properties (pre-establishment) and vine vigour (pests, diseases, available moisture)***

- Remote sensing is a potentially valuable tool for assessment of vineyard variability, and has particular application for mid-season monitoring. Our work has focussed on centimetre- and metre-resolution multispectral remote sensing (in particular the blue (B), green (G), red (R) and infra-red (IR) bands of the visible electromagnetic spectrum). To this end, two key airborne imaging systems were used (multispectral airborne digital imaging system (MADIS) and digital airborne video system (DMSV)). The wavebands were selected for their ability to derive important one-dimensional vegetation indices and for their similarity, in terms of spatial, spectral and radiometric resolution to spaceborne platforms (of which this work was also considered a precursor). Collection of reflectance data at wavelengths corresponding to these parts of the spectrum allowed 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 in agriculture. However, others such as the so-called plant cell density (PCD; IR/R) and vigour index (G/R) may also be useful; indeed, during the life of this project, PCD has become the industry standard for viticulture. In essence, all of these provide information about the amount of photosynthetically active biomass (PAB; Hall et al, 2002). 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 platforms offer on-ground image resolutions comparable to airborne platforms, they currently are significantly more expensive than airborne platforms because the commercial providers of this data do not release small-area (ie vineyard sized) coverage images.

- The utility of the airborne imagery collected at a range of times during the season for prediction of red winegrape characteristics at harvest was found to depend on grapevine phenology. Veraison +/- 2 weeks was shown to be the best time for vineyard image acquisition, and the variation in imagery collected at this time was shown to predict variation in fruit colour and phenolics at vintage (Lamb et al., 2004b). It was also shown to predict yield in the following season.

- The highest correlations between PAB and fruit colour and phenolics at vintage were obtained from imagery with a resolution comparable to the row spacing (ie 3 m). However it should be recognised that these results were obtained in the context of a single-wire trellised vineyard and where the background cover crop was essentially rendered spatially uniform by senescence (Lamb et al., 2004b). A ‘safer bet’ is to therefore use imagery at as high a resolution as can be justified in terms of cost, and what has emerged as a quasi industry standard (50 cm), appears highly appropriate in this regard (Proffitt et al., 2006).

- Given that many vineyards employ physically-restrictive canopy configurations (for example, VSP) and that in some winegrape producing regions the inter-row cover crop or sward may be vigorous throughout the entire growing season (thereby contributing to the PAB signal detected by an overhead sensor) the need for a more rigorous means of extracting descriptors of canopy architecture from vineyard imagery, over and above that of simply contrasting vine canopy against a background of inter-row space, was identified (Lamb et al., 2005c).

- Through a PhD study conducted as a part of the project (Hall, 2003), a methodology for processing very high (~10-cm) spatial resolution remotely sensed imagery of vineyards was developed to acquire spatially referenced values that describe the canopies of individual grapevines over entire vineyard blocks. Correlations were found to exist between image derived canopy descriptors of grapevine canopy architecture (size and density) and fruit quality variables, particularly the anthocyanin and phenolic contents of fruit, total soluble solids and berry size (Hall, 2003; Hall et al., 2003).

- Importantly, image-derived descriptors of canopy size obtained from the 10 cm resolution imagery were found to explain the greatest amount of variance observed in the canopy, but this was not significantly greater than those observed using resolution of the order of the vine-row spacing. 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 (at a cost to the user).

Objective 4: To develop methods for targeted in-field sampling and experimentation for assessing response to management

Our initial approach in this part of the project was to explore the utility of electromagnetic soil sensing (EM38) in vineyards; EM38 was becoming increasingly established as a useful tool in broadacre Precision Agriculture (eg. Sudduth et al., 2001), whilst Evans (1998) had started to use it in vineyards. A further driver for this part of the work was industry reliance on a method of soil survey (McKenzie, 2000 and references therein) that we were concerned may not offer the best means of characterising soil variation. Accordingly, both our key sites (Sunraysia and Coonawarra) were surveyed using on-the-go EM38 sensing. This, and associated work demonstrated that:

- The industry standard method for vineyard soil survey based on the digging of inspection pits located in a 75 m grid, whether used in existing vineyards or prior to vineyard establishment, is fundamentally flawed (Bramley, 2003c); it ignores the expert knowledge of both the land manager and also the soil surveyor and results in the production of soil maps at resolutions that are inconsistent with the objectives of the vineyard manager. 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 or informed vineyard designs. 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.

- Vineyard soil survey based on high resolution proximal soil sensing (for example using EM38 sensing), elevation modelling, the expert knowledge of both the vineyard manager and soil surveyor, and appropriately targeted ground truthing delivers powerful improvements to vineyard soil survey compared to the existing industry standard (Bramley, 2001b, 2001d, 2003c; Lamb and Bramley, 2001; Proffitt et al., 2006).

- Whilst EM38 has been shown to be a potentially powerful vineyard soil survey tool, there is no evidence in support of the view that it is the optimal technology for high resolution soil survey (Bramley et al. 2004; McKenzie et al., 2003). Similarly, it is important that users understand that EM38 provides no *a priori* information about specific soil properties (McBratney et al., 2005); that is, the causes of the variation that it identifies need to be resolved through appropriate targeted ground truthing (collection and subsequent analysis of soil samples from locations which collectively cover the full range of variation in the EM38 signal and other available data layers).

- In spite of the proven potential utility of EM38, some disquiet was expressed from some sectors within the industry as to the widespread, and wholesale employment of EM38 technologies in established vineyards. Given that EM38 is an electromagnetic induction technique, and that the response of the instrument to variations in soil physical properties is reliant on measurements of subtle variations in integrated electrical conductivity in the vicinity of the instrument, the impact of nearby vine trellis wires on instrument performance had simply never been tested.

  An investigation was therefore conducted of the impact of above-ground vine trellising (vertical shoot positioned-VSP configuration and steel posts), with row spacings of 2.5 m, 3.0 m and 3.5 m on apparent conductivity measured using an EM-38 electrical conductivity meter (Lamb et al., 2005). Two-dimensional EC_a profiles of a single test site were generated within a single day under the conditions of (i) absence of any trellising (that is bare field), (ii) wooden end posts and steel mid-row posts only, (iii) wooden/steel posts plus dripper guide-wire, and (iv) wooden/steel posts plus dripper guide-wire plus a combination of cordon, gripper and foliage wires. The EC_a profile of the bare site was found to be modified by all subsequent treatments, with the least modification from steel posts only, and the degree of modification progressively increasing with the addition of wires to the maximum number used. The EC_a values were found to increase from a range of 20-50 mS/m for the bare field to a range of 100-130 mS/m for the assembled trellising, with the amount of increase greatest for the smaller row spacing. As the 2-D profiles were created from EC_a values derived from mid-row measurements, the influence of trellising appeared as a baseline elevation for the 3.0 and 3.5 m row spacings, but for the smaller row spacing the trellising was found to introduce an additional along-row modulation in EC_a values coincident with local maxima occurring at the centre of the gap between steel trellis posts. The results indicate that extreme care must be exercised by an operator to ensure that the EM-38 antenna/sensor unit remains mid-row throughout any transects and that changes in trellising structure/row spacing may introduce artefacts in EM-38 maps.

- Irrespective of the key data layers (remotely sensed imagery, yield maps, high resolution soil maps, elevation models, etc…) used to identify 'zones' within vineyards, key differences between fruit and/or wine quality attributes between the zones are likely to exist (Bramley 2005; Bramley and Hamilton, 2004, 2005, 2006). Thus, targeted sampling based on these data layers is likely to deliver much improved information than random vineyard sampling (Bramley 2001c, 2003c; Bramley and Janik, 2005; Bramley et al., 2004). The project has produced good evidence of the merits of the targeted sampling approach for the purposes of harvest scheduling and whilst no work on the issue of yield prediction has been carried out, it is highly likely that targeted sampling for this purpose is likely to give similar improvements over a random sampling strategy based on the assumption of homogeneity and/or random variation (Proffitt and Malcolm, 2005; Proffitt et al., 2006).

Objective 5: To scope the opportunity for adoption of precision agriculture technologies in the wider Australian grape and wine industry

The null hypothesis of precision agriculture (Whelan and 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." The CRCV1.1.1 project team are confident that, on the basis of the work conducted, and with respect to winegrape production systems, this null hypothesis can be rejected with confidence because we have shown that:

- Vineyards are highly variable and this variability is characterised by a strong spatial structure (see all refs in Appendix 1);

- Patterns of vineyard variability are broadly temporally stable (Bramley and Hamilton, 2004);

- A precision viticulture approach to winegrape production is potentially highly profitable (Bramley and Lamb, 2003; Bramley et al., 2003, 2005b);

- The costs of data acquisition implied by the adoption of Precision Viticulture are small in relation to their value (Bramley and Lamb, 2003a; Bramley and Hamilton, 2005); and

- Adoption of Precision Viticulture has much to offer in terms of supply- or demand-chain management (Bramley et al., 2003, 2005b), and with respect to gaining control over at least some of the elements of *terroir* (Bramley, 2005c; Bramley and Hamilton, 2006).

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 Precision Viticulture is sufficient to warrant adoption of at least some elements (Proffitt et al., 2006). However, further research will improve this understanding and thus facilitate further adoption and wider access to the benefits that such adoption will deliver.

Objective 6: To identify and improve understanding of the key drivers of vineyard variability

Work undertaken towards objectives 1 and 2 focussed on the results obtained from spatial analysis, including cluster analysis, and simple classical statistics. No analysis of our vine nutritional data was undertaken, and neither were multivariate methods employed. Two components of work undertaken in year 5 of the project addressed these issues.

- A total of 16 variables were derived from hand sampling at our Coonawarra and Sunraysia sites at an intensity of approximately 26 samples ha^{-1} over a 3 year period. These were grouped on those that were reflective of yield (Yield per vine, Bunch No., Berry weight), the physical characteristics of the vine (Leaf area, Bunch exposure, Pruning weight, Canopy volume, Canopy density, No. canes pruned, No. buds left for subsequent year, Butt diameter), and juice quality (Concentrations of Colour and Phenolics, Baumé, Titratable acidity (TA) and pH). Not all variables were available for both sites or all years.

- Descriptive statistics (Reid, 2005) suggested gross variation similar to that reported by Krstic et al. (2002) and also supported the strong dependence of vine yield on bunch number (Dunn and Martin, 2003).

- Multivariate analysis involved principal components analysis (including procrustes rotations and biplots), and canonical correlation (Reid, 2005). Biplots of the first two principal components demonstrated a clustering of the variables according to the groupings listed above. This suggests that reducing consideration of vineyard variability to a 3 variable problem (yield, ‘quality’, ‘vine size’) has merit; that is, single indices of these attributes may better enable industry personnel to understand their interactions and may also simplify the process of identifying of zones of characteristic performance.

- Existing Precision Viticulture tools allow ready measurement at high spatial resolution of yield (yield monitoring) and ‘vine size’ (remote sensing). This work has therefore added weight to the need to develop an on-the-go quality sensor (eg. Bramley, 2005; Bramley et al., 2005) and also to the desirability of developing a single index of fruit quality from the commonly measured indices. A research proposal addressing the latter was submitted to

GWRDC (BCX 2280) but was not supported; we remain of the view that development of such an index would produce a tool of significant value to the wine industry.

Analysis of the role of vine nutrition in vineyard variability was undertaken by Dr Joan Davenport, a sabbatical visitor to CSIRO (Appendix 4). Papers outlining this work are in preparation, However, preliminary results (Davenport and Bramley, 2006) suggest that:

- Relationships exist between at least one quality factor and either berry or veraison petiole nutrient concentration at both Coonawarra and Sunraysia for boron (B), iron (Fe), potassium (K), nitrogen (N), phosphorus (P) and sulphur (S). Increases in veraison petiole K were associated with increased pH, and phenolics increased with increasing Zn. As veraison petiole P increased, juice colour decreased and, likewise, increased Zn was associated with decreased berry weight. Sulphur showed a strong but bimodal relationship with TA. Petiole S was very low at the Sunraysia site and much higher at the Coonawarra site. TA decreased with increasing S at Sunraysia while it increased with increasing S at Coonawarra. However, the low point of TA and S at both vineyards was very close, suggesting that the relationship is caused by plant physiology rather than varietal or site differences.

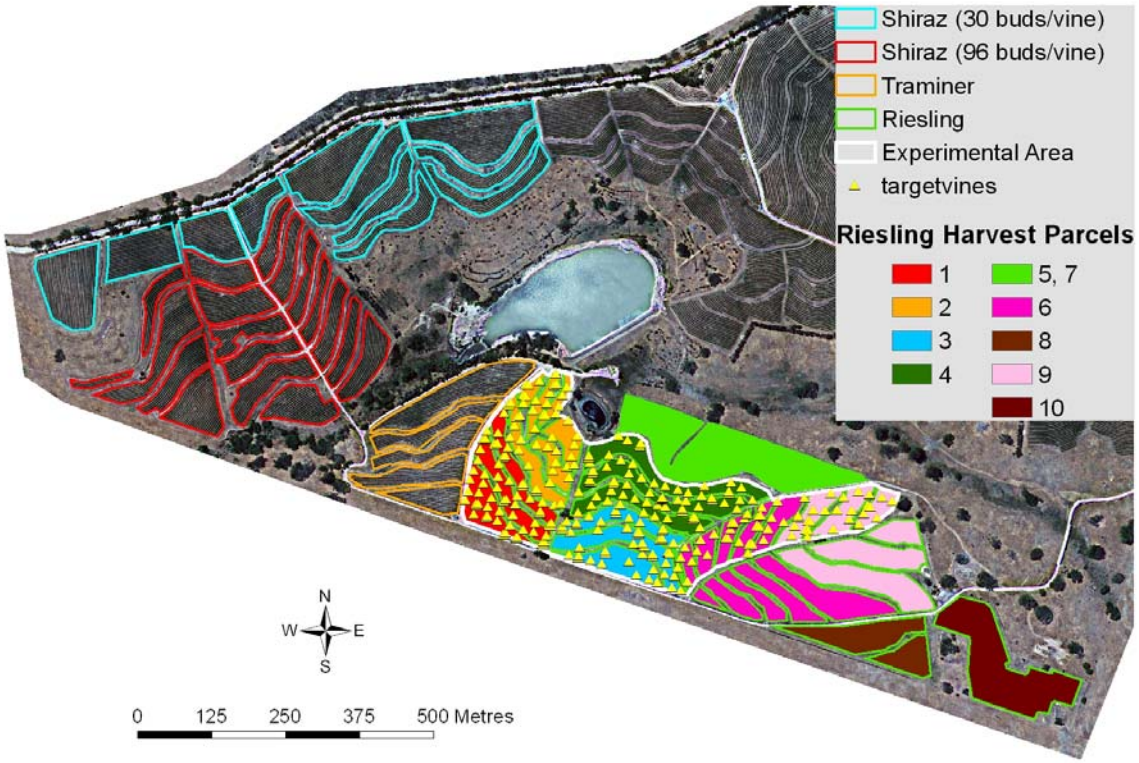
- Similar to petiole S, berry colour and phenolics increased with increasing fruit B at Coonawarra but decreased at Sunraysia. Both petiole and berry B were lower at the Sunraysia site. These data suggest that further research is needed to determine if a high B environment may adversely affect colour and phenolics. Conversely, higher concentrations of both Fe and N were associated with increased colour and phenolics as well as decreased berry weight.

- Overall, the results from this research indicate that tissue sampling could prove useful for predicting and/or managing crop quality. Low tissue N, P, and possibly S were associated with decreases in crop quality, whereas low K and B were associated with improved crop quality.

The above notwithstanding, our major focus in targeting objective 6 was our Eden Valley site where we sought to address a simple question: Given the very strong influence of topographic variation (ie elevation) on vineyard variation at relatively flat sites (Bramley and Hamilton, 2005, 2006; Bramley and Lamb, 2003a; Bramley 2003, 2005c), does it dominate on more steeply sloping sites to the extent that other explanatory data layers can be ignored ?

The Eden Valley site comprises 44.5 ha which is divided into 4 blocks – 2 of Shiraz (9.2 and 9.9 ha, each pruned to differing bud numbers), one each of Gewürztraminer (3.4 ha) and Riesling (22 ha) - all planted on the contour in a number of smaller sub-blocks (Figure 1). The two Shiraz blocks form a predominantly south-eastern facing slope on one side of a deep valley, with the Gewürztraminer and Riesling on the opposite side. All blocks were yield monitored during this work (vintage 2004-2006) and the entire site was surveyed with real-time kinematic GPS from which a digital elevation model was derived (Figure 1b). In addition, a 12 ha sub-section of the Riesling block was used for a vineyard variability study similar to that undertaken in Coonawarra and Sunraysia (years 1-3) and also to provide ground truthing data for the white wine remote sensing study (see objective 8 below); up to 317 target vines were sampled for this purpose (vintage 2004-06; Figure 1a). The range in elevation from highest to lowest point in the entire area is approximately 109 m and within the 12 ha Riesling sub-section, 34.5 m. Unless otherwise indicated, all spatial analysis in this work was done using Arcmap (PC version 9.1; ArcView licence; ESRI, 2005), with supplementary statistical analysis done using JMP (SAS, 2002).

a.



b.

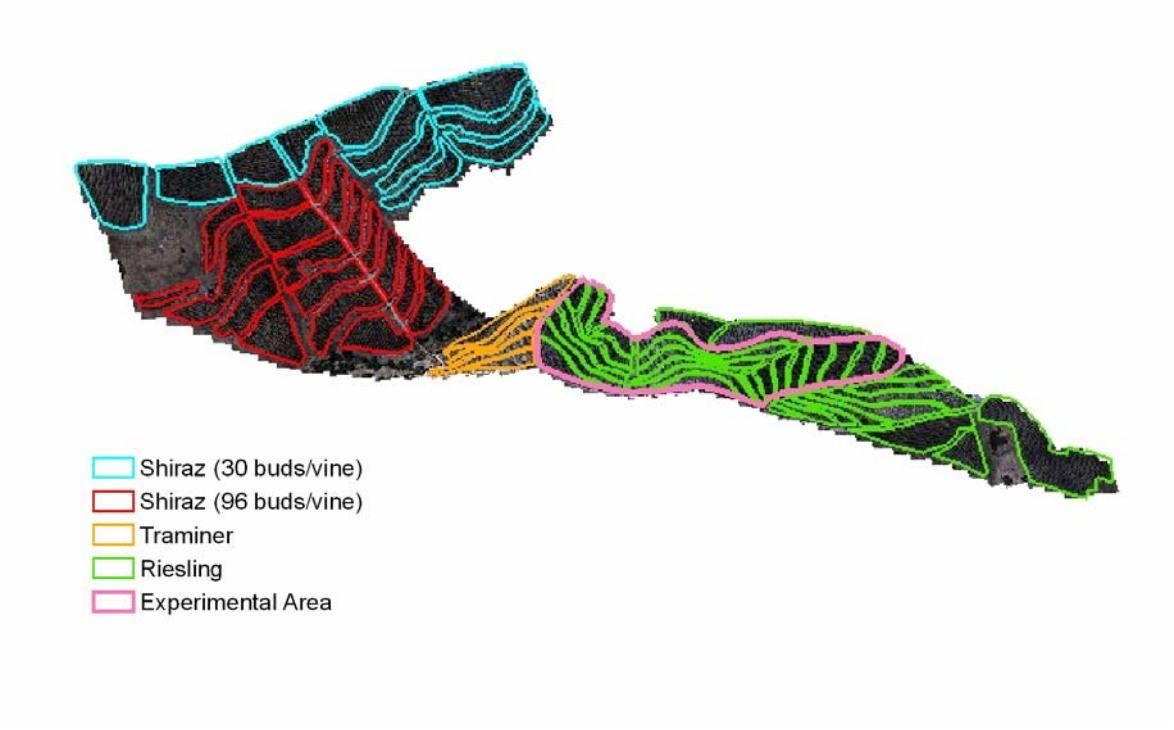


Figure 1. The Eden Valley study site in (a) plan and (b) 3-d view.

- Inspection of a map of aspect derived from the elevation model suggested that topographic variation might be important in terms of its impact on temperature and light interception in addition to any gross effects due to indices such as slope. Accordingly, the elevation model was used as input to two pieces of terrain analysis software:

    - A beta version of THAL (CSIRO Land and Water / CRC for Catchment Hydrology – pers. comm.) was used to derive topographic indices from the elevation model. The indices derived were: Topographic wetness index; upslope area, downslope area and slope %. Further details of these are given in Wilson and Gallant (2000).
    - SRAD (Wilson and Gallant, 2000) was used to examine the effects of topography on variation in temperature and incident irradiation. SRAD operates on mean monthly climate data which were obtained from Bureau of Meteorology records for Mt. Crawford or, in the case of variables that were unavailable for this station, from the closest available weather station (Angaston, Nuriootpa or Adelaide airport). Leaf area development was estimated using the equations of Bindi et al. (1997) and knowing the typical phenology for each variety and the bud number that each was pruned to. The model was only run for the period between budburst and harvest (denoted here by 'season').

      SRAD produces a number of outputs. Those of potential interest to this work were: season and January short wave irradiance; season and January net irradiance; and monthly average air temperature. From these, degree days over the season and for the September to January period were calculated.

- Inspection of the irradiance maps suggested that there was little, if any difference in spatial variation between short wave and net irradiation; these variables were also highly correlated (R^2 >0.99). Since short wave irradiation governs photosynthesis, net irradiation was discarded from the dataset in subsequent analysis. Given also the close correlations between other SRAD or derived outputs for January and the whole season, we decided to focus on January data only. This was considered consistent with the tendency in industry to focus on mean January temperature as a key factor in site selection and discrimination between warm and cool viticultural regions.

- Inspection of the available yield maps, and the PCD imagery in particular, supported the view that, as with other vineyards studied, the patterns of variation were broadly stable in time (Figures 2 and 3). *k*-means clustering of this data was less conclusive in the case of yield, although for PCD, the cluster analysis strongly suggested that variation was temporally stable. We therefore proceeded on the basis that this was the case and examined relationships between topographic indices (topographic wetness index, slope, aspect, upslope and downslope area), indices of temperature and radiation (January short-wave radiation, mean January temperature, sum of degree days during the season) and indices of vineyard performance (mean vigour over 4 years as indicated by average PCD (Figure 2), mean yield over 4 years (Figure 3), pruning weight post vintage '05, and yield per vine bunch number, bunch weight, berry weight, No. berries per bunch, baumé, pH, TA and phenolics measured for each year (2004-06) of the study). In the case of data layers with a *support* of high spatial resolution data (yield, PCD, and the outputs of THAL and SRAD), relationships were examined for data extracted from 100 randomly chosen points within the whole study area; the extracted data were the means of a 3 x 3 array of pixels centred on the extraction point. This analysis was repeated for the Riesling study area. Significant correlations for both areas are detailed in Table 1. For the Riesling study area, data extracted from maps of baumé, TA and phenolics for each of the three years of the study were also analysed (Table 2); these analyses were repeated for raw vine data (Table 2).

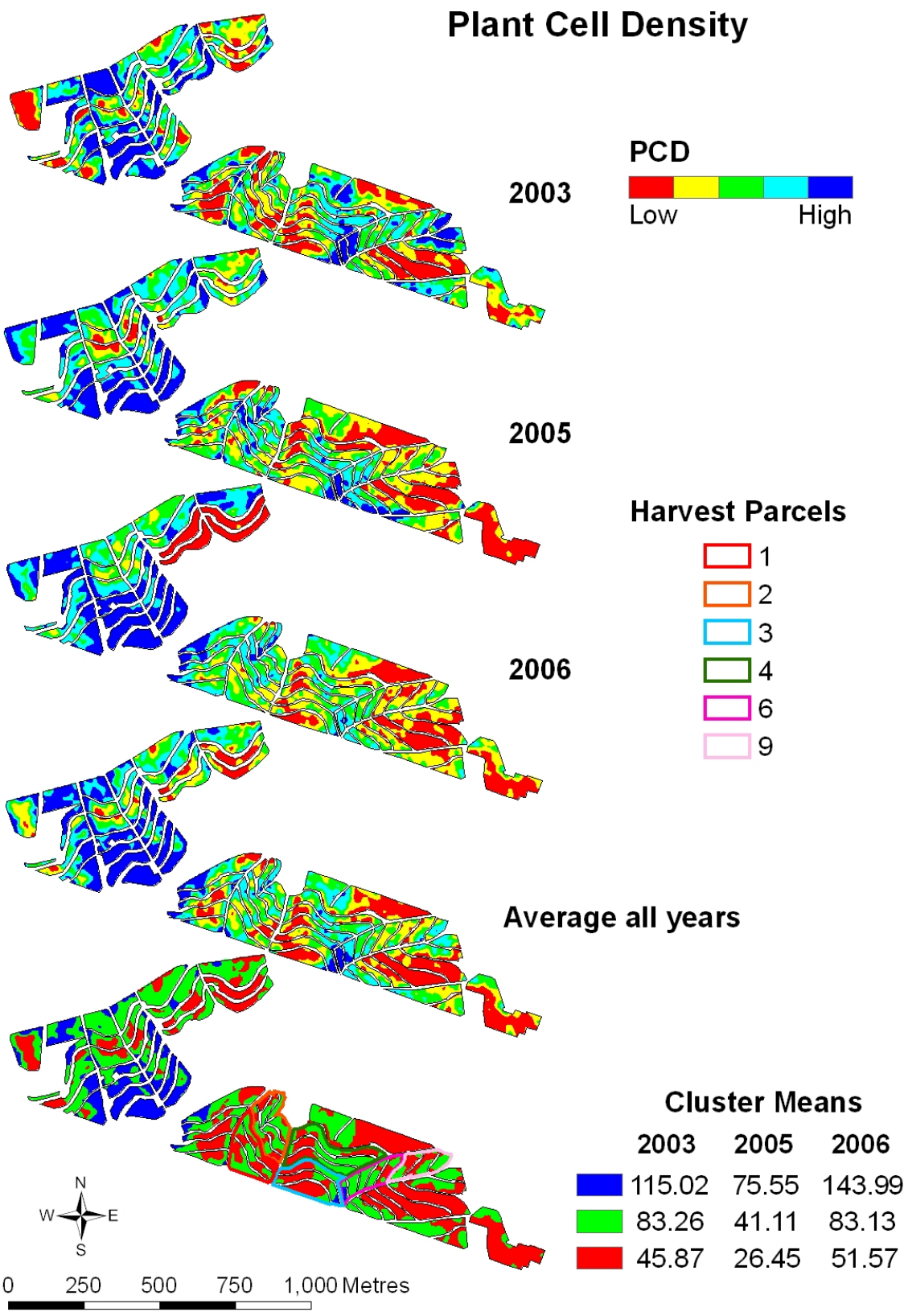


Figure 2. Remotely sensed (PCD) imagery of the Eden Valley study site, 2003-2006. The non vine signal has been removed from these images which have then been smoothed onto our standard grid of 2 m pixels. In addition to imagery for individual years, a map of average PCD was calculated, and *k*-means clustering was used to cluster images from the 3 years into 3 clusters of characteristic vigour.

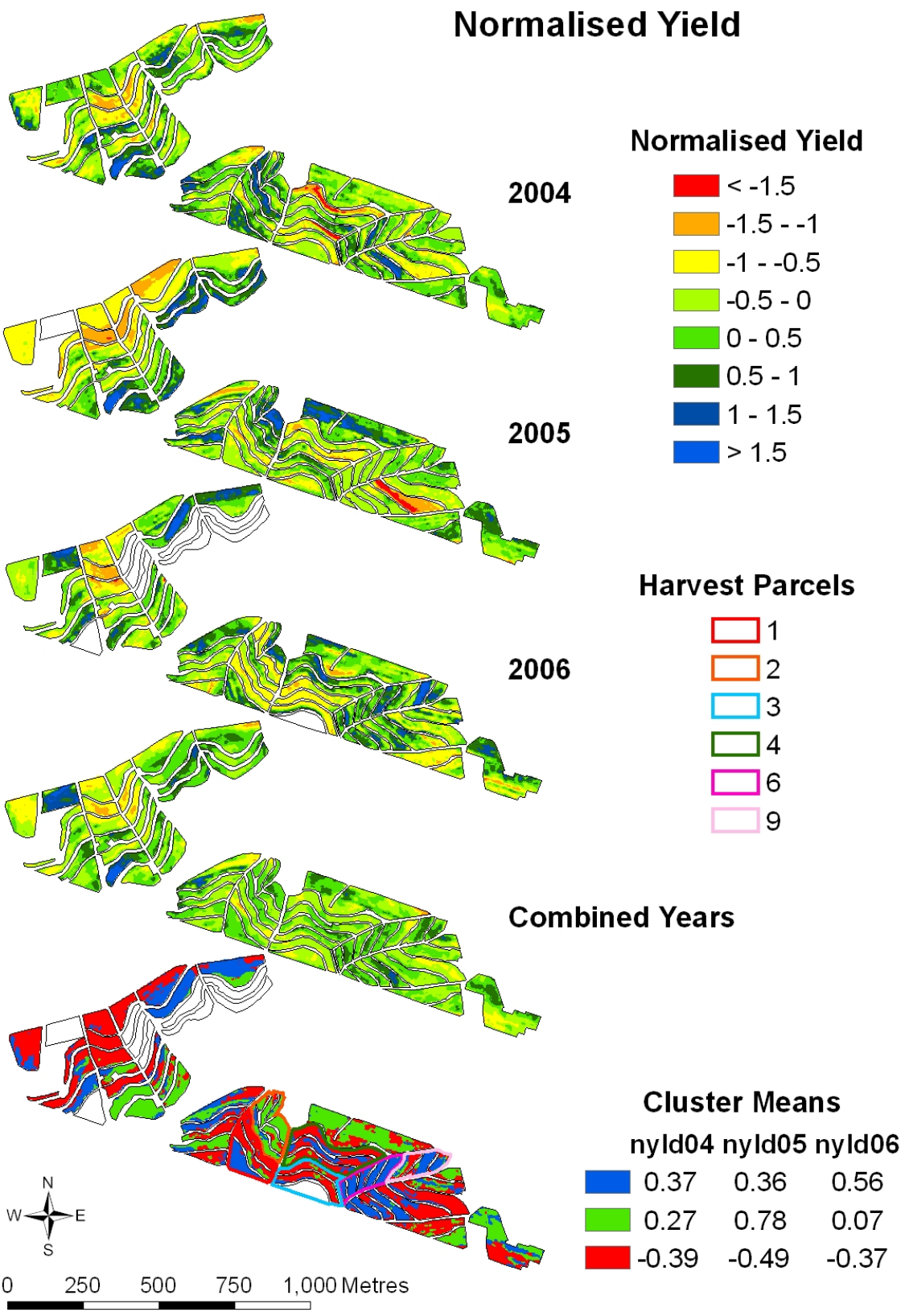


Figure 3. Yield maps for the Eden Valley study site, 2004-2006. Note that the data have been normalised ($\mu=0$, $\sigma=1$) to accommodate between-variety, between-trellis type and between-year differences in yield potential. Also shown is a map of yield clusters identified by *k*-means clustering of the normalised maps for 2004-06.

Table 1. Significant pairwise correlations between topographic, radiation and vineyard performance indices for the whole Eden Valley site and the Riesling study area.[A]

Indices[B]		Whole site		Riesling study area	
		r[C]	Sig.[D]	r[C]	Sig.[D]
Temp	Jan S-W	0.2353	*	-0.3781	***
Sum dd	Jan S-W	0.2893	**	-0.2252	*
Sum dd	Temp	0.9955	***	0.9824	***
Wetness	Temp	0.2806	**	0.3374	***
Wetness	Sum dd	0.2739	**	0.3957	***
Slope	Jan S-W	-0.6778	***	-0.5028	***
Slope	Temp	-0.3861	***	-0.3088	**
Slope	Sum dd	-0.3783	***	-0.3489	***
Slope	Wetness			-0.2556	*
Up	Temp			0.2747	**
Up	Sum dd			0.3246	**
Up	Jan S-W	-0.2355	*		
Up	Wetness	0.8874	***	0.9437	***
Up	Slope	0.3367	***		
Down	Jan S-W	0.2075	*	0.4117	***
Down	Temp	-0.2298	*	-0.4673	***
Down	Sum dd	-0.2082	*	-0.4376	***
Down	Wetness	-0.3854	***	-0.4919	***
Down	Up	-0.4511	***	-0.5473	***
Vigour	Jan S-W	-0.2097	*	-0.2145	*
Vigour	Temp	-0.4330	***		
Vigour	Sum dd	-0.4279	***		
Vigour	Wetness	0.2647	**	0.2492	*
Vigour	Slope	0.2598	**		
Vigour	Up	0.3233	**	0.2600	**
Vigour	Down			-0.3438	***
Yield	Jan S-W			-0.3810	***
Yield	Temp			0.3371	***
Yield	Sum dd			0.2658	**
Yield	Down	-0.2669	**	-0.3710	***
Yield	Vigour	0.1966	*	0.3360	***

[A]For both the whole site and the Riesling study area 100 randomly located points were extracted from the relevant map layers. The extracted values were the means of those in a 3 x 3 array of pixels centred on the point (ie pixel) of data extraction. Note that each pixel corresponds to an area of 4 m^2.

[B]Variables are denoted as follows: Temp = mean January temperature; Jan S-W = January incident shortwave radiation; Sum dd = degree days during the period from budburst to harvest; Wetness = topographic wetness index; Slope = % slope; Up = upslope drainage area; Down = downslope drainage area; Vigour = mean normalised value for plant cell density (PCD; the ratio of reflected infrared:red radiation) obtained from remote sensing at veraison in 2004, 2005 and 2006; Yield = mean normalised yield as measured through yield monitoring at vintage in each of 2004, 2005 and 2006.

[C]r denotes the correlation coefficient.

[D]Sig denotes the significance of the correlation where ***, ** and * indicate significance at $p<0.001$, 0.01 and 0.05.

Table 2. Significant pairwise correlations between topographic, radiation and vine performance indices for the Riesling study area.[A]

Indices[B]		Interpolated data		Raw vine data	
		r[C]	Sig.[D]	r[C]	Sig.[D]
YPV04	Yield			0.2799	***
YPV04	Vigour			0.1777	*
YPV06	Vigour			0.2173	*
YPV06	Jan S-W			-0.1857	*
YPV06	Temp			0.4181	***
YPV06	Sum dd			0.3998	***
YPV06	Wetness			0.1956	*
YPV06	Down			-0.2510	**
YPV06	Up			0.18	*
BchNo04	Temp			-0.2004	*
BchNo04	Sum dd			-0.2273	**
BchNo04	YPV04			0.8153	***
BchNo05	YPV05			0.8515	***
BchNo06	YPV06			0.8452	***
BchNo06	Jan S-W			-0.2212	**
BchNo06	Temp			0.4199	***
BchNo06	Sum dd			0.3807	***
BchNo06	Slope			-0.1814	*
BchNo06	Down			-0.2452	**
Bchwt04	Vigour			0.2353	**
Bchwt04	Wetness			0.2042	*
Bchwt04	Up			0.2125	*
Bchwt04	YPV04			0.6657	***
Bchwt04	Yield			0.3134	***
Bchwt05	Yield			0.1980	*
Bchwt05	YPV05			0.4992	***
Bchwt05	Bchwt04			0.3889	***
Bchwt06	Yield			0.2591	**
Bchwt06	Vigour			0.3024	***
Bchwt06	Temp			0.2439	**
Bchwt06	Sum dd			0.2511	**
Bchwt06	Wetness			0.1827	*
Bchwt06	YPV06			0.6700	***
Bchwt06	BchNo06			0.2447	**
Bchwt06	Bchwt04			0.4825	***
Bchwt06	Bchwt05			0.4674	***
Bywt04	Vigour			0.4097	***
Bywt04	BchNo04			-0.2607	**
Bywt04	Bchwt04			0.3138	***
Bywt05	Vigour			0.1950	*
Bywt05	Temp			-0.1871	*
Bywt05	Sum dd			-0.1852	*
Bywt05	Slope			0.2123	*
Bywt05	YPV05			0.1687	*
Bywt05	Bchwt05			0.2679	**
Bywt05	Bywt04			0.2198	**
Bywt06	Vigour			0.2582	**
Bywt06	YPV06			0.2603	**

Table 2. contd…

Indices[B]		Interpolated data		Raw vine data	
		r[C]	Sig.[D]	r[C]	Sig.[D]
Bywt06	Bchwt06			0.2639	**
Bywt06	Bywt04			0.3062	***
Bywt06	Bywt05			0.1978	***
Bybch04	Yield			0.2011	*
Bybch04	Wetness			0.1808	*
Bybch04	Up			0.1797	*
Bybch04	YPV04			0.6576	***
Bybch04	BchNo04			0.2970	***
Bybch04	Bchwt04			0.7686	***
Bybch05	Yield			0.1687	*
Bybch05	YPV05			0.4576	***
Bybch05	Bchwt05			0.9174	***
Bybch05	Bybch04			0.1706	*
Bybch06	Yield			0.2044	*
Bybch06	Vigour			0.2114	*
Bybch06	Temp			0.2521	**
Bybch06	Sum dd			0.2618	**
Bybch06	Wetness			0.2175	*
Bybch06	Up			0.1854	*
Bybch06	YPV06			0.5449	***
Bybch06	Bchwt06			0.8900	***
Bybch06	Bywt06			-0.1746	*
Bybch06	Bybch04			0.3047	***
Bybch06	Bybch05			0.4148	***
Baumé04	Temp			0.1834	*
Baumé04	Sum dd			0.1960	*
Baumé04	YPV04			-0.4673	***
Baumé04	BchNo04			-0.5619	***
Baumé04	Bywt04			0.4718	***
Baumé04	Bybch04			-0.3803	***
Baumé04	Baumé06	0.2657	**		
Baumé05	Temp	-0.5444	***	-0.2553	**
Baumé05	Sum dd	-0.5627	***	-0.2675	**
Baumé05	Wetness	-0.2390	*		
Baumé05	Slope	0.2890	**		
Baumé05	Vigour	-0.3232	**		
Baumé05	Yield	-0.2267	*		
Baumé05	Baumé04			0.1743	*
Baumé06	Yield	-0.3252	**	-0.2492	**
Baumé06	Vigour			-0.2236	**
Baumé06	Wetness	-0.5124	***	-0.2153	*
Baumé06	Up	-0.5019	***		
Baumé06	Down	0.4633	***		
Baumé06	YPV06			-0.3791	***
Baumé06	BchNo06			-0.2861	***
Baumé06	Bchwt06			-0.2852	***
Baumé06	Bybch06			-0.2668	**
pH04	Wetness			-0.1974	*
pH04	Down			0.2123	*
pH04	YPV04			-0.5243	***

Table 2. contd…

Indices[B]		Interpolated data		Raw vine data	
		r[C]	Sig.[D]	r[C]	Sig.[D]
pH04	BchNo04			-0.5306	***
pH04	Bchwt04			-0.2248	**
pH04	Bybch04			-0.3139	***
pH04	Baumé04			0.4246	***
pH05	Bchwt05			0.1686	*
pH05	Baumé05			-0.2757	**
pH05	pH04			0.4296	***
pH06	Wetness			-0.1725	*
pH06	Slope			0.2155	*
pH06	Down			0.1712	*
pH06	YPV06			-0.2841	***
pH06	BchNo06			-0.3807	***
pH06	Baumé06			0.3646	***
pH06	pH04			0.4914	***
pH06	pH05			0.4988	***
TA04	Temp	-0.2801	**		
TA04	Sum dd	-0.3204	**		
TA04	Slope	0.2225	*		
TA04	Up	0.2002	*		
TA04	Down	-0.2315	*		
TA04	Baumé04	-0.2540	*		
TA04	Vigour			0.1882	*
TA04	YPV04			0.4030	***
TA04	BchNo04			0.3153	***
TA04	Bchwt04			0.2246	**
TA04	Bybch04			0.2022	*
TA04	pH04			-0.4284	***
TA05	Temp	-0.5650	***	-0.1966	*
TA05	Jan S-W	0.2761	**		
TA05	Sum dd	-0.5414	***	-0.1744	*
TA05	Slope	0.2115	*		
TA05	Yield	-0.2105	*		
TA05	Baumé05	0.7274	***	0.6231	***
TA05	pH05			-0.3680	***
TA05	TA04	0.3543	***	0.2151	*
TA06	Temp	-0.3800	***		
TA06	Sum dd	-0.3632	***		
TA06	Vigour	0.4709	***	0.3389	***
TA06	Bywt06			0.2461	**
TA06	Baumé06	-0.2723	**	-0.3152	***
TA06	pH06			-0.3663	***
TA06	TA04	0.2915	**	0.3166	***
TA06	TA05	0.2185	*	0.2578	**
Phen04	Vigour			-0.1925	*
Phen04	YPV04			-0.2103	*
Phen04	Bchwt04			-0.1706	*
Phen04	Bywt04			-0.2647	**
Phen05	Slope	-0.2077	*		
Phen05	Vigour	-0.1977	*		

Table 2. contd…

Indices[B]		Interpolated data		Raw vine data	
		r[C]	Sig.[D]	r[C]	Sig.[D]
Phen05	YPV05			-0.3903	***
Phen05	BchNo05			-0.4853	***
Phen05	Bywt05			-0.2158	*
Phen05	Phen04			0.2410	**
Prune05	Yield			0.2478	**
Prune05	Vigour			0.3441	***
Prune05	Slope			0.2383	**
Prune05	Up			0.1794	*
Prune05	YPV05			0.2092	*
Prune05	Bchwt05			0.2997	***
Prune05	Bywt05			0.2703	**
Prune05	Bybch05			0.2041	*

[A]In the case of correlations between pairs of interpolated data, 100 randomly located points were extracted from the relevant map layers. The extracted values were the means of those in a 3 x 3 array of pixels centred on the point (ie pixel) of data extraction. Note that each pixel corresponds to an area of 4 m^2. For the raw vine data, actual measured values from 137 vines which were common to all 3 years of the study were correlated with values extracted from the relevant map layers at points corresponding to the 137 vine locations. Correlations involving interpolated vine data were only explored for the fruit quality indices; relationships between other indices of vine performance were confined to the raw vine data.
[B]Variables are denoted as follows: Temp = mean January temperature; Jan S-W = January incident shortwave radiation; Sum dd = degree days during the period from budburst to harvest; Wetness = topographic wetness index; Slope = % slope; Up = upslope drainage area; Down = downslope drainage area; Vigour = mean normalised value for plant cell density (PCD; the ratio of reflected infrared:red radiation) obtained from remote sensing at veraison in 2004, 2005 and 2006; Yield = mean normalised yield as measured through yield monitoring at vintage in each of 2004, 2005 and 2006; YPV = yield per m of vine row; BchNo = number of bunches per m of vine row; Bchwt = mean bunch weight; Bywt = mean berry weight; Bybch = mean number of berries per bunch; phen = concentration of phenolics per g berry; Prune = pruning weight; baumé, pH and TA have their normal meaning; and 04, 05 and 06 denote the year of sampling.
[C]r denotes the correlation coefficient.
[D]Sig denotes the significance of the correlation where ***, ** and * indicate significance at $p<0.001$, 0.01 and 0.05.

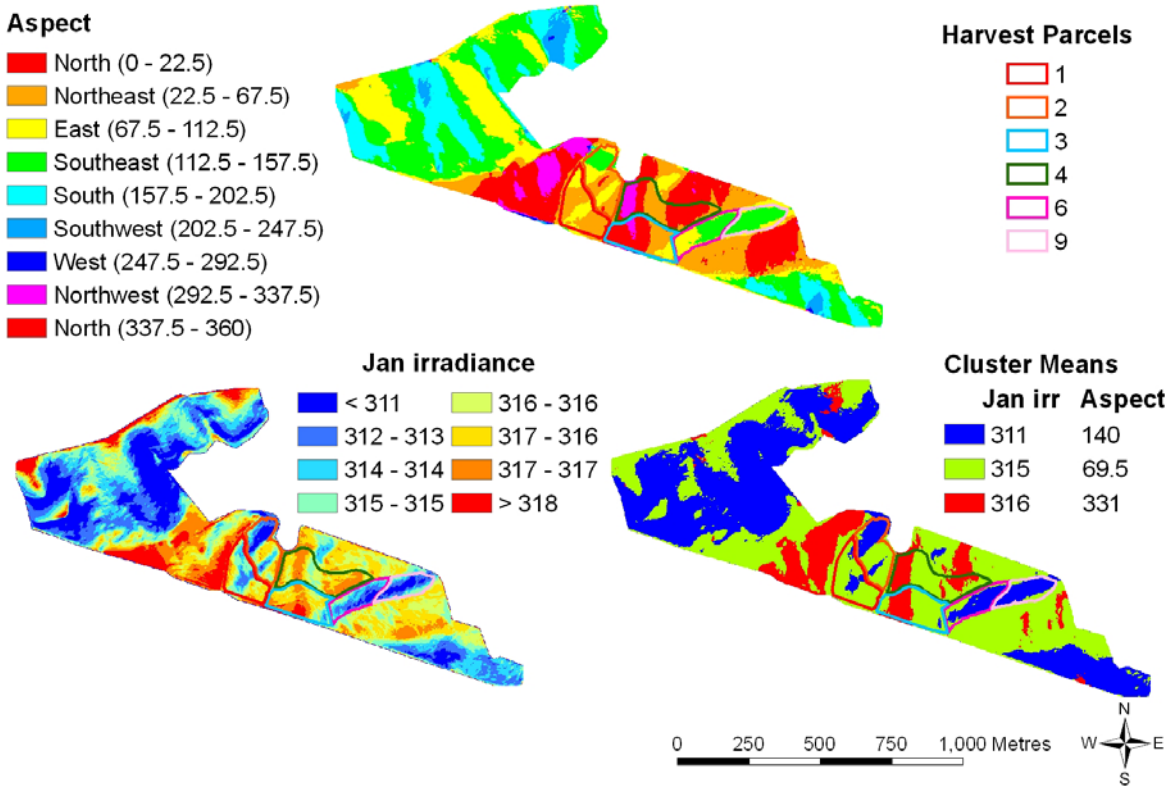
- As is apparent from both Tables 1 and 2, many significant, but generally weak, correlations exist between the variables examined. These indicate that topography is clearly exerting influence over vineyard performance. Also apparent from Table 2 is that many of the individual variables are correlated – both along the lines of general expectations based on existing viticultural knowledge (eg yield and bunch number), and also for individual variables from year to year (eg pH in 2004, 05 and 06). This is encouraging because comparison and cluster analysis of individual data layers (cf Bramley, 2005) did not provide as strong evidence as that obtained from Coonawarra and Sunraysia (see Objectives 1-5 above) of temporal stability in the patterns of vineyard variation. Two possible reasons for this include: that the target vine sampling strategy (26 samples ha^{-1}) is not adequate, in terms of its spatial intensity, for sufficiently robust variogram modelling (Bramley, 2005) to enable delineation of spatial variation at a consistent resolution, and one that enables analysis with data layers derived from more intensely sampled data (eg

yield monitor data, remotely sensed imagery); and/or that the known defects in the ageing irrigation system within the Riesling study area have compromised our study of non-anthropogenic impacts on vine performance, especially with respect to temporal stability.

- The above notwithstanding, topography clearly exerts a significant impact on vine performance (Yield, vigour (Table 1); fruit quality (Table 2)), either directly in terms of landscape position or more indirectly through effects of slope and aspect on incident radiation and temperature. Note that a large upslope area infers a large water catchment and might be expected to lead to more moist soils and therefore greater vigour, whilst a large downslope area at a point infers likely drainage of soil water away from that point. Nevertheless, there are some apparently confounding results: In the Riesling study area, yield is positively correlated with warm temperatures (mean January temperature and sum degree days) but, along with vigour, is negatively correlated with higher incident short-wave radiation. The latter correlation holds for the wider site, for which vigour is depressed by higher temperatures, although when examined for the Riesling alone, temperature is not seen to impact on vigour. As shown in Table 1, temperature is positively correlated with irradiance over the site as a whole, but is apparently negatively correlated within the Riesling study area – perhaps due to an absence of south, south-west and west facing slopes in the Riesling study area ?

- In spite of the limitations imposed by a possible lack of robustness in some of the mapped data layers, and the fact that the significance of differences between cluster means can not be tested for non-kriged (eg imagery, topographic indices) data layers, or for kriged data layers with a low *support* (eg the vine data derived from hand sampling; Bramley, 2005), *k*-means clustering was used to examine spatial associations between the various attributes analysed. Of interest here, and through collaboration with work being done for the CSIRO Food Futures Flagship, is examination of the results of the cluster analysis in light of the existing harvest strategy for the block (Figure 1a). The Riesling study area is harvested in 6 parcels (10 for the whole Riesling block) in numbered order. Parcels 1-4 go into a wine with a retail value of approximately \$18 bottle^{-1}, whilst parcels 6 and 9 (only half of each of these were covered by our sampling strategy; Figure 1a) go into a product with a retail value of \$28 bottle^{-1}. Sensory analysis of small lot wines made from the 6 parcels as part of the CSIRO Flagship project indicated that whilst there were no significant differences in aroma profiles between the wines, they could be differentiated by palate in respect of their acidity, sweetness, smoothness and viscosity and also the presence or otherwise of a tropical flavour. Parcel 9 was significantly more acidic, less smooth and less viscous than the others, whilst parcels 1 and 3 were seen to be the most different; 1 and 6 were the most similar. Inspection of the aspect map (Figure 4) suggests a likely topographic influence here – hence the effort in deriving the indices from both THAL and SRAD (Note that simple correlations involving aspect can not readily be defined given the proximity of 359° to 1°). Clearly, aspect is controlling the incidence of short-wave radiation (Figure 4) and therefore, potential photosynthesis and, through interaction with slope and position in the landscape (upslope area), is controlling temperature (Figure 5). In turn, these factors and their interactions impact on vine growth. Thus, low yield is associated with lower temperatures and lower upslope drainage area (Figure 6.); the latter presumably infers reduced soil water availability.

- Figure 6 also highlights the effect of the size and form of the study area on the possible interpretation of the results of *k*-means clustering. The cluster means for both the yield and vigour-based analyses are similar whether data for the whole site, or just the Riesling study area are examined, yet the degree of spatial structure seen in the Riesling area is markedly affected by the inclusion or otherwise of the steeply sloping east, southeast and south facing slopes (Figure 6).



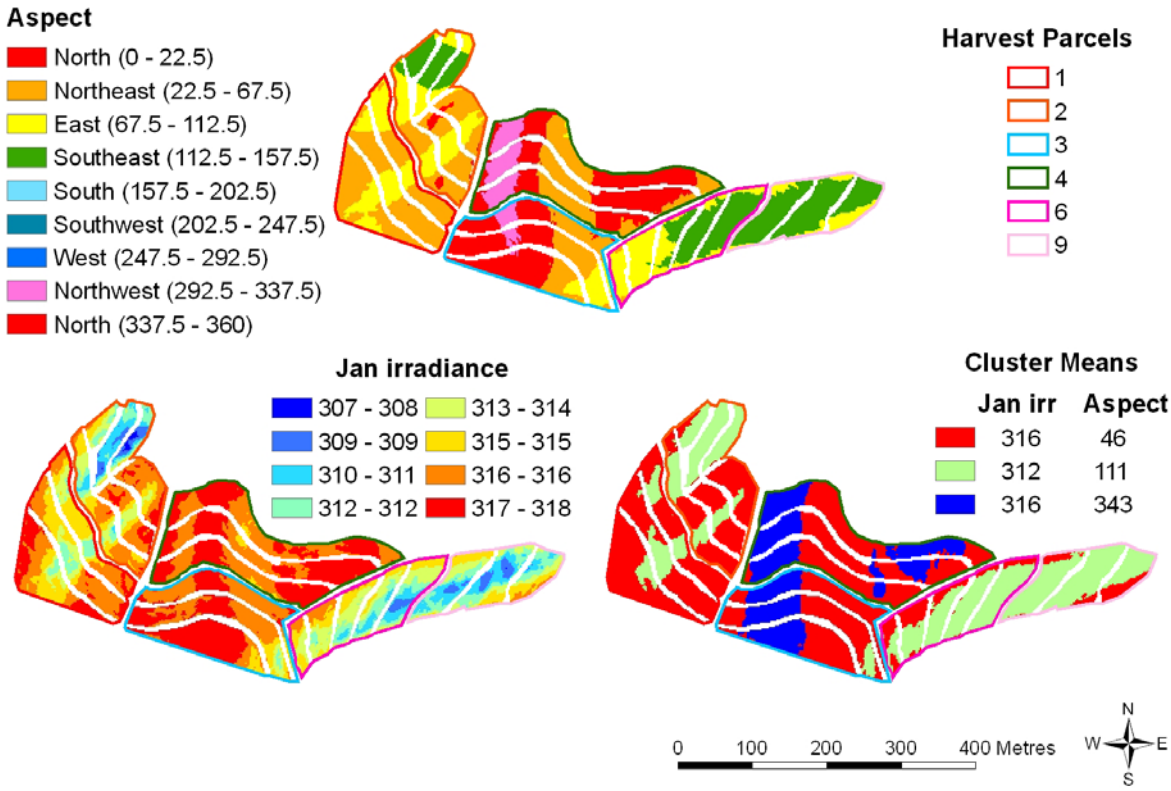


Figure 4 Influence of aspect on January short-wave irradiation over the whole Eden Valley site and in the 12 ha study area planted to Riesling.

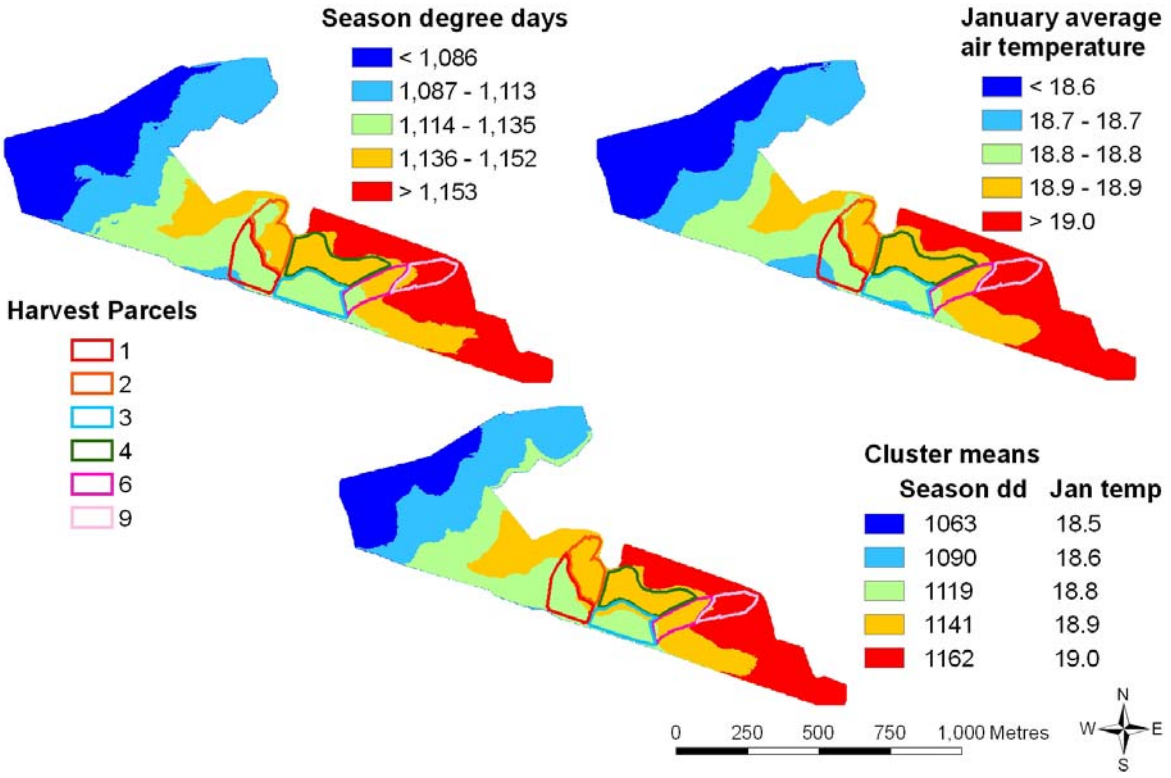


Figure 5. Temperature variation over the Eden Valley study site. Here the individual SRAD outputs have been classified on the basis of 20th percentiles. To facilitate comparison, a 5 cluster solution is shown in clustered map.

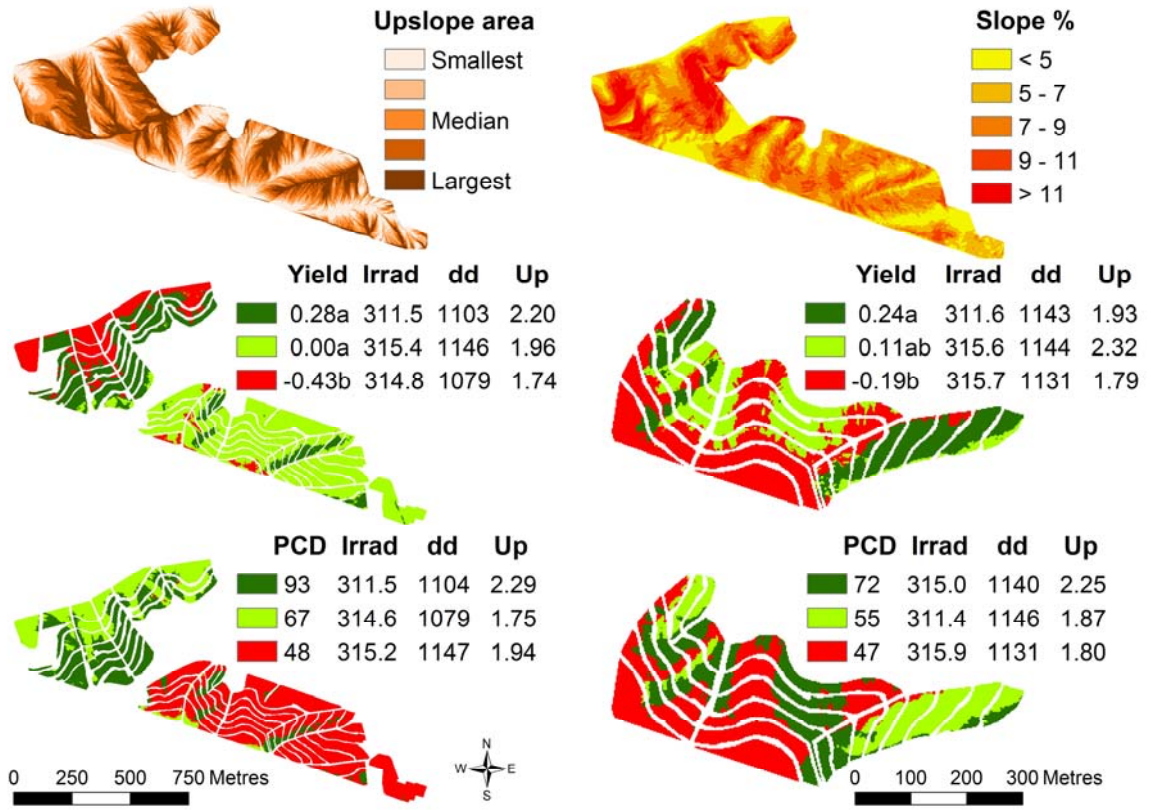


Figure 6. Variation in landscape position (Upslope area) and slope, and the interaction between yield, vigour (PCD), temperature (January short-wave irradiation (Irrad) and season degree days (dd)) and upslope area (Up). For yield, values not connected by the same letter are significantly different ($p<0.05$).

- In regard to the parcelling strategy used at harvest and the yield and quality of these parcels, Figures 7 and 8 are of interest. In the case of fruit quality (Figure 7), it is striking that the existing parcelling makes sense with respect to the clustering of fruit quality, with the possible exception of two sub-blocks to the southwestern side of parcel 6. On the other hand, if yield were to be the criteria for parcel delineation (Figure 8), then some re-organisation might be warranted. The sub-block at the top of the hill within parcel 2 (the southern-most sub-block within the parcel) appears different from the remainder of the parcel, whilst the boundary between parcels 3 and 4 could arguably be moved one sub-block to the north. Based on the sensory evaluation of wines, their typical product streaming (see above) and the apparent impact of topography on vine and fruit attributes, one thing for vineyard management to consider may be the order in which the existing parcels are harvested. The present analysis also suggests that some re-alignment of parcel boundaries may promote greater discrimination between parcels, and therefore greater control over the blending process of parcel wines leading to a bottled product that is closest in terms of its flavour and aroma profile to what the wine maker wishes to place on the market.

- Overall, this work does not allow us to conclude that in steeply sloping country, topographic variation is likely to dominate other factors. Thus high resolution soil survey (which we were not able to do in this project) would probably still be valuable. However, the Eden Valley work enforces the view, which arose in much flatter landscapes, that an understanding of topographic variation may be invaluable in better managing vineyard variability.

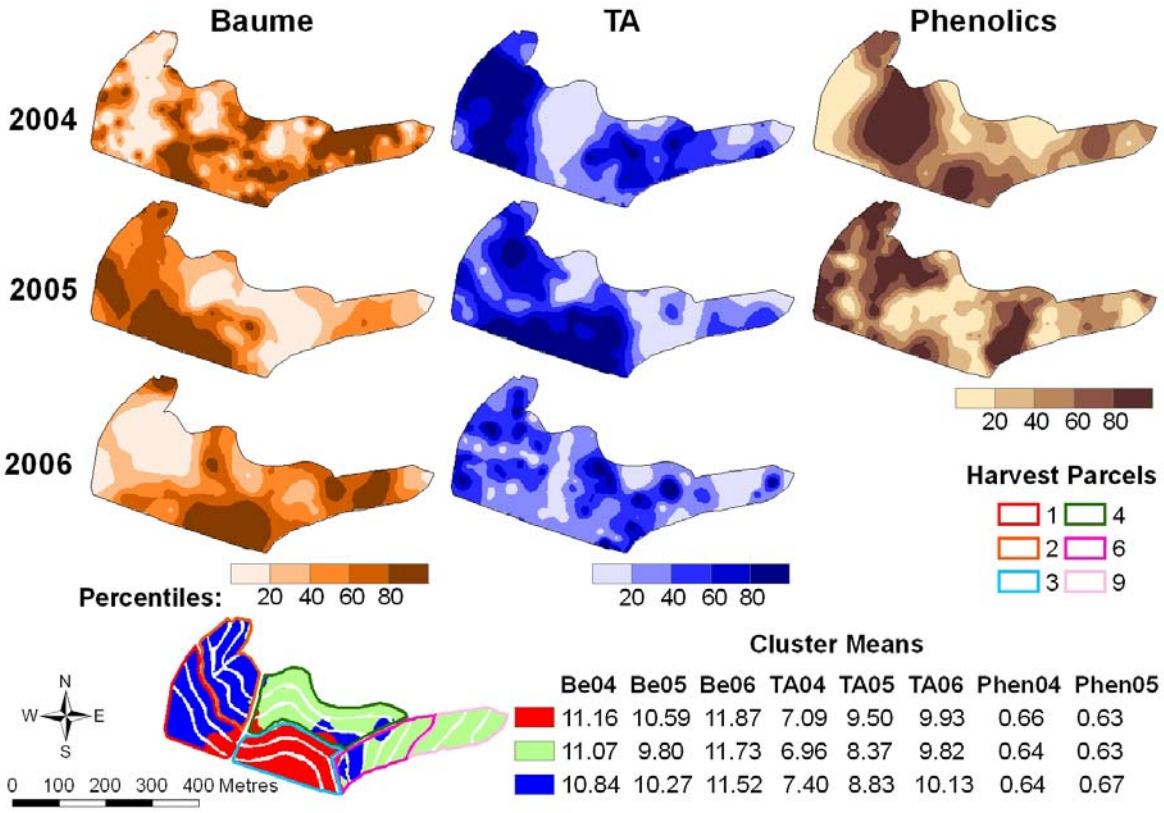


Figure 7. Variation in some indices of Riesling fruit quality and their relationship to the parcelling of fruit during commercial harvest.

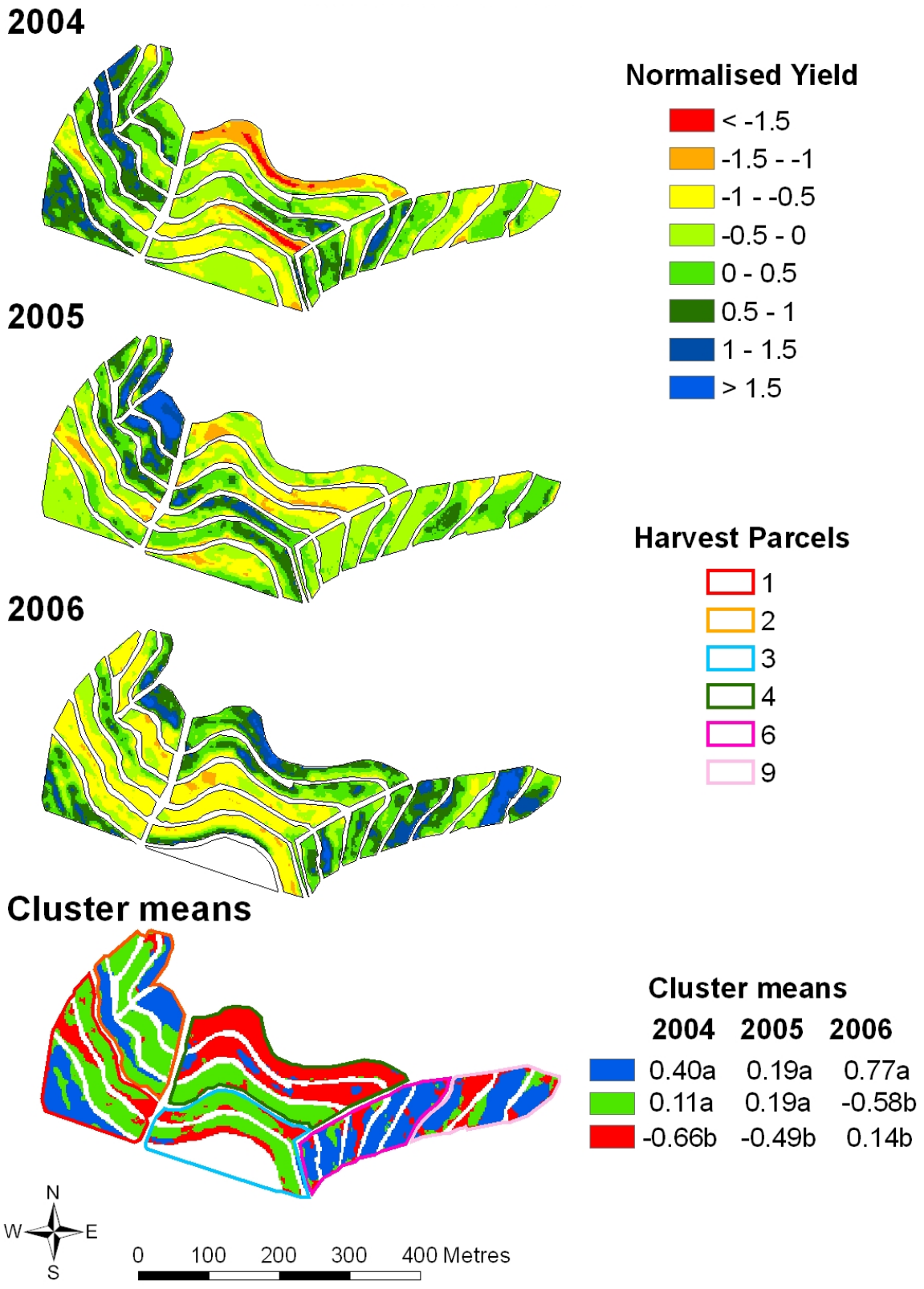


Figure 8. Variation in yield in a block of Eden Valley Riesling and its relationship to the parcelling of fruit during commercial vintage. In the case of the clustered map, means not connected by the same letter are significantly different ($p<0.05$).

Objective 7: ***To evaluate the On-Farm Experimentation (OFE) approach to providing growers with tools that assist them in understanding the variable response of their production systems to management inputs and identify appropriate designs and analysis tools for such experiments***

On-Farm Experimentation (OFE) has been identified as a useful tool for growers to evaluate management practices within their own production systems (Cook et al., 1998; Bramley et al., 2005a). The work conducted here sought to (a) demonstrate the utility of OFE in winegrape production systems, and (b) explore appropriate methods for identifying and understanding variable response to management.

A priori, kriging was assumed the appropriate map interpolation method for this work (Bramley, 2005a; Bramley and Willams, 2001a).

- Analysis of an experiment set up by a company viticulturist on a Padthaway vineyard to explore the use of 'sacrificial canes' to improve fruit quality was used to demonstrate the pitfalls of ignoring underlying spatial variability, and to demonstrate how available spatial information can be used to gather a better understanding of treatment responses (Bramley et al., 2005a). This example confirmed earlier concerns that by ignoring spatial variability, experimental results can be of limited value, or the conclusions drawn from them may even be incorrect. Therefore, further investigations into whole of block experiments, using the entire area of a vineyard block were made.

- An extensive desktop evaluation of whole of block experiments was conducted targeting the designs and feasibility of such experiments, ways of data analysis and the estimation of statistical errors related to trial layouts and types of data recording (Panten et al., 2005). 96 theoretical designs were established for two blocks for which data were available from other studies (Clare and Langhorne Creek) and 38 of them used to evaluate the best procedure to analyse high density data files such as those gathered by yield monitors. Generally, comparisons were made between a yield map interpolated using all available data and maps created by using only data of one 'treatment' area at a time (Panten et al., 2005; Panten & Bramley, 2006b). In these case studies, no real 'treatments' were applied to the vineyard blocks, and so the data could be used to explore the size and effects of statistical errors without the interference of treatment differences. For this type of data it can be concluded that *local* as well as *global* block kriging showed similar results with respect to the average kriging variance and the calculated modified root mean square error (RMSE=E_i).

$$E_i = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(P_i - T_i)^2}$$

P_i = predicted value of one treatment data set
T_i = target value = value created by using all data points

For a perfect fit P_i would be equal to T_i and therefore E_i equal to 0. Goodness of prediction was therefore evaluated on the basis of the closeness of E_i to 0.

In a next step, a procedure was developed to identify areas of the experiment which need to be excluded from the evaluation of the experimental results because of the risk that the kriging variance is higher than the actual treatment differences spatially observed. This procedure is based on the kriging variance and uses confidence intervals to detect areas with uncertainties about treatment effects and was developed on yield monitor data and hand harvested and analysed target vine data (bunch weight, berry weight, Baumé, colour, phenolics). Further investigations will take place into the usefulness of sequential Gaussian simulation for error estimation.

The project is ongoing and will be finalised during the early phase of the follow-up project (GWRDC Project No. CX2275); a paper about the exact procedure will be published when the data analysis is finished. In the interim, we conclude that: (1) spatial analysis of whole of block experiments is possible, (2) treatment differences can be discriminated from kriging errors, and (3) spatial conclusions about treatment effects can be made.

- Two whole of block experiments were established in 2004. The first one on a Merlot block in the Clare Valley focusing on three different mid row treatments to improve water and nutrient availability and thus, invigorate the vines. The second experiment in a Shiraz block in Coonawarra has the aim of evaluating the reduction of vine vigour through canopy management (severe pruning and shoot thinning versus a control treatment) as a means of improving crop quality. Target vine strategies to evaluate treatment results were developed for both experiments resulting in 378 samples in Clare and 406 samples in Coonawarra (Figure 9). Furthermore, yield monitors were used to gather high resolution yield data, EM38 mapping took place to evaluate soil related effects on vine performance and aerial images are used to gather spatial information about vine vigour. Preliminary results of the Coonawarra experiment are discussed in Panten and Bramley (2006b). In summary both trials have been successfully implemented and the second harvest was conducted in 2006. The Clare experiment received a set back when a late frost event in November 2004 destroyed two third of the vineyard but all project targets were accomplished in the 2005/2006 season. Further details with some maps illustrating variable response to the imposed treatments of the Coonawarra trial are given in Panten and Bramley (2006b). Both experiments will be evaluated for a third year in the 2006/2007 season through CX2275 and final conclusions will be drawn and reported on at the end of that project.

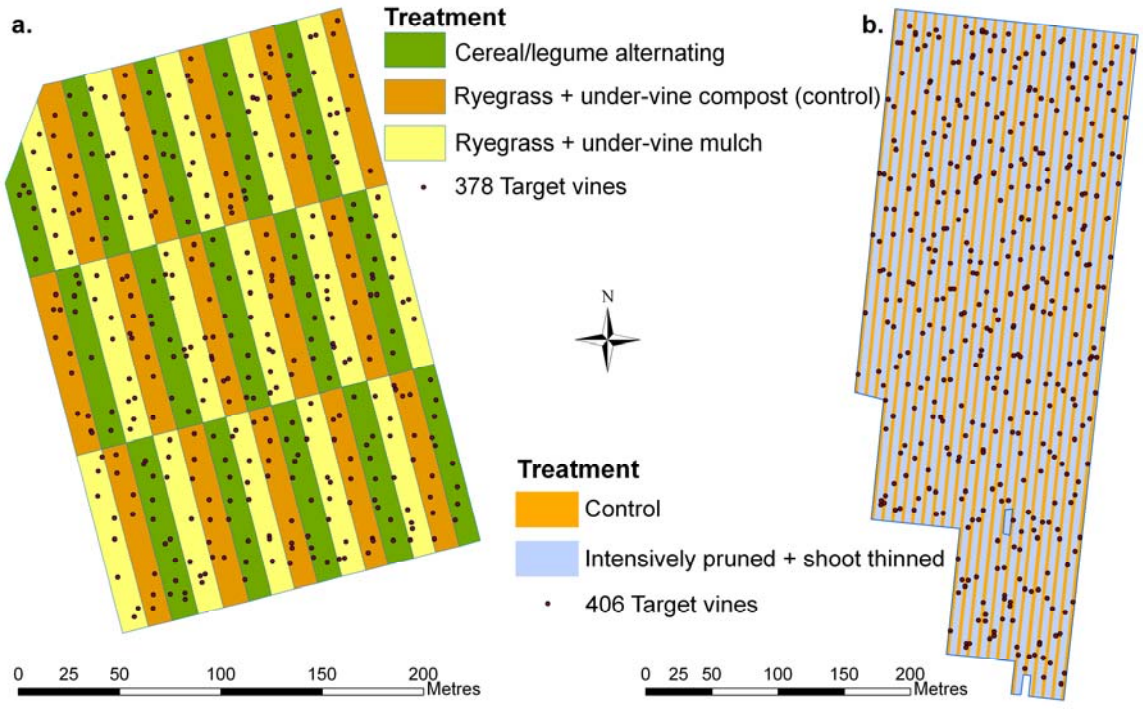


Figure 9. Experimental designs for experiments conducted in (a) Clare and (b) Coonawarra. In Clare, treatments were imposed during the winter of 2004; in Coonawarra, they were imposed at pruning following vintage 2004.

- Of note in this work, in spite of its incomplete state, is the fact that our collaborating vineyard managers had no problem either with the idea of giving the whole block over to experimentation or with the pragmatics of implementing the treatments. Thus, neither saw the complex nature of the experimental design as an impediment to its implementation. Indeed, the Clare experiment ended up with a more complicated design than originally planned, largely at the request of the manager of that site. This is important given the need to continue to derive income during the course of the experiment, and the fact that an experiment comprising a few small plots is an intuitively less risky option than one involving the whole vineyard. On the other hand, the approach used here seeks to enable the vineyard manager to understand the variable response to the management options being explored.

- This work has also started to have an impact on the research community, as evidenced by recent work done in Tasmania (Evans et al. 2006). This is significant given the concerns raised by the year 5 CRCV review panel and the more recent determination of the IRG concerning the integration of considerations of spatial variability into other viticultural research (see Recommendations – below).

Objective 8: ***Through the use of 2-D data derived from remote sensing and on-ground measurements, gain an improved understanding of the environmental processes which determine the anthocyanin levels in red winegrapes.***

Research conducted during years 1-4 identified remote sensing as a means of providing timely and synoptic information of canopy architecture related to anthocyanin levels in Cabernet Sauvignon winegrapes. In particular, the team demonstrated that airborne remote sensing of red winegrape vine canopies at veraison could map canopy PAB (via NDVI), which in itself proved to be a surrogate indicator (inverse) of anthocyanin levels in the fruit at subsequent harvest (Lamb et al., 2004b [11]). However, the investigation was limited to the context of a single-wire trellised vineyard where the background inter-row was essentially rendered spatially uniform by senescence, and the processed airborne data was confined to the widely-used NDVI.

At the same time, research on Shiraz grapes conducted by Downey et al. (2004) concluded that "...shading had little effect on berry development and ripening, including accumulation of anthocyanins and tannins, but significantly decreased flavanoid synthesis". Yet closer examination of the Downey et al. data (Figures 5b, d and f), covering the same seasons investigated in the work of Lamb et al. (2004b), and almost the same geographical region, showed that significantly higher levels of anthocyanins had developed in fruit that were not shaded when measured at harvest time. Thus, the Shiraz data of Downey et al., the Cabernet Sauvignon data of Lamb et al., and subsequent research in Pinot Noir published by Cortell et al. (2005) all indicated a inverse correlation between PAB and anthocyanin development in red winegrapes at harvest. However, further work was required to determine the applicability of remote sensing techniques over a wider range of red winegrape vineyard conditions in Australia, and to seek ways to augment the link between PAB, as relevant to anthocyanin synthesis of red winegrapes, and the descriptors of canopy architecture detected by remote sensing instruments, namely through NDVI and or an equivalent spectral index.

Consequently the research under this objective has focussed on improving the quality/veracity of descriptors of canopy architecture by either remote or on-ground proximal sensing techniques with a view to better understanding the biophysical environment of berries in relation to the production if anthocyanins. In doing so, we sought to develop sensor configurations or processing protocols that could be widely employed in Australian vineyards. In the context of anthocyanin development in red winegrapes, the research thus concentrated on three activities:

1. Illustrate the challenges facing metre-resolution airborne remote sensing in detecting spatial variations in PAB in vineyards with tightly-confined canopies (in this case, VSP)

with vigorous and spatially-variable inter-row plant material (thereby representing the 'other extreme' of possible vineyard conditions);
2. Understand the link between the within-canopy light environment that relates to anthocyanin synthesis and top-of-canopy radiation returning to an overhead (or side-looking) optical sensor of PAB, and develop an appropriate inversion model to link top-of-canopy index measurements (eg NDVI, PCD) with within-canopy light fields relevant to anthocyanin production; and
3. Investigate the applicability of using on-ground, side-looking optical sensors to quantify PAB and whether such data could enhance the veracity of remotely-sensed PAB data.

Research under each activity has progressed to different degrees; Activity 1 is close to completion and data will be available by the end of June, 2006. The multi-layer canopy model of Activity 2 has been constructed and information concerning the performance of NDVI and PCD has been communicated via a number of industry forums; Activity 3 has been completed insofar as all available field data from the 2005 season have been analysed but the necessary dataset from the 2006 season (eg anthocyanin data) is currently incomplete due to the recent completion of harvest.

Activity 1:
Airborne remote sensing of confined canopies in the present of spatially variable inter-row plant material

Figure 10 shows a photograph of a block of Merlot vines with a tightly-confined canopy (VSP-although note the foliage wires are not yet raised into position), a large row spacing (3 m) and a vigorous inter-row cover of native pasture. It is evident that in such vineyard conditions, the vines themselves would contribute only a relatively small number of pixels compared to the inter-row space, and furthermore, that a spatial resolution of 50 cm x 50 cm (considered to be the 'industry standard'), would yield a significant proportion of mixed (ie vine and inter-row) pixels. Furthermore, the practise of lifting foliage using foliage wires acts to remove variability in vine canopies as viewed overhead. Indeed vine vigour can only then be expressed in vertical growth or leaf density as viewed from the side.



Figure 10. Block of c.v. Merlot vines in the Peterson's Armidale (New England, NSW) vineyard site. Vines are at veraison.

a. b.

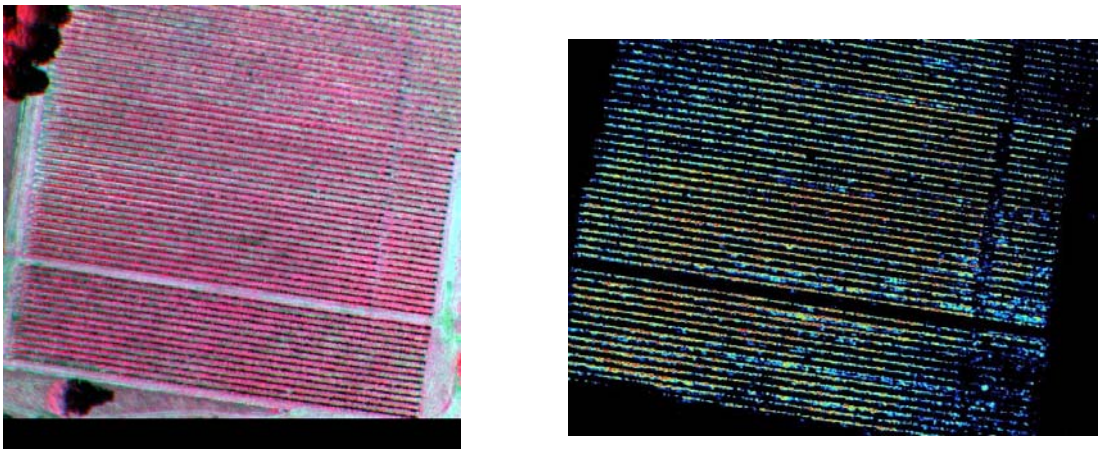


Figure 11. Imagery of the same block of Merlot vines as in Figure 1. (a) Colour infrared image; (b) thresholded NDVI image.

Figure 11a shows a 50 cm-resolution colour-infrared (or false colour) image of the same vineyard and Figure 11b is an NDVI version of the same image. In Figure 11b the image has been 'thresholded' according to a widely-used industry practice, whereby all pixels below a preset NDVI value are set to zero (and subsequently mapped in black). This process works well for vineyards where vines are vigorous and the inter-row plant material is either dead or removed via tillage or slashing. However, Figure 11b illustrates the difficulty in separating the vigorous inter-row plant material from the vines under the vineyards conditions experienced in this vineyard; evidenced by regions of non-black (ostensibly vine) pixels in the inter-row regions or regions of black (ostensibly non-vine) pixels where vines are known to exist.

A number of other image processing techniques were also applied to this type of imagery, including supervised and unsupervised classifications. An iterative supervised classification process yielded improved discrimination of vine and non-vine pixels, although it was significantly more time consuming and errors associated with mixed pixels along the vine/inter-row boundary were nonetheless present (up to 70% in some cases). Further work is in progress to provide a full comparative analysis.

Activity 3:
Understanding the link between the within-canopy light environment that relates to anthocyanin synthesis and radiation returning to an overhead (or side-looking) optical sensor of PAB.

In order to understand the link between in-canopy light field (as related to anthocyanin development) and radiation returned to an overhead or side-looking sensor, a three-layer canopy reflectance-transmittance model was been developed. The canopy model was configured to determine the impact of canopy leaf area index, LAI (projected leaf area per unit ground area) on standard reflectance indices such as NDVI and PCD and thereby identify indices with maximum potential to delineate LAI variations in target vineyards.

The two-layer canopy reflectance model, previously described in Hanna *et al.* (1999), is based on the analytical solution of a two-stream plant canopy model (Sellers, 1985), which has the governing equations:

$$\bar{\mu}\frac{dI_\lambda^{\uparrow}}{d\tau} = I_\lambda^{\uparrow} - \omega_\lambda(1-\beta_\lambda)I_\lambda^{\uparrow} - \omega_\lambda\beta_\lambda I_\lambda^{\downarrow} - \omega_\lambda\beta_0\bar{\mu}ke^{-k\tau} \quad (1)$$

$$-\bar{\mu}\frac{dI_\lambda^{\downarrow}}{d\tau} = I_\lambda^{\downarrow} - \omega_\lambda(1-\beta_\lambda)I_\lambda^{\downarrow} - \omega_\lambda\beta_\lambda I_\lambda^{\uparrow} - \omega_\lambda(1-\beta_0)\bar{\mu}ke^{-k\tau} \quad (2)$$

where, $\bar{\mu}$ is the average inverse diffuse optical depth per unit leaf area in the canopy; $I_\lambda^{\uparrow}$ and $I_\lambda^{\downarrow}$ are the wavelength-dependent upward and downward diffuse fluxes divided by the incident solar flux; τ is the canopy LAI; ω_λ is the sum of the wavelength-dependent single leaf reflectance r_λ, and transmittance, t_λ; β_λ is the wavelength-dependent backscatter distribution function for the diffuse beam; β_0 is the backscatter parameter for the incident beam; and k is the optical depth of the direct beam per unit leaf area.

The two-layer canopy model is generated by solving equations (1) and (2) for $I^{\uparrow}$ and $I^{\downarrow}$ using appropriate boundary conditions for each specified layer. The wavelength-dependent canopy reflectance is computed using:

$$R_\lambda \equiv I_\lambda^{\uparrow}(\tau = 0) \quad (3)$$

where $\tau = 0$ corresponds to the top of the canopy.

A simplified diagram of the 2-layer vine canopy represented in the model is given in Figure 12. In this model the spectral characteristics and LAI of the top vine-leaf canopy (layer a) are considered, along with a second layer of vine leaf material which usually has different reflectance/transmittance characteristics (inner canopy leaves, layer b), and the reflectance characteristics of the underlying soil. The LAI of the layer of inner canopy leaves was initially set to unity and the LAI of the top canopy leaves was varied over the range of 1–10 to mimic vine canopy conditions observed.

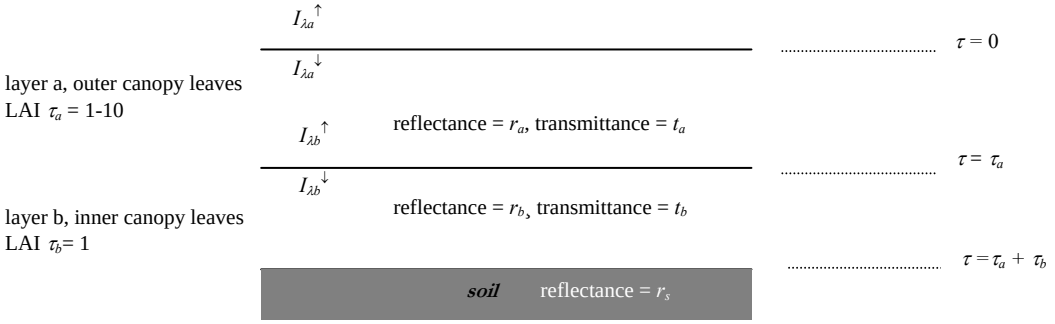


Figure 12. Detailed schematic diagram of the two-layer vine canopy represented in the model.

Reflectance and transmittance characteristics of individual vine leaves, and within-canopy light-field spectra were collected using an ASD field radiometer (Figure 13a) and the "Vine-eye" spectrometer specifically assembled for the task (Figure 13b).

Examples of calculated top-of-canopy NDVI and PCD as functions of increasing LAI are given in Figure 14. Superimposed on Figure 14 are individual values of NDVI and PCD experimentally determined by progressively stacking leaves on top of a novel, zero-reflectance, light trap (Brown et al., 2004).

a.



b.



Figure 13. Instruments used for investigation of the canopy light environment. (a) ASD spectrometer used to collect reflectance and transmittance characteristics of a sample of outer and inner vine leaves; (b) The Vine-Eye spectrometer designed and assembled to collect within-vine light fields (here undergoing post-construction trials).

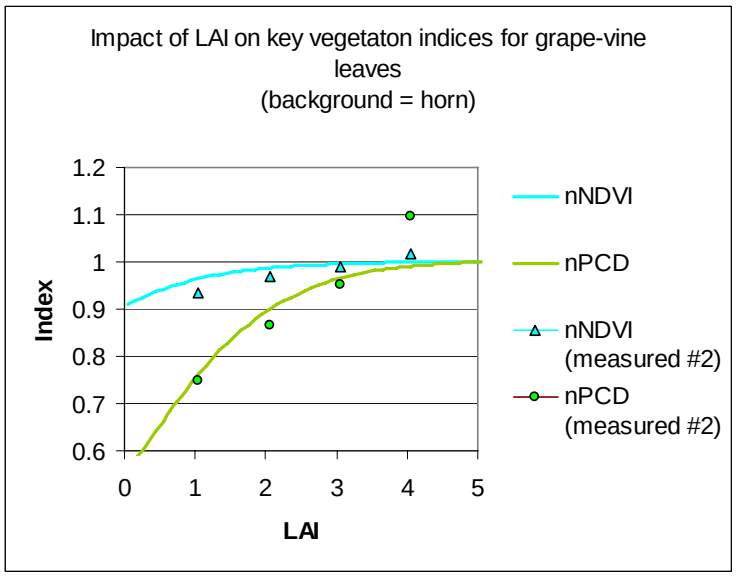
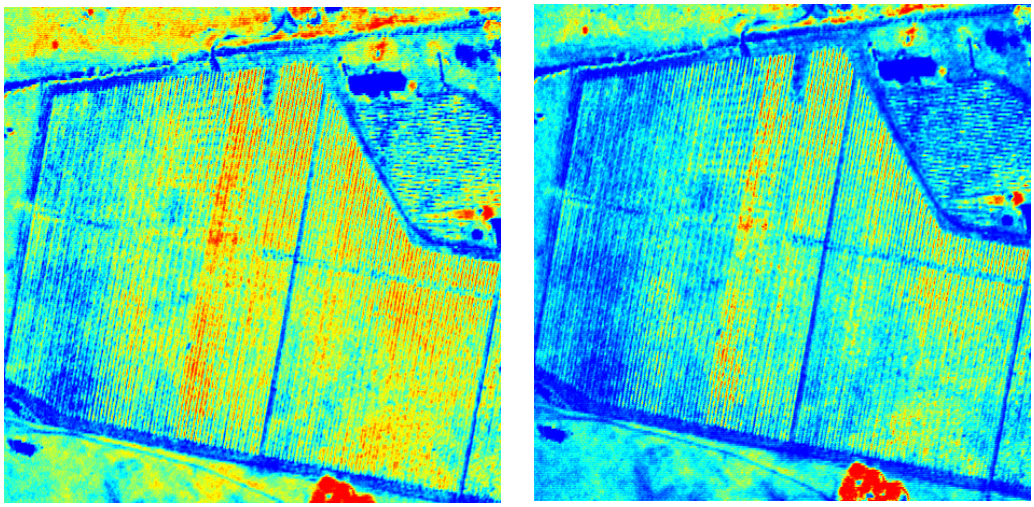


Figure 14. NDVI or PCD as a function of increasing LAI. Solid curves represent calculated values using Equation (3) (from the solution of equations (1) & (2)). Both NDVI and PCD calculations yield a different range of index values and hence are normalised to the max NDVI or PCD value, respectively calculated at LAI = 10. Points represent experimental measurements of NDVI or PCD (again normalised to the maximum observed value) using the apparatus in Figure 4a.

Figure 14 indicates that both NDVI and PCD increase with increasing LAI, to a asymptote at a LAI of approximately 3. This is typical of experimental observations (Hall and Louis 2006 - personal communication). The experimental measured values of NDVI and PCD are also consistent with model predictions. Of particular significance in these data is the fact that PCD values have a greater

dynamic range for higher LAI values (LAI = 1 - 3), suggesting that PCD would give greater discrimination of PAB (via LAI) for vines with greater LAI. This outcome is illustrated in the examples of NDVI and PCD images of the Peterson vineyard (calculated from the same multispectral image) given in Figure 15. The PCD image (Figure 15b) shows greater contrast for the central region of higher-LAI vines than the NDVI image (Figure 15a).

Work is now in progress to construct a set of inversion equations to convert top-of-canopy index values (eg NDVI or PCD) to within-canopy light-field 'spectra', based on physical measurements of canopy PAB, to be compared with actual Vine-Eye measurements. It is envisaged that such a relationship will provide a more accurate set of descriptors for linking top-of-canopy remotely sensed indices to within-canopy anthocyanin production in the fruit.



(a) (b)

Figure 15. An uncalibrated, multispectral image of the Peterson Vineyard (Merlot) converted to (a) NDVI and (b) PCD images. The imagery was acquired close to veraison 2005.

Activity 2:
Quantifying PAB using a side-looking sensor

In order to support the inversion of the multi-layer vine canopy model, an on-ground sensor was constructed using a commercially-available on-the-go, NDVI sensor - the Crop Circle™. Crop Circle was developed by Holland Scientific, USA for use as a downward-looking sensor of maize canopies. The project team designed and assembled a novel, side-looking configuration for use in vineyards (Lamb et al., 2005c). The sensor comprises an array of ultra-bright light-emitting diodes (LED's) that simultaneously emit light in both near infrared (*nir*) and red (*red*) wavelength's, and a pair of photodetectors (Figure 16a). The unit is pointed at vines (Figure 16b), the LED's are pulsed at a certain frequency and the photodetectors, via synchronous detection, measure the reflected signal (from the vine canopy) of both LED's. An on-board data-logger records both red and near infrared reflectance, and instantaneously calculates the NDVI value. As the unit is an active sensor (ie with its own light source), and uses synchronous detection, it is capable of operation irrespective of variations in daylight conditions and can be operated throughout the night. Furthermore, the individual *red* and *nir* reflectance values are available (in post-processing) for calculation of other indices such as the PCD. When operated in conjunction with a DGPS, a map of the selected index (eg NDVI) is generated (Figure 17).

a. b.



Figure 16. The Crop Circle sensor (a) and its deployment by quad bike (b). In (a) the pulsing LED's located in the top of the detector head can be seen (note, only *red* radiation emitted by the LEDs is visible) with the dual photodetectors below. The unit is mounted (b) in such a way that the height may be adjusted to suit different vine canopy heights. The mount design is amenable to the extensive range of quad bikes and tractors used by Australian grape growers.

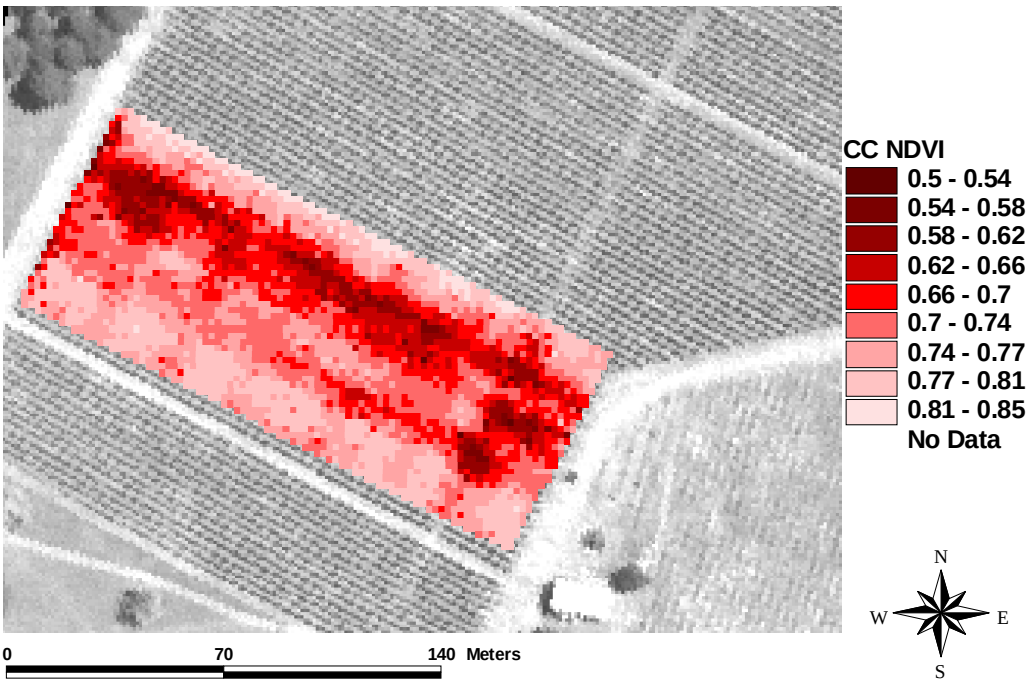
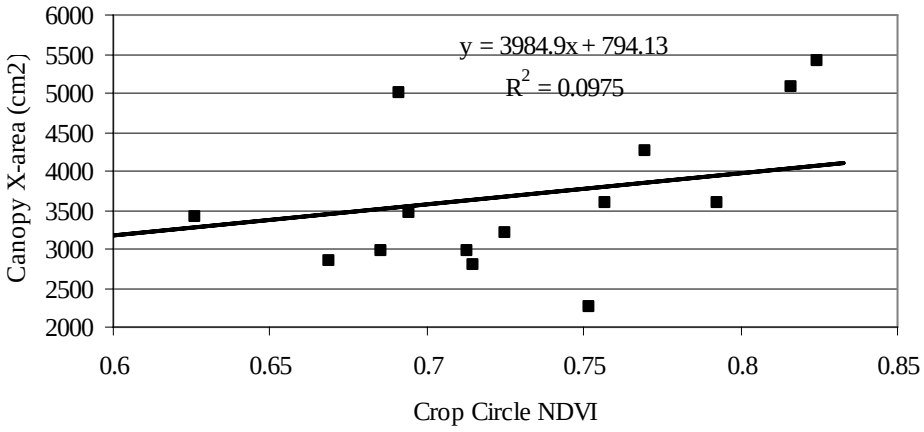


Figure 17. An NDVI map of a block of c.v. merlot (at veraison 2005), created using Crop Circle. Measurements were acquired by sensing the North side of the vines. Note the vine row direction is approximately SE →NW.

a.



b.

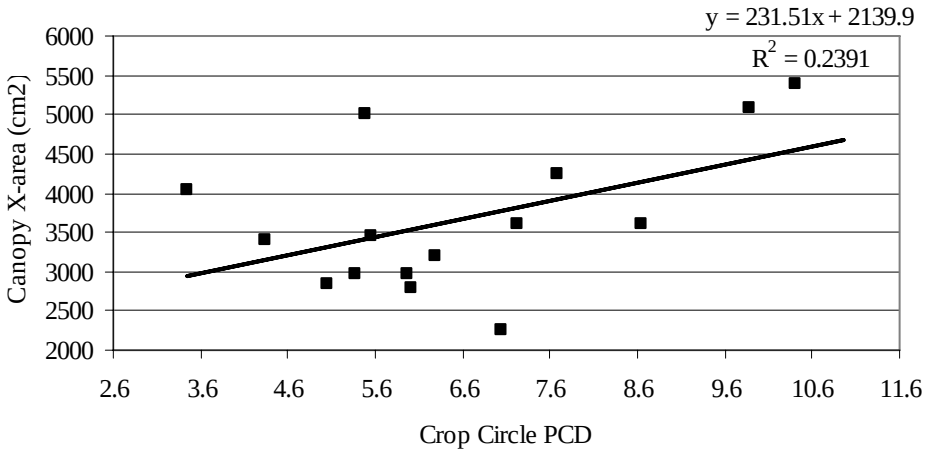


Figure 18. Scatter-plots of vine cross-sectional area (X-area) as a function of (a) NDVI and (b) PCD (n = 15) as measured using the Crop Circle at flowering for Merlot in November 2005.

A preliminary set of experiments were devised in the 2006 season to illustrate the potential of a side-looking sensor to characterise canopy architecture in a similar fashion to that demonstrated by the Project team in 2003 (Hall et al., 2003) using cm-spatial resolution airborne imagery. In this work, we set out to monitor the Crop Circle response to canopy cross-sectional area, as measured from a combination of canopy height and width (across-row) immediately above the vine trunk for a sub-sample of 14 tagged Merlot vines. Measurements of Crop Circle NDVI and PCD were also acquired. Plots of Canopy X-area (cm^2) versus Crop Circle NDVI or PCD are given in Figure 18.

The R^2 values associated with the data shown in Figure 18 are low, although R^2 is higher for PCD than for NDVI. We believe the scatter in the data is attributed to the localised nature of the region within each vine that is illuminated by the Crop Circle unit. In its current mounting configuration, the illumination zone has divergence angle of approximately 32^o horizontal and 8^o vertical. Therefore when operated from a vehicle located in the mid-row position of our research vineyard (vine row spacing = 3 m) this corresponds to an illumination footprint of approximately 0.5 m horizontal x 0.1 m vertical. In these particular NDVI measurements, the illumination footprint was centred directly over the vine trunk and midway between the cordon wire and first foliage wire. As these vines were cane-pruned (as opposed to spur-pruned) the foliage structure within this localised illumination region was observed to be quite variable and this is likely to account for the spread of NDVI values associated with each yield measurement. Optimising the illumination footprint and

sampling regime (for example to take a continuous sweep of measurements along the full extent of each vine) would most likely improve on the nature of the observed correlation between vine yield and Crop Circle NDVI. This is the subject of ongoing investigations.

The 2006 harvest season has only just concluded in this vineyard and lab analyses of anthocyanin content of the grape samples are now underway. Pruning is not scheduled until mid September. A full collation of anthocyanin, yield and canopy PAB data is planned for the 2006 data and will be reported separately.

Remote sensing of vineyards planted to white varieties

In addition to the above work which, like that conducted under Objective 3 (see above), focussed on red winegrape varieties, further work was also conducted in years 5-7 with a focus on white varieties. The Woodbury study site was used to see whether relationships similar to those between remotely sensed canopy descriptors and yield and grape composition proximal data determined for red grape varieties under objective 3 can be established for white grape varieties. Given the sloping terrain of the Woodbury site a second objective was to assess the effect of slope & aspect on vine reflectance values and the subsequent correlations between the remotely sensed canopy descriptors and the proximal field data.

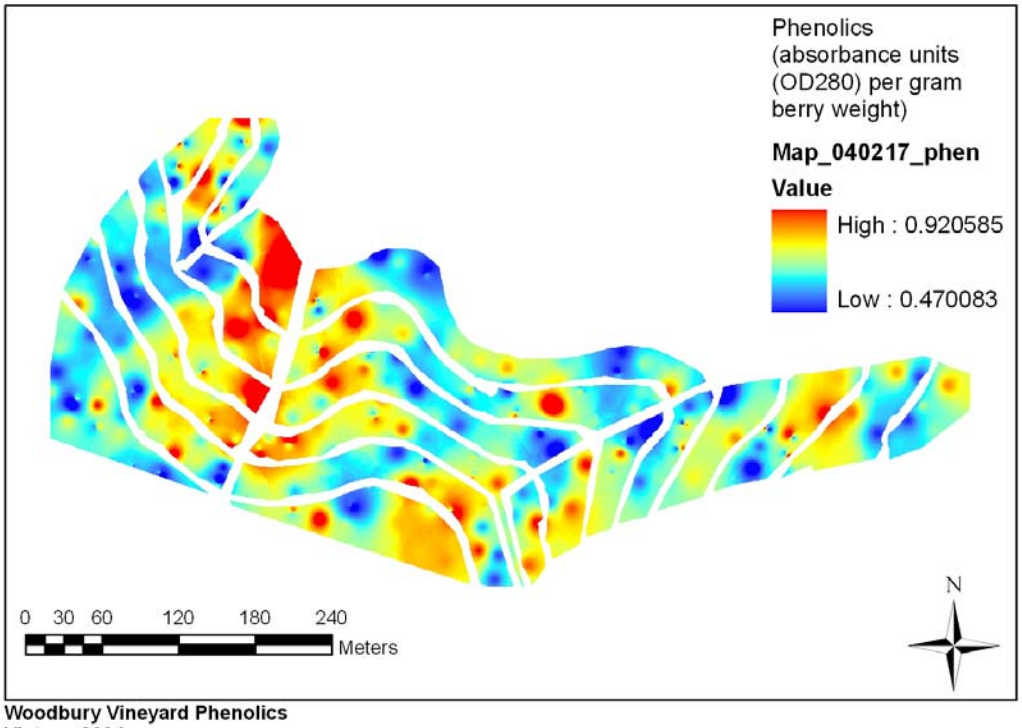
- Remotely sensed data was acquired over the Woodbury F2 Riesling study block for the seasons 2004-2006. All remotely sensed image data was radiometrically and geometrically corrected and calibrated to reflectance.

- A new algorithm (VineClipper) was developed to extract vine canopy data corresponding to the field sample locations for the more complex trellis layout of the Woodbury vineyard. VineClipper has the potential to make the complex process of image data extraction a feasible routine application within the viticulture industry. It has been developed with a more general functionality, allowing data extraction from vineyards with complex trellis layouts. All image data for the 2004-2006 seasons was processed using the new VineClipper algorithm to produce remotely sensed canopy descriptors corresponding to the proximal yield & grape composition field data.

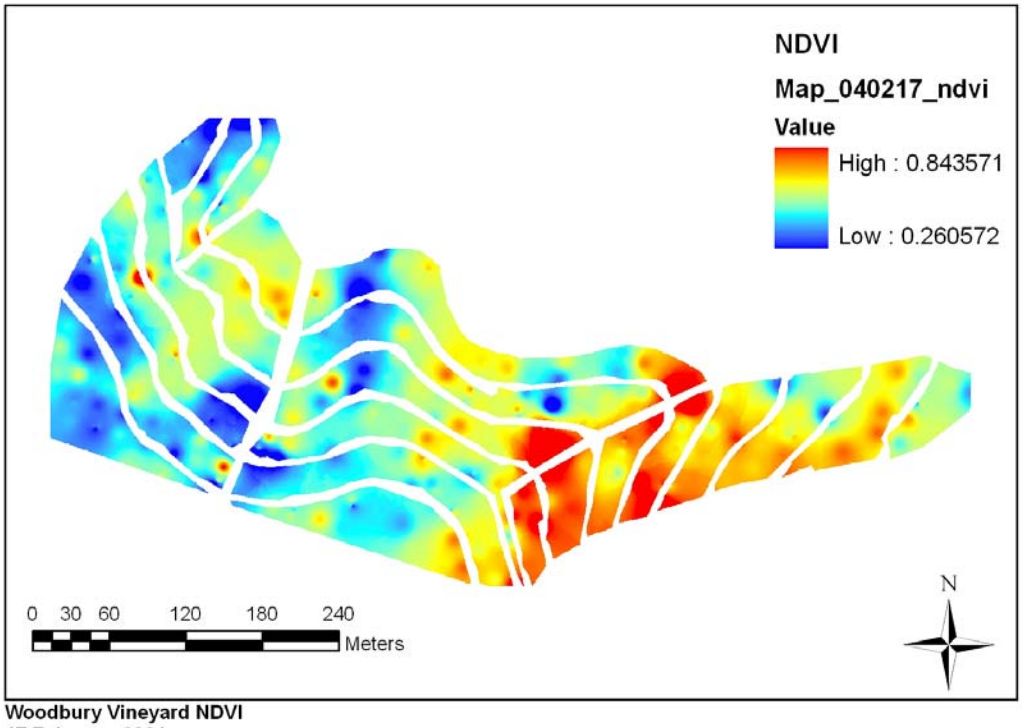
- Initial correlations between the proximal data and remotely sensed canopy descriptors suggest that relationships similar to those established for red grape varieties may also be present for white grape varieties. Work is progressing to establish more complete correlations between canopy size & density descriptors and proximal grape yield & composition.

- A number of topographic correction methods have been applied to the Woodbury imagery. Initial findings suggest that the topographic effect has only a minor effect on the vine reflectance values. Further testing is required to assess the effect of topographic corrections on the correlations between the proximal data and the remotely sensed canopy descriptors.

- Figure 19 shows phenolic data at harvest 2004 (year 1) along with NDVI data extracted from 50 cm multispectral MADIS data flown at veraison in year 1 (17 February 2004). Relatively high phenolic levels were present in the fruit harvested from the western half of the Riesling block. Visual inspection of the imagery indicates relatively low NDVI values in this area and relatively high NDVI values in the eastern side of the block, thus suggesting a possible negative correlation between phenolics and NDVI.



Woodbury Vineyard Phenolics
Vintage 2004



Woodbury Vineyard NDVI
17 February 2004

Figure 19. Phenolics at vintage and remote sensed imagery (veraison) for the Eden Valley site, season 2004.

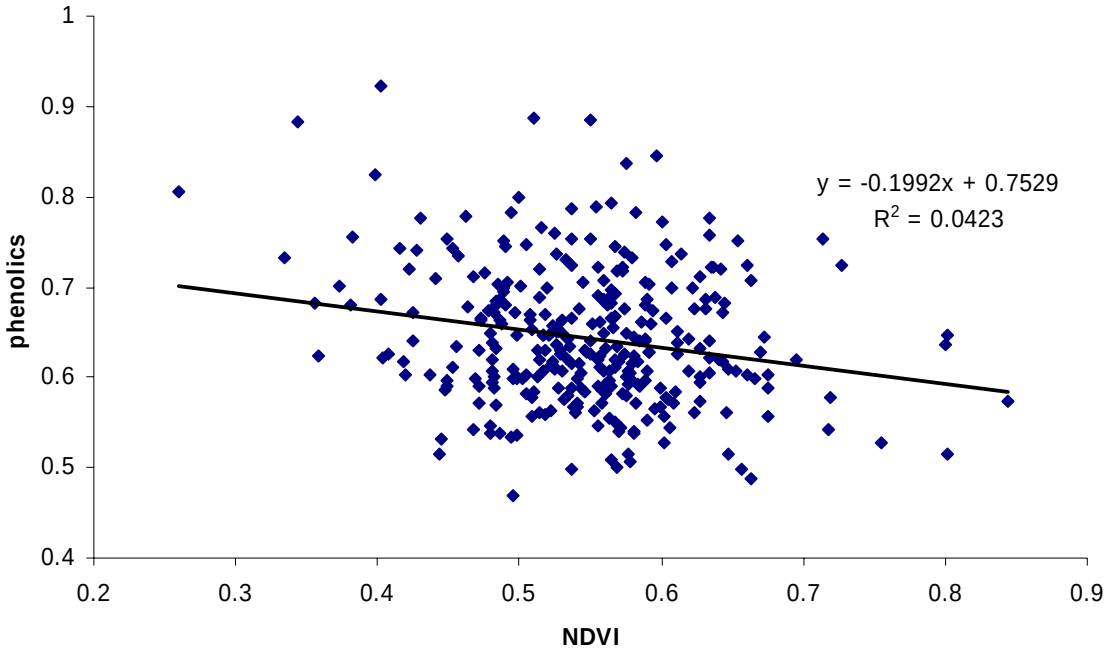


Figure 20. Covariation between phenolics and NDVI – Eden Valley Riesling Block

- Figure 20 shows the relationship between phenolic content of fruit at harvest and the mean NDVI values extracted by VineClipper from 50 cm MADIS veraison imagery. The linear regression R^2 value of 0.0423 is significant at $p < 0.001$. This indicates that there is a very high probability that canopy characteristics, as measured by NDVI, are affecting phenolic development in the fruit, albeit at a low level of effect (4% of the variance explained) and thus, the predictive ability of the regression model, being small. The suggestion of an apparent visual correlation between the phenolic field data and airborne derived vegetation descriptors in Figure 19 is therefore supported. Further analysis will seek to determine what threshold R^2 value (Hall, 2003) is required for an equation such as that shown in Figure 20 to be useful as a vineyard block partitioning tool.

- Table 3 shows the strength of correlation for phenolics and berry weight with NDVI at the four dates of imaging during the 04-05 season. The correlation for berry weight is stronger than that observed for phenolics. However, the only temporal trend that is apparent is for marginally lower correlations near anthesis around 23 January.

Table 3. Fisher z-values for phenolic and berry weight correlations with NDVI during 03-04 season.

Date	z for phenolics	z for berry weight	n
14 Dec 03	-5.18	7.10	318
23 Jan 04	-3.66	3.78	206
17 Feb 04	-3.76	8.88	318
11 Mar 04	-3.43	9.47	318

- A full analysis of the Eden Valley Riesling block data over the three years of the study is currently underway. The focus of this analysis will be to further investigate the relationships between a range of remotely sensed vegetation indices and proximal grape composition and yield data. The results of this analysis will be published in the scientific literature when complete. In the interim, we conclude that although there is a significant effect of canopy characteristics (derived from remotely sensed data) on phenolic development in the fruit, the preliminary results suggest that it is not as strong as that for red wine grape varieties and is unlikely to be useful as a predictive tool. The decrease in the level of correlation as the season proceeded is counter to previous results obtained for red wine varieties (Lamb et al., 2004b); these suggested that the level of correlation between remotely sensed canopy characteristics and phenolic content development in fruit peaked at veraison. The preliminary results from this work with Riesling show that other grape composition measures have higher levels of correlation with NDVI, but further investigation is required to assess the value of remote sensing in making useful maps of various white winegrape composition parameters.

Outcomes / Conclusions

Prior to vintage 1999, Precision Viticulture did not exist. Whilst the level of holistic adoption and integration of spatial technologies into winegrape production remains relatively low, to the extent that the perceived difference between *Viticulture* and *Precision Viticulture* remains, the fact is that this project has been a world leader in understanding vineyard variability and the development of Precision Viticulture. Thus, we have promoted improved understanding of vineyard performance through consideration and survey of variation in the land underlying the vineyard, and of vineyard performance, at high spatial resolution, and have demonstrated the potential benefits of such an approach. As such, the project has contributed to the potential enhancement of Australia's competitive advantage as an efficient producer of good quality, low cost wines. Many Australian winegrape producers have employed at least some of the tools of PV, remotely sensed imagery being foremost amongst these. Were it not for a shortage of appropriate technical support, we believe that the level of adoption of this and other technologies (yield mapping, high resolution soil and topographic survey) would be much greater than it has been.

Recommendations

It is often said that 'it takes much longer to learn how to use a new technology than it does to develop it in the first place.' The work done in this project and the present level of adoption of PV supports this view. It also suggests that there is still much work that could usefully be done. In particular, provision of training to consultants and company viticulturists should be seen as an on-going need and priority, as should effort aimed at developing technology for on-the-go fruit quality sensing. Notwithstanding variation in wine style, simplification and better quantification of fruit quality as a single index would also be valuable.

In its review of the work conducted in this project, a review undertaken as input to project funding decisions with respect to on-going support for CRCV projects, the CRCV Program 1 industry reference group said of this project:

> "*The general consensus was that the research has been extremely well done but is now at the stage were there was little further required. It was felt that it was no longer a 'stand alone project' but that the expertise (resident in the current research team), the information and the tools from this project need to be integrated into other projects. The opinion was expressed that there is no point working on quality specifications until we know how to exploit or act on vineyard zones.*"

The project team strongly disagrees with this view. This report alludes to demonstration of the merits of *zonal management* from both an economic and NRM perspective (eg. Bramley and Hamilton, 2005; 2006; Bramley et al., 2005b; Proffitt et al., 2006). What is needed now is a rethink of the logistics of grape supply to facilitate accrual of the benefits of such management. Indeed, we believe that integration of zonal management into supply chain / demand chain research is essential if the consumer-to-vineyard demand chain paradigm is to form a major part of the platform underpinning the Australian wine industry going forward. Sensibly, such work would also be linked closely to studies of *terroir*.

Furthermore, zonal management has, to date, focused on the differential collection of outputs from the production system rather than differential application of inputs to it (water, fertilizer, sprays, labour, etc…), and the associated economic analysis has been rudimentary at best. A more robust analysis of the economics of Precision Viticulture is warranted, as is examination of variable rate management of inputs to winegrape production. A study along these lines would sensibly draw on research outputs from the GWRDC Soil and Water Initiative.

We are also concerned at the comment on integration of 'the information and the tools from this project' into other projects. This project has enjoyed a high profile both within the CRCV, the Australian wine industry, and indeed, internationally. However, we are only aware of two studies undertaken by Australian viticultural or oenological researchers which have attempted to make use of the outputs from this project – the dried fruits study of Michael Treeby (CRCV 1.1.4) and the recent disease management study of Evans et al. (2006). Clearly, for other researchers to access the expertise that is embodied in the present project team, the provision of on-going funding support for Vineyard Variability researchers will be necessary, lest the members of the present team move on to other areas of work and/or industries as a result of the IRG recommendation that a stand alone Precision Viticulture project is no longer required. This is an issue which warrants the early attention of research funders and managers.

In summary, most of the tools of Precision Viticulture (except quality sensing technologies) have probably been developed; the wine industry (both researchers and practitioners) has a long way to go before it can say that it has learned how to use them.

Acknowledgments

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The senior scientists working on this project (Dr Bramley and Assoc. Prof. Lamb) are also most grateful to the other members of the project team for their efforts over an extended period. Mrs Susie Williams, Dr Kerstin Panten, Ms Angela Reid, Mr David Gobbett, and Dr Joan Davenport (CSIRO), Dr Paul Frazier, Mr Allan Mitchell and Mr Graham Hyde (UNE), and Dr John Louis, Dr Andrew Hall, Dr Michael Kemp, Mr Mark Wilson and Dr Bruno Holzapfel (CSU) have all made valued contributions to the project. We are also grateful to Rachel Calvert and Jan Mahoney (CSIRO) for assisting with the formatting of this report and construction of the CD version of it.

In addition, the CSIRO team is most grateful for the on-going support, cooperation and significant in-kind investment of the staff and management of Foster's Wine Estates and the Wingara Wine Group. In particular, the input of Dr Richard Hamilton, Colin Hinze (now with Taylors Wines), John Matz, Greg Harrold, Greg Pearce, David Edwards, Jonathan Shearer, Adrian Loschiavo

(Fosters Wine Estates), Chris Brodie and Wayne Stehbens (Wingara Wine Group) deserves special mention, as does the input during the early phases of the work of Dr Tony Proffitt (now with AHA Viticulture). We have also benefited considerably from the input of colleagues within the CSIRO Precision Viticulture team including Dean Lanyon, Jackie Ouzman and Damian Mowat, and in the topographic analysis undertaken in the Eden Valley, from the assistance and expertise of Dr John Gallant (CSIRO Land and Water, Canberra).

The CSU team would like to acknowledge the ongoing research support provided by the staff of the Spatial Analysis Unit (SPAN) and access to the high spatial resolution airborne remote sensing system (MADIS). We would particularly like to acknowledge Gary McKenzie, Gail Fuller and Craig Poynter for the considerable contribution that they have given the project in relation to the support, development and operation of the MADIS imaging system.

The UNE team would like to particularly acknowledge the support of Colin Peterson (Peterson's Armidale Vineyard) and Chris Sloane (New England Vineyard Services) for support in using vineyard facilities and in managing field-support staff during sampling. The staff of the UNE Science Engineering Workshop are also gratefully acknowledged for their assistance in constructing the airborne imaging system (UNEBird) and the Crop Circle and Grapesense platforms for on ground deployment. The Technical guidance of Ron Bradbury (UNE), Kyle Holland (Holland Scientific Inc, USA), John-Paul Praat and Kenjie Irie (Lincoln Ventures PL, NZ) and John Lucas (Terrabyte Services) is also acknowledged in the assembly and operational deployment of our UNEBird, Crop Circle, Grapesense and EM38 units, respectively.

Appendix 1: Communication

This project has enjoyed a high profile over the life of the CRCV and has featured in numerous articles in industry media, the CRCV Newsletter and on both radio and television. Similarly, key staff, Drs Bramley and Lamb in particular, have spoken at several field days, industry meetings and research seminars. It is also worth pointing out that all of the work done in this project has been *participatory* in nature and has been dependent on close collaboration with numerous industry personnel including vineyard managers, winemakers and company viticulturists and associated access to vineyards and their associated equipment, infrastructure, and on occasion, staff. As a consequence, the project has benefited from the in-built extension mechanism that derives from this participatory approach and the project team is confident that, within the normal budget and operating constraints of a research project, it has done all it can to facilitate industry awareness of the project and the results generated from it. In addition, the project team have been prolific publishers. A complete listing of publications produced by the project is given below.

*Indicates invited publications

A. Refereed scientific publications

1. **Bramley, R.G.V.** 2005a. Understanding variability in winegrape production systems. 2. Within vineyard variation in quality over several vintages. *Australian Journal of Grape and Wine Research* **11** 33-42.

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

3. ***Bramley, R.G.V.** and Janik, L.J. 2005. Precision agriculture demands a new approach to soil and plant sampling and analysis – Examples from Australia. *Communications in Soil Science and Plant Analysis.* **36** 9-22. (**Invited keynote paper** presented to the 8th International Symposium on Soil and Plant Analysis, Capetown, January 2003).

4. ***Bramley, R.G.V**. and the late Quabba, R.P. 2002. Opportunities for improving the management of sugarcane production through the adoption of precision agriculture – An Australian perspective. *International Sugar Journal* **104** 152-161.

5. Brown, R.B., **Lamb, D.W**. & Sidahmed, M.M. 2004 "Using grape leaf reflectance for spatially variable vineyard management". *Transactions of the ASAE/CSAE*. **Paper 041078**.

6. *Cook, S.E., Adams, M.L., Bramley, R.G.V. and Whelan, B.R..2006 State of precision agriculture in Australia. *In:* Srinivasan, A. (*Ed*). *Precision Farming - a global perspective.* The Haworth Press Inc., Binghamton, New York. In press

7. **Hall, A., Lamb, D.W., Holzapfel, B.** and **Louis, J.** 2002. Optical remote sensing applications for viticulture - a review. *Australian Journal of Grape & Wine Research*. **8** (1): 36-47.

8. **Hall, A., Louis, J.** and **Lamb, D.W.** 2003. Characterising and mapping vineyard canopy using high spatial resolution aerial multispectral images. *Computers & Geosciences*. **29** (7): 813-822.

9. ***Lamb, D.W.** and **Bramley, R.G.V.** 2001. Managing and monitoring spatial variability in vineyard variability. *Natural Resource Management* **4** 25-30.

10. ***Lamb, D.W., Bramley, R.G.V., and Hall, A.** 2004a. Precision Viticulture – An Australian perspective. *Acta Horticulturae* **640** 15-25.

11. **Lamb, DW, Weedon, MM, and Bramley, R.G.V** 2004b. Using remote sensing to predict 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.

12. **Lamb, D.W., Mitchell, A. & Hyde, G.** 2005. Vineyard trellising comprising steel posts distorts data from EM soil surveys. *Australian Journal of Grape & Wine Research* **11** 24-32.

B. Books / Manuals / Editorships

13. ***Bramley, R.G.V.** 2006. Selected entries on Precision Viticulture and related matters in *The Oxford Companion to Wine*, 3rd edition. Edited by Jancis Robinson. Oxford University Press, London. In press. (no PDF Available)

14. **Bramley, R.** 2005b. A protocol for the construction of yield maps from data collected using commercially available grape yield monitors. Supplement No. 1. February 2005. http://www.clw.csiro.au/staff/BramleyR/documents/protocol_supp1.pdf

15. **Bramley, R.G.V.** 2004 (Ed). Managing vineyard variation (Precision Viticulture). Proceedings of workshop 30B held as part of the 12th Australian Wine Industry Technical Conference. http://awitc.com.au/workshops/Workshop_30B_Proceedings.pdf

16. ***Bramley, R.G.V.** (Ed). 2001a. Precision Viticulture – Principles, opportunities and applications. Workshop No. 14 convened for the 11th Australian Wine Industry Technical Conference, Adelaide, October 2001. www.crcv.com.au/research/programs/one/workshop14.pdf

17. **Bramley, R.G.V** and **Williams, S.K.** 2001a. 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.

18. **Hall, A.** 2003. Defining Grapevine and Vineyard Characteristics from High Spatial Resolution Remotely Sensed Optical Imagery. PhD Thesis. Charles Sturt University, 147 pp. No pdf available.

19. **Lamb, D. W.** (Ed). 2001. Vineyard monitoring and management beyond 2000 - Final report on a workshop investigating the latest technologies for monitoring and managing variability in vineyard productivity. Cooperative Research Centre for Viticulture/National Wine & Grape Industry Centre, Charles Sturt University, Wagga Wagga, NSW. www.crcv.com.au/research/programs/one/finalreport.pdf

20. *Proffitt, T., **Bramley, R.**, **Lamb, D.** and Winter, E. 2006. *Precision Viticulture – a user's handbook.* Winetitles, Adelaide. In press. No pdf Available.

C. Edited proceedings and conference abstracts

21. *Arkun, S., Honey, F., Johnson, L., **Lamb, D.**, Lieff, W. and Morgan, G. 2001. Airborne remote sensing of the vine canopy. *In:* Lamb, D.W (Ed) Vineyard monitoring and management beyond 2000 – A workshop investigating the latest technologies for monitoring and managing variability in vineyard productivity. CRC Viticulture, National Grape and Wine Industry Centre, Charles Sturt University, Wagga Wagga, NSW, 7-8-00.

22. **Bramley, R.G.V.** 2002a. The fallacy of managing for the average – Another lesson from Precision Agriculture. 6th Annual Symposium on Precision Agriculture Research and Application. University of Sydney, 9th August, 2002.

23. **Bramley, R.G.V.** 2002b. Towards optimal resource management for grape and wine production. *In:* Blair, R.J., Williams, P.J. and Hoj, P.B. (*Eds*) Proceedings of the 11th Australian Wine Industry Technical Conference. Winetitles, Adelaide. pp. 274-275. Abstract and Poster.

24. **Bramley, R.G.V.** 2001b. 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 Superieure Agronomique de Montpellier, France.

25. **Bramley, R.G.V.** 2001c. Vineyard sampling for more precise, targeted management. *In: Geospatial Information and Agriculture* incorporating Precision Agriculture in Australasia – 5th Annual Symposium. 17-19 July. NSW Agriculture. On CD-ROM: ISBN 1 876346 32 9.

26. ***Bramley, R.G.V.** 2001d. 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.

27. ***Bramley, R.G.V.** 2001e. Research supporting the development of optimal resource management for grape and wine production. *In:* Bramley, R.G.V. (Ed) Precision Viticulture – Principles, opportunities and applications. Workshop No. 14 convened for the 11th Australian Wine Industry Technical Conference, Adelaide, October 2001. www.crcv.com.au/research/programs/one/workshop14.pdf

28. ***Bramley, R.G.V.** 2000a. Measuring within vineyard variability in yield and quality attributes (and other things that vary in vineyards). *In:* Lamb, D.W (Ed) Vineyard monitoring and management beyond 2000 – A workshop investigating the latest technologies for monitoring and managing variability in vineyard productivity. CRC Viticulture, National Grape and Wine Industry Centre, Charles Sturt University, Wagga Wagga, NSW, 7-8-00.

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Appendix 2: Intellectual Property

This project has focussed on the generation of knowledge for industry. No commercialisable IP has been generated.

Appendix 3: References

The bulk of the papers referred to in this report are listed in Appendix 1. In addition, the following publications were referred to:

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Appendix 4: Staff

The following staff have been engaged on this project:

CSIRO Sustainable Ecosystems – Adelaide

Dr Rob Bramley – Principal Research Scientist – 40% time commitment (in-kind)
Mrs Susie Williams – Technical Officer – 100% time commitment (fully funded via this project)
Dr Kerstin Panten – Postdoctoral Fellow - 100% time commitment (fully funded via this project)
Ms Angela Reid* - Biometrician - 100% time commitment (fully funded via this project)
Mr David Gobbett* – Technical Officer - 100% time commitment (fully funded via this project)

*Angela Reid was employed for a 6 month period whilst Susie Williams was absent on maternity leave. David Gobbett has worked on a part-time basis since September 2005 in a job-share arrangement with Susie Williams following her return from maternity leave. During the six months from October 2004, Dr Bramley hosted Dr Joan Davenport on a sabbatical visit from Washington State University, Prosser, USA. Part of the work done by Dr Davenport during her stay involved analysis of a CRCV dataset (petiole nutrients from our Coonawarra and Sunraysia sites) and contributed to Objective 6.

University of New England – Armidale

Assoc. Prof. David Lamb** - 20% time commitment (in-kind)
Dr Paul Frazier – 5 % time commitment (in-kind)
Mr Allan Mitchell – 50% time commitment (funded by this project)
Mr Graham Hyde – 5% time commitment (in-kind)

**During the first two years of the project, David Lamb was employed at Charles Sturt University. He subsequently moved to the University of New England which became a supporting participant in the CRCV as a consequence.

Charles Sturt University – Wagga Wagga

Dr John Louis – Associate Professor (Mathematics and Spatial Science) - 10% time commitment (in-kind)
Dr Andrew Hall – initially, PhD student (fully funded via this project); subsequently Lecturer (Spatial Science) – 10% time commitment (in-kind)
Dr Michael Kemp – Lecturer (Mathematics) – 10% time commitment (in-kind)
Mr Mark Wilson – Technical Officer 10% time commitment (in-kind)
Dr Bruno Holzapfel – Senior Lecturer (Viticulture) – 10% commitment (in-kind), years 1-3 only

Appendix 5: Budget Reconciliation

A budget reconciliation will be provided by the CRCV under separate cover.