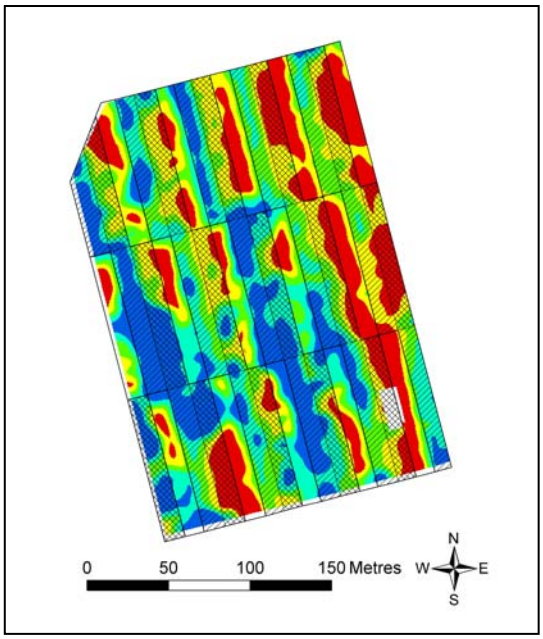
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Grape and Wine Research and Development Corporation

Making sense of vineyard variability - Completion of CRV99/5N – 1.1.1



FINAL REPORT to
GRAPE AND WINE RESEARCH & DEVELOPMENT CORPORATION

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Cover image: Remotely sensed image of vine vigour in a trial block at Penfolds Clare Estate, 2007.

Abstract

The marked spatial variability that is known to exist in vineyards presents problems for people wishing to conduct viticultural experiments – whether these be researchers pursuing advances in viticultural science or growers wishing to evaluate new management strategies. Indeed, traditional plot or panel-based experimental designs are subject to the effects of short-range spatial variation and opportunities for meaningful extrapolation of results to other locations may be limited. A possible solution to these problems is to use a new approach to experimentation in which the whole block or management unit is used for the experiment, and in which the treatment effects are assessed using geostatistical methods.

This project sought to assess the utility of whole of block experimental methods as a means of assessing the variable response of viticultural production systems to management inputs. Two experiments (Coonawarra and Auburn, Clare Valley) focussed on canopy management as a means of improving fruit and wine quality, whilst a third evaluated alternative mid-row management options for enhancing vine vigour in an organically managed vineyard (Clare).

We conclude that this approach offers experimenters an enhanced likelihood of obtaining useful results from their experiments. In particular, it promotes recognition that responses to treatments are variable and that, whilst traditional approaches are aimed at identifying whether treatment A is better than treatment B, through the whole of block approach, it is possible to identify that whilst treatment A gives better results in one part of a block, treatment B may be preferred in another.

In spite of the promise shown in using the whole of block approach, further development of the methods of analysis of results is required in order to make the methodology more accessible. In particular, this should be targeted at development of easy-to-use software.

Executive Summary

Vineyards are variable. However, recent research has highlighted that, armed with the technologies that have collectively become known as Precision Viticulture, grapegrowers and winemakers have a significant opportunity to take advantage of a knowledge of vineyard variability and through appropriately targeted management, to enhance their profitability. Selective harvesting is one possibility, but there is also interest in targeting inputs (eg fertilizer, water, pruning strategy, etc…) for specific production objectives. This then raises the question as to how management strategies should be fine tuned to match the variability in the vineyard, and the prospect that experimentation may be needed in order to identify the best management option. However, one consequence of vineyard variability is that it could significantly affect the results obtained from an experiment, especially if this were located in a small area within a block, perhaps in a series of plots, as in the traditional approach to viticultural experimentation. An alternative approach may be to conduct the experiment over the whole vineyard, and to make use of its variability to assess the variable response to different treatments or management options. Evaluation of this idea was the core focus of this project.

Whole of block experiments were conducted in 3 commercial vineyards in the Clare Valley and Coonawarra; two focussed on canopy management, with a third focussed on management of the inter-row. As might be expected given the variability that is seen in vineyards, the response to the experimental treatments was variable. However, through spatial analysis of the results, the respective vineyard managers were able to see where in the vineyard a particular treatment delivered a benefit, and for any given location, the size of this benefit compared to other treatments. Indeed, a key learning from this project was the enthusiasm for the whole of block approach displayed by our industry collaborators. Of particular note is the fact that one of the experiments studied was established at the behest of the company viticulturist and prior to any involvement from the team working on this project. Our Clare experiment also ended up with a more complicated design than we originally intended, again at the behest of the vineyard manager. In all cases, the experimental treatments were implemented by the same vineyard employees who carry out normal operations and in no case did the project team encounter any negative feedback in regard to what was being attempted or asked of the staff. We therefore conclude that neither the scale of whole of block experiments nor their implementation are an impediment to adoption.

The results obtained in this work show that just as vineyards are variable, so too are the responses to changes in management strategy (ie experimental treatment). This is important because it highlights the fact that just as the tools of Precision Agriculture promote this new experimental modus operandi, adoption of Precision Agriculture depends on experimentation being a key part of the overall approach to management. Thus, in order to target management, aside from identifying ‘zones’ for which targeted management is appropriate, grapegrowers and winemakers need a basis for selecting alternative management strategies that are appropriate to their particular enterprises and the variation within them; whole of block experimentation provides the tool by which such decisions may be made.

With the foregoing in mind, we recommend that GWRDC and the industry promote the extension of this new approach to experimentation. In particular, researchers should be strongly encouraged to adopt it. Through GWRDC, the Australian wine industry has now invested a considerable sum in research aimed at gaining a better understanding of vineyard variability and how it might be managed. It would therefore be somewhat incongruous if a larger amount were to be invested on an on-going basis into research based on the more traditional ‘plot’ based experimental approach. Vineyard variability is highly significant and it should not be ignored !

The above notwithstanding, an obvious limitation to adoption of the whole of block approach is a lack of training and general expertise in spatial analysis, both in industry and the research community. The current non-availability of easy-to-use software for the spatial analysis of the results of whole of block experiments is an obvious impediment to progress. It is therefore

recommended that research funding is spent on a project to package the methods used here into something that can be used by a broad constituency.

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Background

Recent research, largely conducted as part of CRCV project 1.1.1 (GWRDC Project CRV99/5N), has demonstrated 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). Fruit quality has also been shown to be variable; its patterns of spatial variation tend to follow those for yield (Bramley, 2005a), although not necessarily in the same rank order (Bramley and Hamilton, 2005). Variation in vine vigour, as indicated by remotely sensed imagery (Hall et al., 2002) is also marked and has potential as an indicator of fruit quality variation (Lamb et al., 2004). This work, and the associated development of Precision Viticulture (Bramley and Proffitt, 1999; Proffitt et al., 2006), 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, 2005b; Bramley and Hamilton, 2005; Bramley et al., 2005b).

Notwithstanding the progress made in the aforementioned research, the question remains as to how grapegrowers and winemakers should go about targeting management ? An obvious response to this question is that they should do some experiments in their own vineyards. However, since we know that vineyards are spatially variable, additional problems arise: where should experiments be located ?; and on what basis should the results obtained be translated to locations beyond the experimental area, whether these be other parts of the same vineyards, other vineyards on the same property or in the same region, or vineyards even further afield ?

The traditional approach to viticultural experimentation (and sampling) is to use randomised designs, often comprising small experimental units (single vines or panels of vines) and statistical methods based on analysis of variance (ANOVA). A major limitation of such plot-based trials is that they will only reveal information of an experimental treatment response for those parts of the field with the same prevailing conditions; they should not be used to draw conclusions for other areas which may, for example, have different soil properties. Thus, the value of the information gained is limited.

A related shortcoming of the traditional plot-based approach is that whilst it involves randomisation and blocking in an attempt to exclude the effects of spatial variability, for all practical purposes, treatments are randomly located in the absence of consideration of any inherent underlying vineyard variation (Figure 1a, b). As Figure 1c illustrates, attempts to accommodate the effects of underlying variation by the use of a stratified randomised design run the risk of treatment effects being masked by the underlying inherent variation. Furthermore, even where underlying variation is considered with plots located in ‘like areas’, both the researcher and vineyard manager remain faced with the problem of how to extrapolate the experimental results to dis-similar areas, which will certainly exist within a single vineyard block (Figures 1b, c).

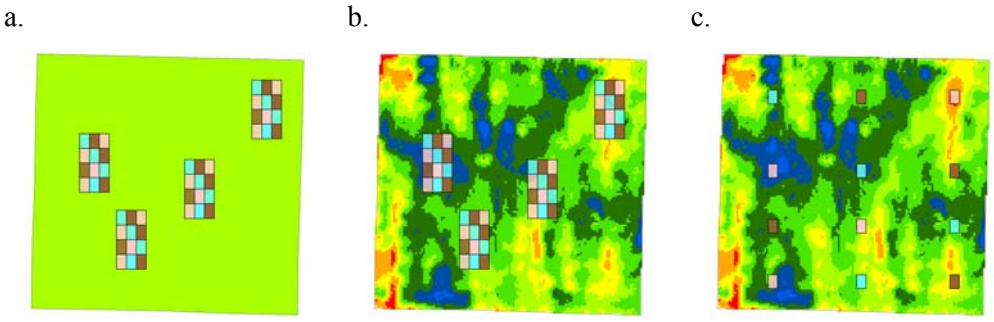


Figure 1. Possible locations for a classical vineyard experiment (a) in the absence of knowledge of underlying variation, (b) using one of the same designs but where information about underlying variation is available (in this case, a yield map), and (c) in an attempt to accommodate the effects of the underlying variation.

For robust decision making, especially when Precision Agriculture (PA) is used for the targeting of management strategies, farmers (and indeed scientists !) need to know what the crop response to a certain management practice is likely to be across the whole range of soil and climate conditions of the farm or field where the management practice is to be applied. If the chosen area for a traditional plot based experiment is heterogeneous and the replicates are placed on areas with differing soil properties (Figure 1b), the experimenter will hopefully use covariates (eg soil clay content) to assist in the statistical analysis of the trial results. But even the use of covariates in the analysis of experiments only adds a component to a linear model and so the likelihood remains that treatment effects will be concluded to be the same everywhere.

The obvious need for farmers to apply experimental results over the whole management unit and the increasing amount of knowledge about spatial variation gained by using PA technologies such as GPS, GIS and sensors recording data at high spatial resolution, led to the idea of conducting on-farm trials over whole fields. This was first attempted in broadacre cereal production over 10 years ago (Adams and Cook, 1997; Cook et al., 1999). Lanyon and Bramley (2004) demonstrated the potential power of this approach in vineyards, but were somewhat constrained by the lack of a robust method for analysing the experimental results. Expansion of this work was a key part of CRCV Project 1.1.1 but for a variety of reasons could not be completed during the life of the CRCV. Completion of this work was thus the core focus of this project.

Project Aims and Performance Targets

Following from the above, and as detailed in the project proposal, this project had the following objectives:

1. Complete the evaluation of the whole-of-block approach to experimentation commenced in CRCV 1.1.1;
2. Provide recommendations as to appropriate designs and methods of analysis for such experiments; and thereby
3. Provide growers with tools that assist them in understanding the variable response of their production systems to management inputs.

Accordingly, the following outputs and performance targets were foreshadowed:

Outputs and Performance Targets 2006-07

Outputs	Performance Targets
1. Information on the value of the whole-of-block experimentation approach as a means of understanding the variable response of their production systems to management inputs	Pre-vintage field data collected at key experimental sites (By end vintage 2007)
2. Appropriate (geo)statistical and GIS-based methodologies for the analysis of experimental results presented for growers and their consultants	Protocol for whole-of-block experimentation in vineyards published in web-accessible format (Target date: March 2007)

Outputs and Performance Targets 2007-08

Outputs	Performance Targets
1. Information on the value of the whole-of-block experimentation approach as a means of understanding the variable response of their production systems to management inputs	▪ Small lot wines made and sensory analysis complete (By November 2007) ▪ Final project report to GWRDC (including CRCV-phase of the project; By December 31st, 2007)

During the course of the project, it became necessary to negotiate a modification of the agreed Outputs and performance targets for 2007-08. One of our key experimental sites (Katnook Estate, Coonawarra) was so heavily impacted by frost in late 2006 that the vineyard manager made the early decision that it would not be harvested at vintage 2007. In the interests of making the most of the project and maximising delivery against the intended project objectives, we were able to import a whole of block experiment implemented by Taylors Wines at Auburn which had somewhat similar objectives to the Katnook Experiment. The revised Outputs and Performance Targets were as follows:

Outputs and Performance Targets 2007-08

Outputs	Performance Targets
1. Information on the value of the whole-of-block experimentation approach as a means of understanding the variable response of their production systems to management inputs	▪ Sensory analysis of treatment-specific wines made by Taylors complete (By November 2007) ▪ Final project report to GWRDC (including CRCV-phase of the project; By December 31st, 2007)

In addition, and in view of a developing collaboration on methods of analysing the results of whole of block experiments between the project team and researchers at Rothamsted (UK), which lead to Dr Kerstin Panten visiting the UK in late 2006, GWRDC agreed that the development of a protocol for whole of block experimentation be deferred and included as part of the delivery of this report.

Methods

As outlined by Bramley and Lamb (2006), two whole of block experiments were established in 2004 at sites in the Clare Valley and Coonawarra; as indicated, a further site (Auburn, Clare Valley) was added to the project in 2006. It is important for readers to note that this project was much more focussed on appropriate experimental methodologies than the specific objectives of particular experiments. Thus, our strategy in site selection was to choose sites at which the vineyard managers were pre-disposed to experiment, were interested in collaborating in the development of the whole of block approach and had issues that they wanted to investigate through experimentation. Thus, our role was predominantly focussed on experimental design and the conduct and analysis of the experiment rather than the specific objectives of the experiments.

Clare

i. Site description and experimental objectives

The Clare site (Foster's Wines) is a 4.8 ha block of Merlot which had been planted on own roots in 1998 with a row spacing of 3 m and vine spacing of 1.5 m; the canopy is trained to a 'loose' Ballerina system. The block comprises 61 rows which, prior to establishment of the experiments, had a ryegrass

(*Lolium perenne*) floor cover in the mid-rows. The ryegrass was established in 2002 and 2003. Whilst the block was established using 'conventional' practices (ripping, application of mineral fertilizers, etc…), its proximity to another block which was under organic management, and the fact the irrigation systems (and thus fertigation) in these blocks were linked, meant that it was managed in a quasi-organic system from soon after establishment. Subsequently, a three year transition period to full organic vineyard management ended in 2005 when it was certified as organic.

The soils in this block are duplex with sandy loam topsoils overlying a medium to heavy clay sodic subsoil (Lanyon and Bramley, 2004; 2006) which restricts root growth. As reported by Bramley (2003, 2005b), salinity in the adjacent block was having a detrimental impact (5-27%) on vine productivity; at least some effect of salinity was also expected in this block, and this, along with the weak growth, possibly associated with the organic management, and the effects of drought, conspired to make the canopy very small in much of the block (Figure 2). The vines are drip irrigated and in a normal year receive approximately 0.5 and no more than 1.0 ML ha^{-1}; due to the drought conditions experienced during this project, the vineyard received substantially less than 0.5 ML ha^{-1} y^{-1} in the 2005/2006 season and no irrigation at all during 2006/2007.

Two major concerns of the vineyard manager led to the establishment of the Clare experiment. First, he was concerned that the organic production system may have been placing a constraint on vine nutrition resulting in low yield and vine vigour. Second, he was concerned that the permanent ryegrass cover crop in the mid-rows may have been competing with the vines for water and nutrients. Thus, the vineyard manager's experimental objectives were to investigate the merits of different mid-row treatments as a means of enhancing vine vigour and grape yield.

ii. Experimental design

Three treatments were applied in autumn 2004. The first involved retention of the ryegrass, supplemented by application of mulch under the vine row (RGM). The second involved replacement of the ryegrass with alternating mid-rows planted to either cereal (*Triticum triticosecale*) and legume (*Vicia faba*), in both cases reverting to bare soil during summer (CL). Finally, a control treatment comprised retention of the ryegrass supplemented by application of compost under the vine row (RGC). Because of the non-availability of organic legume seeds in 2004, both sides of the CL treatment were planted with cereal that year.

Each treatment was imposed in 'strips' comprising 4 mid-rows according to the design shown in Figure 3. As a consequence, 3 vine rows within in each strip were available to record vine responses to the treatments. Buffer rows which have two different treatments either side were not sampled.

During the early phase of our work on whole of block experimentation, a detailed desk analysis of possible designs was carried out by Dr Kerstin Panten (Bramley and Lamb, 2006). Whilst this was constrained somewhat by access to appropriate software for spatial analysis, our initial conclusions were that experiments would desirably be kept simple in terms of the number of treatments evaluated, but would be as highly replicated as possible, with relatively complex spatial arrays in order to maximise our ability to robustly interpolate the results over the whole vineyard. As will be discussed later, we have since formed the view that providing the treatments are highly replicated, there is little need for treatments to be implemented in complex spatial arrays. Obviously, this makes implementation of whole of block experiments easier for vineyard managers. Nevertheless, the initial view that more complex spatial arrays would facilitate interpolation led us to use the 'splits' in the treatment strips shown in Figure 3. Interestingly, the vineyard manager and staff charged with implementing the treatments were unconcerned about these 'splits' in terms of the possibility of them making the trial establishment more difficult than if the treatments had been applied to whole rows.

a.



b.



Figure 2. The Clare experiment at (a) flowering (November, 2006) and (b) vintage (March, 2006). Note the small size of the vines in both (a) and (b), and also the different mid-row treatments (a).

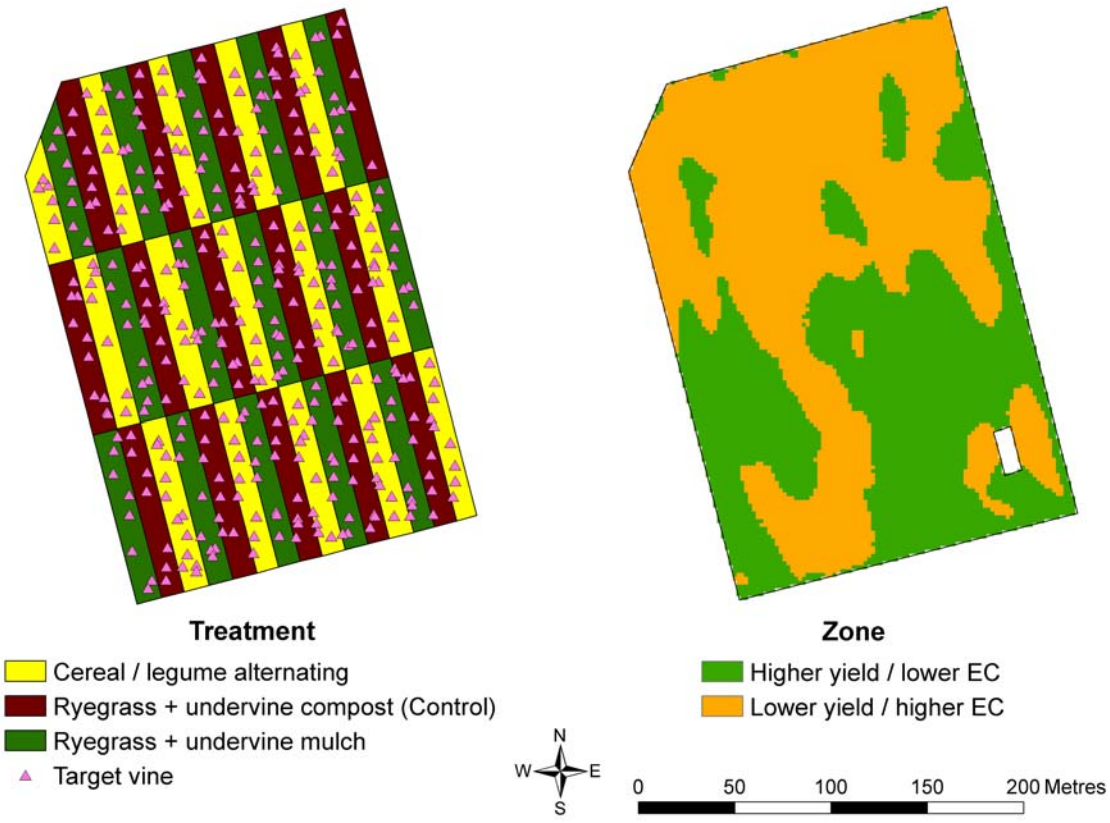


Figure 3. The Clare experiment showing the experimental design and target vine sampling strategy (left map), and 'zones' or 'potential performance classes' (right map). The latter were defined on the basis of *k*-means clustering of the 2004 (pre-experiment) yield map and an EM38 soil survey. Previous work in an adjacent block had strongly suggested that the primary driver of the EM signal was soil salinity.

iii. Data collection

Since the point of this experiment was to evaluate means of increasing vine vigour and yield, and also to make data acquisition as simple as possible for growers wishing to adopt this approach to experimentation, our intention was to use remote sensing and yield monitoring as the primary tools by which treatment responses would be measured. However, as a form of 'insurance', we also established a hand sampling strategy (Figure 3). This was based on the conventional wisdom in the geostatistics literature that at least 100 sampling points are required for derivation of a variogram (eg Webster and Oliver, 2001), together with the observation (Bramley and Lamb, 2006) that a sampling intensity of around 26 samples ha^{-1} enabled production of robust maps of vineyard variation.

Yield monitoring, EM38 soil survey and remote sensing

High resolution yield data were recorded with a Farmscan yield monitor in 2004 before the experiment was implemented and processed according to the yield mapping protocol of Bramley and Williams (2001). A series of unfortunate circumstances prevented collection of yield data subsequently. In late 2004, a large part of the block was so badly affected by frost that only the much less affected remainder was harvested at vintage 2005. In both 2006 and 2007, the effects of drought and/or the logistics of harvesting a low yield meant that only portions of the block were yield monitored.

Aerial images were acquired at veraison in 2004, 2005, 2006 and 2007 at 50 cm resolution from a commercial provider. The red (R) and near infrared (NIR) bands were used to calculate the plant cell density index (PCD = NIR/R) after the images were rectified to the block boundary and after background (ie non-vine) signals were eliminated using a supervised classification. Neighbourhood statistics were used to resample the PCD index to the same 2 m grid used for interpolation of yield and EM38 maps. Apparent electrical conductivity (EC_a) was recorded at high spatial resolution using an on-the-go EM38 sensor (horizontal dipole) on the 1st of November 2004; every row was surveyed at approximately 11 km/h with a 1 second logging interval.

Plant sampling and analysis

126 target vines were identified for each treatment evenly spread throughout the experimental area (Figure 3). The vines were geo-referenced using a differentially corrected global positioning system (dGPS) with an horizontal accuracy of about ± 50 cm. As indicated, a severe frost event during flowering 2004 affected about 60 % of the vineyard. Therefore only parts of the vineyard were harvested and sampled in 2005. However, in 2006 all 378 target vines were manually sampled along 1 m of the row centred on the trunk. This was also the case in 2007, although the extremely low yield in 2007 meant that some analyses were only undertaken on a selected subset of target vines. On each sampling occasion, the number of bunches and their total mass were recorded. Berries were randomly stripped from bunches from the entire length of the bunch to give a representative sample of berries for each vine. Sampled berries were then mixed and triplicate samples of 50 berries weighed for determination of mean berry weight. These were then frozen (–30°C) for analysis of colour and phenolics at a later date. Juice was extracted from approximately 200 randomly selected berries using a small bag press and analysed immediately for their pH, titratable acidity (TA) and total soluble solids (Baumé) using standard industry methods (Iland et al., 2000). The concentrations of colour and phenolics in homogenates of 50 berry samples (see above) were analysed at a later date using standard spectrophotometric methods (Iland et al., 2000).

Petiole samples were collected during veraison 2005, flowering 2005, veraison 2006 and flowering 2006. On the first three sampling occasions, 60 target vines were sampled. Twenty petioles opposite the basal bunch (flowering) and the fifth leaf along the shoot from the basal bunch (veraison) were sampled. At flowering 2006 all 378 target vines were sampled to allow spatial data processing and treatment response evaluation. Petioles were washed, dried at 40 ºC and ground. Total nitrogen content was analysed by dry combustion (Leco CNS-2000) on all samples, whilst the other major and minor nutrients (P, S, K, Ca, Mg, Na, Fe, Mn, Zn, Cu, B, Al) were also analysed for the 60 samples collected from the first three sampling campaigns by measuring their concentrations in a nitric acid digest by Inductively Coupled Plasma-Optical Emission Spectrometer (ICP-OES; Zarcinas et al., 1987).

Soil sampling and analysis

The EC_a map was used for targeted soil sampling (20-30 cm soil depth) at 10 locations in the mid-row on the 29th of September 2005. Total soil moisture was analysed gravimetrically. The soils were dried, sieved (< 2mm) and analysed for a range of soil properties, including electrical conductivity in a 1:5 soil:water extract ($EC_{1:5}$), pH in a 1:5 soil:water extract ($pH_{1:5}$) and in a 1:5 soil:0.01M calcium chloride extract (pH_{CaCl2}), soluble chloride (Cl^-) in a 1:5 soil:water extract with the automated colour method and total cation exchange capacity (CEC; Ca^{2+}, Mg^{2+}, Na^+, K^+) in a 1M ammonium chloride extract. The standard methodology of Rayment and Higginson (1992) was used for all analyses. Mid infrared (MIR) prediction of soil particle size composition and volumetric water release characteristics (Janik et al., 1998) was conducted on finely ground (< 0.2mm) soils.

iv. Statistical analysis and mapping

Descriptive statistical analysis, *k*-means clustering, analysis of variance (ANOVA) and Tukey-Kramer t-tests were performed using JMP (SAS, 2005); other statistical analysis was carried out as described below. Maps were produced in Arcview (ESRI, 2005) using the Spatial Analyst extension.

The yield and EM38 data were kriged onto a 2 m grid following the protocol of Bramley and Williams (2001) using the local block kriging function of VESPER (Minasny et al., 2005) and exponential variograms. A pre-experiment, and thus treatment independent yield map, together with an EM38 soil survey was used to delineate so-called 'potential performance classes' (PPCs)[A] using *k*-means clustering (Cupitt and Whelan, 2001). Two PPCs were identified (Figure 3), one representing lower yield (mean = 5.9 t/ha) and higher EC_a (mean = 0.99 dS/m), and the other, higher yield (mean = 10.4 t/ha) and lower EC_a (mean = 0.66 dS/m); henceforth, these are denoted as LY and HY. The apparent interaction between yield and salinity is consistent with the previous work of Bramley (2003) in an adjacent vineyard block.

Geostatistical analysis of treatment effects

With respect to the spatial analysis of treatment effects in whole of block experiments, the method used by Bramley et al. (2005a) and Lanyon and Bramley (2004, 2006) involved simple comparison of separate, treatment-specific maps, which were independently interpolated for each treatment using ordinary kriging (eg Webster and Oliver, 2001). In the case of treatment effects assessed through hand sampling of a limited number of target vines, this considerably reduced the spatial resolution of the maps, and thus the robustness of the assessment of comparative treatment effects. The reason for this was that, in addition to the need to interpolate the effects of one treatment over areas occupied by another, the much lower data density associated with hand sampling (eg Figure 3) compared to that provided by a yield monitor, meant that the *support* of each map was at the low end of what geostatisticians consider acceptable. Our initial intention in this project was to use modified experimental design as a way around this issue. Whilst the desk study conducted during the early CRCV phase of this project (Bramley and Lamb, 2006) suggested that there may be merit in this strategy, especially when coupled to sequential Gaussian simulation (Prof. Peter Dowd, Faculty of Engineering, Computer and Mathematical Sciences, University of Adelaide – pers. comm.), we were unable to implement this analytical methodology and in any case were concerned that it would be too complicated for all but the most geostatistically savvy, and would therefore not be readily adoptable by industry.

However, further to a collaborative relationship developed with Rothamsted Experiment Station, UK (Drs Murray Lark and Tom Bishop – note that Dr Bishop is now at the University of Sydney), we were able to access a new approach to the analysis of 'landscape scale' experiments (Bishop and Lark, 2006). This method is based on the assumption that the observed responses (eg yields) to a set of different treatments may be regarded as realizations of spatially auto-correlated and cross-correlated random variables. Thus, through the combined use of linear models of coregionalisation and co-kriging (Webster and Oliver, 2001), the treatment responses to different treatments can be estimated for any part of the experimental site using the data pertaining to all treatments. This allows the estimation of contrasts between different treatments measured at different locations over regions of different size and shape (Bishop and Lark, 2006). Computer code for the implementation of this analytical method were provided by Dr Lark.

[A]This procedure for the delineation of PPCs is the same as that used in Precision Agriculture for delineation of the more familiar 'management zones'. However, management zones are typically delineated using *k*-means clustering of several data layers, usually collected over a few seasons, and so within the limits imposed by the availability of data, are robust. Since we had limited pre-experiment data available in this project, we use the more cautious term *potential performance class*; ultimately, there may be little pragmatic difference between PPC and management zone, but we prefer PPC here to reflect the limited data used for their delineation.

All variables were tested for normal distribution using skewness and octile skew as a measure of asymmetry (Brys et al., 2003; 2004). If the calculated skewness for attributes was outside the range of -1 and 1 or for octile skew, outside a range of -0.2 and 0.2, the data were transformed to match the normality criteria (Lark et al., 2006). As indicated, the treatment response data were then analysed spatially using the method of Bishop and Lark (2006).

For mapping of treatment effects, Bishop and Lark (2006) recommend cokriging and found that standardized ordinary cokriging (SOCK) was the best predictor for treatment responses and contrasts. We therefore used SOCK to estimate these at the nodes of the same 2-m grid using for mapping over the vineyard. The statistical significance of treatment differences was tested for each grid cell using the kriging variance of the contrast and evaluating the standardized normal variable z (Bishop and Lark, 2006). If $|z| > 1.96$ treatment differences are regarded significant at the 5 % level and if $|z| > 1.654$ and < 1.96 the differences are regarded significant at the 10 % level. Of course, any other significance level can be chosen, such as 1 % or 0.1 %.

Coonawarra

i. Site description and experimental objectives

The Coonawarra site (Katnook Estate; Figure 4) is a 6 ha section within a larger block of Shiraz which was planted on its own roots in 1995 in 2.5 m rows with a 1.5 m vine spacing and a vertically shoot positioned (VSP) trellis. The dominant soil in the block is a black clay. No irrigation is used in this vineyard.

The vineyard manager and winemaker at this site were concerned about grape quality in this particular block and, suspecting that the problem related to excessive vine vigour, wanted to try to improve it through modification of canopy management. If successful, the intention was to use the grapes for a higher priced product stream than was the case prior to the experiment being implemented.

The prevailing canopy management strategy prior to the experiment was to use spur pruning to 45-50 buds and shoot trimming during the season as required. The target was to reduce vine vigour and berry size to change the grape juice and wine composition (Smart and Robinson 1991; Matthews and Anderson 1988; Johnstone et al. 1996) through a combination of spur pruning to 35 buds, shoot thinning during the season and shoot trimming. Because of the increase in number of manual canopy operations and therefore the higher labour costs involved, a key aspect of the experiment was to prove that the new management strategy would guarantee higher quality grapes and wines than the existing management. Even though no spatial data recording had been carried out before the trial was set up, it was generally known that the vigour of the canopy varied throughout the block and both vineyard manager and winemaker were keen to explore the whole of block experimental idea.

During October 2006, three severe frost events impacted so badly on this site that a decision was made almost immediately by the vineyard manager and winemaker that the block would not be harvested the following vintage. Given also their necessary focus on managing the block for production in 2008, the trial was reluctantly abandoned in its third year.

ii. Experimental design

The experiment was established during the winter of 2004. The experimental area comprised 55 vine rows with a mixture of ryegrass (*Lolium perenne*) and coxfoot (*Dactylis glomerata*) established in the mid-rows. Two different treatments were implemented: a control, which amounted to retention of the existing canopy management (spur pruning to 45-50 buds with trimming as required), and the more severe pruning plus shoot thinning and trimming treatment outlined above (SPST - spur pruning to 35

buds, shoot thinning twice during the season and shoot trimming as required). Both treatments were implemented by vineyard staff.

One variation to the control treatment took place before vintage 2005 when bunch thinning was conducted to reduce the crop load. The treatments were established in a 1 row (control) to 2 row (SPST) pattern with no buffer rows between treatments given the discrete nature of canopy management; note the contrast to the Clare experiment in which the treatments were applied to mid-rows, thus necessitating buffer rows. In addition, 156 target vines were located for each treatment and geo-referenced using dGPS. In contrast to the Clare experiment, and in view of the absence of on-the-go fruit quality sensing technology, the sampling of these target vines was critical to the measurement of treatment response and thus, to assessment of spatial variation in this response. Figure 4a illustrates the experimental layout. Note that, in the first instance, the experiment was implemented over a larger portion of the block than the 6 ha shown in Figure 4a, but when it became apparent that a previous experiment conducted by the vineyard manager was exerting a marked residual effect on vigour, as indicated by remotely sensed imagery, this section (the central area in Figure 4a) was omitted from our trial.

iii. Data collection

As at Clare, all sample vines were geo-referenced using dGPS.

Yield monitoring and remote sensing

High resolution yield data were recorded with a Farmscan yield monitor in both 2005 and 2006. The data were separated by treatment and harvest date and processed according to the yield mapping protocol of Bramley and Williams (2001). Because of the time span between the first and last harvest event (2005: 20 days; 2006: 6 days) the yield data were normalized (mean of zero, standard deviation of 1) to remove any effects of these harvest intervals on the yield data; subsequent data analysis used these normalized yield data.

Aerial images were obtained at veraison in 2005 and 2006 and were processed in the same way as for Clare.

The above notwithstanding, it should be noted that since the experimental objectives at this site were to explore options for improving fruit quality, the collection of yield monitor data and remotely sensed imagery was much more targeted at the identification of inherent vineyard variability which might impact on the expression of treatment effects, rather than the measurement of the treatment effects themselves.

Plant sampling and analysis

All 312 target vines were manually harvested immediately prior to vintage in both 2005 and 2006. Twelve randomly selected bunches per vine, 6 from each side, were sampled and weighed and the average bunch weight determined. Berry samples were then taken from these bunches using the procedure described for Clare for determination of berry weight and the average number of berries per bunch, and following a period of storage (-30 ºC), these samples were used for analysis of colour and phenolics (Iland et al., 2000). As at Clare, juice pH, TA and Baumé was determined for fresh samples. An exception to this was in 2005 when only 40 of the 312 samples were analysed for pH and TA due to the lack of access to an autotitrator; spatial analysis and mapping of these parameters was therefore not possible in 2005.

Table 1. Cluster means for two potential performance classes derived from *k*-means clustering of PCD data (2005 and 2006) and normalized yield (2005).

Cluster	PCD 2005	PCD 2006	Normalized yield 2005
1	6.72	3.42	0.23
2	5.90	2.96	-0.28

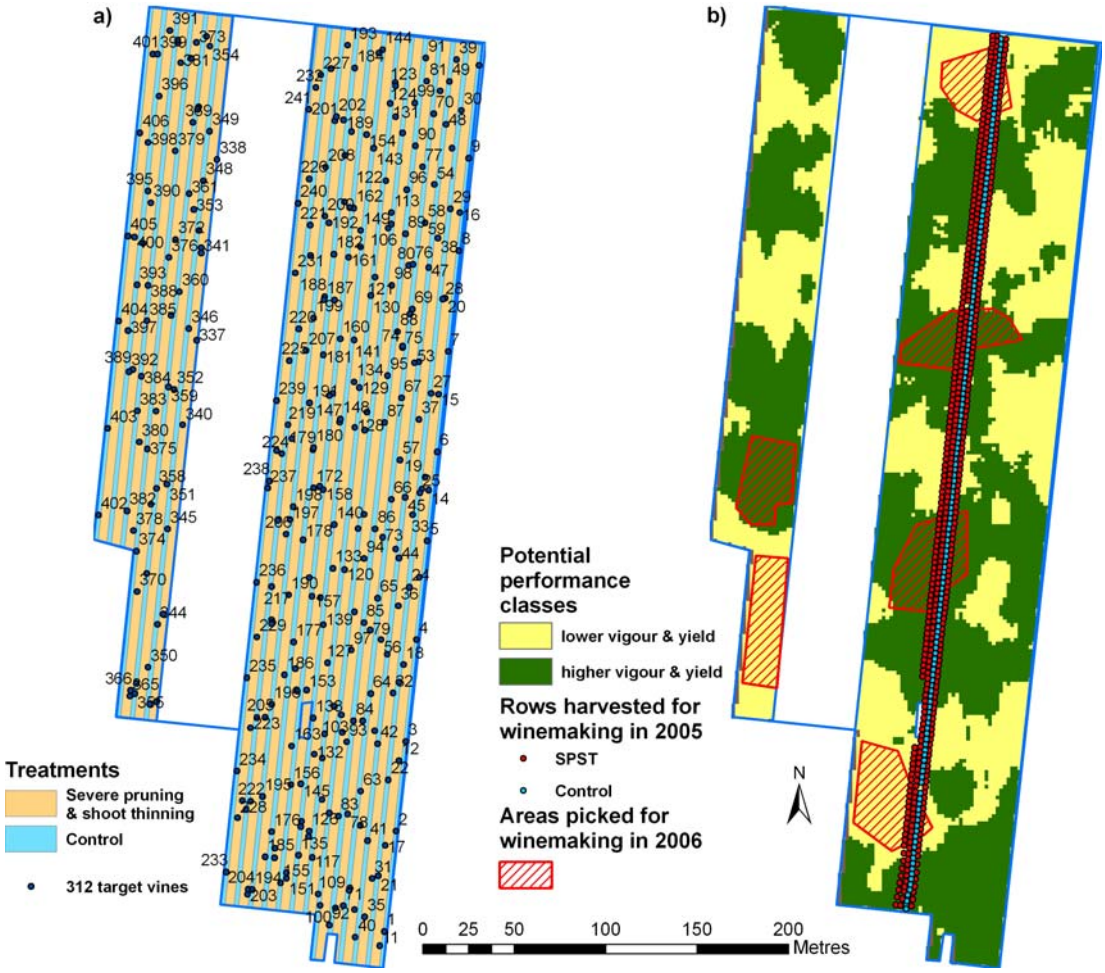


Figure 4. Experimental layout of the Coonawarra trial and (a) location of target vines. Also shown in (b) are the areas sampled for wine making in 2005 and 2006, together with vigour classes delineated using *k*-means clustering of PCD imagery obtained in 2005 and 2006 and the 2005 yield map.

Rainfall

Rainfall data were recorded locally at the vineyard over the last 32 years and these were used to estimate seasonal variation (Figure 5).

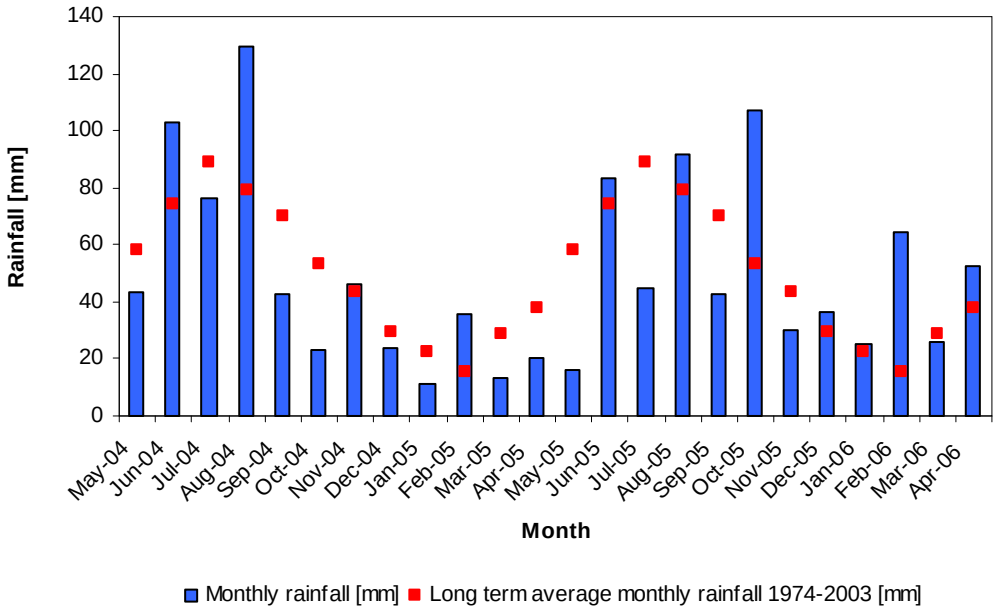


Figure 5. Monthly rainfall between May 2004 and April 2006 in comparison to the long term average (1974-2003) for Coonawarra. Marked differences between the pre-vintage periods in 2005 and 2006 are highlighted by the yellow boxes.

iv. Statistical analysis and mapping

The methods used for both descriptive statistics and spatial analysis were broadly the same as for the Clare site. In addition, and similar to what was done in Clare, 2 potential performance classes were delineated by *k*-means clustering of the PCD data from 2005 and 2006 as well as the normalized yield map from 2005 (Figure 4b). Cluster means are listed in Table 1.

v. Winemaking and sensory analysis

Since the objective of this trial was to explore options for improving fruit and wine quality, winemaking and sensory analysis formed an important element of this experiment. In 2005 one wine for each treatment was produced by the collaborating winery at their smallest commercial scale (1 t ferments) to evaluate treatment response differences. The fruit used for this was harvested from the rows indicated in Figure 4b. The wines were subsequently tasted and scored informally by the winemaker. In 2006, and in view of the results obtained the previous year (see below), small-scale wine making was conducted to establish wine quality differences between the treatments and, in addition, the potential performance classes (PPC, see statistical analysis - above). Five wines were made by Provisor with three fermentation replicates (50 kg each ferment) at the Hickinbotham-Roseworthy wine science laboratory. The fruit used for these was harvested from the areas indicated in Figure 4b and were as follows:

1. Control treatment - high PPC
2. Control treatment - low PPC
3. SPST treatment - high PPC
4. SPST treatment - low PPC
5. Control treatment - mixed PPC

The last of these was designed to simulate the control wine which would have been made had the block been harvested as a single management unit, as opposed to selectively harvested on a PPC basis. All wines were made according to the same standard protocol; there was no malolactic fermentation.

After an informal assessment, quantitative descriptive sensory analysis of the wines (Lawless and Heymann, 1998) was conducted by Provisor Pty Ltd.

In addition to assessment of wines, an assessment of fruit quality was also conducted by the local wine maker at the same time as the grapes were picked for small-scale wine making in 2006. He also scored the wines using the company's internal ranking from 1 to 5. A rating of 1 is considered as 'Ultra premium' (> $50/bottle), 2 as 'Super premium' (> $40/bottle), 3 as 'Premium' (> $20/bottle), 4 as 'Premium commercial' ($10-15/bottle) and 5 as "non usable" for their production; such fruit is usually sold to other entities.

Modified wine colour density, modified wine hue, modified SO_2 resistant pigments, total red pigments, total phenolics and total anthocyanins were measured on the small-scale wines using the standard methods of Iland et al. (2004).

Auburn

The Auburn experiment (Taylors Wines) was brought into this project in view of our inability to continue the Coonawarra trial in season 2007, and took advantage of the fact that Taylors had independently established their own whole of block experiment during the pruning season following vintage 2006. Its inclusion in this project was therefore opportunistic; our role was mainly focussed on the analysis of results. The fact that the experimental objectives were very similar to those at Coonawarra was highly serendipitous as far as the present project was concerned. Here, the objective was, once again, to explore canopy management in response to perceptions of excessive vigour, as a means of improving fruit and wine quality; comparison between the canopy management strategies as a function of the cost of implementing them was a secondary objective.

i. Site description and experimental design

The experiment was set up in an 8 ha Shiraz vineyard near Auburn in the Clare Valley during the winter of 2006. The experimental area comprised 50 drip irrigated vine rows with 3 m row spacing and a 1.5 m vine spacing. Three different canopy management strategies were applied in winter 2006. The control treatment was a VSP trellising system, spur pruned to 2 buds per spur resulting in approximately 30 buds per metre (VSP). A single wire lift was done during late flowering. The first treatment was similar to the control except that the canopy was allowed to sprawl (Sprawl); as such, it was a cheaper variant of the control since no foliage wires were used. Finally, a sacrificial cane, or kicker cane treatment (KC) was implemented in which 4 canes per vine with approximately 10 buds were retained at pruning and later cut just before veraison. Bramley et al. (2005a) describe a previous experiment in Padthaway involving kicker canes and provide details of the physiological objectives of this strategy. The three different treatments were applied in a regular, highly replicated pattern comprising strips one row wide (Figure 6); as at the other sites, the treatments were implemented by vineyard staff. All treatments were irrigated equally with approximately 0.65 ML ha^{-1} being applied.

ii. Data collection

As at Clare, unless otherwise indicated, all data were geo-referenced using dGPS.

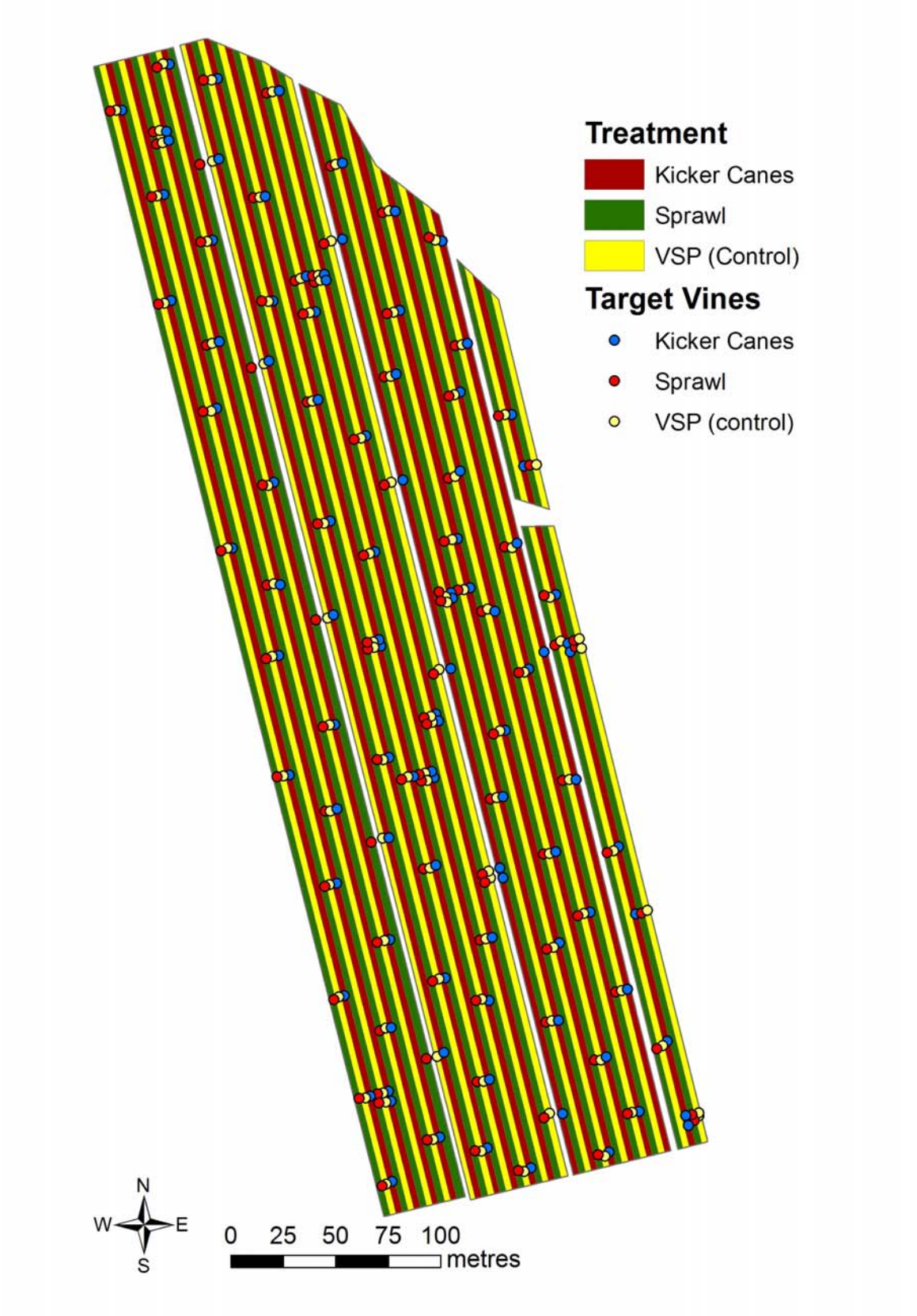


Figure 6. Experimental design and sampling strategy for the Auburn experiment. Note the close proximity of target vines for each treatment. This sampling strategy was a key outcome from early use of the Bishop and Lark (2006) method of experimental analysis.

Plant sampling and analysis

One hundred target vines were located for each treatment for the purpose of recording treatment response in terms of fruit quality and to permit spatial analysis of results. Given that by the time we became involved in this trial, we had become attuned to the methods of experimental analysis of Bishop and Lark (2006), the target vines for the different treatments were located in close proximity to each other. At vintage 2007, all 300 target vines were manually harvested; 12 bunches per vine, 6 from each side, were randomly sampled and weighed. These samples were then processed following the method described for Coonawarra for assessment of the same fruit and vine attributes.

Yield monitoring, RTK-GPS, EM38 and remote sensing

High resolution yield data was recorded with 2 'Advanced Technology Viticulture' Grape Weighers (ie 2 harvesters in operation) at vintage 2007 and processed according to the yield mapping protocol of Bramley and Williams (2001). Aerial images were available for veraison 2006 (prior to establishment of the experiment) and also for both flowering and veraison 2007 in season 2006-07. This imagery, which as at the other sites was of 50 cm resolution, was processed as described for the other sites. Note however that, as with the Coonawarra experiment, since the experimental objectives at this site were to explore options for improving fruit quality, the collection of yield monitor data and remotely sensed imagery was much more targeted at the identification of inherent vineyard variability which might impact on the expression of treatment effects, rather than the measurement of the treatment effects themselves.

An RTK-GPS and apparent electrical conductivity (EC_a) soil survey (horizontal dipole) was conducted in late November 2006 to generate a digital elevation model (DEM). These data were also collected primarily as a means of acquiring background information about vineyard variability and its possible drivers within the block.

iii. Statistical analysis and mapping

The methods used for both descriptive statistics and spatial analysis were broadly the same as for the Clare site. In addition, and similar to what was done in Clare, potential performance classes (PPCs) were delineated using *k*-means clustering of the DEM and PCD data from veraison 2006 and 2007 (Cupitt and Whelan, 2001). In this instance, consultation with the viticulturist informed the clustering process; EM38 data were not used for this analysis and classification of the data into three clusters was preferred as best representing the local knowledge of vineyard variability (Figure 7).

iv. Winemaking and sensory analysis

Small-scale winemaking and sensory analysis was conducted to investigate wine quality differences between the treatments and PPCs. Due to the high costs of this part of the work, wines were not made for all possible combinations of treatment and PPC. This was also a reflection of a concern that yields in the lower potential performance class might not be sufficient for the small scale winemaking, and the view of the vineyard manager that, due to their low yield, vines from the low PPC amounted to small proportion of the total vineyard production and so played a less important role in the winemaking from the block as a commercial entity than vines in the medium and higher PPCs. Thus, Provisor were engaged to make four wines with three fermentation replicates corresponding to the following combinations of treatment and PPC:

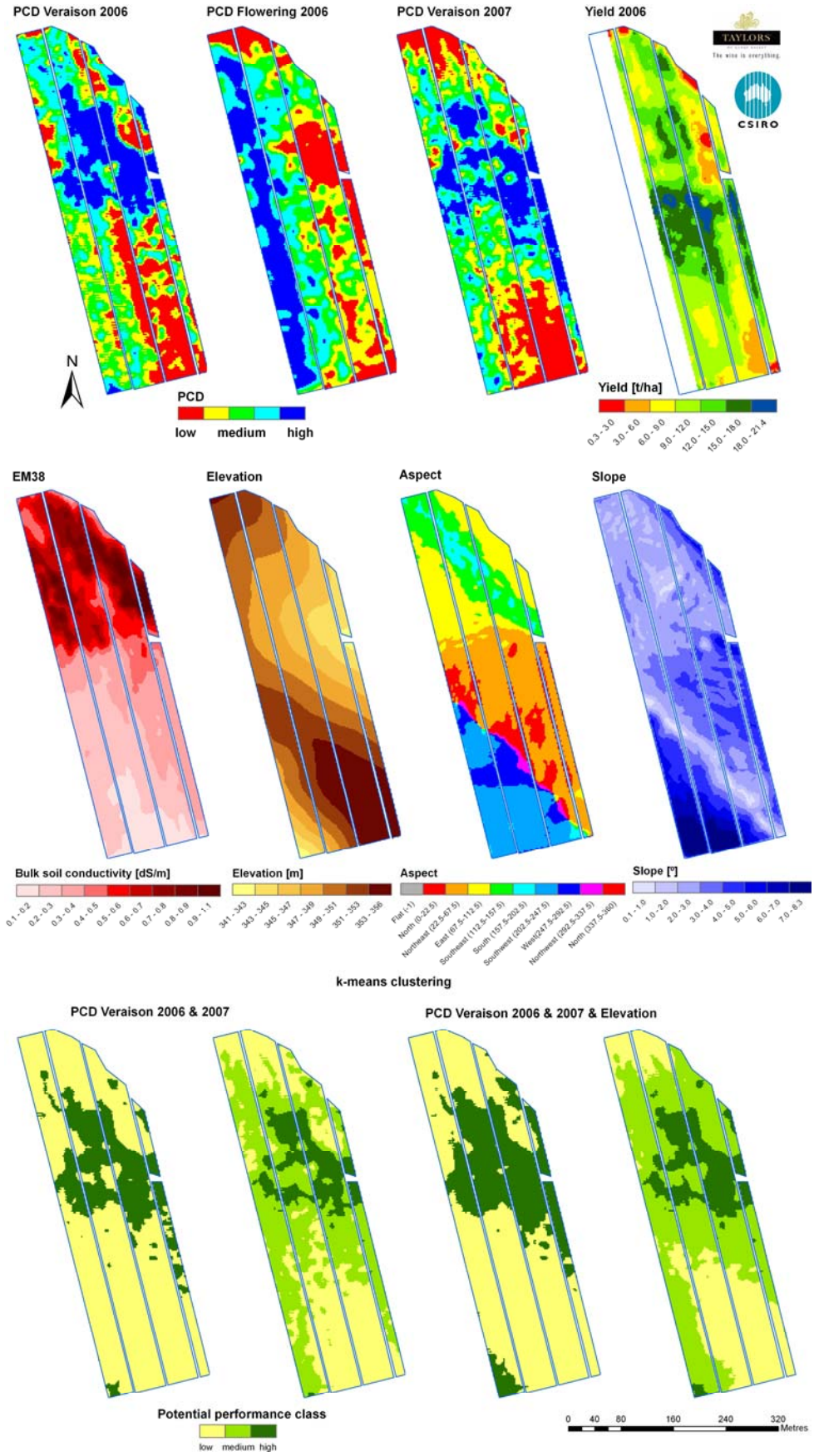


Figure 7. Possible data layers for *k*-means clustering to define potential performance classes at Auburn.

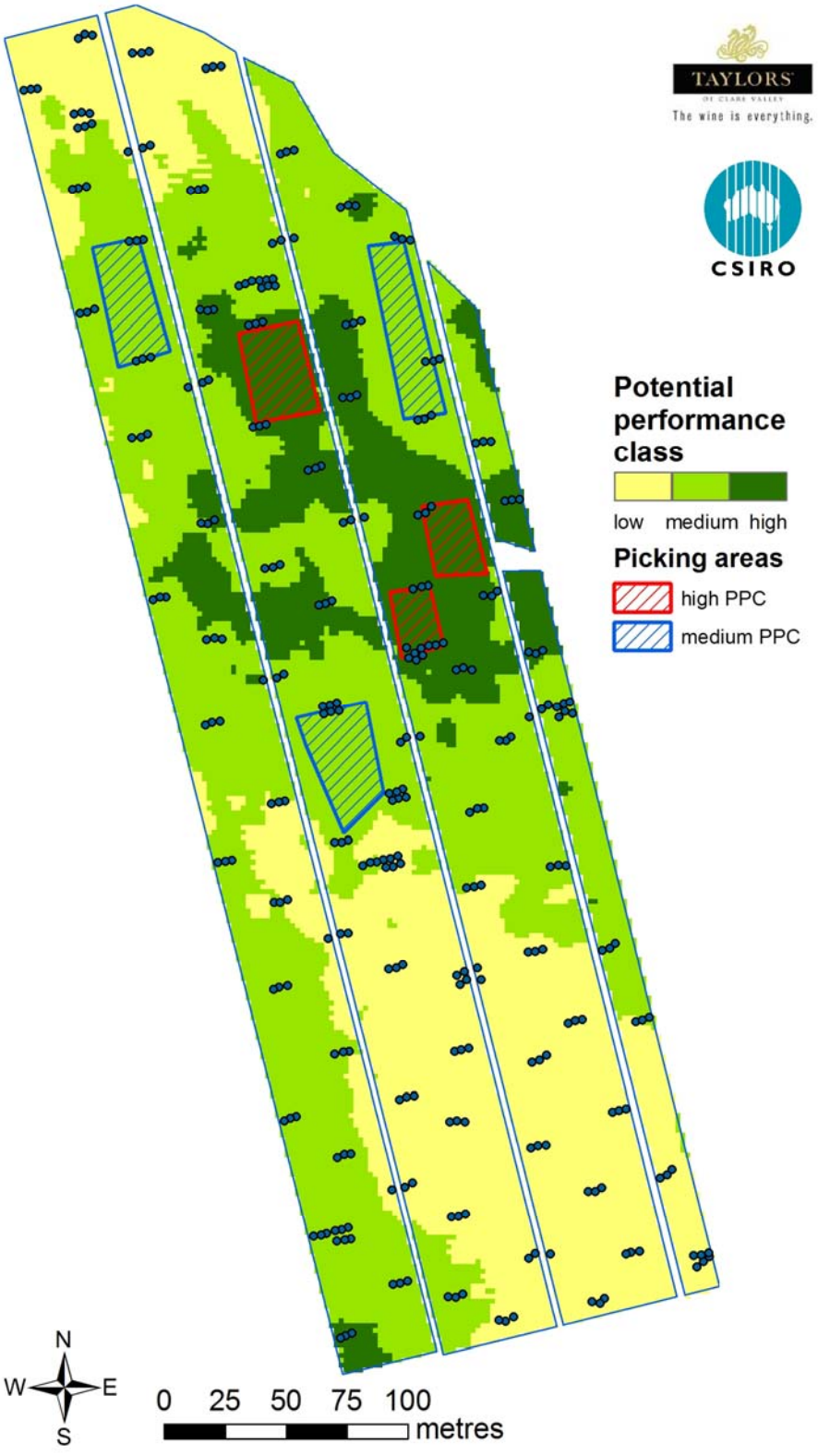


Figure 8. Areas of medium and high PPC picked for small-lot winemaking at the Auburn site – Vintage 2007.

1. Control treatment and medium PPC
2. Control treatment and higher PPC
3. KC treatment and medium PPC
4. KC treatment and higher PPC

Figure 8 shows the vineyard areas that were sampled for winemaking.

The same standard winemaking protocol was used for these wines as was used in the Coonawarra small-scale winemaking; there was no malolactic fermentation. Following bottling, quantitative descriptive sensory analysis of the resulting wines was conducted.

Results and Discussion

Clare

Simple inspection and manipulation of remotely sensed imagery collected at veraison showed that the cereal/legume treatment had a positive, albeit spatially variable, impact on vine vigour (Figures 9 and 10). In the second season after imposition of the treatments, this effect was only discernible by comparison of the 2006 image with a pre-experiment (2004) image after the respective images had been normalised to remove any effects of differing seasonal conditions and of differences in the prevalent atmospheric conditions during image acquisition. However, by veraison in the third year after treatment imposition, the beneficial effects of the cereal/legume treatment on vine vigour was clear without any manipulation of the imagery (Figure 10). On the other hand, there was no obvious difference between the RGC and RGM treatments. These observations are important in that they highlight the value of remotely sensed imagery for the assessment of treatment effects on vine vigour, in addition to being a useful tool for delineation of PPCs or indication of inherent vineyard variability (eg Figures 3, 4 and 7).

Table 2 shows the results of an analysis of treatment effects over the 3 years of data collection, ignoring any consideration of spatial variation. Few differences between treatments were observed in 2005, presumably due to the limited time since imposition of treatments and/or the effects of frost. However, over time, the Cereal/Legume treatment began to deliver significant benefits in terms of increasing all yield components except for berry weight. These were generally matched by a reduction in the concentrations of colour (anthocyanins) and phenolics; whether the magnitude of these was sufficient to affect the product stream that the fruit was deemed suitable for was not investigated. Also evident from Table 2 is that the use of mulch as opposed to compost delivered no benefit.

Notwithstanding the results presented in Table 2, Figures 9 and 10 clearly indicate that treatment response was spatially variable. It was therefore of interest to assess the treatment effects on a per PPC basis. When this is done (Table 3), the significance of the difference between treatment effects is markedly increased whilst the differences between the PPCs is also strongly evident. Thus for example, whereas Table 2 suggests that in 2006, there was no significant treatment effect on berry weight across the block as a whole, Table 3 demonstrates that in fact, there were significant berry weight differences between the PPCs and that, whilst there was no significant treatment effect in the high PPC, there was a significant difference between the CL and RGC treatments in the low PPC. Indeed, Table 3 indicates that in general, treatment effects were greater in the inherently lower vigour areas of the vineyard than the relatively higher vigour areas. These results provide compelling evidence of the value of considering vineyard variability prior to the establishment of viticultural experiments and of the possible shortcomings of the traditional plot-based approach (Figure 1) in which homogeneity is either assumed, or its effects are assumed to be accommodated by randomisation and blocking.

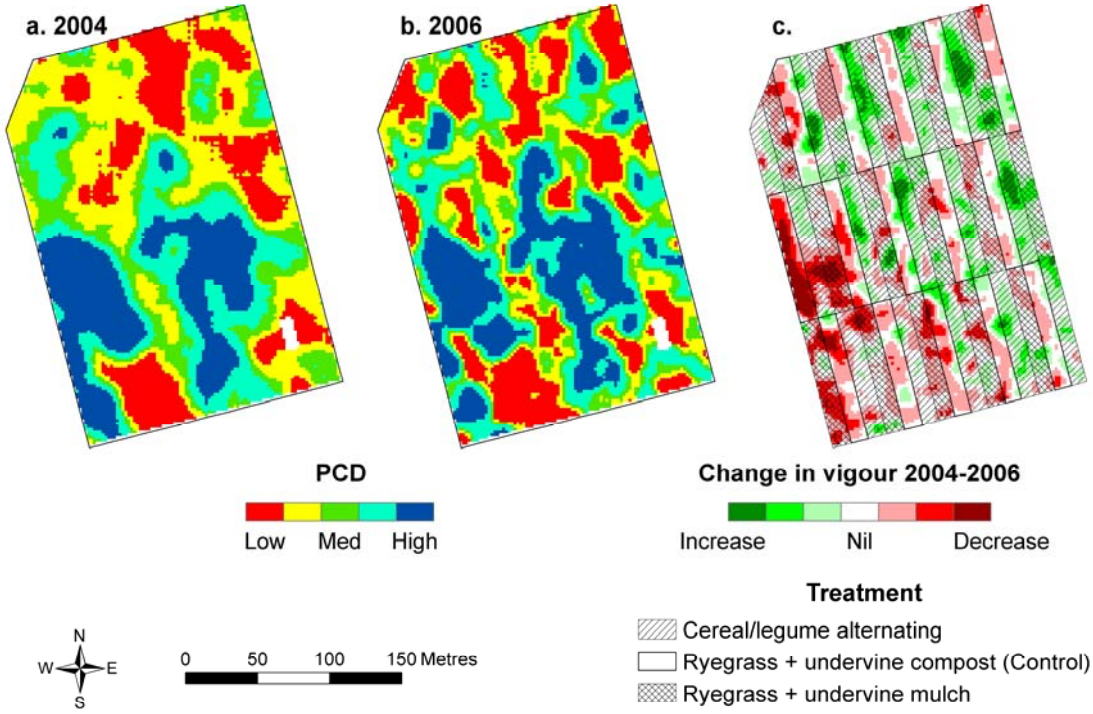


Figure 9. The effect of mid-row treatment on vine vigour as measured using remote sensing. Here, both the 2004 (pre-experiment image) and 2006 images have been normalised to a common basis. The difference between these is shown in (c) which clearly indicates that higher vigour tends to be associated with the cereal/legume treatment.

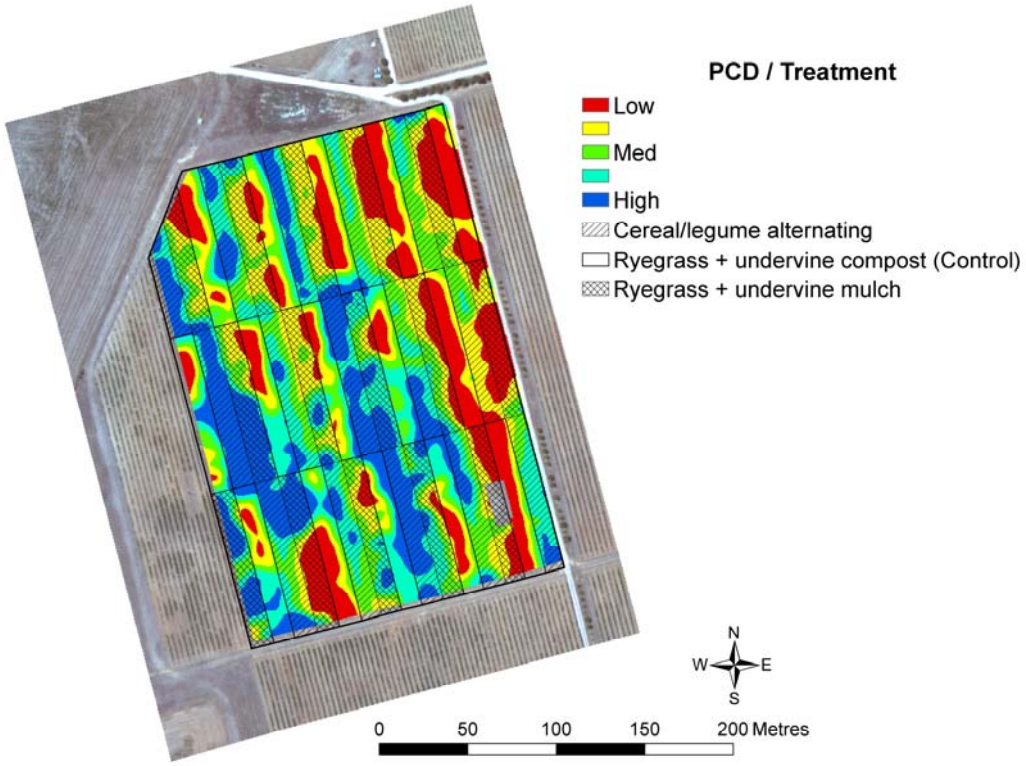


Figure 10. PCD image of the Clare experiment (veraison 2007) showing the beneficial effect of a cereal/legume mid-row in enhancing vine vigour.

Table 2. Analysis of treatment effects[A] on vine performance parameters in 2005[C], 2006 and 2007.

	Attribute	Treatment RGC	RGM	CL	ANOVA[B] *p*
2005	Yield (kg/m)	1.61[a]	1.18[a]	1.69[a]	ns 0.0665
	Bunch no.	35[a]	31[a]	37[a]	ns 0.2078
	Bunch weight (g)	43[a]	37[a]	43[a]	ns 0.1383
	Berry weight (g)	0.95[a]	0.88[b]	0.91[a,b]	* 0.0285
	Berries / bunch	45[a]	41[a]	47[a]	ns 0.2612
	pH	3.56[a]	3.62[a]	3.56[a]	ns 0.2103
	TA (g/L)	7.05[a]	6.87[a]	7.22[a]	ns 0.4274
	Baumé (º)	13.2[a]	13.3[a]	13.3[a]	ns 0.8832
	Anthocyanins (mg/g)	1.35[a,b]	1.39[a]	1.31[b]	* 0.0242
	Phenolics (a.u./g)	1.55[a,b]	1.57[a]	1.49[b]	* 0.0425
	n[A]	*39*	*35*	*47*	
2006	Yield (kg/m)	2.82[b]	2.95[b]	3.81[a]	*** 0.0003
	Bunch no.	45[b]	43[b]	56[a]	*** <0.0001
	Bunch weight (g)	57[b]	63[a,b]	68[a]	** 0.0024
	Berry weight (g)	0.77[a]	0.82[a]	0.81[a]	ns 0.0819
	Berries / bunch	71[b]	76[b]	84[a]	*** <0.0001
	pH	3.57[a]	3.59[a]	3.47[a]	ns 0.3987
	TA (g/L)	5.98[a]	5.57[a]	6.21[a]	ns 0.1231
	Baumé (º)	13.9[a]	13.6[b]	13.3[c]	*** <0.0001
	Anthocyanins (mg/g)	1.49[b]	1.50[b]	1.39[a]	*** 0.0009
	Phenolics (a.u./g)	1.77[b]	1.76[b]	1.67[a]	*** 0.0002
	n	*126*	*126*	*126*	
2007	Yield (kg/m)	0.73[b]	0.93[b]	1.73[a]	*** <0.0001
	Bunch no.	28[c]	36[b]	48[a]	*** <0.0001
	Bunch weight (g)	17[b]	20[b]	33[a]	*** <0.0001
	Berry weight (g)[D]	0.51[a]	0.41[a]	0.59[a]	ns 0.0947
	Berries / bunch[D]	44[a,b]	41[b]	57[a]	* 0.0129
	Baumé (º)[D]	13.2[a]	13.3[a]	13.4[a]	ns 0.6972
	n[D]	*126/19*[D]	*125/20*[D]	*126/20*[D]	

[A]Values not connected by the same letter are significantly different ($p<0.05$; Tukey-Kramer *t*-test).
[B]Levels of significance indicated by: ns = not significant ($p>0.05$), * = $p<0.05$, ** = $p<0.01$, *** = $p<0.001$).
[C]Due to the frost in late 2004, only a limited sample set from the least frost affected vines was collected at vintage 2005.
[D]Because of the low yield in 2007, insufficient fruit were available for some analyses. Accordingly, berry samples were only collected from a limited subset of vines; other measures were made on all vines.

Table 3. Analysis of treatment effects[A] on vine performance parameters in 2005[C], 2006 and 2007 as a function of potential performance class (PPC; Figure 3). See Table 2 for an explanation of footnotes.

		RGC		RGM		CL		
	Attribute	Low PPC	High PPC	Low PPC	High PPC	Low PPC	High PPC	ANOVA[B] *p*
2005	Yield (kg/m)	2.07^{a,b}	1.49^{a,b}	0.98^{a,b}	1.26^{b}	1.36^{a,b}	2.11^{a}	* 0.0118
	Bunch no.	41^{a}	33^{a}	29^{a}	32^{a}	32^{a}	42^{a}	* 0.0363
	Bunch weight (g)	50^{a}	41^{a}	33^{a}	38^{a}	40^{a}	46^{a}	ns 0.1036
	Berry weight (g)	0.87^{a,b}	0.97^{a}	0.83^{b}	0.90^{a,b}	0.86^{b}	0.96^{a}	*** <0.0001
	Berries / bunch	58^{a}	42^{a}	40^{a}	42^{a}	46^{a}	48^{a}	ns 0.0529
	pH	3.73^{a}	3.51^{b,c}	3.69^{a}	3.59^{a,b,c}	3.62^{a,b}	3.48^{c}	*** <0.0001
	TA (g/L)	5.56^{c}	7.47^{a}	6.30^{b,c}	7.07^{a,b}	6.61^{b,c}	7.92^{a}	*** <0.0001
	Baumé (º)	13.4^{a}	13.2^{a}	13.4^{a}	13.3^{a}	13.3^{a}	13.2^{a}	ns 0.8371
	Anthocyanins (mg/g)	1.38^{a}	1.34^{a}	1.37^{a}	1.40^{a}	1.32^{a}	1.29^{a}	ns 0.1047
	Phenolics (a.u./g)	1.63^{a}	1.52^{a,b}	1.59^{a}	1.57^{a}	1.55^{a}	1.43^{b}	** 0.0012
	n	*8*	*31*	*9*	*26*	*26*	*21*	
2006	Yield (kg/m)	1.26^{d}	4.21^{b}	1.91^{d}	3.93^{b,c}	3.20^{c}	5.21^{a}	*** <0.0001
	Bunch no.	35^{b}	53^{a}	37^{b}	49^{a}	54^{a}	59^{a}	*** <0.0001
	Bunch weight (g)	35^{d}	76^{a}	48^{c}	77^{a}	60^{b}	87^{a}	*** <0.0001
	Berry weight (g)	0.66^{c}	0.87^{a}	0.71^{b,c}	0.92^{a}	0.77^{b}	0.92^{a}	*** <0.0001
	Berries / bunch	53^{d}	86^{a,b}	68^{c}	84^{b}	79^{b}	96^{a}	*** <0.0001
	pH	3.89^{a}	3.25^{b}	3.76^{a}	3.42^{b}	3.66^{a}	3.28^{b}	*** <0.0001
	TA (g/L)	5.15^{c}	6.81^{a}	4.97^{c}	6.17^{a,b}	5.45^{b,c}	6.98^{a}	*** <0.0001
	Baumé (º)	14.3^{a}	13.6^{b,c}	13.8^{b}	13.5^{b,c,d}	13.3^{c,d}	13.1^{d}	*** <0.0001
	Anthocyanins (mg/g)	1.64^{a}	1.36^{b,c}	1.63^{a}	1.38^{b}	1.45^{b}	1.24^{c}	*** <0.0001
	Phenolics (a.u./g)	1.89^{a}	1.67^{b}	1.86^{a}	1.66^{b}	1.73^{b}	1.53^{c}	*** <0.0001
	n	*59*	*67*	*61*	*65*	*88*	*38*	
2007	Yield (kg/m)	0.20^{c}	1.20^{b}	0.38^{c}	1.46^{b}	1.47^{b}	2.34^{a}	*** <0.0001
	Bunch no.	18^{e}	37^{c}	29^{d}	43^{b,c}	46^{a,b}	54^{a}	*** <0.0001
	Bunch weight (g)	8^{c}	25^{b}	11^{c}	28^{b}	30^{b}	42^{a}	*** <0.0001
	Berry weight (g)[D]	0.21^{c}	0.79^{a}	0.24^{c}	0.58^{a,b}	0.46^{b}	0.73a	*** <0.0001
	Berries / bunch[D]	29^{d}	58^{a,b}	33^{c,d}	48^{b,c}	42^{b,c,d}	72^{a}	*** <0.0001
	Baumé (º)[D]	13.8^{a}	12.6^{c}	13.9^{a}	12.9^{b,c}	13.6^{a,b}	13.1^{a,b,c}	*** <0.0001
	n^{D}	*59/9*	*67/10*	*61/10*	*64/10*	*88/10*	*38/10*	

The previous discussion notwithstanding, comparison of Figures 9 and 10 with the PPCs identified in Figure 3 does not suggest as strong a relationship between vine vigour and PPC as might have been expected. One reason for this might be the effects of the imposed treatments. Spatial analysis of the results of the experiment using the Bishop and Lark (2006) method is therefore most illuminating (Table 4; Figures 11-14).

In Figures 11-14, the treatment effects and comparisons between them have been mapped in a triangular arrangement. At the corners of each triangle are maps of the attributes of interest shown for each individual treatment. The maps in between these show the significance of the difference of per pixel comparisons between the maps either side of them (ie in the corners); in this way, areas where one treatment delivers a statistically significantly different response to another can be seen. It should be noted however, that as discussed in the Materials and Methods section, the method of Bishop and Lark (2006) requires that the data be normally distributed, and so where this is not the case, transformation of the data has been used. Back transformation of kriged data is problematic (eg Webster and Oliver, 2001), and as a consequence, we have presented many of the maps in their transformed form; in Figure 11 for example, a log transformation was required for normalisation of yield in 2006 whilst a square root transformation was used for 2007. For this reason, many of the map legends use a low-medium-high scale.

Table 4 summarises the results in terms of the proportion of pixels (ie proportion of total vineyard area) for which the treatments are significantly different. Note however, that neither Table 4 nor the difference maps shown in Figures 11-14 make any inference as to the size of the difference between the response to two treatments. Maps of the magnitude of this difference could be readily produced in the case of untransformed attributes, but partly due to the problems of back-transformation, and for the purposes of this report, we have chosen the presentation used in Figures 11-14.

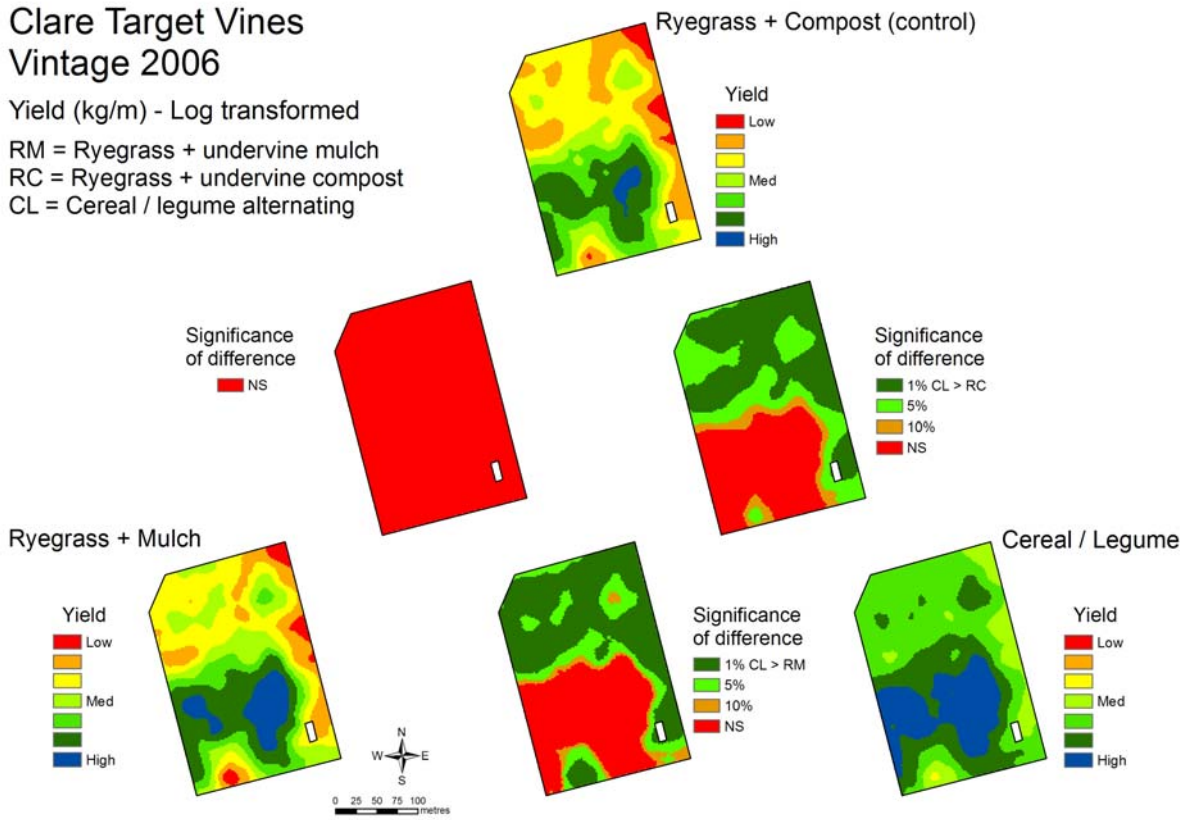
As can be seen from Table 4 and Figures 11-14, the CL treatment generally results in an improvement in the components of yield by comparison with the RGM and RGC treatments, and possibly as a consequence of this, a reduction in berry chemistry values. However, the significance of these treatment differences is highly spatially variable. Furthermore, whilst the *patterns* of spatial variation in the individual treatment maps are broadly stable over the two years for which map data are available, patterns of the significance of the difference between treatments are apparently much less temporally stable (Figures 11-13). This may be due to seasonal effects and/or to the fact that being perennials with significant storage organs, grapevines may take some time to exhibit the effects of changes in mid-row management strategy. On the other hand, there is good agreement between the patterns seen in all the maps in Figure 11 (yield) and in Figure 12 (bunch number) – as might be expected (Dunn et al., 2005). Similarly, areas producing fruit of low colour concentration correspond to areas of higher yield – again, the expected result (eg Bramley, 2005a). Thus, the observation of apparent instability in the significance of treatment effects suggests that the prevalent practice of conducting viticultural research in projects of 3 years duration probably serves the industry much less well than it ought. Indeed, it is a matter of some regret that the present experiments cannot be continued further. Whatever, the observed marked spatial variability in treatment response and in the significance of differences between treatment effects is strongly supportive of the notion that the whole of block approach offers considerable advantage over the traditional plot based approach to viticultural experimentation.

So much for spatial variation in treatment effects. Of interest to the vineyard manager is what might be driving this variation – key information to assist with the extrapolation of experimental results to other blocks or properties. Table 5 summarises the results of soil analysis carried out on a limited number of samples from within the experimental area; these were located in such a way that the full range of variation in EM38 values (Figure 15) was sampled. Regression analysis indicated strong and expected correlations between the EM38 signal and total soil moisture ($r = 0.780$, $p<0.05$), $EC_{1:5}$ ($r = 0.782$, $p<0.05$) and clay content ($r = 0.615$, $p>0.05$), and thus were in agreement with the observations of Bramley (2003) made in a neighbouring vineyard that EM38 at this site is predominantly reflecting soil salinity. The preponderance of EC_a values greater than about 0.6 dS/m (Figure 15) is indicative

Table 4. Summary of treatment effects at Clare in 2006 and 2007 when analysed using the method of Bishop and Lark (2006)[A].

Comparison	CL vs RGC (Control)		RGM vs RGC (Control)		CL vs RGM	
	2006	2007	2006	2007	2006	2007
Yield per m	CL > RGC 34 ns 66 ^ 60 * 36 **	CL > RGC 31 ns 69 ^ 49 * 18 **	100 ns	RGM > RGC 92 ns 7 ^ 4 * <1 ** RGC > RGM < 1 *	CL > RGM 36 ns 64 ^ 58 * 43 **	CL > RGM 100 **
Bunch No.	CL > RGC 42 ns 58 ^ 23 *	CL > RGC 20 ns 80 ^ 61 * 19 **	100 ns	RGM > RGC 91 ns 9 ^ 2 *	CL > RGM 40 ns 60 ^ 46 * <1 **	CL > RGM 34 ns 66 ^ 42 * 6 **
Bunch weight	CL > RGC 84 ns 16 ^ 3 *	CL > RGC 38 ns 62 ^ 38 * 9 **	100 ns	RGM > RGC 99 ns <1 *	CL > RGM 98 ns 2 ^	CL > RGM 12 ns 88 ^ 77 * 36 **
Berry weight	99 ns 1 ^		RGM > RGC 93 ns 6 ^ 3 * RGC > RGM <1 **			
Berries/bunch	CL > RGC 100 *		100 ns		CL > RGM 39 ns 61 ^ <1 *	
Baumé	RGC > CL 11 ns 89 ^ 73 * 34 **		RGC > RGM 84 ns 16 ^		RGM > CL 68 ns 32 ^ 10 *	
Colour concentration	RGC > CL 87 ns 13 ^ 8 *		RGM > RGC 95 ns 3 ^ 2 * RGC > RGM 2 ^ <1 *		RGM > CL 54 ns 46 ^ 24 * 2 **	
Phenolics concentration	RGC > CL 81 ns 19 ^ 11 * <1 **		RGC > RGM 94 ns 4 ^ 2 * RGM > RGC 2 ^ <1 *		RGM > CL 59 ns 41 ^ 18 * <1 **	

[A]The numbers reported are the % of pixels within the mapped vineyard area for which the treatment differences are significant at p<0.1 (^), p<0.05 (*) or p<0.01 (**).



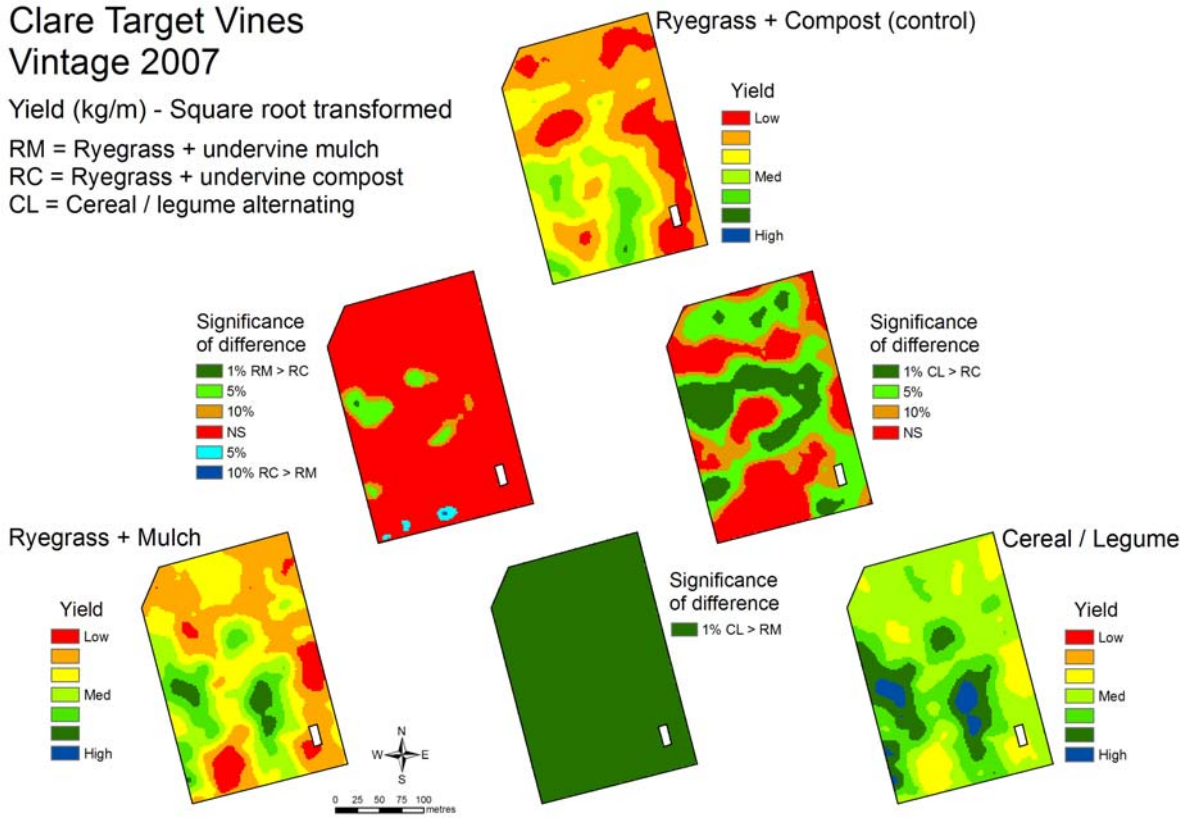
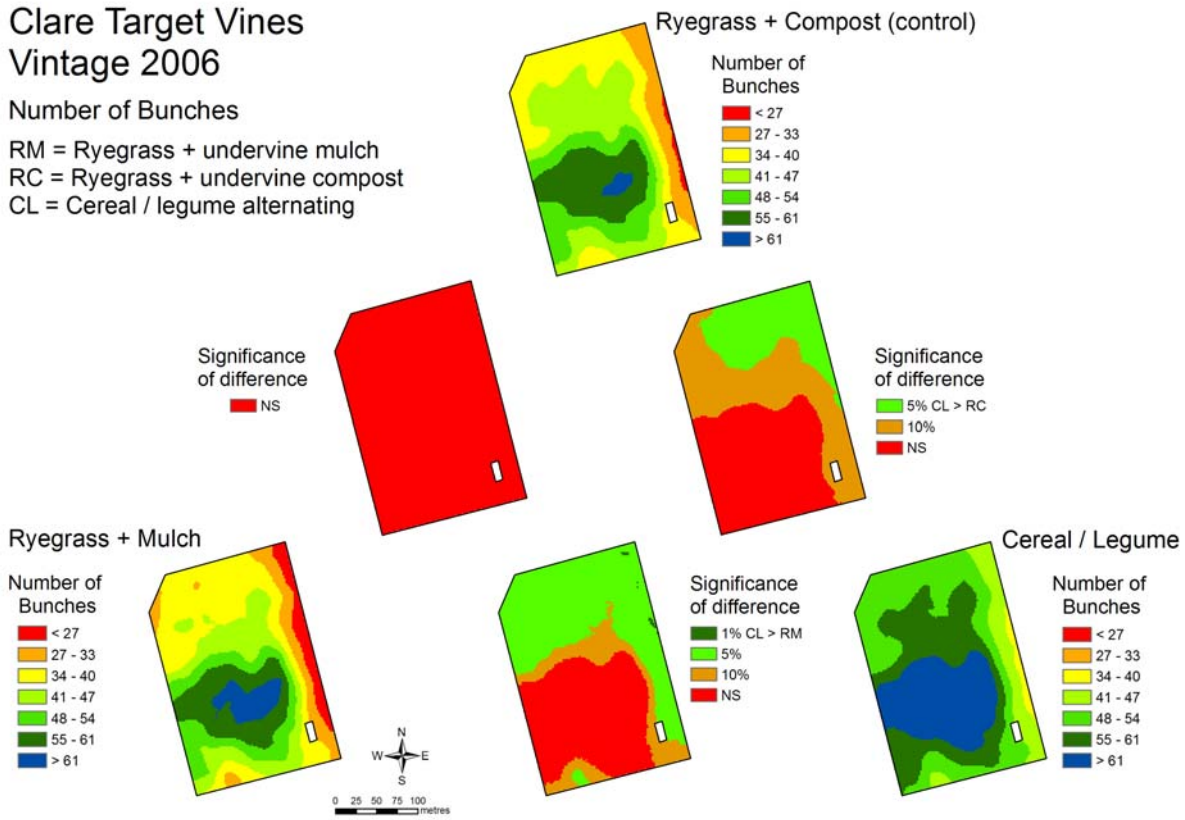


Figure 11. Variation in the yield response in 2006 and 2007 to selected mid-row management options at the Clare site and the significance of the difference between treatments. See text for further explanation of this display of results.



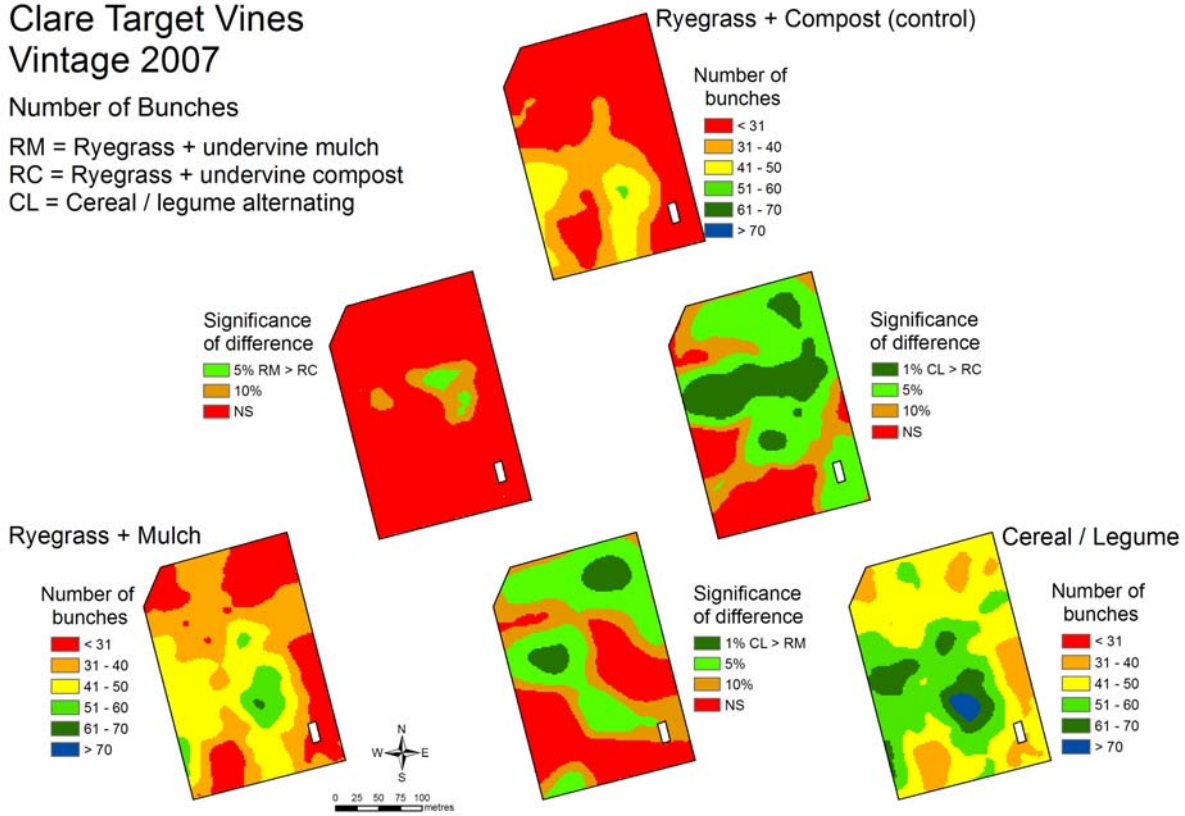
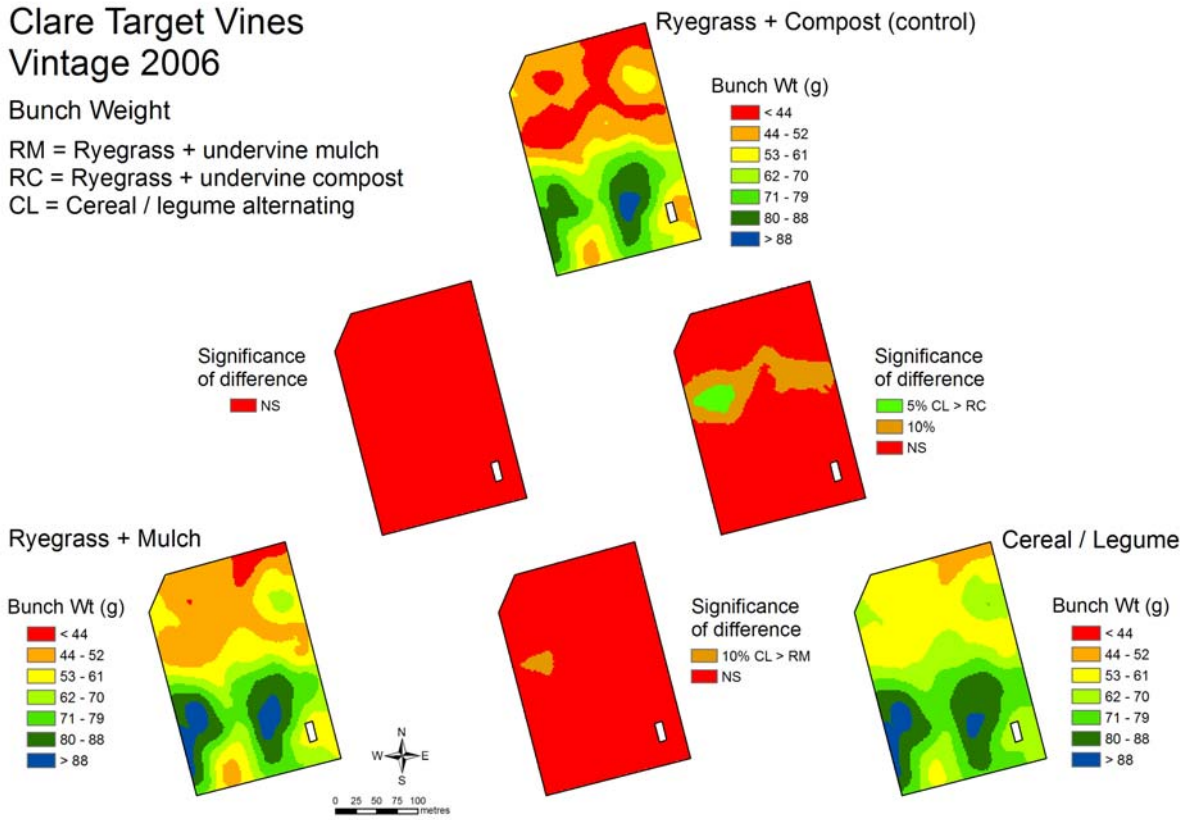


Figure 12. Variation in the effects of selected mid-row management options on bunch number at the Clare site in 2006 and 2007.



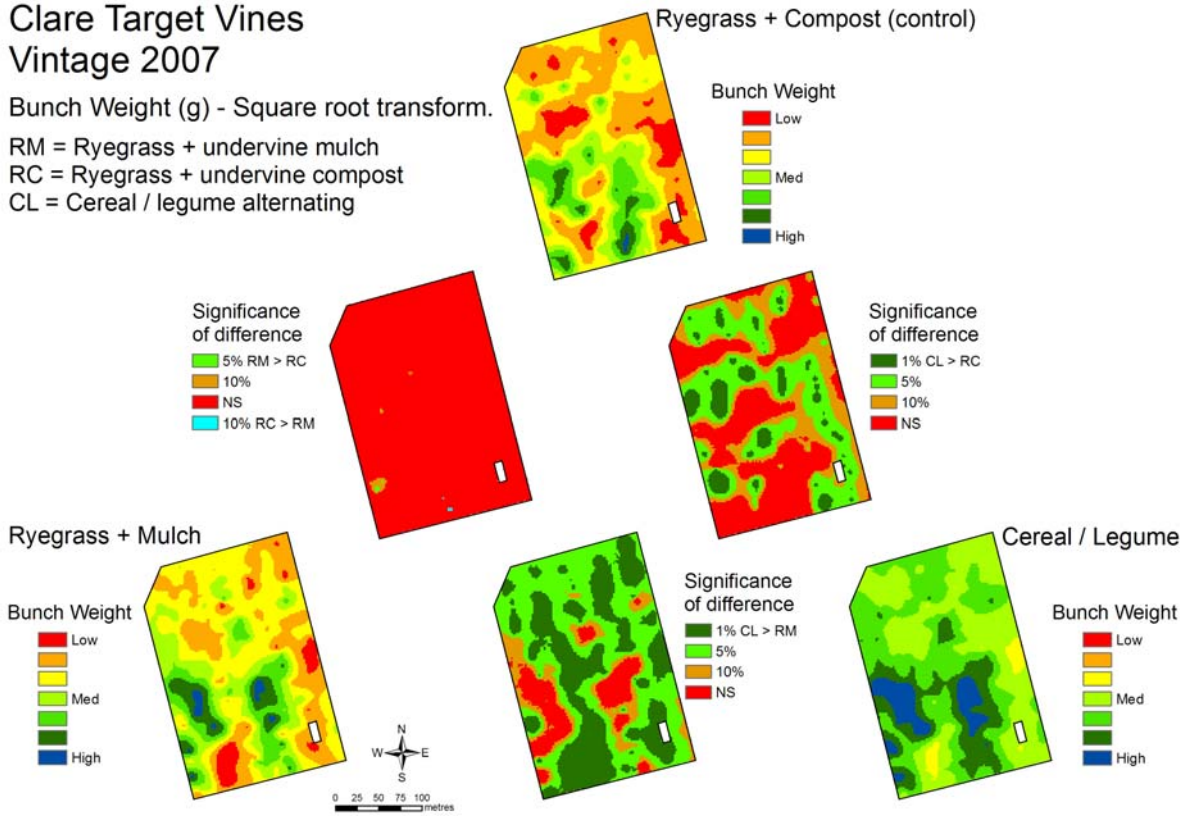


Figure 13. Variation in the effects of selected mid-row management options on bunch weight at the Clare site in 2006 and 2007.

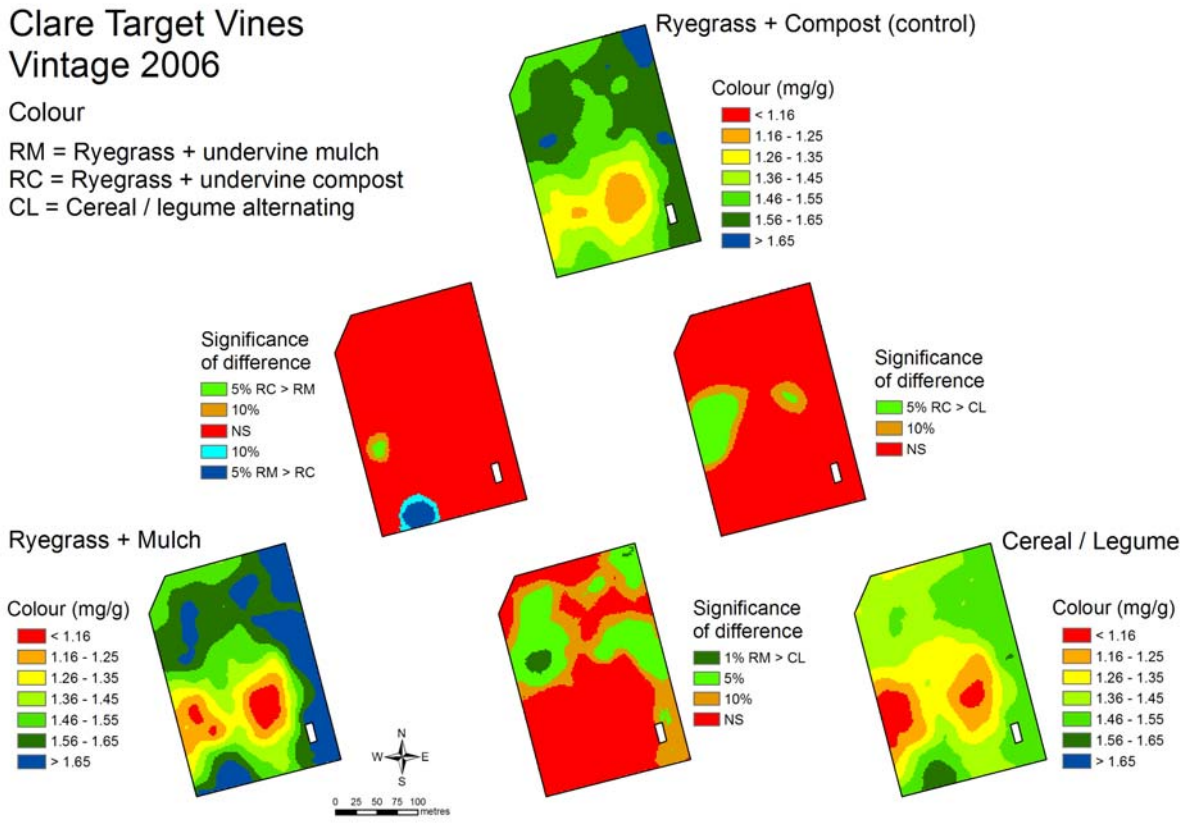


Figure 14. Variation in the effects of selected mid-row management options on colour (concentration of anthocyanins) at the Clare site in 2006.

Table 5. Mean and range for selected soil properties (20-30 cm depth increment, n=9) sampled from locations chosen to cover the range of values of EC_a obtained through high resolution EM38 soil survey.

Soil property	Mean	Range
$EC_{1:5}$ (dS/m)	0.10	0.03-0.22
$pH_{1:5}$	7.0	6.3-8.3
pH_{CaCl2}	5.9	5.1-7.5
Cl^- (mg/L)	25.9	9.2-75.1
CEC (cmol(+)/kg)	14.5	9.4-18.1
Clay (%)	44	38-52
Silt (%)	31	21-42
Sand (%)	25	18-31
θ_v (%) at 10 kPa	32	27-35
θ_v (%) at 50 kPa	26	21-31
θ_v (%) at 1500 kPa	16	11-21

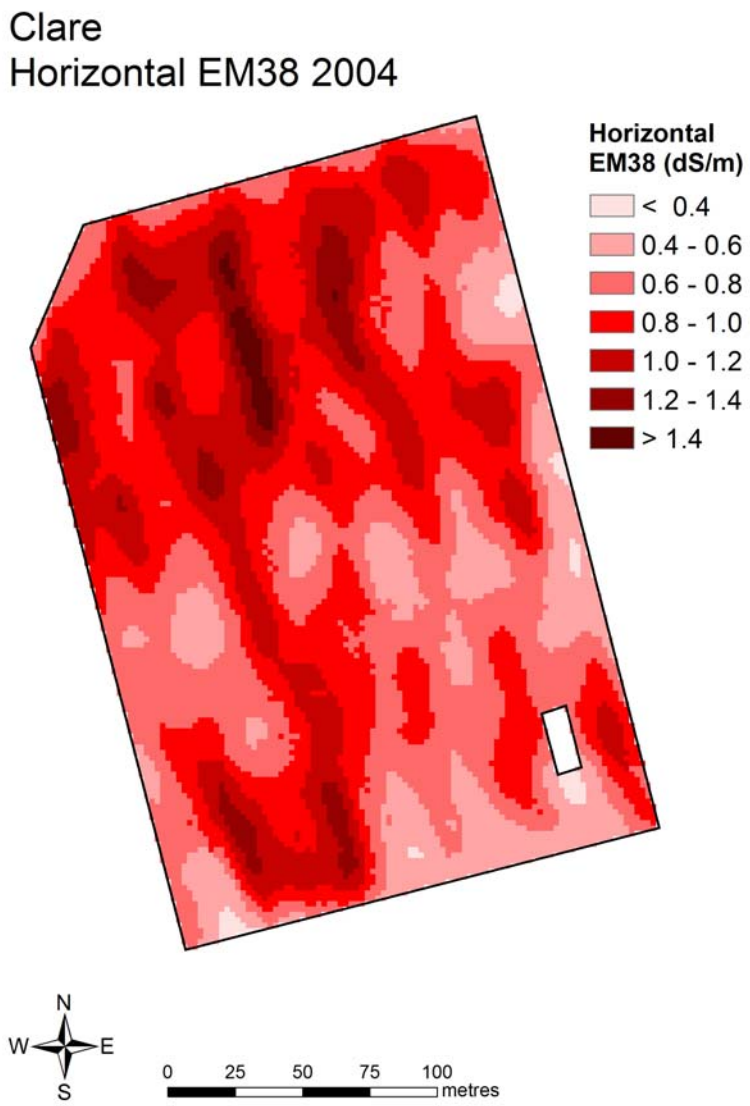


Figure 15. Variation in apparent electrical conductivity (pre-experiment), as measured by EM38 soil survey at the Clare site.

of soil salinity, whilst comparison of the $EC_{1:5}$ results (Table 5) with the data of Cass et al. (1995) also suggests that the soils in the experimental area are predominantly saline.

With the introduction of the legume in the CL treatment, it was to be expected that more nitrogen would be available for the vines in the CL treated areas. Table 6 shows the petiole N status by treatment and PPC. Even though no certified legume seeds were available for the first trial year, when there was consequently no legume planted, it can be seen that more nitrogen uptake took place in the CL treatment. This remained the case over the duration of the experiment, although it is notable that petiole N status was lower in the 2006-07 season than in 2005-06. It is suggested that the combined effect of reduced and ever decreasing water availability starting during the 2005/2006 season when the irrigation dams were empty, with better performing vines may be the cause of the lower nitrogen concentrations in the petioles at veraison in 2006 and flowering in the following season.

Table 6. Significance of between-treatment differences in mean petiole nitrogen (%) content at veraison and flowering 2005 and 2006 for the block as a whole and on a PPC basis[A].

	Treatment			ANOVA[B]
	RGC	RGM	CL	*p*
Veraison 05	0.61[a]	0.60[a]	0.66[a]	* 0.0468
Flowering 05	0.97[b]	1.01[b]	1.40[a]	*** <0.0001
Veraison 06	0.49[b]	0.51[b]	0.55[a]	** 0.0017
Flowering 06	1.14[b]	0.98[c]	1.20[a]	*** <0.0001
n[C]	*20/126*	*20/125*	*20/126*	

	Low PPC	High PPC	Low PPC	High PPC	Low PPC	High PPC	
Veraison 05	0.60[b]	0.62[a,b]	0.60[b]	0.60[b]	0.61[a,b]	0.70[a]	* 0.0154
Flowering 05	0.85[c]	1.08[b,c]	0.88[c]	1.15[b]	1.21[b]	1.60[a]	*** <0.0001
Veraison 06	0.54[b]	0.45[c]	0.52[b]	0.49[b,c]	0.59[a]	0.51[b]	*** <0.0001
Flowering 06	1.16[a,b]	1.13[b]	1.02[c]	0.94[d]	1.23[a]	1.15[a,b]	*** <0.0001
n[C]	*10/59*	*10/67*	*10/61*	*10/64*	*10/88*	*10/38*	

[A]Values not connected by the same letter are significantly different at the 5 % level (Tukey-Kramer *t*-test).
[B]Significance denoted by * ($p<0.05$), ** ($p<0.01$) and *** ($p<0.001$).
[C]The second number of *n* relates to the sampling during flowering 2006.

Coonawarra

As was the case at Clare, whether or not the inherent vineyard variability was factored into the analysis had a marked effect on the interpretation of experimental results, although in the Coonawarra experiment, matters were complicated by the confounding effect of season. Thus, whereas at vintage 2005, six of eight measured attributes showed significant differences between the more severe pruning and shoot thinning (SPST) treatment compared to the control over the block as a whole, only bunch weight and the number of berries per bunch showed a significant treatment effect at vintage 2006 (Table 7). Including consideration of inherent variability by classifying the data on the basis of PPCs (Figure 4) improved discrimination of treatment effects, but in particular indicated quite distinct differences in vine performance between the lower and higher PPCs (Table 8).

Like those obtained at Clare, these results demonstrate how the effects of different treatments may be moderated by spatial variation in the underlying characteristics of the vineyard. Thus, the results again support the view that for a small plot experiment conducted in the same vineyard, the effects of heterogeneity between sub blocks (replicates) may well outweigh the treatment effects – a problem which can only be resolved using a geostatistical approach of data analysis. As at Clare, we resolved this problem by using the method of Bishop and Lark (2006); Table 9 summarises the results.

In 2005, the SPST treatment led to a significant ($p<0.01$) improvement in fruit quality throughout the block, as evidenced by the enhanced colour (concentration of anthocyanins), phenolics concentration and increased maturity (Baumé); there were no significant differences in bunch or berry weights. Paradoxically, the SPST treatment led to almost no significant change in fruit quality in 2006, but did significantly increase bunch size (Table 9; Figure 16). It is therefore obvious that the vineyard manager's objective of reducing berry size and increasing the skin/flesh ratio through the modified pruning strategy was not achieved. Given the confounding seasonal effects, it is not clear what the reason for this might be. Suffice to say that late season rainfall in 2006 (Figure 5) may have

Table 7. Effect of severe pruning and shoot thinning on selected vine performance attributes measured on 312 target vines at the Coonawarra site at vintage in 2005 and 2006[A].

	Attribute	Treatment Control	SPST	ANOVA[B] *p*
2005	Bunch weight (g)	105[a]	97[b]	* 0.0124
	Berry weight (g)	1.25[a]	1.25[a]	ns 0.8732
	Berries / bunch	84[b]	78[a]	** 0.0042
	pH[C]	3.32[b]	3.39[a]	** 0.0060
	TA (g/L)[C]	9.06[a]	9.85[a]	ns 0.1417
	Baumé (º)	13.2[b]	15.0[a]	*** <0.0001
	Anthocyanins (mg/g)	1.40[b]	1.80[a]	*** <0.0001
	Phenolics (a.u./g)	1.04[b]	1.32[a]	*** <0.0001
2006	Bunch weight (g)	104[b]	124[a]	*** <0.0001
	Berry weight (g)	1.26[a]	1.29[a]	ns 0.2227
	Berries / bunch	81[b]	95[a]	*** <0.0001
	pH	3.44[a]	3.42[a]	ns 0.0696
	TA (g/L)	5.91[a]	5.96[a]	ns 0.4073
	Baumé (º)	13.8[a]	13.8[a]	ns 0.9722
	Anthocyanins (mg/g)	1.73[a]	1.70[a]	ns 0.5496
	Phenolics (a.u./g)	1.26[a]	1.25[a]	ns 0.7672
	n	*156*	*156*	

[A]Values not connected by the same letter are significantly different ($p<0.05$; Tukey-Kramer *t*-test).
[B]Significance denoted by: ns = not significant ($p>0.05$), * = $p<0.05$, ** = $p<0.01$, and *** = $p<0.001$.
[C]*n* = 20 for these analyses.

Table 8. Interaction between treatment and PPC on vine performance attributes measured on 312 target vines at the Coonawarra site at vintage in 2005 and 2006[A]. Footnotes are as per Table 7.

	Attribute	Treatment Control Low PPC	Control High PPC	SPST Low PPC	SPST High PPC	ANOVA[B] *p*
2005	Bunch weight (g)	99[b,c]	111[a]	89[c]	106[a,b]	* 0.0259
	Berry weight (g)	1.22[b]	1.28[a]	1.23[b]	1.27[a,b]	* 0.0104
	Berries / bunch	81[a]	83[a]	72[b]	83[a]	*** <0.0001
	pH[C]	3.35[b]	3.30[b]	3.46[a]	3.32[b]	** 0.0013
	TA (g/L)[C]	8.03[c]	9.99[a,b]	8.85[b,c]	10.97[a]	*** <0.0001
	Baumé (º)	13.5[c]	12.8[d]	15.4[a]	14.7[b]	*** <0.0001
	Anthocyanins (mg/g)	1.56[b]	1.24[c]	1.97[a]	1.62[b]	*** <0.0001
	Phenolics (a.u./g)	1.12[c]	0.97[d]	1.41[a]	1.23[b]	*** <0.0001
2006	Bunch weight (g)	90[c]	117[b]	113[b]	136[a]	*** <0.0001
	Berry weight (g)	1.19[b]	1.33[a]	1.22[b]	1.35[a]	*** <0.0001
	Berries / bunch	74[c]	87[b]	91[b]	99[a]	*** <0.0001
	pH	3.45[a]	3.43[a]	3.42[a]	3.42[a]	ns 0.1291
	TA (g/L)	5.79[b]	6.02[a]	5.86[a,b]	6.07[a]	** 0.0032
	Baumé (º)	14.2[a]	13.4[b]	14.0[a]	13.5[b]	*** <0.0001
	Anthocyanins (mg/g)	1.93[a]	1.54[b]	1.84[a]	1.56[b]	*** <0.0001
	Phenolics (a.u./g)	1.37[a]	1.16[b]	1.33[a]	1.17[b]	*** <0.0001
	n	*76*	*80*	*79*	*77*	

Table 9. Comparison between the SPST and control treatments at Coonawarra in 2005 and 2006 when analysed using the method of Bishop and Lark (2006)[A].

	Shoot thinned (ST) vs Control (C)	
	2005	2006
Bunch weight	100 ns	ST > C 1 ns 99 ^ 64 *
Berry weight	100 ns	ST > C 98 ns 2 ^ <1 *
Berries/bunch	100 ns	ST > C 100 *
Baumé	ST > C 100 **	100 ns
pH[B]		100 ns
TA[B]		ST > C 98 ns 2 ^ <1 * C > ST <1*
Colour	ST > C 100 **	100 ns
Phenolics	ST > C 100 **	100 ns

[A]The numbers reported are the % of pixels within the mapped vineyard area for which the treatment differences are significant at $p<0.1$ (^), $p<0.05$ (*) or $p<0.01$ (**).
[B]Insufficient pH and TA data were available for spatial analysis in 2005.

led to dilution of berry chemistry values. Whether or not this is so, these results, like those from Clare lend weight to the view that viticultural experiments need to be conducted over several seasons, and not just the one or two years permitted by the standard 3 year project.

As indicated, the treatment effects were also evaluated by sensory analysis of wines. Table 10 presents the scores attributed to fruit and wine by the collaborating winemaker. Based on his assessment, the 2005 wines derived from the SPST treatment would have been channelled into a different product line than the control, resulting in an increase in the retail value of production of $5-10 per bottle. Note however, that in 2005, the two treatment wines were made and assessed independently of any consideration of PPC. With hindsight, this is regrettable given that the winemaker scoring of both fruit and wine emphasised the difference between the high and low PPC and not between the treatments even though, contrary to the results presented in Table 9, the fruit scores assigned during picking were

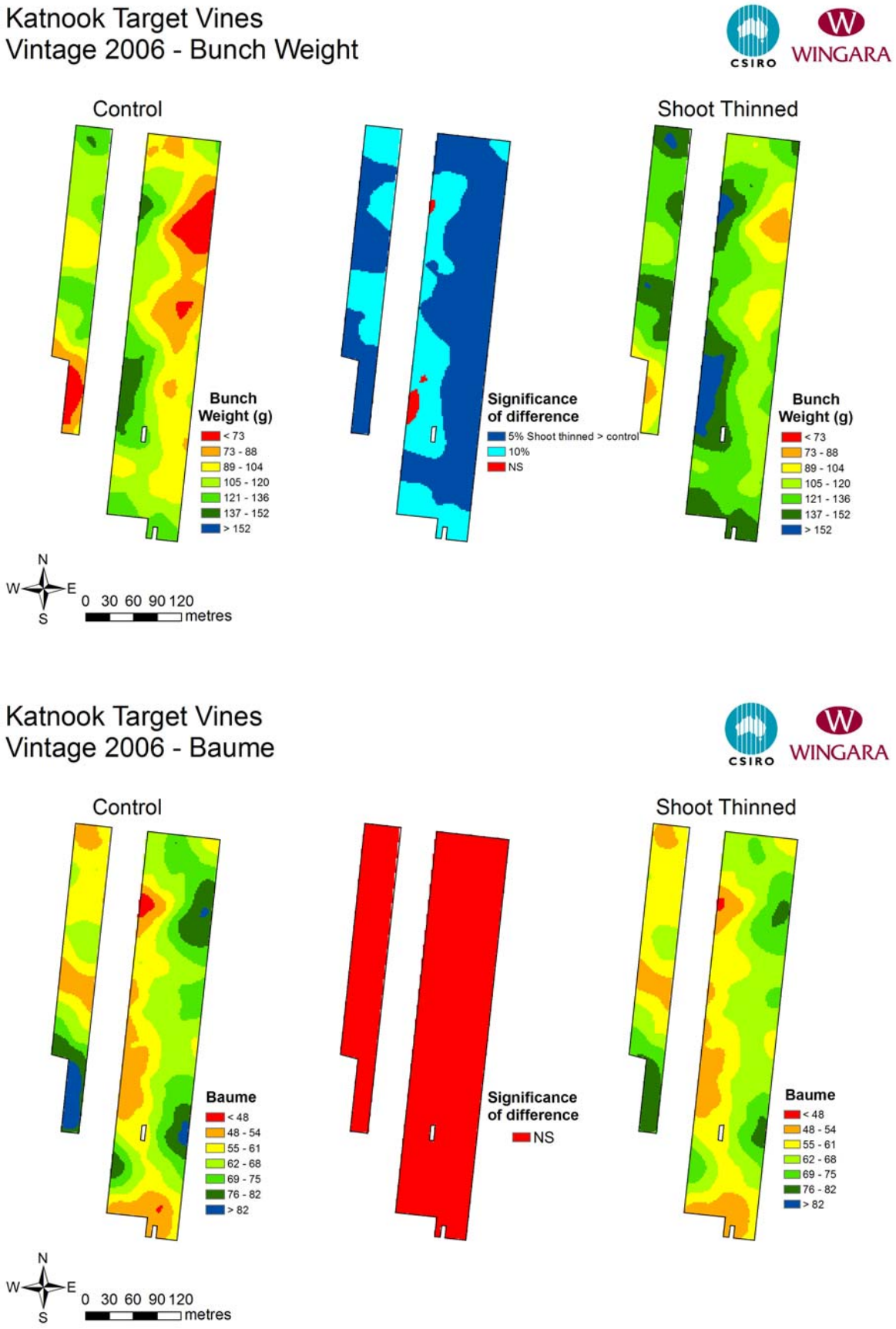


Figure 16. Spatially variable effect of severe pruning and bunch thinning on bunch weight and Baumé at the Coonawarra site in 2006.

Table 10. Winemaker scores for Coonawarra grapes and wines (1 = best; 5 = worst)

	Control			SPST	
Wine 2005		4		3+	
	Block av.	Low PPC	High PPC	Low PPC	High PPC
Grapes 2006		4+	5+	3+	4+
Wine 2006	5+	4+	5+	4+	5+

Table 11. Results of descriptive sensory analysis of the five Shiraz wines made in 2006. Data are mean scores from a 15 point scale (1 = lowest, 15 = highest)[A].

	Attributes	Treatment					ANOVA[B]
		Block average	Control Low PPC	Control High PPC	SPST Low PPC	SPST High PPC	*p*
Aroma	Red fruit	4.5[b]	3.9[b]	4.6[b]	4.2[b]	5.3[a]	** 0.0030
	Dark fruit	5.1[b]	6.0[a]	4.8[b]	6.1[a]	4.7[b]	*** <0.0001
	Dried fruit	3.5[b]	4.1[a,b]	3.7[b]	4.3[a]	3.6[b]	* 0.0453
	Confection	2.8[a]	2.8[a]	3.0[a]	3.0[a]	3.3[a]	ns 0.3846
	Floral	2.4[a]	2.6[a]	2.6[a]	2.6[a]	2.7[a]	ns 0.7641
	Leafy	2.7[a]	2.9[a]	3.0[a]	2.9[a]	2.8[a]	ns 0.8175
	Mint	1.9[a]	2.1[a]	1.9[a]	2.1[a]	1.9[a]	ns 0.6820
	Meaty	2.8[a]	2.2[b]	2.5[a,b]	2.4[a,b]	2.2[b]	ns 0.0815
	Sweet Spice	3.1[a]	3.4[a]	3.1[a]	3.3[a]	3.1[a]	ns 0.8708
	Mocha	2.3[a]	2.7[a]	2.5[a]	2.6[a]	2.3[a]	ns 0.3679
	Peppery	2.3[a,b]	2.6[a]	2.4[a,b]	2.4[a,b]	2.2[b]	ns 0.3464
	Earthy	2.4[a]	2.3[a]	2.3[a]	2.5[a]	2.4[a]	ns 0.9279
	Tobacco	2.7[a]	3.0[a]	2.7[a]	2.6[a]	2.5[a]	ns 0.4705
	Sweaty	2.9[a]	2.5[a]	2.6[a]	2.4[a]	2.5[a]	ns 0.5779
	Rubbery	3.3[a]	3.1[a]	3.1[a]	2.8[a]	2.8[a]	ns 0.7084
By Mouth	Acidity	6.5[a]	6.5[a]	6.5[a]	6.7[a]	6.5[a]	ns 0.9889
	Ripe berry	4.9[b]	5.9[a]	5.1[b]	5.8[a]	4.8[b]	** 0.0045
	Unripe berry	4.6[a]	3.7[b]	4.2[a,b]	4.1[a,b]	4.5[a]	ns 0.0670
	Savoury	2.9[a]	2.7[a]	2.8[a]	2.8[a]	2.8[a]	ns 0.9665
	Fruit Persistence	5.1[b]	6.1[a]	5.1[b]	5.9[a]	4.9[b]	** 0.0033
	Body	5.0[b,c]	5.9[a]	5.0[b,c]	5.6[a,b]	4.6[c]	** 0.0025
	Viscosity	4.4[b,c]	5.0[a]	4.3[c]	4.9[a,b]	4.1[c]	** 0.0084
	Drying	5.2[a]	5.1[a]	4.7[a]	5.3[a]	5.0[a]	ns 0.7080
	Tannin Texture	5.1[a]	5.4[a]	5.1[a]	5.6[a]	4.8[a]	ns 0.4582
	Bitterness	2.1[a]	2.5[a]	2.3[a]	2.3[a]	2.4[a]	ns 0.6878
	Warmth	5.3[a,b]	6.0[a]	4.9[b]	5.8[a]	5.3[a,b]	ns 0.0792

[A]Values not connected by same letter are significantly different ($p<0.05$; Student's *t*-test).
[B]Significance of difference: ns = not significant ($p>0.05$), * = $p<0.05$, ** = $p<0.01$, *** = $p<0.001$.

better for the SPST treated vines. Overall, Table 10 suggests that the fruit and wine quality in 2006 was lower than in 2005, a result which is consistent with the suggested impact of late season rainfall.

Full descriptive sensory analysis of the 2006 wines confirms that the differences between the PPCs were greater than the effects of the SPST treatment (Table 11). Significant differences between the lower and higher PPCs can be observed for 'red fruit', 'dark fruit' and 'dried fruit' aromas as well as 'ripe berry', 'fruit persistence', 'body' and 'viscosity' by mouth (Table 11); Figures 17 and 18 show a subset of the descriptive sensory analysis attributes.

The sensory results are supported by the chemical analysis of the five small scale wines (Table 12). Most analysed attributes show significant differences between the lower and higher PPC, but for any given PPC, not between treatments. Table 12 also suggests that the characteristics of the block average wine were dominated by the high PPC.

Overall, the wine results show the same contrasting results between years for treatment effects as the target vine analysis; the merits of the SPST treatment are unclear. Nevertheless, the distinctly different results for the two PPCs again show the benefit of knowledge about vineyard variability and the influence it may have on experimental outcomes. With the availability of tools to map treatment responses spatially, information can be gained about where in the vineyard each treatment is beneficial. Even though in this particular case study no additional knowledge could be gained from the mapping process, the spatial information about vine vigour and yield were very important for local evaluation of treatment responses. With continued collection of spatial data in subsequent years (remote sensing, yield mapping, etc…), an improved delineation of PPCs should be possible leading to improved decision making about both differential canopy management and targeted harvesting. Significantly, and in spite of the fact that frost brought an early end to this experiment, the manager of the Coonawarra site (who was positively disposed towards experimentation as a management tool prior to this work) was positive at the end of the trial about both the whole of block approach, and the use of spatial data more generally for improved vineyard management.

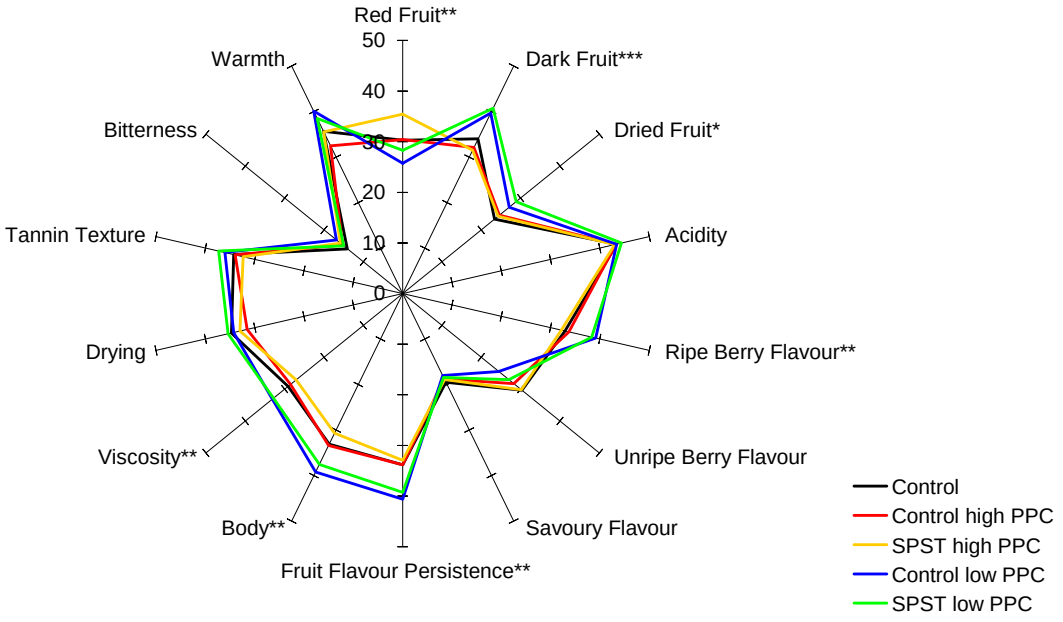


Figure 17. Selected mean ratings from sensory analysis of Coonawarra wines in 2006. Significant differences are denoted by: * ($p<0.05$), ** ($p<0.01$) and *** ($p<0.001$).

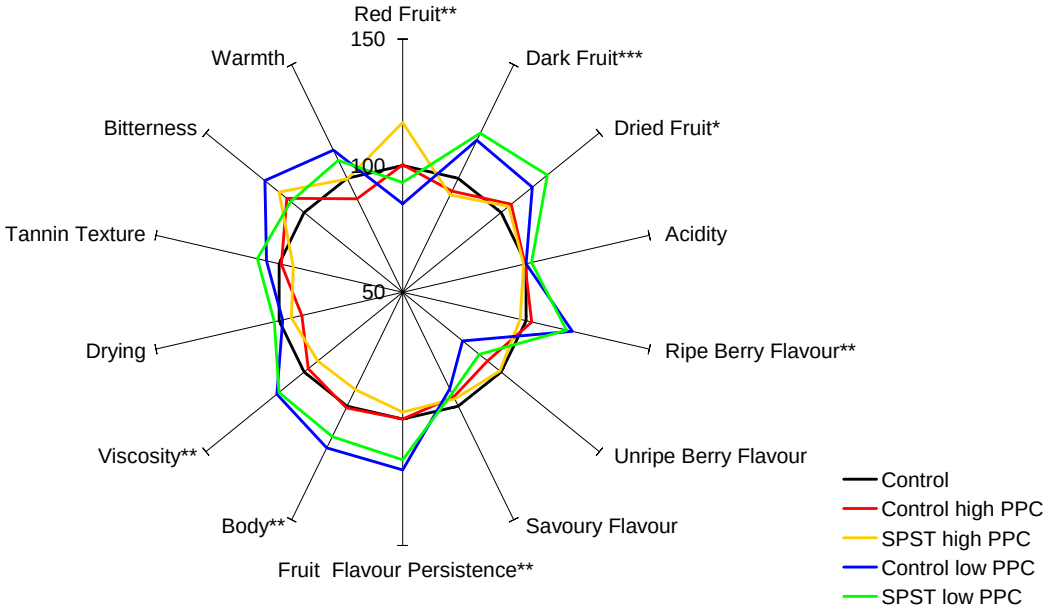


Figure 18. Selected mean ratings from sensory analysis for the 2006 wines. Results are plotted in terms of their difference (%) from the control wine (=100 %). Significant differences are denoted by: * ($p<0.05$), ** ($p<0.01$) and *** ($p<0.001$).

Table 12. Effect of PPC and the SPST treatment on selected chemical attributes of 2006 wines[A].

		Treatment				
		Control		SPST		ANOVA[B]
Attributes	Block average	Low PPC	High PPC	Low PPC	High PPC	*p*
Wine colour density	32.0^{a,b}	34.5^{a}	30.0^{b,c}	34.2^{a}	28.4^{c}	** 0.0084
Wine hue	0.51^{b}	0.77^{a}	0.48^{b}	0.71^{a}	0.49^{b}	*** <0.0001
SO_2 resistant pigments	7.6^{b}	13.3^{a}	6.3^{b}	12.1^{a}	5.9^{b}	*** <0.0001
Total red pigments	21.0^{b}	30.3^{a}	19.2^{b}	27.6^{a}	17.1^{b}	*** 0.0005
Total phenolics	30.3^{b}	45.3^{a}	26.9^{b}	43.1^{a}	24.1^{b}	*** <0.0001
Total anthocyanins	168	164	172	149	147	ns 0.1877

[A]Values not connected by same letter are significant different (Student's *t*-test, $\alpha = 0.05$).
[B]Significance of difference: ns = not significant ($p>0.05$), * = $p<0.05$, ** = $p<0.01$, *** = $p<0.001$.

Auburn

As with the other vineyards studied, the Auburn vineyard showed marked variability in all the various attributes measured (eg Figures 19-22). However, there were few areas in which significant differences were seen between treatments and these were generally too small for targeted management to be deemed worthwhile by the viticulturist (Figures 20-22). Taking colour as a surrogate for quality (Francis et al. 1999; Gishen et al. 2002), the experimental treatments clearly have little impact (Figure 20). On the one hand, this suggests that the additional costs associated with management of the VSP canopy could usefully be saved through implementation of the cheaper sprawl. However, the lack of any real improvement in fruit quality in the kicker cane treatment – a result similar to that obtained in an earlier Padthaway experiment (Bramley et al., 2005a) - suggests that whilst attractive on the basis of physiological first principles, this strategy is generally insufficiently aggressive to deliver fruit quality improvement of a magnitude that would attract the interest of winemakers. Indeed, berry weight in the kicker cane treatment was either not significantly different ($p>0.1$) to that in VSP and sprawl treatments, or was only significantly reduced compared to the other treatments in a small area (approximately 9% of the experimental area; Figure 21); kicker canes are expected to reduce berry size in addition to vigour (Bramley et al., 2005a).

Whilst the spatial analysis suggests little difference between the treatments, analysis of target vine data on a PPC basis showed significant differences in vine performance between the PPCs (Table 13). This result strongly suggests that in this vineyard, inherent vineyard variability exerts a much stronger effect on vine performance than the canopy management options explored in this experiment. Consistent with this conclusion is the finding that, when assessment of treatment effects was analysed on a per PPC basis (data not shown), no significant treatment effects were apparent in the high vigour zone, except for the expected decrease in berry weight in the KC treatment (cf discussion of spatial analysis above). Similarly, in the medium vigour zone, the KC treatment resulted in a significant ($p<0.05$) reduction in berry weight and Baumé, but also unexpectedly resulted in a significant ($p<0.001$) reduction in the concentrations of colour and phenolics. In the low vigour zone, the only treatment effect was significantly reduced ($p<0.05$) juice pH in the KC treatment.

In light of these results, there was little surprise that the sensory analysis of small-lot wines yielded little additional information. Indeed, in duo trio testing (Meilgard et al., 1999) of differences between the wines, the only perceivable difference was between the VSP and KC wines in the high vigour PPC (Table 14). Accordingly, a full descriptive analysis was not undertaken on these wines, although the tasting notes derived from an informal assessment of the wines indicate that whereas the VSP high PPC wine had ‘medium’ fruit intensity, was ‘medium’ bodied and had a finish of ‘short’ fruit length, the KC high PPC wine had ‘low-medium’ fruit intensity, was ‘light-medium’ bodied and had a finish of ‘low-medium’ fruit length. All wines were described as being of ‘high’ acidity with flavour and aroma dominated by ‘ripe berries’, ‘confection’, ‘pepper’, ‘sweet spice’ and ‘savoury’, and deep red-purple in colour.

In some respects, the results obtained from this experiment were somewhat disappointing; the project team, including the company viticulturist, were hoping for something more substantial to emerge. On the other hand, the viticulturist expressed satisfaction at having learned that Kicker Canes are an insignificantly aggressive tool to properly combat the high vigour and reduced fruit quality which occurs over a significant part of the block. Furthermore, and in view of the results obtained, his future plans include implementation of a targeted strategy based on management of the mid-row in the High PPC using species which will effectively compete with the vines for soil water in order to improve the performance of this vineyard block. It was agreed that this plan was well informed by the experimental results obtained.

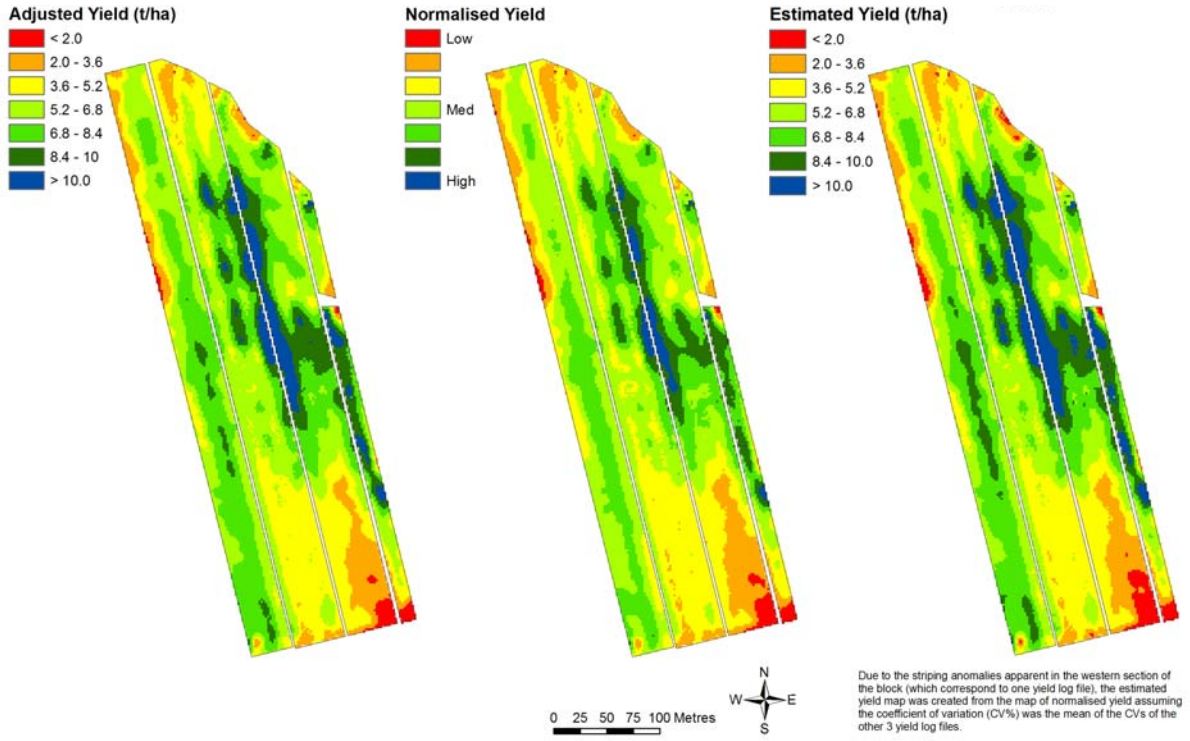


Figure 19. Yield (vintage 2007) at the Auburn site. As has been commonly reported elsewhere, the range of variation in yield in the block was of the order of ten-fold. Note that 'Adjusted yield' refers to the need to calibrate the yield monitor data back to the tonnage measured at the winery weighbridge; the 'Normalised yield' map is constructed after normalisation of the data (mean of zero, standard deviation of 1) and iterative data trimming so that dataset is constrained within 3 standard deviations of the mean (Bramley, 2005c); and 'Estimated yield' is derived as explained in the note to the map.

Table 13. The effect of PPC or inherent vigour on vine performance at the Auburn site.[A]

PPC	High	Med	Low	Significance (p)[B]	
n	50	152	96		
Bunch Wt (g)	72.9a	63.5b	41.0c	***	< 0.0001
Berry Wt (g)	0.86a	0.77b	0.65c	***	< 0.0001
Berries / Bunch	84.8a	82.1a	61.8b	***	< 0.0001
Baumé	13.6a	13.9b	14.5c	***	< 0.0001
TA	6.78a	6.50b	6.53ab	*	0.0295
pH	3.52a	3.54a,b	3.57b	**	0.0099
Colour (mg/g)	1.24a	1.40b	1.58c	***	< 0.0001
Phenolics (au/g)	1.24a	1.32b	1.52c	***	< 0.0001

[A]Note that the experimental treatments have been ignored in this analysis which simply compares pooled results for all treatments on a per PPC basis.
[B]Values not connected by the same letter are significantly different (comparison of pairs using Tukey-Kramer HSD); * = $p<0.05$; ** = $p<0.01$; *** = $p<0.001$

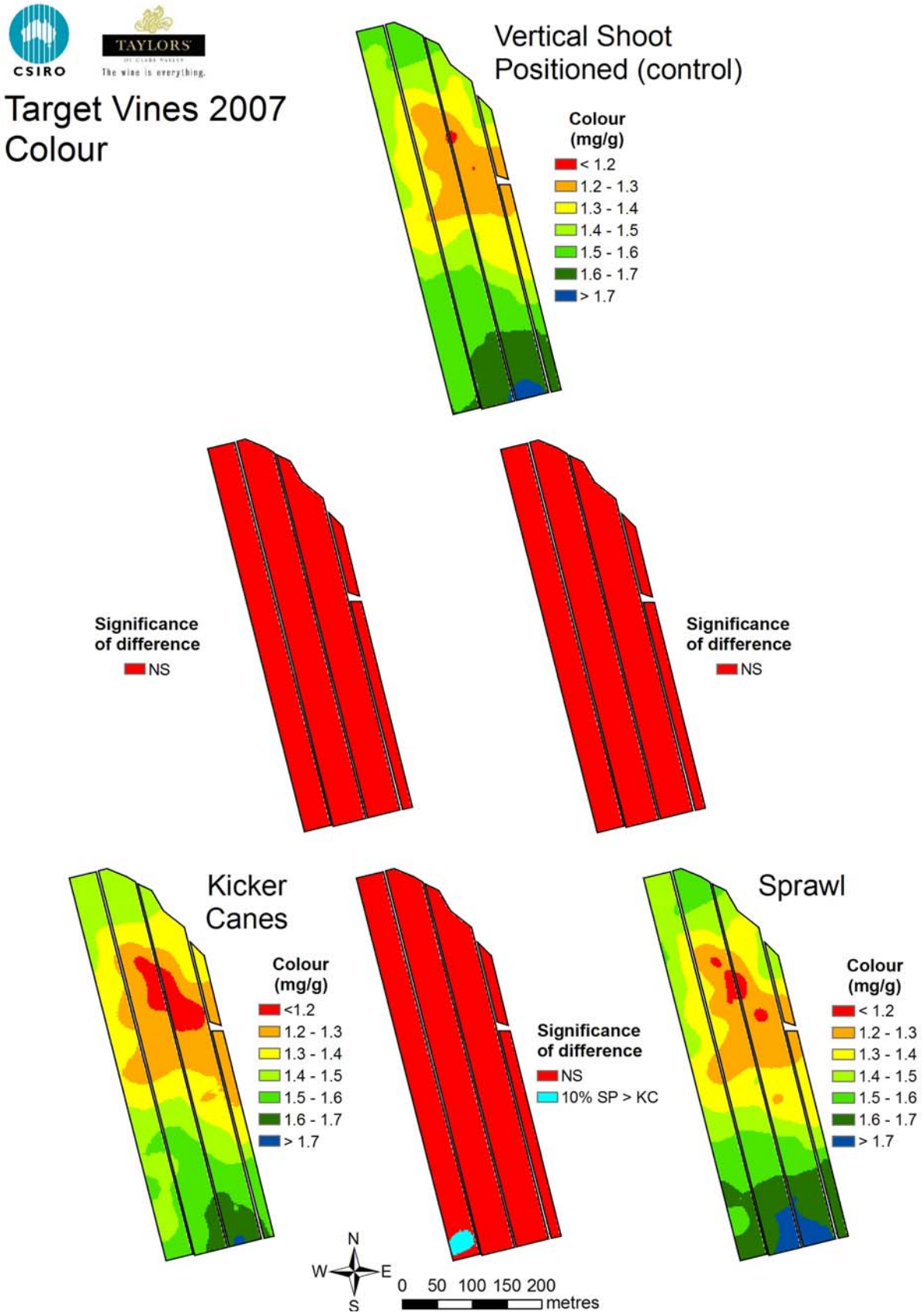


Figure 20. Variation in colour (total anthocyanins) concentration at the Auburn site, vintage 2007. Assuming that colour is a reasonable surrogate for quality in Shiraz, it can be seen that the various canopy management strategies tested here exerted no significant effect ($p>0.1$) on colour.

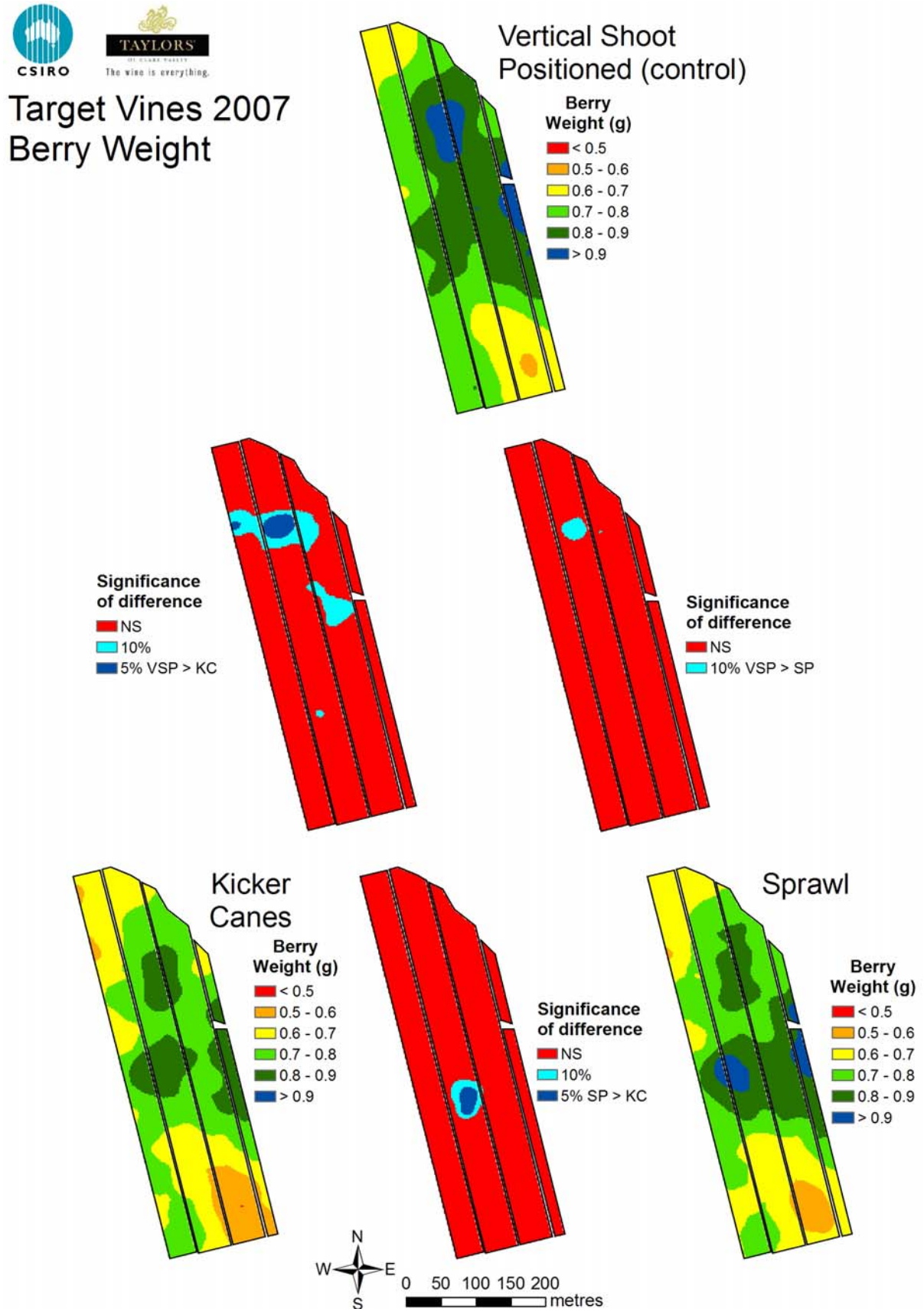


Figure 21. Variation in berry weight at the Auburn site, vintage 2007. Assuming that colour is a reasonable surrogate for quality in Shiraz, it can be seen that the various canopy management strategies tested here exerted no significant effect ($p>0.1$) on colour.

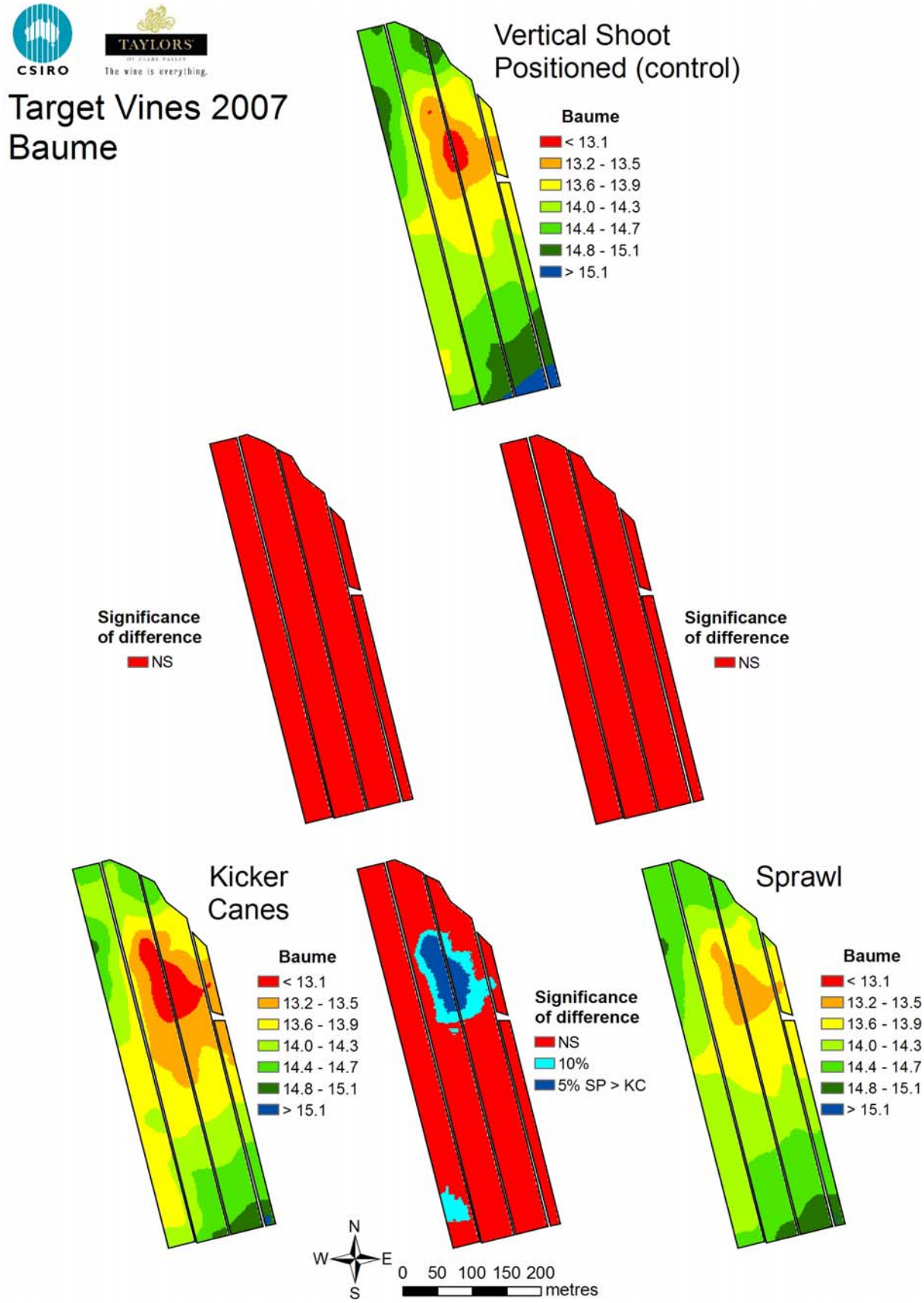


Figure 22. Variation in Baumé at the Auburn site, vintage 2007. The area of lower Baumé which can be seen for all 3 treatments corresponds to an area of higher yield (Figure 19).

Table 14. Results of duo-trio tests of sensory differences between small-lot wines produced from the areas shown in Figure 8.

Wine 1	Wine 2	No. of correct responses	Significance[A]
VSP medium PPC	KC medium PPC	13/26	ns
VSP high PPC	KC high PPC	17/26	*
VSP medium PPC	VSP high PPC	12/26	ns
KC medium PPC	KC high PPC	13/26	ns

[A]ns denotes not significant ($p>0.05$); * denotes significant ($p<0.05$).

Pragmatic considerations

One of the key deliverables foreshadowed from this work was a Protocol for whole of block experimentation in vineyards; given the enthusiasm of our industry collaborators, we were hopeful of being able to deliver such a protocol. However, in light of the complexity of the methods of analysis of results, and the non-availability of easy to use software which would facilitate this, we are strongly of the view that providing industry with such a protocol at this stage would possibly lead to unrealistically raised expectations. Nevertheless, we have drafted 'Recommendations for the establishment of whole of block vineyard trials' (Appendix 6) and would be pleased to discuss with GWRDC how their communicators might usefully make these available to interested practitioners. The following issues are pertinent.

i. Experimental design and layout

As stated, at the start of this project and in the absence of knowledge of, or access to, the Bishop and Lark (2006) method, we were of the view that we would have to use analytical methods similar to those employed by Lanyon and Bramley (2004) for analysis of the experiments conducted here. Concerned at the loss of data occasioned by 'guard rows', coupled with the problem of having to interpolate over large 'gaps' occupied by treatments other than the one being mapped, and the basic desirability for robust variogram analysis of having target vines that are separated by a wide range of distances including some that are close together, we felt that designs which tended toward the more complex spatial patterns may be better than simple strips. However, based on the results reported here and with access to the Bishop and Lark (2006) methodology, there is no reason to suppose that the more complicated Clare design offered any benefit over those used in Coonawarra or Auburn. On the other hand, the use of co-kriging and linear models of co-regionalisation in the Bishop and Lark (2006) methodology is certainly facilitated by the target vines being co-located, as they were in the Auburn experiment (Figure 6). This in turn, is arguably made easier in simple strip designs, as Figure 6 illustrates.

The above having been said, it is important to recognise that in many respects, the experiments conducted here and by Lanyon and Bramley (2004) and Bramley et al. (2007a) have a strong 'proof of concept' element to them in that they have sought to develop an experimental approach which will really come into its own when, rather than depending on sampling of 'target vines', treatment responses can be measured solely by on-the-go technologies such as yield monitors, quality sensors (once developed) or by remotely sensed imagery (eg Figures 9, 10) or proximal fruit or canopy sensors (eg Bramley et al., 2007b). It is somewhat ironic that a variety of circumstances conspired against the effective use of such technologies in this project ! Nevertheless, the high data density that becomes possible with such technologies renders most considerations of experimental design redundant (other than the need for guard rows as appropriate), and ease of implementation will dictate that simple replicated strips will be the preferred design.

It is nevertheless worth re-emphasising that our experience in this project was that neither the collaborating vineyard managers nor their staff had any difficulty with what it was that we were asking them to do, whether in terms of the targeted pruning used in Coonawarra and at Auburn, or the more complicated split-strip pattern of mid-row management implemented in Clare. Indeed, all our collaborators warmed to the simple fact that they could wander through the experiment and have a look for themselves for any discernible differences in treatment effects in the different parts of their blocks.

ii Analysis of Results

Most people who are not trained in geostatistics and spatial analysis perceive them as complicated. By any measure, the Bishop and Lark (2006) methodology *is* complicated and there is no question that the lack of easy-to-use, commercially available software for analysis of results is therefore a significant impediment to the adoption of the whole of block approach. Whilst users could revert to the kind of map algebra based methods used by Bramley et al. (2005a) and Lanyon and Bramley (2004), which nevertheless required the use of kriging for interpolation of treatment specific maps, the fact that the Bishop and Lark (2006) method uses all of the data to map each treatment, rather than just the data pertaining to that treatment alone, greatly enhances the likelihood that robust treatment-specific maps will be produced compared to the simpler Lanyon and Bramley (2004) method. Furthermore Lanyon and Bramley were anecdotally criticised by the research community on the basis that the simple map algebra-based method did not promote analysis of the statistical significance of treatment effects. Whilst we remain of the view that most farmers (irrespective of the crop being grown) do not make their decisions based on $p<0.05$, or any other statistical measure for that matter, preferring measures such as benefit:cost and "can I be bothered ?", the Bishop and Lark (2006) method addresses this criticism not only by providing such statistics, but by promoting the ability to map the statistical significance of the difference between treatments. For this reason, we believe it should be strongly preferred to less exacting methods and that instead, effort should be put into making it more widely accessible. Thus, Appendix 6 only provides half of the promised protocol; considerable developmental work is required before the other half can be provided. Nevertheless, grapegrowers and winemakers should be encouraged to proceed with their experiments, and to facilitate this by engaging people with appropriate skills to assist with the analysis of results.

Conclusions and Recommendations

The work conducted in this project has considerably advanced our understanding of how to conduct and analyse viticultural whole of block experiments. Importantly, it has also demonstrated their power and the opportunity that they present to growers and researchers alike in helping to understand that, just as vineyards are variable, so to are the responses to changes in management strategy (ie experimental treatment). This is a very important learning because it highlights the fact that just as the tools of Precision Agriculture (PA) promote this new experimental modus operandi, so too does adoption of PA depend on experimentation being a key part of the management of winegrowing. Thus, in order to target management, aside from identifying 'zones' for which targeted management is appropriate, grapegrowers and winemakers need a basis for selecting alternative management strategies that are appropriate to their particular enterprises and the variation within them; whole of block experimentation provides the tool by which such decisions may be made. It is therefore recommended that GWRDC and the industry promote the extension of this new approach to experimentation. Critically, and in particular, researchers should be strongly encouraged to adopt it. Through GWRDC, the Australian wine industry has now invested a considerable sum in research (including this project) aimed at gaining a better understanding of vineyard variability and how it might be managed. It would therefore be somewhat incongruous if a larger amount were to be invested on an on-going basis into research based on the more traditional 'plot' based experimental approach. Vineyard variability is highly significant and it should not be ignored !

The above notwithstanding, an obvious limitation to adoption of this approach is a lack of training and general expertise in spatial analysis within both industry and the research community. The current non-availability of easy-to-use software for the spatial analysis of the results of whole of block experiments is an obvious impediment to progress. It is therefore recommended that research funding is spent on a project to package the methods of Bishop and Lark (2006) into something that can be used by a broad constituency.

The latter becomes all the more significant in light of what has arguably been the most important aspect of this project – the enthusiasm for the whole of block approach on behalf of our industry collaborators. Of particular note is the fact that the Auburn experiment was established at the behest of the company viticulturist and prior to any involvement from the team working on this project, and the fact that the Clare experiment had a more complicated design than we originally intended, again at the behest of the vineyard manager. In all cases, the experimental treatments were implemented by the same vineyard employees who carry out normal operations and in no case did the project team encounter any negative feedback in regard to what was being attempted or asked of these staff. Thus, we conclude that this small sample of vineyard managers likes the approach and in no way views its scale or implementation as an impediment to adoption. For this, if for no other reasons, the project team are of the view that this project has been a notable success.

Acknowledgments

This work was jointly and variously funded by CSIRO Sustainable Ecosystems (CSE) and Australia's grapegrowers and winemakers through their investment body the Grape and Wine Research and Development Corporation. Support from the latter was matched by the Federal Government. The project also benefited greatly from the in-kind support of Foster's Wines, Wingara Wine Group and Taylors Wines. The project team is grateful to all these organizations and their vineyard staff for their support, and in particular, to John Matz, Dr Richard Hamilton, Chris Brodie, Wayne Stehbens and Colin Hinze. In addition, we would not have been able to complete the spatial analysis of our experimental data without the considerable and greatly appreciated assistance of Drs Tom Bishop (now at the University of Sydney) and especially Murray Lark (Rothamsted Experimental Station, England) who hosted a visit (funded through the CSE Staff Development Fund) from Kerstin Panten during the project. The input and assistance of colleagues at CSIRO Sustainable Ecosystems including Susie Williams, Jackie Ouzman, Dean Lanyon, Renata Ristic, Damian Mowat and Rachel Calvert is also gratefully acknowledged, as are the efforts of Chris Day and Briony Liebich (Provisor Pty Ltd) for conducting the winemaking and sensory analysis (Coonawarra and Auburn). Drs Tony Proffitt (AHA Viticulture) and Richard Hamilton (Foster's Wines) made helpful comments on an earlier draft of this report.

Appendix 1: Communication

This project has generated or contributed input to the following publications (***** denotes invited paper):

1. **Bramley, R.** 2006. Practical applications of precision viticulture. *Precision Ag News* **3** 18-23.
2. **Bramley, R.** 2007. Precision Viticulture: Tools to assist in understanding vineyard variability and achieving desired flavor outcomes. *In:* Walter-Peterson, H. (*Ed*). Proceedings and Program of 'Viticulture 2007'. New York State Agricultural Experiment Station, Cornell University, Geneva, NY USA. *****
3. **Bramley, R.G.V.** 2007. Spatial data and experimentation should be an essential part of optimal grape and wine production. *In:* Blair, R.J.; Williams, P.J.; Pretorius, I.S. (Eds) Proceedings of the Thirteenth Australian Wine Industry Technical Conference, 29 July to 2 August, 2007, Adelaide, South Australia. Australian Wine Industry Technical Conference Inc., Adelaide, South Australia. *In press.* *****
4. **Bramley, R.G.V.,** Evans, K.J., Gobbett, D.L., Panten, K. and Scott, E.S. 2007. Optimising strategies for control of powdery mildew through whole of block experimentation. *In:* Blair, R.J.; Williams, P.J.; Pretorius, I.S. (Eds) Proceedings of the Thirteenth Australian Wine Industry Technical Conference, 29 July to 2 August, 2007, Adelaide, South Australia. Australian Wine Industry Technical Conference Inc., Adelaide, South Australia. *In press.*
5. **Bramley, R.G.V.,** Evans, K.J., Gobbett, D.L., Panten, K. and Scott, E.S. 2007. Optimising strategies for control of grapevine powdery mildew through whole of block experimentation. *In*: *Back to Basics: Managing Plant Disease.* Proceedings of the 16th Biennial Australasian Plant Pathology Society Conference. Australasian Plant Pathology Society Inc. Adelaide. pp. 149.
6. Panten, K. and **Bramley, R.G.V.** 2006. Understanding vineyard variability. Washington Association of Winegrape Growers meeting. www.wawgg.org/files/documents/Kerstin_Panten_abstract.pdf *****
7. Panten, K. and **Bramley, R.** 2006. A new approach to viticultural experimentation. *Australian and New Zealand Grapegrower and Winemaker – Annual Technical Issue* **509a**, 7-11.
8. Panten, K. and **Bramley, R.G.V.** 2007. Using the whole of block approach to measure spatially variable responses to experimental treatments in vineyards. *In:* Fountas, S., Aggelopoulou, A., Gemtos, F., & Blackmore, S. (Eds), Poster paper proceedings, 6th European Conference on Precision Agriculture, 3-6 June 2007, Skiathos, Greece.
9. Panten, K. and **Bramley, R.G.V.** 2007. Exploring canopy management as a tool to improve wine quality using whole of block experimentation. *In:* Blair, R.J.; Williams, P.J.; Pretorius, I.S. (Eds) Proceedings of the Thirteenth Australian Wine Industry Technical Conference, 29 July to 2 August, 2007, Adelaide, South Australia. Australian Wine Industry Technical Conference Inc., Adelaide, South Australia. *In press.*
10. Proffitt, T., **Bramley, R.**, Lamb, D. and Winter, E. 2006. *Precision Viticulture – A new era in vineyard management and wine production.* Winetitles, Adelaide. ISBN 0 9756850 4 X. *****

In addition, four papers are in various stages of preparation for publication in refereed journals – one is currently 'in review' with *Precision Agriculture* whilst three others are intended for the *Australian Journal of Grape and Wine Research*. Once these are published, we will forward copies to GWRDC.

Appendix 2: Intellectual Property

This project has focussed on the generation of knowledge for industry. No commercialisable IP has been generated as part of this project which has applied existing techniques to a new situation.

Appendix 3: References

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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 (0.15 FTE; in-kind)
Dr Kerstin Panten – Postdoctoral Fellow (1 FTE to March 2007; funded by this project)
Mr David Gobbett and Mrs Susie Williams – Technical Officers (1 FTE combined; funded by this project)

Appendix 5: Budget Reconciliation

A budget reconciliation will be provided by CSIRO under separate cover.

Appendix 6: Recommendations for the establishment of whole of block on-farm trials

This note highlights some key issues that growers interested in whole of block experimentation should consider before establishing an on-farm trial. It is suggested that this note be read in conjunction with the Final Report on GWRDC Project No. CSL06/03, copies of which are available from GWRDC.

Background

Traditional agricultural experiments are usually established in fields with the least possible soil heterogeneity and therefore the results are only applicable under similar conditions. Growers faced with variable conditions (ie all of them !) need to know how the response to new management options might vary according to the typical variation over space and time found in their vineyards. Whole of block experiments can help in gaining the necessary knowledge by distributing the treatments over whole management units rather than in small plots, and by employing geostatistical methods for analysis of results.

Prerequisite

It follows from the above that whole of block experiments will only be beneficial if the vineyard or block is variable.

Research has shown that vineyards are most unlikely to be uniform - as most vineyard managers will be well aware. Nevertheless, it will be beneficial to gather some data before the experiment is set up to be able to quantify and locate the variability. Several opportunities for data collection are available and these may depend on the planned treatments, the cause of the inherent variability and the availability of particular tools for characterising it. A full discussion of these issues is given in *Precision Viticulture – A new era in vineyard management and wine production* by Tony Proffitt, Rob Bramley, David Lamb and Erika Winter (Winetitles, Adelaide). However, in summary, we note the following:

- The most easily accessible information is remotely sensed imagery. No special software and skills are needed to view the results. However, it has to be remembered that the imagery (commonly shown as PCD and/or NDVI values) is only qualitative and will need to be quantified by ground truthing.
- Yield monitors with dGPS connection allow georeferenced recording of yield during vintage and therefore gather quantitative data directly. The analysis of yield data and production of maps requires some special software and knowledge which can be outsourced if necessary. The yield monitoring and dGPS equipment for the harvester needs to be rented, bought or acquired as part of the service provided by a harvesting contractor.
- Soil surveys using soil sensing equipment such as the EM38 are especially recommended when it is suspected that observed variation in vine performance might be linked to soil variability. EM38 soil survey is now readily available from a number of contractors. Note that if the EM38 signal is to be related to specific soil properties, it will be necessary to conduct some soil sampling and analysis.
- Digital elevation models are very often useful in explaining observed variability. Again, a number of contractors are able to provide these, often in tandem with soil survey.

The collection of some base data before the experiment/trial is established will also help to delineate potential performance classes (PPC) or management zones within the vineyard and may also permit observation of treatment effects over time.

Design

Because the major focus when analysing experimental results will be on the estimation of treatment differences employing geostatistical procedures, certain issues need to be considered when designing the experiment.

- Systematic designs are more suitable than randomized designs. Note that statisticians who are not trained in spatial statistics will tend towards randomized designs. Thus, if help in designing a whole of block experiment is needed, growers should make sure that, in addition to being a good statistician, the person they are seeking help from has a good understanding of geostatistics and of the philosophy behind the whole of block experimental approach.
- Some areas of the block might need to be excluded from data analysis because of the effects of external factors or the combined effects of more than one treatment – for example, when spray drift or severe frost occurs, or when the treatments are applied in the mid-row. In the latter case, some rows will have different treatments either side of them and so will have to be excluded from the analysis of single treatment effects (Figure 1).
- Too many treatments can cause problems in the data analysis if treatment replicates are distanced too far from each other. In general, 2-4 treatments are appropriate for this kind of experiment, but careful consideration needs to be given to how many rows each treatment will be applied to. In the case of an experiment comparing different canopy management strategies, when each treatment is only one row wide and replicated throughout the block, the experimenter might be able to compare 4 different canopy management strategies, even though 3 would be a 'safer' and a simpler option. However, in an experiment comparing different mid-row management strategies, treatments will need to be at least two mid-rows wide, with collection of experimental data from the single row in between these. For obvious reasons, a smaller amount of useful data can be collected from this type of experiment than would be the case in a canopy management experiment because some rows will have each treatment either side of it (Figure 1). Thus, to minimize the 'loss' of useful data which arises from rows with different treatments on either side, the experimenter might consider the application of each treatment to 'strips' comprising 3 or 4 mid-rows. To ensure that spatial correlations between replicates can still be readily derived from such experiments, we recommend that no more than 2-3 treatments should be applied. On highly variable blocks with short range variability (ie where the variation occurs over short distances), 2 treatments might be the limit.
- Splits along the row (Figure 1) are only necessary if the pre-experiment vineyard variability shows obvious row effects.

For the geostatistical evaluation of treatment differences, all data recorded need to be georeferenced by differentially corrected GPS. In addition, the following points also need to be considered:

- Data recorded at high spatial density, such as yield monitor data, need to be carefully screened; data which can not be clearly identified to a specific treatment, perhaps due to positional errors arising from the GPS, should be discarded.
- Manually recorded data, such as bunch counts or measures derived from samples collected by hand (eg titratable acidity), must be collected from at least 100 locations (or vines) per treatment for the spatial analysis to be robust. It is desirable to have these data collected from points that are reasonably systematically distributed over the whole block, with the exception of about 15-20 % of the sampling points which should be in close proximity to another sampled location (Figure 2). If the sampling locations for the first treatment are specified, the sample location for the other treatments should be located close to the ones from the first treatment, as this facilitates an important aspect of the spatial analysis of treatment effects.

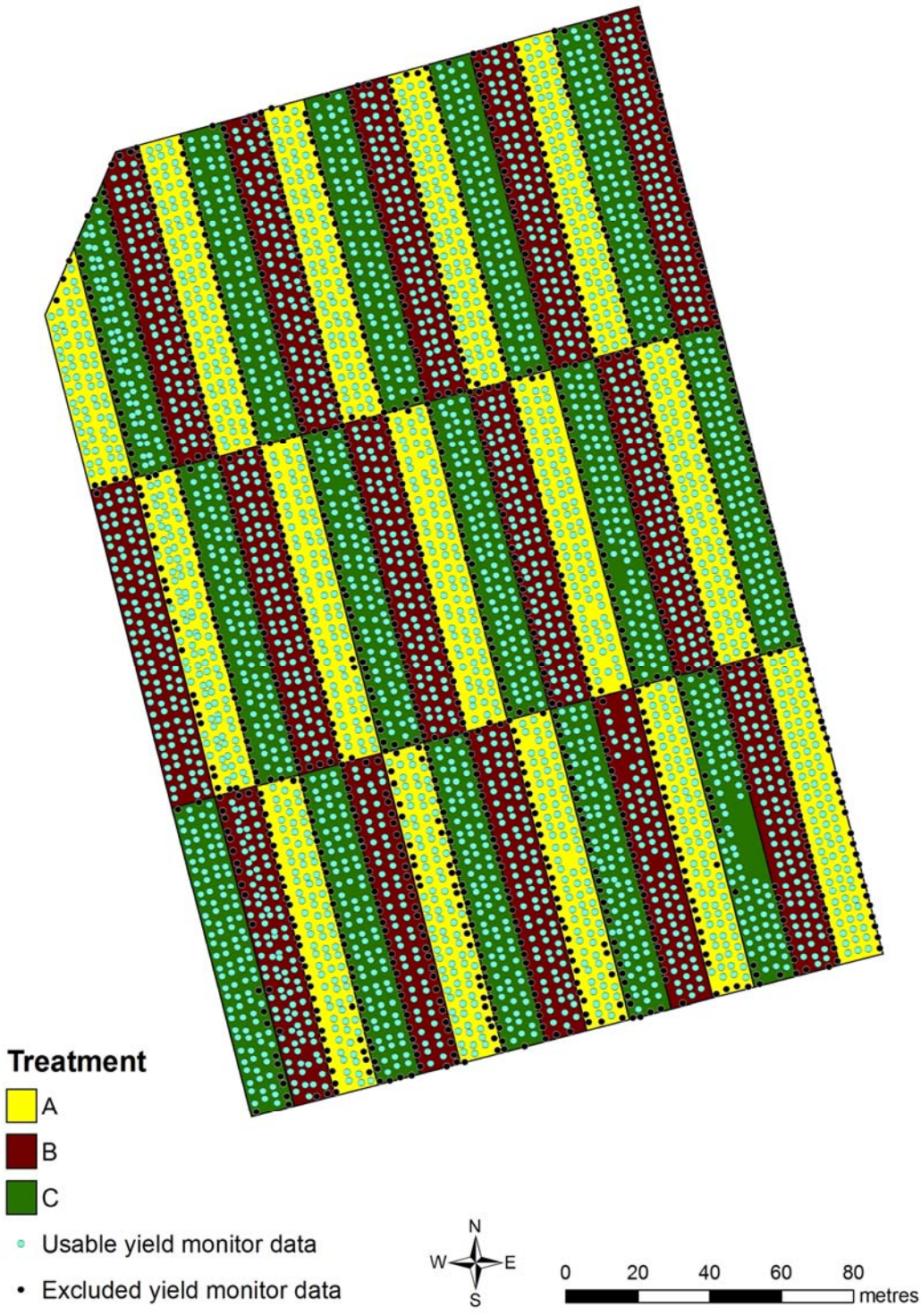


Figure 1. Data exclusion in mid-row experiments. In this example, the treatment strips are 4 mid-rows wide. As a result, every 4th row has different treatments either side of it and so the data for those rows (in this case collected by a yield monitor) need to be excluded from the analysis of treatment effects. In this example, a 1.5 m buffer has been applied in GIS to each treatment area (rows are 3 m wide) and data points outside the buffer have been excluded. Care is needed with this procedure however, as it can lead to useful data being inadvertently excluded – as is illustrated here. An alternative, more precise, but more time consuming method would be to include/exclude data on a row by row basis according to the actual alignment of rows with treatments.

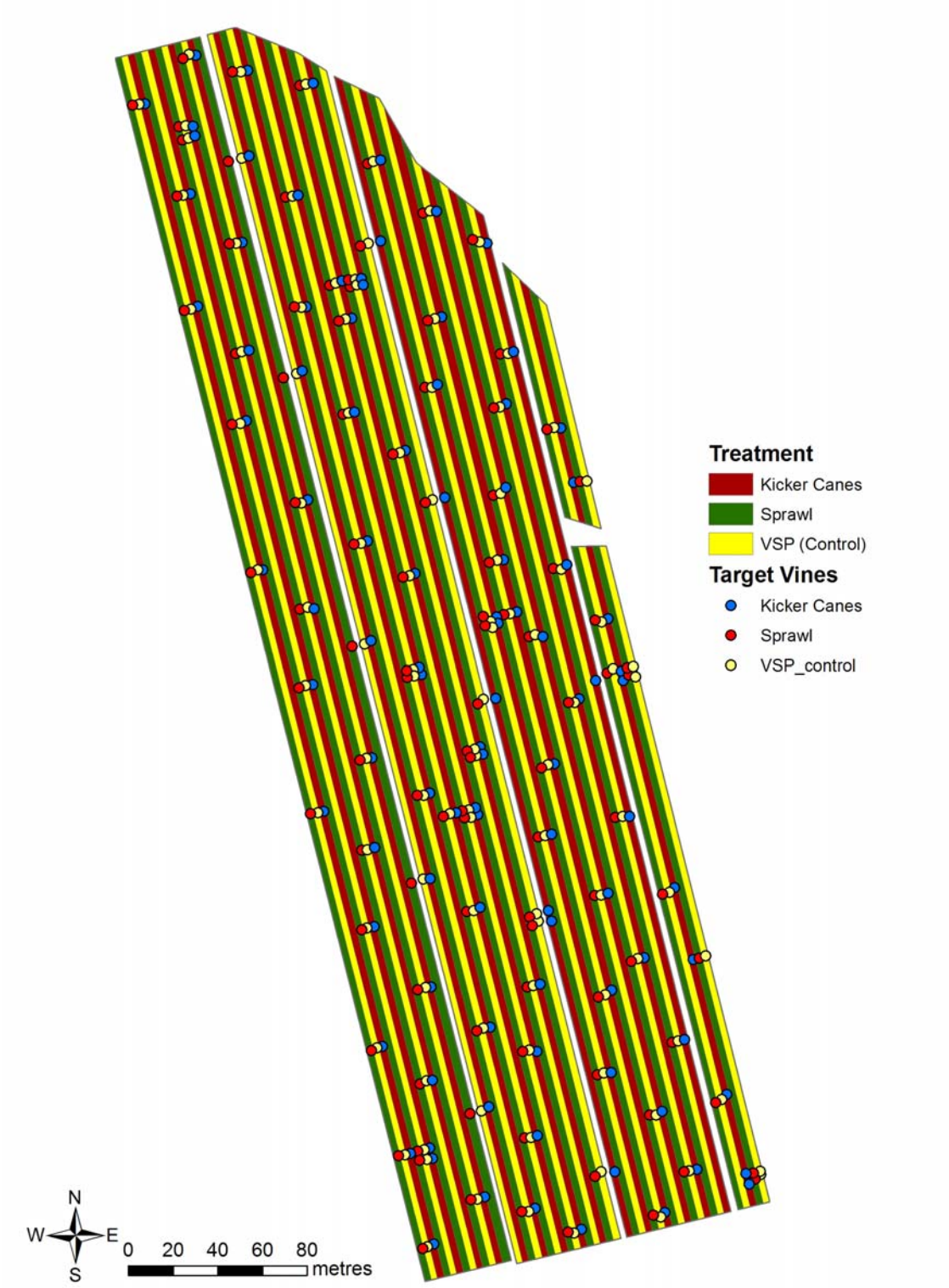


Figure 2. An example of a whole of block experiment showing the location of 'target vines'. In this example, different canopy management strategies were being evaluated for effect on fruit quality – which is why, in the absence of an on-the-go fruit quality sensor, target vines were needed at all. Note that target vines for one treatment are located close to those for others, and that some 'sets' of target vines have been placed close to others, even though the overall sampling design is regular. Note also that, because this is a canopy management experiment in which a treatment in one row has no effect on another, each treatment strip is only one row wide.

Further considerations

Temporal variability can only be evaluated by experiments applied over more than one season. Unlike annual crops such as grains, it is possible for the same vines to be re-sampled in consecutive years. Even though vine to vine variation may be large, year to year comparison of the *same* vines is certainly beneficial. It is therefore valuable to mark the sample locations carefully for further sampling. We have found cattle tags loosely attached to vine trunks to be useful for marking vines.

Data analysis

It is beyond the scope of this note to provide a detailed guide on data analysis. A simple method of data analysis involves the production of treatment-specific maps followed by comparison of these in GIS using simple map algebra. However, the more sophisticated procedure described in the Final Report on GWRDC Project No. CSL06/03 is preferred. In the course of time, we hope that software which guides the entire data analysis process will be available. It is strongly recommended that growers wishing to analyse whole of block experiments enlist the assistance of an experienced spatial statistician (sometimes called a *geostatistician*) – preferably one with a good understanding of Precision Agriculture.