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Using remote sensing to predict grape phenolics and colour at harvest in a Cabernet Sauvignon vineyard: Timing observations against vine phenology and optimising image resolution

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Abstract

Optical remote sensing can provide a synoptic view of grapevine photosynthetically-active biomass over entire vineyards both rapidly and cost-effectively. Such output offers viticulturists and winemakers a management tool of enormous potential with red grape varieties, especially if canopy architecture (defined in this way) can be linked to production of phenolics and colour in ripe grapes. Accordingly, this paper describes such associations for a Cabernet Sauvignon vineyard in Australia's cool-climate Coonawarra region. A link is established between physical descriptors of grapevine canopies (derived from remotely-sensed images), and subsequent measurements of grape phenolics and colour. High-resolution images were acquired on three occasions during each of two consecutive growing seasons and post-processed to a range of on-ground resolutions. The strength of correlation between those images and berry properties (both total phenolics, and colour levels at harvest), varied according to spatial resolution and vine phenology at the time of imaging. An image resolution corresponding approximately to row spacing resulted in the strongest correlations between berry constituents and image-based data on all occasions. Referenced to grapevine phenology, correlations were initially weak (insignificant) at bud-burst, reached maximum strength at veraison, then diminished somewhat as grapes ripened. Prospects for applying such remotely-sensed imagery (at an appropriate resolution and timing), to predict berry phenolics and colour at harvest, are discussed.

Abbreviations

dGPS differential global positioning system; **EM** electromagnetic; **GPS** global positioning system; **GIS** geographical information system; **NDVI** normalised difference vegetation index; **PAB** photosynthetically-active biomass

Keywords: *multispectral imaging, Precision Viticulture, remote sensing, grapevine canopy, grapevine vigour, grapevine phenology, photosynthetically-active biomass (PAB), grape colour, grape phenolics, terroir*

Introduction

Flavonoids in grapes, and their subsequent presence in extracted juice, are important determinants of wine quality. While present in both red and white grapes, flavonoids exist at much higher concentrations in red grape varieties, and especially in skins, where they constitute a significant group of compounds that influence wine style, aroma and flavour. Three key subgroups of flavonoids include anthocyanins, flavonols, and tannins. While tannins occur in both white and red varieties, anthocyanins are specific to red grapes and are primarily responsible for red wine colour. By contrast, flavonols are colourless. They probably confer UV protection in both white and red grapes, and act as co-pigments for anthocyanins in red grapes. The third and quantitatively largest sub-group of flavonoids (or tannins) include mostly polyphenolic compounds including flavan-3-ol monomers such as catechin and proanthocyanidin polymers, and contribute significantly to mouthfeel and colour stability with anthocyanins in red wines. This large and diverse group of compounds is commonly referred to collectively as tannins, and is synonymous with the generic term 'phenolics' or 'total phenolics' as used here. Tannins reside primarily within the skin cells of grape berries, although some tannins occur in seed, stems and berry flesh (Coombe 1990, Kennedy et al. 2000, Souquet et al. 2000).

Overall, the synthesis and accumulation of flavonoids in grapes is greatly influenced by bunch exposure to sunlight (Winkler et al. 1974, Pirie and Mullins 1980, Archer and Strauss 1989, Jackson 2000). Consequently, the location of grapes within a given canopy, as well as canopy density and size, will influence the development of flavour and colour in red winegrapes by virtue of light-driven variation in skin flavonoids (Smart and Robinson 1991, Downey et al. 2004).

In approaching this issue of canopy size from a perspective of remote sensing, Hall et al. (2002) encapsulated the combination of vine-leaf biomass and leaf chlorophyll content in their definition of photosynthetically-active biomass (PAB), a term that integrates canopy size, density and vigour. *A priori*, high-PAB vines would be likely to shade bunches from direct sunlight to a greater extent than would low-PAB grapevines (Mabrouk and Sinoquet 1998), and as a corollary, average bunch temperatures would be lower and light climate within larger canopies would be more heavily attenuated. Accumulation of flavonoids would be altered accordingly, so that some quantitative relationship might exist between PAB at critical phenological stages and flavonoid content at harvest. The present project was undertaken to explore that possible link.

Grapevine PAB is influenced by numerous physical, biological and chemical factors, including spatial variations in topography, physical and chemical characteristics of soils and the incidence of pests and diseases. The spatial variation in such factors within a vineyard will cause a spatial variation in canopy development and consequently grape colour and phenolic content at harvest. Recent work (Bramley 2001) has demonstrated that considerable spatial variation exists with quality indicators such as colour and total phenolics across individual vineyards. From a management point of view, such variation could result in an overall reduction in wine quality. Given the likelihood of increased differentiation in pricing between grapes based on quality attributes (Winemakers Federation 1996), vineyard management decisions would then need to accommodate such spatial variability in quality in order to produce categories of grapes with higher unit value.

Pricing decisions will, however, rely on accurate and reliable data that describe spatial variability for indicators of grape quality; especially colour and total phenolics. Traditional methods of generating such data are generally time consuming and expensive (Lamb and Bramley 2001). As a general rule, measurement of basic fruit quality and yield variables takes between ten and thirty minutes per sampling location. The move toward rapid *in situ* measurement of grape colour and total phenolics is therefore welcome, but such measurements are still constrained by lack of appropriate sensor technology. A system has now been devised to sense grape phenolic composition of harvested fruit using optical-fibre-based visible-NIR spectroscopy (Celotti et al. 2001), but pre-harvest assessment within a vineyard still remains a challenge.

As an alternative to proximal sensing, multispectral airborne remote sensing is capable of providing a non-intrusive, instantaneous and synoptic view of grapevine PAB in vineyards and vineyard blocks (Hall et al. 2002, Lamb and Bramley 2001). Given the links between canopy PAB and grape quality in red winegrapes, the potential exists for generating synoptic information concerning spatial variations in quality attributes such as colour and total phenolics. To date, remote sensing of spatial variations in vine PAB (or its equivalent) has been linked to spatial variations in grape yield (Baldy et al. 1996, Lamb et al. 2001), and fruit maturity (Johnson et al. 2001, Bramley et al. 2003). With regard to spatial variation in maturity, remotely sensed imagery has been used to divide blocks into zones to facilitate segmented harvests. Fruit of given ‘quality’ from different zones can then be batched for separate winemaking, but delineation of those zones remains somewhat arbitrary.

Given those developments, a quest for additional predictive applications using imagery of different spatial resolutions seemed warranted. Accordingly, this paper now presents results from a detailed investigation of links between remotely-sensed descriptors of vine canopy vigour at different phenological development stages, and subsequent measurements of total phenolics and colour in harvested fruit. The studies were undertaken on Cabernet Sauvignon grapes in a cool climate vineyard (Coonawarra region) in Australia. The potential of remote sensing at key phenological stages as a viticultural management tool for predicting grape quality at harvest is then discussed.

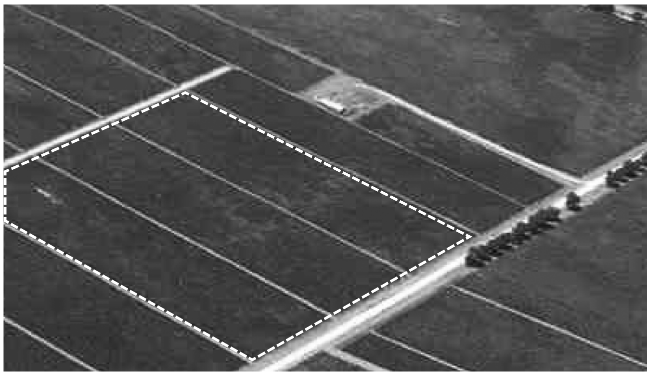

Figure 1. Black and white aerial photograph of the target vineyard, acquired February 2000, showing the three separate blocks (dotted line) of Cabernet Sauvignon imaged and subsequently sampled.

Materials and methods

Vineyard site and measurement of grape quality

The investigation was completed in a 7.3 ha block of Cabernet Sauvignon located in the Coonawarra region of South Australia (37° 17′ S, 140° 48′ E) during the 1999–2000 and 2000–2001 growing seasons. The vines, planted on their own roots in 1974, were trained onto a single wire with 3 m row spacing and rows orientated approximately north-south (Figure 1). Dates of major phenological development stages and a summary of the management applied to this block over the two consecutive growing seasons studied in this work are given in Table 1. Dates corresponding to key phenological stages or vine management in Table 1 differed by no more than twelve days between the two seasons.

During harvest (both seasons), grape samples were hand-picked from 190 vines distributed evenly through-

Table 1. Dates of major phenological development stages and key management applied to the vineyard site during the 1999–2000 and 2000–2001 growing seasons.

Stage/Management	1999–2000 season	2000–2001 season
Pruning	By end of August	By end of August
60% woolly bud	14 September	19 September
60% green tip	20 September	28 September
Budburst (60% leaf emergence)	27 September	5 October
5–6 leaves unfolded (80%)	11 October	23 October
75% flowering	3 December	28 November
75% fruit set	15 December	12 December
Berries pea size	22 December	18 December
Irrigation (25 mm via travelling irrigator)	mid-January	mid-January
Veraison	9 February	7 February
Harvest	8 April	6 April

out the vineyard block. The exact location of each vine was measured using a differential global positioning system which had a measurement accuracy of approximately ± 50 cm. The grapes were immediately packed in a cool-box for transhipment to the laboratory and following subsequent sub-sampling, were stored frozen prior to further analysis. Grape colour (mg anthocyanins/gram berry weight) and total phenolics (280 nm absorbance units per gram berry weight) were subsequently measured following the procedures of Iland et al. (2000).

Airborne multispectral imaging

Multispectral airborne images of the target vineyard site were acquired using Charles Sturt University's airborne video system (ABVS) (Louis et al. 1995). The ABVS comprises 4 CCD video cameras in a 2 × 2 array and an IBM-compatible computer containing a 4-channel framegrabber board. Each camera captures a static image in a separate waveband governed by an interchangeable filter. For this research, the standard vegetation wavebands of blue (450 nm), green (550 nm), red (650 nm) and near-infrared (770 nm) were used. Each filter had a band-pass of 25 nm and each camera was fitted with a 12 mm focal-length lens. Images of the vineyard site were acquired at an altitude of 1,000 m (±10 m) above ground level, resulting in a spatial resolution of 60 cm and an image coverage of 14 ha. Three image overflights were conducted during both seasons. However, the date of each overflight was different in each season to provide a complete dataset of imagery at six different time intervals following budburst. The dates of image overflights and calculated time after budburst are given in Table 2.

Image overflights were conducted at a carefully selected time on each occasion to ensure that illumination conditions were similar, thereby minimising calibration errors associated with using images in digital number (rather than reflectance) format. Each image was corrected for camera-induced geometric and radiometric distortions, and rectified to map coordinates using the image pro-

Table 2. Dates of image overflights and time relative to budburst calculated using principal dates from Table 1.

Season	Overflight date	Days post-budburst
1999–2000	2 November	36
	30 November	64
	16 March	170
2000–2001	14 December	70
	20 February	138
	5 April	182

cessing software ER Mapper (Earth Resource Mapping, San Diego, California, USA). Geometric distortion in the imagery results from imperfections in the lens and appears as barrel or pin-cushion distortion in the imagery. Radiometric distortions are inherent brightness variations in imagery due to the combination of camera lens and iris. Radiometric and geometric distortions were both corrected following the procedure outlined in Spackman et al. (2000). Image rectification (assigning map coordinates to individual image pixels) was then completed using 16 ground control points (readily identifiable features, of known dGPS coordinates, in images) which comprised the ends of selected vine rows. Due to inherent misalignment of the four cameras relative to each other (a maximum error of approximately 1 pixel), band-to-band registration was also completed using ER Mapper.

Linking on-ground measurements to airborne imagery and extracting image pixel values for each vine

Ground coordinates of individual sampled vines often failed to coincide exactly with the location of the vines in the geo-rectified imagery. This was a consequence of spatial errors in locating individual vines with the dGPS, and residual errors in removing geometric distortions from the imagery. In order to check the coincidence of sampled vines with vines in the imagery, the ground coordinates of every sampled vine were overlayed onto the georectified imagery and checked. The location of those points that were not coincident with the centre of the vine rows (always on the eastern side of the row centres) were consistent with the fact that the actual on-ground measurements of vine coordinates were completed by a person, equipped with a dGPS mounted in a back-pack, standing and leaning into the vine from the eastern side of each vine row. An automated process was therefore developed where, for points that were not coincident with vine centres, the ground-coordinates were progressively shifted west in the imagery until the vine centre was reached (defined by a local maximum value in near-infrared reflectance).

Pixel values, for each of the blue, green, red and near-infrared wavebands, were then extracted from single pixels representing the centre of each sampled vine, as well as from groups of pixels representing larger areas centred on the centre of each sampled vine. The pixel combinations and their corresponding on-ground dimensions are summarised in Table 3.

Table 3. Pixel combinations extracted from imagery for each waveband (blue, green, red and near-infrared) at each sampled vine location in the vineyard and corresponding area on the ground.

Number of pixels extracted per vine	Centred on	Area on ground
1	Vine centre	60 cm × 60 cm
3 × 3	Vine centre	1.8 m × 1.8 m
5 × 5	Vine centre	3.0 m × 3.0 m

Calculation of NDVI from extracted pixel values

Spectral vegetation indices reduce the multiple-waveband data at each image pixel to a single numerical value (index), and many have been developed to highlight changes in vegetation condition. A detailed discussion of the use of vegetation indices in remotely sensed imagery of vineyards is given elsewhere (Hall et al. 2002). In this present work, values for Normalised Difference Vegetation Index (NDVI), the most widely used indicator of plant vigour or relative biomass (Lamb 2000, Hall et al. 2002), were calculated from the extracted single-pixel or multiple-pixel values using the relationship below (Rouse et al. 1973):

$$\text{NDVI} = \frac{(\text{near infrared}) - (\text{red})}{(\text{near infrared}) + (\text{red})}$$

where 'near infrared' and 'red' were the pixel values in the near-infrared and red waveband respectively. Taking the 3 × 3, and 5 × 5 pixel groups, average NDVI was calculated. Even though the imaging campaign was designed to reduce differences in illumination conditions (namely, selection of appropriate clear sky-conditions, time of day for similar solar elevations and azimuth), some small variations in the range of NDVI values were observed in imagery. Ultimately, and to ensure that such variations are canopy-related rather than environmental, imagery would be collected in reflectance mode rather than digital numbers. Other researchers, in an attempt to address the issue of variable environmental conditions when acquiring multi-temporal imagery, either normalise NDVI (or similar index) values, or alternatively bin them into high, medium and low values for each image (for example Dobrowski et al. 2003). However in this present analysis, rather than collecting all data into a single dataset, relationships between NDVI and quality indices were assessed on an individual image basis, thereby allowing use of 'raw' rather than binned NDVI values.

Results and discussion

Results from simple linear correlation analyses between extracted NDVI and colour, as well as between NDVI and total phenolics, are summarised in Tables 4 and 5, respectively.

Data presented in Tables 4 and 5 suggest that the strength of correlations between extracted NDVI and measured total phenolics and colour increases (becomes more negative) when larger areas of pixels are averaged around the centre of field-sampled vines in the imagery.

Table 4. Pearson correlation coefficients for NDVI against colour for extracted pixel groups, each centred on the 190 sample vines in the vineyard.

Season	Days post-budburst	NDVI-single pixel	NDVI 3 × 3	NDVI 5 × 5
1999–2000	36	0.01	0.04	**0.06**
	64	–0.07	–0.09	**–0.11**
	170	–0.48	–0.53	**–0.57**
2000–2001	70	–0.13	–0.22	**–0.23**
	138	–0.27	–0.40	**–0.43**
	182	–0.21	–0.25	**–0.25**

Table 5. Pearson correlation coefficients for NDVI against total phenolics for extracted pixel groups, each centred on the 190 sample vines in the vineyard.

Season	Days post-budburst	NDVI-single pixel	NDVI 3 × 3	NDVI 5 × 5
1999–2000	36	–0.01	0.04	**0.12**
	64	–0.07	–0.10	**–0.08**
	170	–0.49	–0.53	**–0.56**
2000–2001	70	–0.30	–0.39	**–0.38**
	138	–0.36	–0.53	**–0.59**
	182	–0.29	–0.26	**–0.24**

This is consistent with the results of Lamb et al. (2001) who used imagery of 20 cm resolution and increased the sample or pixel size of the imagery (by averaging groups of pixels) to produce larger pixels which were a mix of vine and inter-row space. Such mixed pixels are an integration of both vine size and vine density information. Where the 20 cm imagery was sub-sampled to 3 m resolution, similar to the vine-row spacing, the complex vine structure information evident in the high resolution imagery (size and shape, density) was reduced to a simple relative-mix of vine and non-vine signature, and were found to provide a clearer indication of the location of high and low PAB vines. In this current work, sampling groups of 5 × 5 pixels is equivalent to a ground footprint of 3 × 3 m, which coincides with the 3 m spacing between adjacent rows.

The Pearson correlation coefficients for the NDVI calculated from the 5 × 5 pixel groupings (NDVI 5 × 5) are plotted against days post-budburst in Figure 2. Superimposed on the scatter-plot of Figure 2 are the key phenological stages listed in Table 1.

In Figure 2, correlations between extracted NDVI values and either total phenolics or colour grow stronger (more negative) after budburst. Maximum strength is reached around veraison, and then decreases from approximately 130 days post budburst. There is clearly an association between the spatial distribution of canopy PAB and the distribution of total phenolics and colour in the grapes from an early stage in fruit development. This is consistent with the hypothesis that microclimate, taken here to imply exposure to sunlight and average bunch temperature will influence both total phenolics and

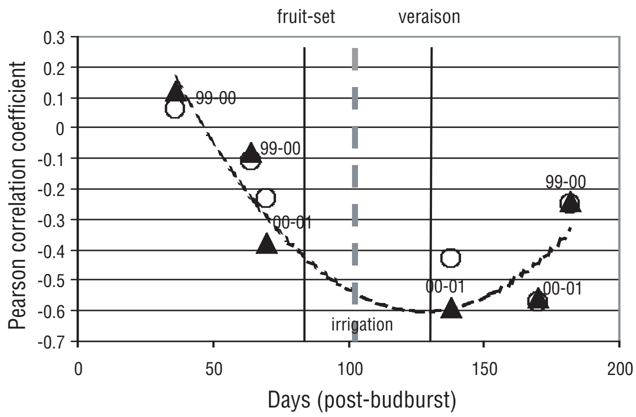

Figure 2. Trend line for Pearson correlation coefficients for NDVI (5 × 5) against colour (○) and total phenolics (▲) as a function of days post-budburst; 99–00 and 00–01 indicate the growing season of the corresponding data.

colour. However, light exposure and average bunch temperature, while both likely to be negatively correlated to PAB (Mabrouk and Sinoquet 1998), can have an opposite effect on the synthesis of phenolics and colour. Too high a bunch temperature may inhibit anthocyanin accumulation, even in the situation of adequate light interception (for example, Hasselgrove et al. 2000). The fact that PAB and total phenolics/colour exhibit significant negative correlations in this work implies that the accumulation of such compounds in the grapes is predominantly light-limited. The trend in Figure 2 is also consistent with the fact that phenol synthesis in red winegrapes begins early during berry development (in Figure 2, fruit set was approximately 80 days post-budburst). Similarly, anthocyanin production becomes pronounced only after veraison, (in Figure 2, approximately 130 days post-budburst) (Hasselgrove et al. 2000, Jackson 2000). Synthesis of phenolics tends to decline and may cease following veraison (Hasselgrove et al. 2000, Jackson 2000). For this particular field site, the spatial profile of total phenolics and anthocyanins would have been 'imprinted in the grapes' between 50 and 150 days post-budburst and would be closely linked to the spatial profile of canopy PAB (NDVI) as detected via remote sensing. Furthermore, berry size generally increases with fruit or leaf shading (Morrison 1988, Hasselgrove et al. 2000), a phenomenon most likely to be associated with high levels of canopy PAB (NDVI). Larger berries would also strengthen the negative correlation between NDVI, total phenolics and colour due to increased dilution of skin constituents by expressed juice during sample preparation.

Results of simple linear regression analyses between extracted NDVI (5 × 5) and both total phenolics and colour, for images acquired on 16 March 1999 and 20 February 2000 (images closest to veraison for each of the two sampling seasons) are summarised in Table 6. Based on these regression equations, maps showing total phenolics and colour (created from the NDVI imagery) are given in Figures 3 and 4.

Following veraison (indicated in Figure 2), a change in the strength of correlation between NDVI, total

Table 6. Summary of simple linear regression analyses (n = 190) between extracted NDVI (5 × 5) and total phenolics and colour measurements for images acquired on 16 March 1999 and 20 February 2000 (closest to veraison for each season).

Season/Parameter	Regression equation	R^2	*P* stat (95%)
1999–2000			
Total phenolics, TP	TP = –3.02 (NDVI) + 3.02	0.32	4.5×10^{-17}
Colour, C	C = –4.14 (NDVI) + 3.11	0.33	1.0×10^{-17}
2000–2001			
Total phenolics, TP	TP = –3.17 (NDVI) + 2.25	0.35	6.9×10^{-16}
Colour, C	C = –2.51 (NDVI) + 2.07	0.19	1.9×10^{-8}

phenolics and colour (approximately 150 days after budburst), can be attributed to two sets of factors. Firstly, the absolute content of anthocyanins in fruit may have decreased as previously observed with numerous red winegrape varieties (Somers 1976, Keller and Hrazdina 1998, Hasselgrove et al. 2000). Indeed, Hasselgrove et al. observed anthocyanins per berry to actually decrease in 'exposed berries' of Shiraz 46 days post veraison, close to the time at which the PAB-phenolics/colour association was observed to weaken in this work. The second set of factors could relate to the onset of water stress, and associated leaf fall at different times in different regions of the vineyard. This vineyard site is typical of vineyards in the Coonawarra Region, where the terra rossa soils are characterised by a layer of light-red clay topsoil and underlying limestone parent material. Figure 5 is a map of soil depth in this particular vineyard (Bramley et al. 2000) which has been shown to control plant-available water (PAW; Bramley and Lanyon 2002). This map indicates the depth from surface to underlying parent limestone. Comparison of this map with Figures 3 and 4 reveals that the lower levels of measured total phenolics and colour, and hence higher-PAB vines (higher NDVI), are coincident with areas of deeper soil. Generally, for a given season, deeper soils support greater root growth, which in turn supports increased vine vigour (Smart and Robinson 1991) and retention of leaves.

In both the 1999–2000 and 2000–2001 seasons, hot-dry conditions prevailed following veraison (Anon 2002) and the water-holding ability of the soil, as determined by the depth of topsoil (Bramley and Lanyon 2002), would have played a significant role in determining water availability. At the time of irrigation, the initial contrast between regions of apparently high-PAB versus low PAB match canopy development in varying depths of soil. This is shown schematically in Figure 6(a). Following irrigation, it is likely that the vines in the regions of shallow topsoil would have succumbed to water stress sooner than those in the deeper topsoil regions. The loss of PAB in the vines located in the shallow topsoil, a combination of loss of leaf chlorophyll and leaf-fall, would have acted to increase the difference in PAB between the regions already associated with differences in total phenolics or colour, and hence increase the strength of the correlation

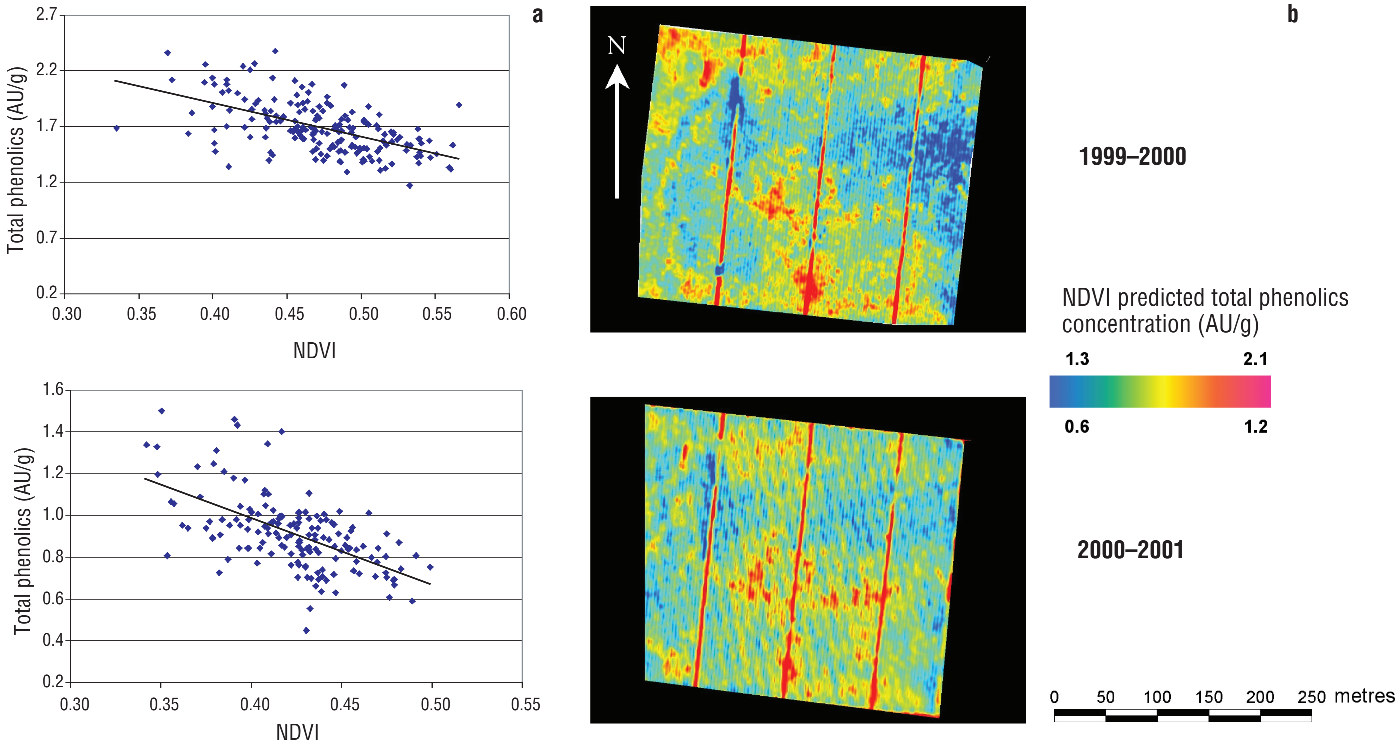

Figure 3. (a) Scatter-plots of NDVI (5 × 5) values versus total phenolics (absorbance units per gram berry weight) and (b) total phenolics maps created from NDVI (5 × 5) imagery, acquired close to veraison for 1999–2000 and 2000–2001 seasons. The tilted red lines through the total phenolics maps correspond to the wide corridors of exposed, scenesced covercrop/bare soil between adjacent blocks. Differences in NDVI range between seasons correspond to differences in range of canopy PAB.

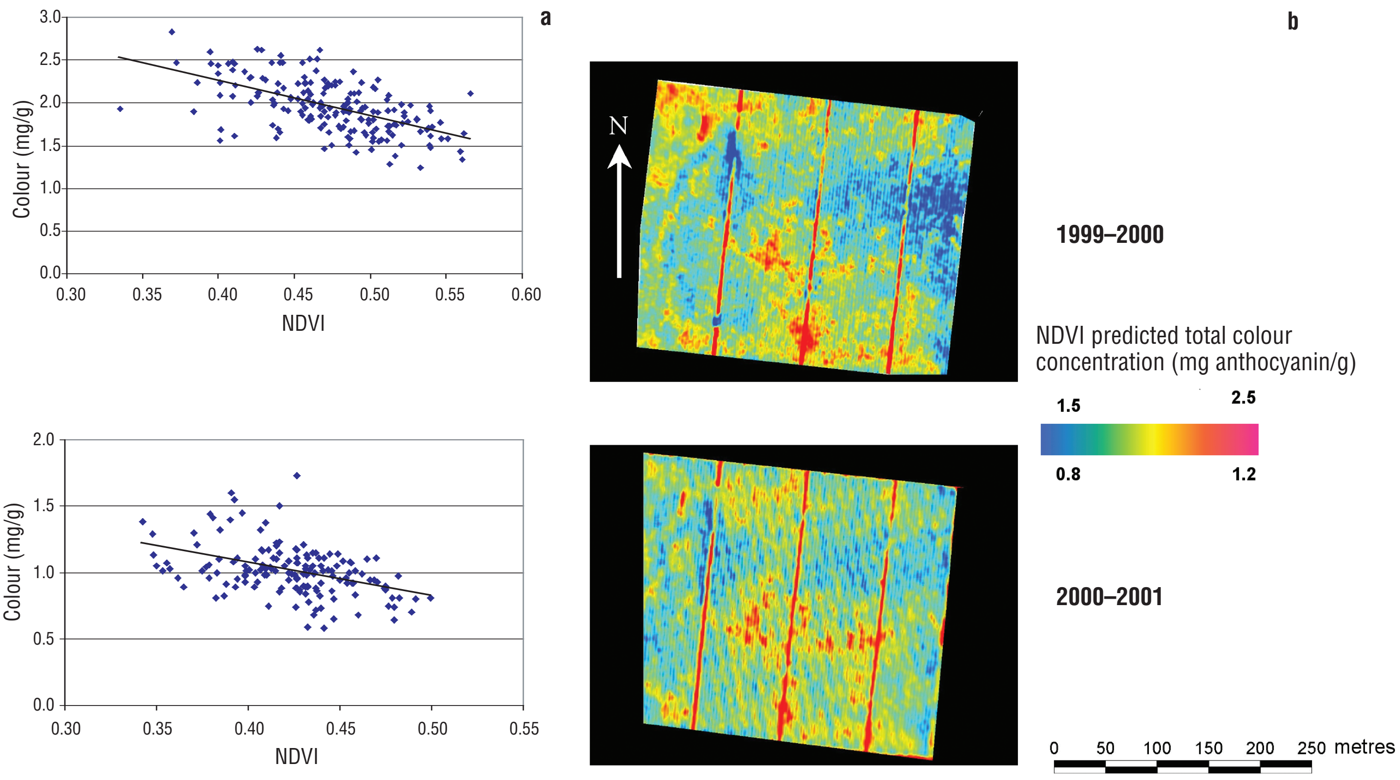

Figure 4. (a) Scatter-plots of NDVI (5 × 5) values versus colour (mg anthocyanins/gram berry weight) and (b) Colour maps created from NDVI (5 × 5) imagery, acquired close to veraison for 1999–2000 and 2000–2001 seasons. The tilted red lines through the total colour maps correspond to the wide tracts of exposed, scenesced covercrop/bare soil between adjacent blocks. Differences in NDVI range between seasons correspond to differences in range of canopy PAB.

between the high-PAB and low-PAB (NDVI) vines and these quality attributes (Figure 6(b)). Delayed leaf-fall from the high-PAB vines on deeper-soil, most likely commencing after production of phenolics in the grapes had ceased, would then reduce the difference in PAB between the regions (Figure 6(c)) and therefore reduce the strength of the spatial correlation between the NDVI and the spatial phenolics and colour profiles as measured on the ground. In a management scenario where soil water is non-limiting, we anticipate that the strength of the correlations between NDVI and total phenolics and colour would have remained high until harvest time. Validation of that scenario is the subject of ongoing work.

Remote sensing in vineyards is currently limited to detecting and mapping variations in canopy attributes such as vine PAB (Hall et al. 2002 and references therein). By implication, spatial variation in other quantities such as yield or berry properties are then inferred from that canopy index. A question thus arises as to optimal timing for remote sensing which is intended for yield and/or quality prediction. In this present work, a correlation between remotely-sensed vine PAB and total phenolics and colour in a Cabernet Sauvignon vineyard was demonstrated. Moreover, the strength of that correlation was shown to vary in a systematic way with grapevine phenology, with predictive value strongest around veraison.

From an operational point of view, the appropriate imaging window necessary to gain an accurate insight into spatial variations of grape quality, as described for example by colour or total phenolics, would have been centred on veraison. Vine PAB maps generated earlier than this would have yielded little in the way of management data related to grape quality. Maps generated later than this would have meant that either degradation of accumulated phenolics/colour compounds, or the impact of water stress on the vine canopy, would have changed the spatial vine-PAB profile from that at veraison when the canopy was likely to have exerted its greatest influence on phenolic content of grapes at harvest.

The strongest correlation between PAB and total phenolics/colour required imagery at a resolution comparable to the vine-row spacing. That coincidence implies an underlying importance for vine size as a component of PAB. This same coincidence has practical implications for the use of remote sensing as a means of discriminating between regions of differing fruit quality.

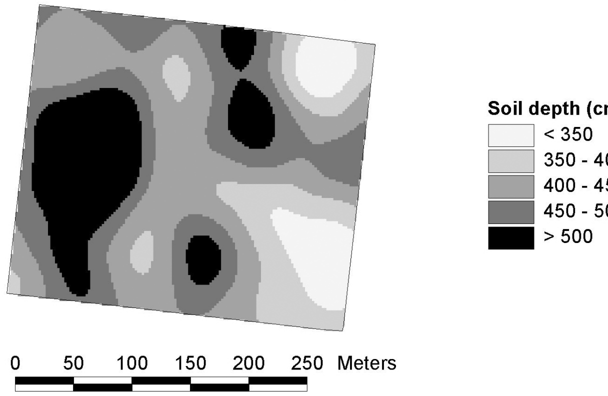

Figure 5. Soil depth (depth to underlying limestone parent material) map for the Coonawarra vineyard site. Data of Bramley et al. (2000).

Regarding the cost-effectiveness of remote sensing, higher-resolution imagery could be used to extract information from vine-only pixels, thereby providing information such as leaf-only spectra. However, extraction of such information may introduce an unnecessary and additional level of complexity to data analysis (and at an added cost to the user). Furthermore, a descriptor of the overall vine size may be omitted from the output and this may significantly reduce the value of generated data for the user. On balance, and mindful of operational needs in remote sensing, coarser-resolution data can generally be acquired more easily from airborne sensors. Moreover, increased coverage can then enable a reduction in the unit cost of acquiring such data (e.g. Lamb 2000). Indeed, and as a future alternative to air-borne sensors, satellite-borne instruments such as those on board Quickbird or Ikonos satellite systems are capable of providing multi-spectral data of similar resolution (Lamb et al. 2001b). Significantly, the per-hectare cost of acquiring such data is likely to decrease as satellite-borne instruments become more widely used for resource monitoring, so that satellite imagery may well become a viable alternative to present analyses that are derived from on air-borne instrument platforms.

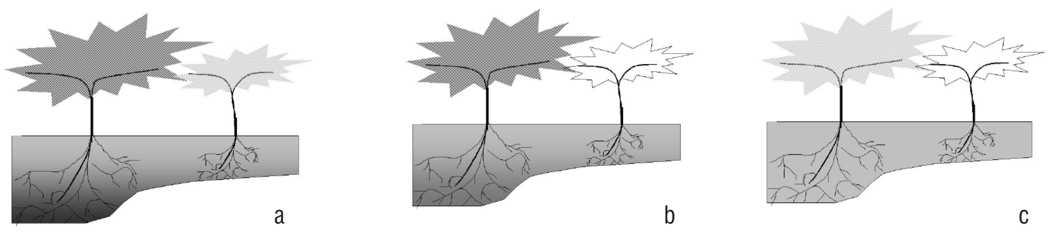

Figure 6. The impact of soil depth on changing the contrast between high- and low-PAB vines. (a) Deeper topsoil promotes more vigorous vine development and higher PAB during the growing season. There is a large difference in PAB observed between vines growing in the two regions. (b) Following irrigation, the deeper topsoil retains moisture and vines in shallow topsoil lose PAB as a result of water-deficit. The difference between PAB of vines in the regions of deep and shallow topsoil is increased. (c) The vines in the deep topsoil now respond to the delayed water deficit. The difference between PAB of vines in regions of deeper and shallow topsoil is now reduced.

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