TERROIR AND PRECISION VITICULTURE: ARE THEY COMPATIBLE ?

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Abstract

Aims: The aims of this work were to see whether the traditional regionally-based view of terroir is supported by our new ability to use the tools of Precision Viticulture to acquire detailed measures of vineyard productivity, soil attributes and topography at high spatial resolution.

Methods and Results: A range of sources of spatial data (yield mapping, remote sensing, digital elevation models), along with data derived from hand sampling of vines were used to investigate within-vineyard variability in vineyards in the Sunraysia and Padthaway regions of Australia. Zones of characteristic performance were identified within these vineyards. Sensory analysis of fruit and wines derived from these zones confirm that contrasting wines may derive from different areas within the same, uniformly-managed vineyard.

Conclusions: The performance of vineyards is variable whether yield, fruit quality, wine quality, wine style or value is the measure of interest. The tools of Precision Viticulture enable both growers, winemakers and researchers to see that within vineyards deemed characteristic of a region, terroir is spatially variable at the within-vineyard scale.

Significance and impact of the study: Whilst precision viticulture raises questions about the utility of the concept of terroir at regional scales, it has much to offer in promoting robust understanding of the impacts of soil and land attributes on grape and wine production, and thus, how management practices might be modified to gain greater control over fruit and wine quality. Accordingly, at least some of the elements of terroir can be considered to be manageable.

Keywords: vineyard variability, grape yield, wine quality, spatial scale, Australia

Résumé

Objectifs : Les objectifs de ce travail sont de montrer si la façon traditionnelle d’appréhender le terroir à l'échelle régionale est confirmée par notre nouvelle capacité à utiliser les outils de la viticulture de précision afin d’obtenir des mesures détaillées sur la productivité du vignoble, les variables du sol et la topograhie à haute résolution spatiale.

Méthodes and résultats : Différentes sources de données spatiales (cartographie des rendements, télédétection, modèle numérique de terrain) ainsi que des données provenant d’échantillonnage manuel de vignes ont été utilisées pour étudier la variabilité des vignobles de Suraysia et de Padthaway, régions d’Australie. Des zones de comportement caractéristique ont été identifiées à l’intérieur de ces vignobles. Les analyses sensorielles des fruits et des vins provenant de ces zones confirment que des vins contrastés peuvent provenir de différentes zones à l'intérieur d’une même parcelle conduite uniformément.

Conclusions : La performance des vignobles est variable en ce qui concerne le rendement, la qualité du fruit et du vin, le style du vin ou sa valeur. Les outils de la viticulture de précision permettent aux producteurs, aux vinificateurs and aux chercheurs de voir qu’à l’intérieur même des vignobles considérés comme caractéristiques d’une région, le terroir est variable spatialement à l’échelle intra-parcellaire.

Signification and impact de l’étude : Alors que la viticulture de précision soulève des questions sur l’utilité du concept du terroir à l’échelle régionale, elle a beaucoup à offrir en favorisant une forte compréhension des effets du sol et des caractéristiques du terrain sur la production de raisins et de vins, et de ce fait, comment les pratiques du management pourraient être modifiées, afin de mieux contrôler la qualité du fruit et du vin. En conséquence, au moins certains éléments du terroir peuvent être considérés comme modulable par la gestion technique du vignoble.

Mots clés : variabilité du vignoble, rendement, qualité du vin, échelle spatiale, Australie

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INTRODUCTION

Recent research conducted in Australian vineyards 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). This work, and the associated development of Precision Viticulture (Bramley and Proffitt, 1999), 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.*, 2005).

It is not unreasonable to ask whether we should be surprised by these results ? After all, the fact that land is variable, irrespective of the scale of inspection, is well understood. Thus, no two vineyards are the same, no two wine regions are the same and neither, of course, are any two wine producing countries (Figure 1). One consequence of this variation is that some connoisseurs of wine are readily able to discriminate between wines of differing origin. Herein lies at least a part of the basis for the concept of *terroir* (eg Seguin, 1986) or *sense of place* (eg Goode, 2005) - the English equivalent gaining increasingly common usage - and in particular, its use as a means of establishing a point of difference in an increasingly competitive marketplace.

Of course, at the local and property scale, grapegrowers and winemakers have known that vineyards are variable for as long as they have been growing grapes and making wine. But in the absence of the tools of Precision Viticulture (PV), which now allow them to observe, quantify, precisely locate and react to the variation, they have had to treat it as *noise* (Cook and Bramley, 1998), and so have managed large blocks as though they were uniform. The wine industry therefore faces an interesting paradox. On the one hand, and in spite of some acknowledgment of the importance of issues of scale to terroir (Vaudour, 2002; Deloire *et al.*, 2005), much is made of the gross variations between vineyards and regions (eg Laville, 1990) which lead to relatively subtle differences between wines; this is especially so in so-called Old-World winegrowing countries such as France. On the other hand, what may be quite large variations at the local, vineyard and block scales have tended to be ignored or masked.

Work conducted in France (Tisseyre *et al.*, 2001), Spain (Arno *et al.*, 2005), Chile (Ortega and Esser, 2003) and the USA (Cortell *et al.*, 2005) suggests that vineyard variability is not a peculiarly Australian phenomenon. Indeed, the work of Taylor *et al.* (2005) suggests that there are strong similarities between the vineyards of Europe and Australia in terms of their spatial variability. This should be no surprise given that in all the aforementioned (and other) Australian examples, variation in vineyard performance has been closely related to variation in topography and/or soil properties (Bramley, 2003; Bramley and Hamilton, 2005 and references therein), a finding which raises questions as to the utility of the concept of terroir.

Clearly, the traditional view of terroir being reflective of soil and land attributes (Seguin, 1986; Laville, 1990; van Leeuwen *et al.*, 2004) is appropriate; but at what scale is it appropriate ? For example, does the wine produced from the vineyard shown in Figure 1a most reflect the terroir of this particular vineyard, or of either the region

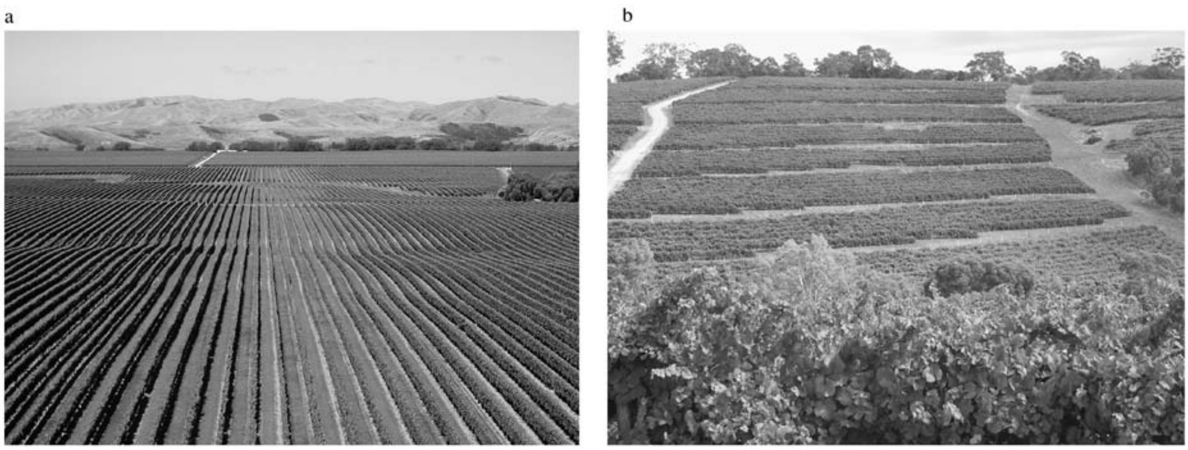

Figure 1. Contrasting vineyards from (a) the Marlborough region of New Zealand, and (b) the Eden Valley, Australia.

(Marlborough) or country (New Zealand) in which it is located ? If, as some purists might argue, the answer is “this particular vineyard”, it is then legitimate to ask whether the wine reflects this vineyard in terms of its dominant gravely soils, the silty hollows which dissect them, or some integration of the two ?

Similarly, given that there is more than 100 m difference in elevation between the top and bottom of the slope shown in Figure 1b, it is legitimate to ask in what respects wines produced from the uppermost, or lowest blocks on the slope, are reflective of the terroir of the Eden Valley as a whole ? Clearly, the vineyards shown in Figure 1 are markedly different, but is it sensible to ignore the differences within them ? This latter question is the main focus of this paper and is considered using examples from the Padthaway and Sunraysia grapegrowing regions of Australia.

MATERIALS AND METHODS

Two vineyards were used for this work. The first is a 4.3 ha vineyard in the Padthaway region of South Australia which was planted to Shiraz (own roots) in 1971. This site is characterised by a 1.8 m deep hollow (approximately 0.8 ha) in its centre, which is thought to be due to a sink-hole in the underlying limestone. The soils at this site are a mix of red and black sandy clay loams; the black soils predominate in the hollow, whilst the red soils, which are somewhat similar to the terra rossa soils of the Coonawarra region, predominate throughout the remainder of the block. The mean daily maximum and minimum January temperatures for Padthaway are 28.1 and 12.0°C, whilst the mean annual rainfall is 502 mm, most of which falls in winter when the vines are dormant. Accordingly, the vineyard is irrigated as required, typically receiving 0.4 ML irrigation ha^{-1} y^{-1} via a drip system.

The second vineyard is a 12 ha vineyard in the Sunraysia region of north-west Victoria which was planted to Cabernet Sauvignon in 1994. Of particular interest in this study is an 8.2 ha section which was planted on own roots; the remaining 4 ha is on a range of rootstocks and was not used for this study. Sunraysia is considered to be a warm, dry region, with mean daily maximum and minimum January temperatures of 32.0 and 16.5°C. Mean annual rainfall is only 289 mm and irrigation is therefore essential; approximately 5 ML ha^{-1} y^{-1} is applied. Soils at this site are duplex, comprising sandy topsoils of varying depths (20-70 cm) over calcareous clay subsoils.

A mix of spatial data were collected at both sites. Remotely sensed digital multispectral video imagery (Hall *et al.*, 2002) was collected at veraison (Lamb *et al.*, 2004) for the Padthaway site in 2001, 2005 and 2006 and for the Sunraysia site in 2004, 2005 and 2006. In both cases, the so-called Plant Cell Density index (PCD) was used; that is, the ratio of reflected infrared:red light (PCD = NIR/R) which gives a surrogate measure of vine vigour (Hall *et al.*, 2002). Yield mapping was carried out at Padthaway in 1999, 2004 and 2006, and in 2004-2006 in Sunraysia, using mechanical harvesters fitted with a differentially corrected global positioning system (dGPS; accurate to approximately ± 50 cm in the horizontal planes) and either a HarvestMaster™ or Farmscan™ yield monitor, or a modified HarvestMaster™ system in which the sonic beam yield sensors were replaced with a weigh frame and load cells. Yield maps were produced following the protocol of Bramley and Williams (2001) and Bramley (2005). Both sites were also surveyed with a real-time kinematic GPS (RTK; accurate to approximately ± 2 cm in both horizontal and vertical planes) from which digital elevation models were derived using the TOPO to RASTER command in ArcGIS (ESRI, 2005) which is based on the ANUDEM model of Hutchinson (1989). Further details of the methods of spatial and statistical analysis used in this work are given in Bramley and Hamilton (2004) and Bramley (2005); JMP (SAS, 2005) was used for statistical analysis.

Immediately prior to vintage, measurements were made of a number of vine and fruit attributes on a 1 m section of row centred on the trunks of a selected number of geo-referenced target vines. In Padthaway (vintage 2004, 2005 and 2006), 10 randomly-chosen target vines were identified in both the hollow and remainder of the block and measurements made of yield, bunch number and the mean berry weight (from which mean bunch weight and the number of berries per bunch were calculated). Baumé, juice pH, titratable acidity (TA) and the concentrations of colour and phenolics were also analysed using standard methods (Iland *et al.*, 2000). The two sets of samples were collected on the same day. In Sunraysia (vintage 2005 and 2006), a different sampling strategy was used. Here, the target vines were located in zones of characteristic performance (Bramley and Hamilton, 2004, 2005; Bramley, 2005) identified by *k*-means clustering of the data underlying the yield maps and PCD imagery obtained in 2004 and 2005. Clustering solutions for 2-5 clusters were produced and the solution with the greatest number of significant differences between cluster means in the different years was used as the basis for dividing the vineyard into zones of characteristic performance. In this way, low vigour/low yield and high vigour/high yield areas were identified in which a number of randomly-chosen target vines were located. Twelve bunches were randomly sampled from each target vine with 6 taken from either side of the row. These were analysed in a similar way to the Padthaway samples. In addition to the vine and fruit sampling at the Sunraysia site, a 200 kg sample of fruit was harvested from within each zone and used for small-lot winemaking (50 kg ferments in triplicate) following a standardised winemaking protocol. For both the target vine and winemaking samples, sampling in the low vigour/low yield and high vigour/high yield zones was done with a view to sampling at a constant target maturity of 24 °brix (13.3 °Bé). This meant that in both 2005 and 2006, sampling of the high vigour/high yield zone took place approximately one week after sampling of the low vigour/low yield zone.

RESULTS

Both the Padthaway and Sunraysia vineyards were spatially variable with respect to both yield and vigour (figures 2 and 3). Consistent with earlier work, which shows soil and topographic variation to be a key driver of vineyard variability (Bramley, 2003, 2005a,b; Bramley and Hamilton, 2004, 2005), the patterns of variation were closely associated with the underlying topographic variation (Figure 4) and, as a consequence, were stable in time (Figures 2 and 3). Thus, at Padthaway, greater vine vigour and higher yields were seen in the hollow (Figures 2 and 4a), which acts as a natural drainage feature in which the black soils remain moist for longer into the season than the red soils in the remainder of the block. In addition to increased yield and vine vigour, vines in the hollow were also characterised by significantly greater bunch and berry weights compared to the rest of the block (Table 1), and had less mature fruit at vintage with significantly lower concentrations of colour and phenolics (except in 2006 - discussed below). Of greatest

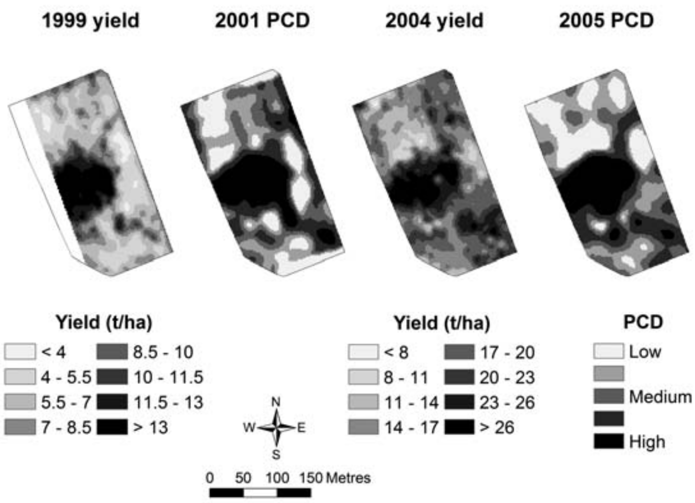

Figure 2. Variation in a 4.3 ha Padthaway vineyard with respect to yield and vigour (PCD), 1999-2005.
In the case of the imagery, the colour ramp is stretched over the full range of PCD values in any given year. Thus, the absolute values for low, medium and high will vary from year to year.

Table 1. Zone-based means for selected vine and fruit properties at the Padthaway site sampled from the high yield/high vigour (H) and low yield/low vigour (L) zones shown in Figure 4[A].

	2004			2005			2006		
	H	L	Sig[B]	H	L	Sig[B]	H	L	Sig[B]
Yield (kg)	12.4	8.5	**	9.5	4.3	***	6.0	4.3	*
No. Bunches	111	117	ns	109	83	*	86	80	ns
Bunch weight (g)	112.1	76.2	**	85.1	51.9	***	69.6	54.2	*
Berry weight (g)	1.30	0.90	***	1.40	1.06	***	1.18	0.99	***
Berries / bunch	86	83	ns	61	49	**	58	55	ns
Baumé	12.3	13.6	***	13.0	14.3	**	14.0	14.6	***
pH	3.93	3.33	ns	3.25	3.29	*	3.31	3.38	***
TA (g/L)	6.30	7.51	**	8.62	8.10	ns	6.86	5.77	***
Colour (mg/g)	1.13	1.82	***	1.26	1.89	***	1.51	1.75	*
Phenolics (a.u/g)	0.81	1.21	***	0.99	1.35	***	1.13	1.25	ns
Winemaker assessment	C	high B		D	A				

A: Data reported are the means of samples collected a few days prior to vintage from a metre of vine row centred on the trunk of target vines. Ten randomly located vines were sampled in each of the zones shown in Figure 4a.
B: Statistical significance based on Students t-test where ***, **, * and ns indicate $p<0.001$, $p<0.01$, $p<0.05$ and no significant difference ($p>0.05$).

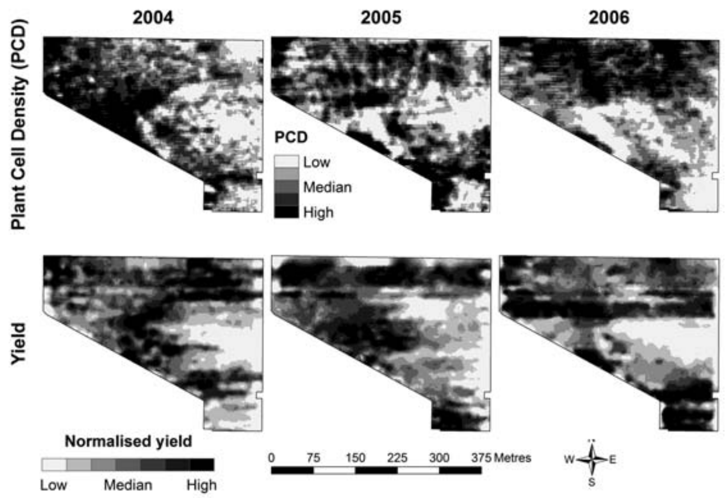

Figure 3. Variation in an 8.2 ha Sunraysia vineyard with respect to yield and vigour (PCD), 2004-2006.
Note that the yield maps have been normalised ($\mu=0, \sigma=1$) to accommodate the effects of inter-annual variation. The mean yields in 2004 and 2005 were 20.2 and 17.5 t ha-1. In the case of the imagery, the colour ramp is stretched over the full range of PCD values in any given year. Thus, the median and absolute values for low and high will vary from year to year.

Table 2. Zone-based means for selected vine, fruit and wine properties at the Sunraysia site sampled from the high yield/high vigour (H) and low yield/low vigour (L) zones shown in Figure 4[A].

	2005			2006		
	H	L	Sig[B]	H	L	Sig[B]
Harvest date	Mar 7	Feb 27		Mar 2	Feb 21	
Bunch weight (g)	78.4	68.4	ns	111.7	79.7	***
Berry weight (g)	0.91	0.88	ns	1.05	1.03	ns
Berries / bunch	86	77	*	106	77	***
Baumé	13.4	13.9	**	13.6	13.6	ns
pH	3.56	3.47	*	3.54	3.53	ns
TA (g/L)	7.93	6.71	***	6.96	6.39	*
Colour (mg/g)	1.20	1.35	*	0.84	1.28	***
Phenolics (a.u/g)	1.13	1.24	*	1.05	1.40	***

A: Data reported are the means of samples collected a few days prior to vintage from a metre of vine row centred on the trunk of target vines. Vines were sampled in each of the zones shown in Figure 4a. In 2005, the number of vines sampled was 6 (H)and 11 (L) whilst 13 vines were sampled in each zone in 2006.
B: Statistical significance based on Students t-test where ***, **, * and ns indicate p<0.001, p<0.01, p<0.05 and no significant difference (p>0.05).

significance however, was the winemaker's sensory assessment of the fruit immediately prior to harvest (Table 1). This was such that in both 2004 and 2005, fruit from the hollow was considered of sufficiently lower quality than that in the remainder of the block to warrant implementation of a selective harvesting strategy with fruit from the two zones assigned to different product streams. Bramley and Hamilton (2005) and Bramley *et al.* (2005) describe how this was done and discuss the economic implications of this strategy. Suffice to say here that it delivered significant economic benefits with respect to both grapegrowing and especially winemaking, given that in 2004 for example, the C grade fruit from the hollow could be expected to go into a product which sells for approximately \$14 bottle^{-1} whilst the wine made from the high-B grade fruit in the remainder of the block would sell for approximately \$24.50 bottle^{-1}. Had the block been harvested as a single unit, the fruit would have been assigned to a low-B grade product stream; that is, a wine with a retail value of approximately \$18 bottle^{-1}.

At Sunraysia (Figures 3 and 4b), there were similar differences between the low and high yielding zones with respect to selected indices of vine performance and fruit quality (Table 2). Furthermore, descriptive sensory analysis of the 2005 wines, conducted using a trained panel (Drs Ciarán Forde and Patrick O'Riordan, Food Science Australia - personal communication), indicates that the two zones produced markedly different wines. That from the low yielding, low vigour zone on higher ground with shallower, sandier soils was perceived to have greater colour intensity, aroma impact, pepper, spice

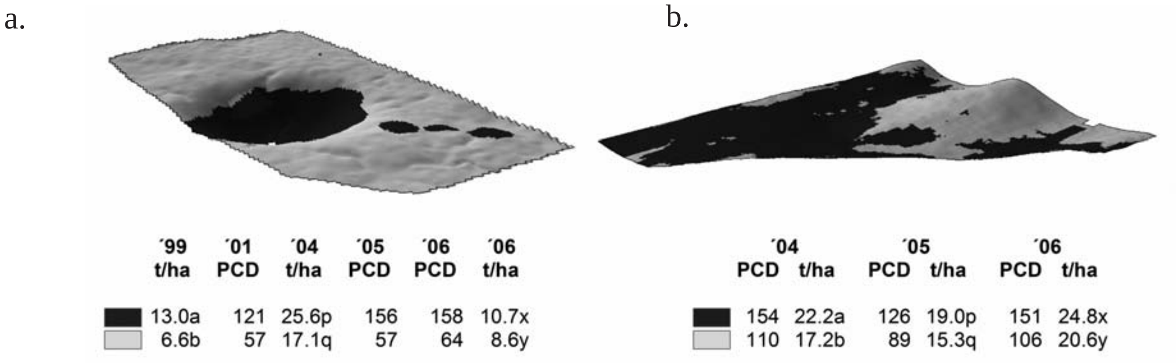

Figure 4. Topographic variation in vineyards in (a) Padthaway (4.3 ha) and (b) Sunraysia (8.2 ha), and zones of characteristic performance identified through *k*-means clustering of yield maps and remotely sensed imagery. The legends indicate the mean values for yield and PCD in each zone and year. In the case of yield, numbers not connected by the same letter are significantly different ($p<0.05$). The range of elevation (lowest to highest point) was approximately 2.2 m in Padthaway and 4.6 m in Sunraysia.

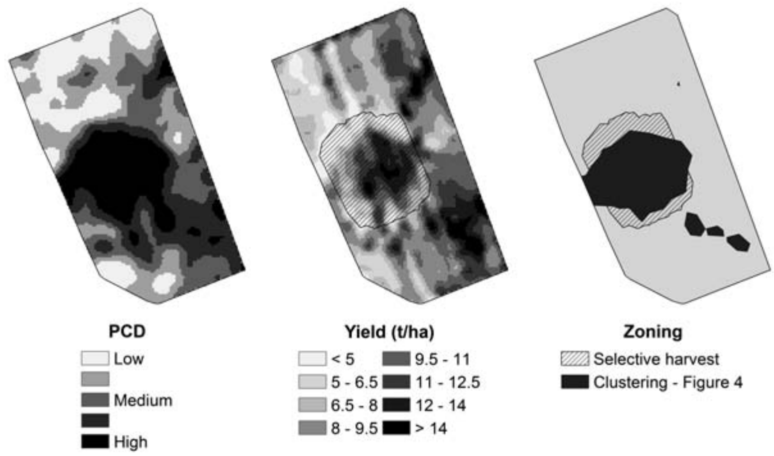

Figure 5. Vine vigour (PCD), yield and zonation in a 4.3 ha Padthaway vineyard, 2006. The right hand map shows the delineation of the high yielding zone based either on the selective harvesting strategy used or *k*-means clustering as in Figure 4. For operational simplicity during harvesting, the boundary of the high yielding zone in the hollow was delineated by sight by the harvesting staff and recorded using a marker in the yield monitor file.

and tobacco flavours and a stronger after-taste or finish than the wine made from the high vigour zone. The latter was characterised as having a more earthy aroma and a much weaker after-taste.

Overall, one might summarise these results by saying that the terroir of both vineyards is spatially variable, and that this variability is matched by variation in the wines produced from different zones within them.

At the Padthaway site, prior to vintage 2004, the vineyard manager planted lucerne in the mid-row in the hollow in an attempt to *pump out* the excess soil moisture in this area and thus, minimise its impact on vine vigour and yield. As Figure 2 and Table 1 suggest, this strategy delivered no benefit in either 2004 or 2005; note that 2004 was an inherently higher yielding year. The remotely sensed imagery obtained at veraison in 2006 (Figure 5) suggests that no benefit accrued from the lucerne in 2006 either, even though by this time, it was very well established. However, the 2006 yield map suggests that in fact, the lucerne did deliver a significant benefit. Thus, around the perimeter of the hollow, where the excess of soil moisture compared to the remainder of the block is presumably much less than in its deepest parts, the yield has been substantially reduced (Figure 5). This effect is highlighted by the difference between the delineation of the high yielding hollow based on *k*-means clustering of the data (Figure 4a) and identification of the hollow by harvesting staff (Figure 5). In other words, in 2006 the high vigour/high yielding zone is smaller than the hollow as defined by variation in elevation. Indeed, and in contrast to the result shown in Figure 4a, there is no significant difference ($p>0.05$) between the mean yield of the hollow and remainder of the block when the elevation-based delineation of the hollow is used. Imprecise zone delineation may also be the reason for the much reduced difference between the target vines in the hollow compared to the remainder of the block in terms of the concentrations of phenolics and colour in the fruit (Table 1), bearing in mind that the same target vines were used in each year of the study. However, a very hot period during January - a critical flavour development stage - may also have been the cause of thes generally lower quality of both parcels. Thus, whilst the assessment of fruit quality conducted by the winemaker suggested that the two parcels were different in their sensory attributes, resulting in them being assigned to different products, these were at the same price point in marked contrast to 2004 and 2005 (Table 1). Overall however, the 2006 results suggest that the planting of lucerne has been effective in reducing the gross differences between the hollow and the remainder of the block in terms of both yield and the quality of fruit and wine.

DISCUSSION

Clearly, the performance of vineyards is variable whether yield, fruit quality, wine quality, wine style or value is the measure of interest. It is ironic that in Old-World countries where great importance is attached to terroir, and where considerable tradition is attached to both grapegrowing and winemaking, its impacts have, in the main, only been considered at regional scales (eg Laville, 1990), as a consequence of which, few cause and effect relationships between soil and land attributes and wine characteristics have been established. Indeed, the lack of importance attached to vine nutrition with respect to fruit and wine quality (Seguin, 1986) may be a direct consequence of investigating this issue at regional scale. Similarly, the pre-occupation with the effect of soil hydrological properties on wine style and quality (Seguin, 1986; van Leeuwen *et al*., 2004) may be, at least to some extent, an artefact of the prohibition of irrigation in many Old-World regions. On the other hand, “scant attention” has been paid to soil and its complex interaction with winegrapes in the New World (White, 2003), in spite of a more liberal approach to adoption of new technologies, such as soil moisture monitoring, and the associated opportunity for advancing understanding. The results for Padthaway in 2006 are therefore important because they strongly suggest that at least some elements of terroir may be manageable. Further work in this study will examine vine, fruit and wine differences with respect to specific soil properties and vine nutrient status.

As the present results indicate, the tools of Precision Viticulture enable both growers, winemakers and researchers to see that terroir may vary within vineyards. Indeed, vineyards producing wines that are deemed characteristic of a region, may in fact be capable of producing contrasting wines from different areas within the same management units. As White (2003) suggests, the true influence of terroir can only be satisfactorily studied for small areas mapped at large scale, an idea that is strongly supported by the results presented here. Furthermore, such studies, supported by the use of Precision Viticulture, may promote development of a more robust digital terroir function than the regionally derived site index of Tesic *et al*. (2002); the recent work of Taylor (2004) strongly supports this view. Thus, whilst precision viticulture raises questions about the utility of the concept of terroir at regional scales, it has much to offer in promoting robust understanding of the impacts of soil and land attributes on grape and wine production, and thus, how management practices might be modified to gain greater control over fruit and wine quality, and indeed, over at least some of the aspects of terroir. It may therefore also offer Old World producers the opportunity to refine wines from terroir-based classifications to more regularly meet the expectations for the region from season to season.

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REFERENCES

ARNO J., BORDES X., RIBES-DASI M., BLANCO R., ROSELL J.R. and ESTEVE J., 2005. Obtaining grape yield maps and analysis of within-field variability in Raimat (Spain). *In: Stafford, J.V. (Ed) Proceedings of the 5th European Conference on Precision Agriculture*. Wageningen Academic Publishers, The Netherlands. p. 899-906.

BRAMLEY R., 2003. Smarter thinking on soil survey. *Aust. NZ Wine Ind. J.*, **18** (3), 88-94.

BRAMLEY R.G.V. 2005a. Understanding variability in winegrape production systems. 2. Within vineyard variation in quality over several vintages. *Aust. J. Grape and Wine Res*., **11**, 33-42.

BRAMLEY R.G.V., 2005b. Acquiring an informed sense of place - Practical applications of precision viticulture. *Proceedings of the 11th Romeo Bragato conference*, 25-27 August, 2005, Gisborne, New Zealand. New Zealand Winegrowers, Auckland. This paper is also available in *Aust. NZ Wine Ind. J.*, **21** (1), 26-33.

BRAMLEY R., 2005. A protocol for the construction of yield maps from data collected using commercially available grape yield monitors. *Supplement N° 1. February 2005. http://www.clw.csiro.au/staff/BramleyR/documents/protocol_supp1.pdf*

BRAMLEY R.G.V. and HAMILTON R.P., 2004. Understanding variability in winegrape production systems. 1. Within vineyard variation in yield over several vintages. *Aust. J. Grape and Wine Res*., **10,** 32-45.

BRAMLEY R.G.V. and HAMILTON R.P., 2005. Hitting the zone - Making viticulture more precise. *In: Blair, R.J, Williams, P.J. and Pretorius, I.S. (Eds) Proceedings of the 12th Australian Wine Industry Technical Conference*. Winetitles, Adelaide. p. 57-61.

BRAMLEY R.G.V. and PROFFITT A.P.B. 1999. Managing variability in viticultural production. *Grapegrower and Winemaker*, **427**, 11-16. July 1999.

BRAMLEY R.G.V., PROFFITT A.P.B., HINZE C.J., PEARSE B. and HAMILTON R.P., 2005. Generating benefits from Precision Viticulture through selective harvesting. *In: Stafford, J.V. (Ed) Proceedings of the 5th European Conference on Precision Agriculture*. Wageningen Academic Publishers, The Netherlands. p. 891-898.

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

COOK S.E. and BRAMLEY R.G.V., 1998. Precision agriculture - Opportunities, benefits and pitfalls. *Aust. J. Exp. Agric.*, **38**, 753-763.

CORTELL J.M., HALBLEIB M., GALLAGHER A.V., RIGHETTI T.L. and KENNEDY J.A., 2005. Influence of vine vigor on grape (*Vitis vinifera* L. cv. Pinot Noir) and wine proanthocyanidins. *J. Agric. Food Chem*., **53**, 5798-5808.

DELOIRE A., VAUDOUR E., CAREY V., BONNARDOT V. and van LEEUWEN C., 2005. Grapevine responses to terroir: A global approach. *J. Int. Sci. Vigne Vin*, **39**, 149-162.

ESRI, 2005. ArcGIS Desktop v9.1. *Environmental Systems Research Institute*, Redlands, CA, USA.

GOODE J., 2005. *The science of wine: From vine to glass*. University of California Press, Berkeley.

HALL A., LAMB D.W., HOLZAPFEL B. and LOUIS J., 2002. Optical remote sensing applications in viticulture - a review. Aust. *J. Grape and Wine Res.*, **8**, 36-47.

HUTCHINSON M.F., 1989. A new procedure for gridding elevation and stream line data with automatic removal of spurious pits. *J. Hydrol.*, **106**, 211-232.

ILAND P., EWART A., SITTERS J., MARKIDES A. and BRUER N., 2000. *Techniques for chemical analysis and quality monitoring during winemaking*. Patrick Iland Wine Promotions, Campbelltown, South Australia.

LAMB D.W., WEEDON M.M. and BRAMLEY R.G.V., 2004. Using remote sensing to map grape phenolics and colour in a Cabernet Sauvignon vineyard - the impact of image resolution and vine phenology. *Aust. J. Grape and Wine Res.*, **10**, 46-54.

LAVILLE P., 1990. Le terroir, un concept indispensable à l'élaboration et à la protection des appellations d'origine comme à la gestion des vignobles: le cas de la France. *Bull. O.I.V*. 709-710, 217-241.

ORTEGA R. and ESSER A., 2003. Precision Viticulture in Chile: Experiences and potential impacts. *In: Ortega, R. and Esser, A. (Eds) Precision Viticulture*. Proceedings of an international symposium held as part of the IX Congreso Latinoamericano de Viticultura y Enologia, Chile. Centro de Agricultura de Precisión, Pontificia Universidad Católica de Chile, Facultad de Agronomía e Ingenería Forestal, Santiago, Chile. p. 9-33.

SAS, 2005. JMP Version 6. SAS Institute Inc. Cary, NC, USA.

SEGUIN G., 1986. Terroirs and pedology of wine growing. *Experientia*,**42**, 861-873.

TAYLOR J. A., 2004. Digital terroirs and Precision Viticulture: Investigations into the application of information technology in Australian vineyards. *PhD thesis*. Faculty of Agriculture, Food and Natural Resources, The University of Sydney. www.usyd.edu.au/su/agric/acpa/pag.htm.

TAYLOR J., TISSEYRE B., BRAMLEY R. and REID A., 2005. A comparison of the spatial variability of vineyard yield in European and Australian production systems. In: Stafford, J.V. (Ed) *Proceedings of the 5th European Conference on Precision Agriculture*. Wageningen Academic Publishers, The Netherlands. p. 907-914.

TESIC D., WOOLLEY D.J., HEWETT E.W. and MARTIN D.J., 2002. Environmental effects on cv Cabernet Sauvignon (*Vitis Vinifera* L.) grown in Hawke's Bay, New Zealand. 2. Development of a site index. *Aust. J. Grape Wine Res*., **8**, 27-35.

TISSEYRE B., MAZZONI C., ARDOIN N. and CLIPET C., 2001. Yield and harvest quality measurement in precision viticulture - application for a selective vintage. I*n: Blackmore, S. and Grenier, G. (Eds) ECPA 2001 - 3rd European Conference on Precision Agriculture* 1. Agro Montpellier, Ecole Nationale Supérieure Agronomique de Montpellier, France. p. 133-138

VAN LEEUWEN C., FRIANT P., CHONÉ X., TREGOAT O., KOUNDOURAS S. and DUBOURDIEU D., 2004. Influence of climate, soil and cultivar on terroir. *Am. J. Enol. Vitic*., **55**, 207-217.

VAUDOUR E., 2002. The quality of grapes and wine in relation to geography: Notions of terroir at various scales. *J. Wine Res.*, **13**, 117-141.

WHITE R.E., 2003. *Soils for fine wines*. Oxford University Press, New York.