Chapter 3: New Technologies and Opportunities for Australian Viticulture

3.1 Introduction

Precision Agriculture is based on information technology. For the successful implementation of PA, farmers will need production information provided to them in an accurate, efficient and cheap manner on a variety of seasonally stable and variable production parameters. Over the past decade a myriad of environmental and crop monitoring equipment has been marketed to growers. These range from hand-held to satellite-borne systems. This chapter looks at some of the new technologies now available for viticulturists to collect site-specific environmental and production information on their vineyards.

3.2 Yield Monitoring

One of the main production attributes of interest to most farmers is quantity (yield). For winegrapes however, yield is not as influential on profitability as it is in many other crops (Smith, 2003). This is due mainly to the relatively large price differential between quality grades which makes quality a major determinant in profitability. Despite this it is still important for a grower to understand how yield is varying across the vineyard. The ability to improve yield without compromising quality should be a goal of the grower. While knowledge of winegrape quantity and quality are both important in viticulture this section will only focus on measuring quantity. The issue of winegrape quality monitoring is deliberately avoided here and will be addressed later in Chapter 8.

Traditionally winegrapes were hand harvested. However, since the development of the mechanical harvester in the 1960s more and more vineyards are opting for mechanical harvesting (Morris, 2000). Machine harvesting generally has a considerably lower cost than hand harvesting and also requires less labour resources which may be problematic in rural areas (Corby, 2001). The recent expansion in scale of the Australian viticulture industry has been possible through increased mechanization, particularly mechanized harvesting. Nowadays the majority of Australia’s grape harvest is machine harvested and hand harvesting is restricted to super premium or boutique wines and small family run vineyards. While many large companies have invested in limited yield monitoring capabilities there is only one current contract harvesting company offering the system as standard for smaller growers (Smith, 2003). This is expected to change as the larger wine companies put more pressure on contract growers to deliver a more consistent harvest.

3.2.1 Mechanical Harvesting

Although various approaches have been tried, the most successful mechanical harvesters have been over-the-row harvesters that shake berries from the vine (Morris, 1994). In Australia shaking is usually done with flexible horizontal strikers (bow rods) mounted on both sides of the vine. The efficiency of mechanical harvesting is strongly influenced by the machinery settings, in particularly the number of bow rods, rpm of the striking mechanism and ground speed (Morris, 1994). The tuning of the harvester requires a particular level of expertise and adjustments often have to be made between varieties and canopy management strategies. The efficacy of harvesters is also reliant on the setup of the vineyard. This includes not only correct row and vine spacing but trellising
systems and pruning strategies (Morris, 2000). Most harvesters have a mechanical guidance systems to ensure that the harvester is centred on the row to minimise damage to the vines.

When the vine is shaken by the harvester, fruit is usually dislodged as individual berries or clusters. The dislodged fruit is caught on paddles suspended below the vine. The fruit is then pushed onto a series of conveyor belts and bucket elevators before it is off-loaded into a support bin (see Figure 3.1 for a pictorial explanation). Newer models released in Australia now contain small inbuilt bins that allow the harvester to operate even while support bins are being changed over. In Europe where vineyard rows are shorter and yields lower, these harvesters are the norm and usually operate without a support bin by off-loading grapes at the end of rows. Extractor fans are located at critical points on the conveyor belt to remove any leaf or cordon material from the fruit before it is off-loaded. The presence of a magnet is also important to remove any metallic artifacts which can cause serious problems later in the vinification process (Morris, 1994).

The dislodgement of berries rather than clusters exposes more of the berries to the environment and hastens the onset of enzyme activity. Fruit should be transported as soon as possible to the winery to avoid oxidation (colour loss), browning, off-flavours and microbial growth (Morris et al., 1979). To avoid this situation grapes should be picked at low grape (not atmospheric) temperature and delivered to the winery within 12 hours of harvest, preferably sooner. For machine harvested sparkling wines even time periods of 30 minutes from harvest to crush have resulted in distinct differences in wine styles (Corby, 2001). The addition of SO$_2$ even at low concentrations (100ppm) will slow the onset of bacterial spoilage and oxidation (Morris et al., 1979).

### 3.2.2 Yield Sensors

While protocols have been developed for yield mapping hand harvested crops (Schueller et al., 1999) the process is often slow and time consuming. Recent advances in product tracking technologies (Praat et al., 2003) have automated part of the process however mechanical harvesting still provides the best opportunity to mount real-time automated yield sensors. There are numerous sensors that may be used to measure yield in crops. For grain crops impact sensors are preferred, cotton yield monitors utilise light arrays while horticultural crops generally use load cell sensors. If linked to a positioning system, typically a Differential Global Positioning System (DGPS), the output from these sensors can be georeferenced and mapped. Once the sensors are installed and calibrated they usually require very little attention.

The first attempt at winegrape yield monitoring in Australia was undertaken by engineers at the University of Melbourne in conjunction with SouthCorp Pty. Ltd. during the 1998 vintage (Hamilton, 2003). They used load cells mounted on a bin gondola to measure the increase in mass as the crop was unloaded from the harvester into the bin (Figure 3.2). For winegrapes this is an imprecise system. The vibration of the bin as it moves along the row produces an error signal that is of a similar magnitude to the harvest signal. The system was set up for research purposes only and not considered viable for commercial applications (Hamilton, 2003).

The first attempt at a commercial system for grapes was developed by HarvestMaster Pty. Ltd. HarvestMaster have a commercial load cell system, HM-500, developed for yield monitoring of horticultural crops particularly root crops. This was adapted to measure the mass of grapes transversing
Figure 3.1: The process of mechanical harvesting - The vine is shaken by the beater rods (A) causing the fruit to fall onto paddles (B) suspended under the vine. The motion of the harvester shuffles the grapes onto a conveyor belt (B). The conveyor belt transports the grapes to the back of the harvester where they are carried up the back of the harvester in a bucket elevator (C) and deposited on a cross conveyor belt (C). Extractor fans (C) remove any leaf debris and the grapes are conveyed to the discharge conveyor belt (D) and into a bin (E).
the discharge conveyor of the grape harvester. However due to the small mass of winegrapes on the sensor and vibrations from the movement of the harvester, the signal:noise problem described above resulted in the scrapping of the load cell system and the adoption of an ultrasonic system (Davenport et al., 2001).

As a result of the problems with the HM-500 an ultrasonic grape yield monitoring system, HM-570, was developed by HarvestMaster in conjunction with researchers at Washington State University in 1996-97 (Wample et al., 1998). The HM-570 utilises an array of 3-5 ultrasonic sensors suspended over the discharge conveyor belt (Muffoletto, 1998) (Figure 3.3). The ultrasonic sensors record the height of material on the conveyor by measuring the time for the ultrasonic pulse to rebound to the

Figure 3.2: Images of the Gondola weighing system developed by the University of Melbourne and Southcorp wines showing (A) the complete system, (b) the location of the load cells on the gondola and (C) the mobile field computer used for data collection mounted in the tractor cab. (Courtesy of Richard Hamilton, SouthCorp Pty. Ltd.)
sensor. Height is inversely related to the return time of the ultra sonic pulse. The system produces an instantaneous volumetric, rather than mass, measurement. The conversion of the volumetric measurement to a mass requires density (which is assumed constant). Harvest bins are physically weighed and a calibration co-efficient determined to adjust the output from the sensor. The sensor output is then georeferenced with the output from a DGPS and stored in a mobile field computer.

The use of a constant density will introduce error into the yield estimate. Varietal differences in berry size and grape moisture content as well as the stage of ripeness and the grape:must ratio in the harvester will affect the density of the harvested material. Varietal differences are particularly problematic and the yield sensor requires re-calibration when moving between varieties (Robert Bramley, CSIRO Land and Water, Adelaide, pers. comm.). The HM-570 was commercially released into Australia in the 1999 and 2000 vintages by Gregoire Australia however the system was not a commercial success and is no longer supported in Australia. Use by researchers at CSIRO and the University of Sydney found the system to require very high maintenance. The sensors needed to be constantly monitored to ensure they were working correctly. Recalibration between varieties was also problematic. If the system was nursed then good results were obtainable however commercial applications cannot justify the level of attention given by researchers.
A third system has been developed by Farmscan Pty. Ltd. Australia based on a return to the use of load cells. They used research from a previous attempt to develop a small grain load cell sensor to solve the problem of signal:noise ratio by increasing the frequency of sampling (Ole Hanson, Computronics, Perth, pers. comm.). Installation of the system involves removing a section of the bed of the discharge conveyor and inserting a load cell weight bridge that is slightly elevated above the bed (Farmscan, 2001). As the belt traverses over the weight bridge measurements are taken and an estimation of yield derived. This system is a direct mass measurement thus the volumetric to mass conversion problems encountered with the HM-570 are avoided. The use of load cells however introduces a new error from the yaw and pitch of the discharge conveyor. This can be corrected through the incorporation of a tilt sensor on the discharge conveyor (Farmscan, 2001). Results from trials in Spain and Australia have been promising and the system is now available for limited commercial release in Australia and has been trialled in the United States of America for the 2003 vintage. From personal experience the Farmscan system is much more robust, both in its construction and the calibration, thus requires less maintenance than the HM-570. A direct comparison of the two systems has yet to be performed to my knowledge.

In France, Pellenc Pty. Ltd. have also been developing an in-house yield and quality monitor for use on their harvesters. While the previous systems described are designed to be retro-fitted to various makes of harvesters, this system has been developed specifically for Pellenc models with onboard storage bins and will be factory fitted. It is likely that this system will come as a standard feature on future Pellenc harvesters in much the same way that impact yield sensors are now standard on grain combine harvesters. At the time of writing little material was available publicly on the Pellenc monitors. To my understanding the system also uses a load cell array. Unlike the Farmscan it is unable to measure a continuously moving belt and requires the conveyor belt to stop while the reading is taken. The load cells are located under the conveyer just prior to the fruit being deposited into the onboard bins. A reference load cell with a known weight is located near the sensor to correct for the errors induced from vibrations and the pitch and roll of the machine. A sensor system is required for each onboard bin thus typical two sensors are needed per harvester. The principal advantage of the reference weight is the ability to fix the calibration of the sensor in the factory.
When operating yield measurements are obtained at 1s intervals. (Bruno Tisseyre, ENSAM, Montpellier, pers. comm.).

As mentioned previously some protocols for yield mapping hand-harvested crops have been developed (Scheuller et al., 1999, Gillgren et al., 2003). In the future these protocols may not be necessary. Work has begun at the University of Adelaide on the development of a grape harvesting mobile robot to mechanically hand harvest premium grapes (Sabetzadeh et al., 2001). If successful, a yield sensor and GPS could easily be incorporated into the robot and yield mapping done automatically.

3.2.3 Yield convolution and data filtering

Yield convolution (mixing) within harvesters has been identified as an error factor in grain yield estimation/measurement (Whelan, 1998, Blackmore, 2003). While no research on convolution in grape harvesters was found it would seem that the effect is small compared to that observed in grain crops. There is obviously a degree of mixing within the length of the harvesting unit (~2m) however the fairly fast off-load speed (typically 8 -12s) and slow ground speed (0.5-0.8ms⁻¹) produces only a small area over which the error will be present. There is little opportunity and no evidence that grapes become “trapped” in the harvester and are recirculated as has been noted in other harvesters (Whelan, 1998, Boydell et al., 1999).

While convolution has not been reported as a large problem, some expert filtering of the data is required to remove artifacts that may be caused by variations in harvester speed, noise from machine vibration and uneven terrain and coarse resolution (Lamb et al., 1995). There are a variety of filters available that automatically remove erroneous data (Blackmore and Moore, 1999, Pringle, 2001, Thyleen and Giebel, 2000, Noack et al., 2003) and some have been incorporated into existing GIS packages for easy use like the ERDAS compatible filter of McGuire (2004). If two harvesters are operating in the same block then the data needs to be standardized to negate any machine or calibration specific effects (Blackmore and Moore, 1999). For the use of low-cost GPS units re-alignment of the data onto the rows is a possibility using dead-reckoning or “map-matching” algorithms (Taylor and Blewitt, 1999).

3.2.4 Quality Sensors

The only on-the-go quality sensor development, for which some results have been shown, is being privately funded by Pellenc Pty. Ltd to be paired with their yield sensor (Bruno Tisseyre, ENSAM, Montpellier, pers. comm.). Again the general application of this sensor may be limited as it is being designed for factory fitting rather than retro-fitting to older or other models. Davenport et al. (2001) in their review were unaware of any quality sensors. While no real-time sensors are commercially available (the Pellenc system is expected soon) the issue of grape quality and rapid measurement with new techniques is one being actively pursued in Australian viticulture and will be discussed later in Chapter 8. The development of an on-the-go quality sensor that can be retro-fitted is of major importance for the continued development of precision management in Australia.

3.3 Variable-Rate Technology (VRT) in the Vineyard.

Excluding harvest, the main machinery operations in the vineyard are the maintenance of interrow cover crops, soil management (for example fertilization, aeration and mowing) and canopy manage-
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3.3.1 Controllers

Variable-rate application is often possible with existing machinery that is retro-fitted with a variable-rate controller. A variety of controllers that can be retro-fitted are already commercially available, for example Dickey-John Land Manager, Mid-Tech Legacy/TASC/AgLogix, Hiniker 8605, Micro-trak MT-3405 F/MT-9000, Rawson Control Systems’ Accu-rate, AgLeader PFadvantage, TeeJet 854, Raven Viper, Valmont Acc-Pulse to name a few. The previous development of these variable-rate controllers and the associated technology for broadacre production should allow for the rapid adoption of the technology in the viticulture industry. However, as is often the case the limiting factor in adoption is our level of knowledge and decision support capabilities rather than the technology (Searcy, 1995).

3.3.2 Variable Rate Vineyard Machinery

A principal piece of vineyard machinery that will benefit from VRT is the sprayer. Spray applications for a variety of reasons, particularly pests and diseases, are regularly applied to the vineyard. The effectiveness of spray applications is a function of canopy size, shape and density (Manktelow and Pratt, 2000). The vigour and shape of vine canopies can be ascertained by remote sensing (Dobrowski et al., 2002, Hall et al., 2003) thus this information should be useful in varying spray pressure and amount through the vineyard to improve the effectiveness of application. The potential risk of many diseases, particularly fungal pathogens, is related to the micro-climate of
the canopy (Ellis, 1994; Ellis and Erincik, 2002). The identification of enclosed, potentially humid and still canopies should help identify potential disease hotspots and allow directed risk management spray applications. This approach has yet to be tried in vineyards, possibly due to the fact that only recent developments in remote sensing have allowed canopy quantification however it would seem a logical step in precision vineyard management. A further hindrance, as Manktelow and Praat (2000) observed, is that most current agrochemical labels, thus spray applications, fail to account for differences between sprayer types, canopy structures or the degree of pest/disease risk.

When linked to a multispectral camera, sprayers have been developed to identify and selectively spray weeds/plant material at resolutions of <1cm² against the soil background (Hanks, 1995). This has permitted a reduction in herbicide use of up to 85% in some instances. While initially developed for fallow broadacre usage these sensors have been adapted for row crops and commercial sprayers are available like the Avidor Weedseeker (Figure 3.5). These selective sprayers are particularly important in non irrigated vineyards where weeds under the canopy compete for soil moisture or it is desirable to spray suckers and shoots beneath the vine canopy.

Another major vineyard management practice that may potentially profit from VRT is mechanical pruning. Over 80% of Australian vineyards are now mechanically pruned (Morris, 2000). Pruning is an important vineyard management technique for controlling vine growth and the quality and quantity of production (Smart and Robinson, 2001). Hand pruning affords the grower precise control over the number of buds that are left however mechanical pruning is cruder and usually requires a subsequent hand-pruning to tidy up the vines. Incorporation of information on canopy growth, from either remote or proximal sensors (see the following section) within season may allow for more targeted mechanical pruning thus reducing the effort needed in the subsequent hand pruning. Research is also being conducted in France to automatically measure the amount of site-specifically pruned material in the vineyard (Bruno Tisseyre, ENSAM, Montpellier, pers. comm.). Pruned cane weights have been correlated to leaf area (Cohen et al., 2000) and yield (Morris and Cawthorn, 1981).

Fruit thinning and leaf removal are other vineyard processes that are becoming increasingly mechanized (Morris, 2000). Mechanical thinning, when used properly and prudently, has been shown to advance maturity, increase acidity and anthocyanin concentration, lower pH and stabilise yield (Petrie et al., 2003). The development of sensors or calibrations to estimate crop load may help in the development of variable rate thinning.

3.3.3 Variable-Rate Irrigation

Over the past 5 years considerable research has gone into the development of variable-rate irrigation (VRI) sprinkler systems (Evans et al., 2000, Sadler et al., 2000). This research has concentrated on overhead- or drop-sprinklers particularly on centre-pivot irrigation systems. These systems use Bermuda (or asco) valves to shut off the supply of water to the sprinkler head thus are essentially binary systems. Application rates are controlled by turning sprinklers off or varying the speed of the pivot as it walks around the field. Sprinkler heads are generally banked along the pivot so that one solenoid will control several sprinkler heads. This is done to minimise the hardware and cost of the system. To date trials with this system have been very promising (Perry et al., 2002) and commercial systems do not appear too far off (Pocknee et al., 2003).
For many vineyards in the western USA this technology will be immediately applicable to vineyards due to the proliferation of overhead sprinklers. For the Australian viticultural industry, drip irrigation is the most common form of irrigation making the majority of the industry incompatible with existing technology. Drip systems are much more difficult to site-specifically control due to the large number of drippers. The use of different sized apertures provides one way that irrigation can be varied, however this is a permanent situation and once installed the grower has little flexibility in altering irrigation rates without replacing drippers. While this may be beneficial for water use at certain stages of growth it is likely to be adverse at others and may create problems with fertigation and any other management strategies implemented through irrigation (Sadler et al., 2000). Precision drip irrigation appears to be less suited to VRT than sprinkler irrigation. Ideally aperture size would be able to respond to the soil moisture around the dripper.

3.4 Remote Sensing

3.4.1 Introduction

Remote sensing can be defined as “the science and art of obtaining information about an object, area, or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area, or phenomenon under investigation” (Lillesand and Kiefer, 1994). This definition does not specify the distance that the sensor is located from the object of interest which may range from millimetres to thousands of kilometres. Often the term ‘proximal sensor’ is used for terrestrial based sensors while ‘remote sensor’ is reserved for air- or space-borne sensors. For the first section of this discussion on the background of remote sensing the term remote sensing will be used to encompass both proximal and remote sensors. In the second section on “Applications to viticulture” remote and proximal sensors will be discussed separately.

Most remote sensing techniques utilise the electro-magnetic (EM) spectrum. Sensors are designed to detect and record the reflectance or emission of radiation from an object. This radiation may range from the Visible-UV wavelengths through the Near-, Mid- and Far-Infrared (NIR, MIR and FIR), microwave and gamma ray regions of the EM spectrum. Passive sensors utilise radiation from naturally occurring sources, such as sunlight or radioactive decay, whilst active sensors generate their own radiation. The reflectance or emittance of radiation from an object is captured by a sensor at a specific wavelength (or range of wavelengths) and nowadays generally stored digitally. However remote sensors do not necessarily have to be digital, that is conventional cameras may be used and images from these sensors can be digitised by scanning (Davenport, 2003). This allows existing ‘hard copy’ images or data to be utilised. However these images require the presence of standard colour cards if they are to be “calibrated” to light wavelengths (Davenport, 2003).

The applications of remote sensing to agriculture, environmental sciences and natural resource management are numerous and too extensive to describe here. Remote sensing has been used for converting point samples to whole field maps, mapping crop yield, mapping soil properties, monitoring seasonally variable soil and crop characteristics, determining the causal effects of observed variability in production, addressing time critical crop management, mapping climatic/meteorological conditions and producing digital elevation models (DEM) from stereopairs (Moran et al., 1997). The aim of this review is to briefly provide a background to remote sensing, the application of remote sensing to viticulture to date, discuss the types of remotely sensed information currently available to viticultur-
3.4.2 Background

3.4.2.1 The Question of Resolution

When discussing remote sensing the topic of resolution is always at the fore. The resolution of a particular sensor can be described in four different ways - spatial, temporal, radiometric and spectral resolution (Lamb et al., 2001, Verbyla, 1995). If the resolution of the data for any of these attributes is incorrect for the target application then the usefulness of the data is compromised.

Spatial resolution refers to the smallest detectable object on the ground (Hall et al., 2002) and in digital remote sensing this equates to the final image pixel size (Verbyla, 1995). Image pixel size is a function of the available image-forming pixels in the sensor and the height of the sensor above the ground. The interaction of these two parameters determines the overall area in the image, also referred to as the image footprint. For a given sensor there is a trade off between spatial resolution and footprint size. The higher the altitude of the sensor the larger the footprint and the coarser the spatial resolution (Verbyla, 1995). Satellite sensors with a fixed elevation provide data at a constant footprint and spatial resolution that varies with the sensor. Aerial platforms are more flexible and can create images with decimetre spatial resolution (Lamb et al., 2001). However they are generally flown to produce ~100ha footprints at 1-2m spatial resolution (Hall et al., 2002).

Temporal resolution refers to the revisit time of the sensor (Verbyla, 1995). For satellite sensors the revisit time is determined by their orbital path. Some modern satellites are now able to direct the sensor off-nadir to decrease the revisit time however this usually substantially increases the cost of the data. Revisit time is also proportional to latitude with higher latitudes having greater image overlap (Verbyla, 1995) thus shorter temporal resolution. The presence of cloud/haze may also complicate imagery and decrease the effective temporal resolution. Aerial platforms are generally much more flexible for temporal resolution. They are also less susceptible to cloud interference as they may be able to fly below high cloud layers (Hall et al.,
Radiometric resolution is specified by the number of values available to record the intensity of radiation at a given wavelength for a given pixel (Lamb, 2001). Remote sensors usually operate at either 8-bit \(2^8 = 256 \text{ values}\) or 10-bit \(2^{10} = 1024 \text{ values}\) (Hall et al., 2002).

Spectral resolution refers to the number of wavebands that can be simultaneously recorded at each pixel in the image (Hall et al., 2002). It may also refer to the bandwidth of the wavebands being measured (Verbyla, 1995). Sensors are usually categorised as either panchromatic (1 waveband), multispectral (2-10 wavebands) or hyperspectral (>10 wavebands). Panchromatic and multispectral sensors tend to have much wider bandwidths (with panchromatic broader than multispectral) (Verbyla, 1995) to pick up broad trends in the reflectance spectra while hyperspectral bandwidths tend to be narrower (2.2-12nm) (Arkun et al., 2001, Hall et al., 2002) to allow more precise analysis. The term hyperspectral is used quite loosely in remote sensing. Most hyperspectral remote sensors typically record between 10-60 wavebands due to limitations in data processing. Thus while the camera itself may have hyperspectral capabilities (>200 bands) the image is only dekaspectral. The term superspectral is becoming more commonly associated with these dekaspectral sensors.

With current technology there is often a trade off between the types of resolution - especially spectral and spatial. Sensors are only capable of collecting a certain amount of data. Thus if more spectral resolution is required then spatial resolution must be sacrificed to keep the amount of data being processed below a maximum threshold. The converse is also true. This trade off generally occurs only with hyperspectral sensors as multispectral sensors do not have sufficient spectral resolution to create problems with data flow through.

### 3.4.2.2 Correction

As well as resolution the other main concern with remotely sensed data is the issue of data correction. This proceeds on the assumption that the sensor has been properly calibrated prior to use. Satellite sensors nowadays tend to be well calibrated, however, sensors based on aerial platforms are more problematic and care must be exercised when using aerial digital or video data (Moran et al., 1997). Data correction is needed for atmospheric interference, off-nadir effects, cloud screening, frame registration and data mosaicing and geometric correction (Verbyla, 1995).

Most atmospheric data correction of satellite images nowadays has been simplified and sped up through the development and use of automated radiative transfer models (Ouarzeddine and Belhadj-aissa, 2000). Off-nadir effects, especially in aerial based sensors are generally corrected using the bidirectional reflectance distribution function (Moran et al., 1997). When taking aerial images it is important that the altitude of the sun is sufficiently high to negate shading effects and that the image is taken on the principle solar plane (flying toward or away from the sun) (Arkun et al., 2001).

Generally, for satellite imagery, a simple single geometric registration can be used for an entire region due to the large footprint of the image (Moran et al., 1997). Geometric rectification is generally performed using either affine coordinate transformations or polynomial models (Verbyla 1995). For very high spatial resolution satellites and aerial sensors geometric registration and mosaicing of multiple images can be problematic and time consuming (Moran et al., 1997). Automatic registration can be done if the pitch, yaw and roll of the plane are accounted for, however the accuracy of such
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a geo-rectification is generally of the order of 20 pixels (Moran et al., 1997). For aerial data in particular it is recommended that the end user proceed with their own geo-rectification using known ground control points (GCPs) from either previously rectified images or a GPS receiver (Verbyla, 1995).

In general the correction of aerial data lags behind satellite (Moran et al., 1997) however the disadvantages are offset by desirable characteristics such as low cost, real-time capabilities, flexible spectral bands and band widths and data redundancy with overlapping frames (Mausel et al., 1992).

3.4.3 Applications to Viticulture

3.4.3.1 Remote Sensing - Optical Sensors

In Australia, remote sensing data has been by far the most sought after viticultural production information. Problems with reliability and usefulness of yield and proximal crop sensors in horticultural crops have led to a greater reliance on remotely sensed imagery. Since the inception of the Cooperative Research Centre for Viticulture’s Precision Viticulture program in 1999, the area of viticultural imagery purchased in Australia has grown from ~200ha (mainly for research) to ~30,000ha for the 2003 vintage (David Lamb, University of New England, NSW, pers. comm.). This represents ~15% of all plantings in Australia. Furthermore, with modern satellite sensors the entire viticultural area has been imaged and archived thus this figure could rapidly increase with the retrospective purchase of images.

A variety of imagery is available to viticulturists with a wide variety of spatial and temporal resolutions, however choice in spectral and radiometric resolution is much more limited (Table 3.1). Investigations by researchers at Charles Sturt University have identified imagery with a spatial resolution equivalent to the interrow spacing (generally 3-3.3m) as sufficient for vineyard blocks (Lamb et al., 2001, Hall et al., 2002). When the spatial resolution approximates the interrow space then the image pixel is a mixed pixel of the canopy and interrow response. The mixed pixel contains information about both canopy size and density (Lamb et al., 2001). Visually this resolution produces a clear differentiation of areas of different vigour. Imagery with a coarser resolution, for example 25m² Landsat or 20m² SPOT imagery, is unacceptable as the small nature of many vineyard blocks, 1-2ha, results in the generation of insufficient pixels per block for adequate analysis and interpretation (see Figure 3.6). Imaging at finer resolutions (<1.5m) provides much more information, especially on the interrow. However these images may be visually disorientating and/or create distortions (Lamb et al., 2001). For fine resolution data to be utilised it requires further post-processing to remove noise for example the “Vinecrawler” algorithm of Hall et al. (2003). Such methods are able to identify and eliminate the interrow response and then identify both the size and shape of individual vines. This approach may allow for the spectral response of individual vines to be matched to vine growth or production measurements (particularly quality). This capability will become more important as hyperspectral imagery becomes more freely available.

With so much imagery currently being purchased by industry what is and can be done with the information? The primary interest to growers appears to be the mapping of vigour within and across blocks (Hall et al., 2002). Thus, the images currently supplied often focus on indices of plant growth such as Normalised Difference Vegetation Index (NDVI), Relative Vigour Index (RVI), Plant Cell
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<table>
<thead>
<tr>
<th>NAME</th>
<th>Spectral</th>
<th>Spatial (m)</th>
<th>Swath width (km)</th>
<th>Off-nadir</th>
<th>Radiometric (bands)</th>
<th>Temporal (days)</th>
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<td>185</td>
<td>No</td>
<td>8</td>
<td>16</td>
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<td>QUICKBIRD</td>
<td>Panchromatic (1 band)</td>
<td>&lt;1m</td>
<td>16.5-18</td>
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<td></td>
<td>1-3.5 (off-nadir)</td>
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<td>MS (4 bands)</td>
<td>2.5m</td>
<td>16.5-18</td>
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<td>11</td>
<td>1-3.5 (off-nadir)</td>
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<td>8</td>
<td>26 (nadir) 1-2 (off nadir)</td>
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<tr>
<td></td>
<td>Panchromatic (1 band)</td>
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<td>60</td>
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<td>8</td>
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<td></td>
<td>VMI (5 bands)</td>
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<td>Yes</td>
<td>8</td>
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<td>8</td>
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<td></td>
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<td>Wide Field (2 bands)</td>
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<td>~1400</td>
<td>Yes</td>
<td>7</td>
<td>5?</td>
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Table 3.1: Spectral, Spatial, Radiometric and Temporal specifications for satellite-borne sensors used in Australian agriculture
**Table 3.1**: Spectral, Spatial, Radiometric and Temporal specifications for satellite-borne sensors used in Australian agriculture (cont)

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Resolution</th>
<th>Radiometric</th>
<th>Incidence Angle</th>
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<td>SPIN 2</td>
<td>2</td>
<td>40</td>
<td>8-15</td>
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</tr>
<tr>
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<td>ERS</td>
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<tr>
<td><strong>ENVISAT</strong></td>
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<td>RADARsat-1</td>
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<td>Standard</td>
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<td>100</td>
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<tr>
<td>Wide</td>
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<td>150</td>
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<td>300</td>
<td>Yes</td>
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<tr>
<td>ScanSAR wide</td>
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<td>Extended High Incidence</td>
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<td>75</td>
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<tr>
<td>Extended Low incidence</td>
<td>28</td>
<td>75</td>
<td>Yes</td>
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</table>
Density Ratio (PCD or PCR), Photosynthetic Vigour Ratio (PVR), Plant Pigment Ratio (PPR) or some proprietary index based on the response in the red and NIR regions of the electro-magnetic spectrum (Figure 3.8 illustrates some examples of these indices). Vine vigour is of interest to the grower as differences in vigour are often influenced by variable environmental conditions and can produce variability in the quality and quantity of production (Hall et al., 2002). This causal link has lead to the investigation of the relationship between remote imagery and grape quality at various organisations around the globe (such as Vintage 2001, Cooperative Research Centre for Viticulture (CRCV)) although results of these studies are only now starting to be published.

Vigour in viticulture generally refers to the rate of vine (shoot) growth. From a remotely sensed perspective vigour is a factor of both vine size and photosynthetic activity (or the photosynthetically active biomass (PAB) (Hall et al., 2002)). Vine vigour (as traditionally measured) and PAB are correlated as vigorous vines are generally characterised by larger and/or denser canopies. The estimation of PAB is most easily achieved by using imagery with a spatial resolution equivalent to the interrow spacing (Hall et al., 2002). This allows the canopy spectral signature and canopy size to be combined into a signal measurement (demonstrated in Figure 3.7).

Efforts have also been made to correlate remote sensing with the leaf area index (LAI) of vines (Montero et al., 1999, Nemani et al., 2001, Johnson et al., 2001, Johnson et al., 2003, Johnson 2003). Knowledge of the spatial variability in LAI of a vineyard is desirable as LAI has been linked to grape characteristics and wine quality (Smart and Robinson, 1991). LAI is also an important parameter in many ecosystem models as a key variable in estimating water loss, photosynthesis and radiation penetration (Nemani et al., 2001). Traditional ground based methods of canopy measurement are often time and scale limiting thus there is a strong interest in developing cheaper, faster measurements, like remote sensing, that are applicable at multiple scales (Dobrowski et al., 2002). All studies to date on the use of remote sensing in viticulture have found strong linear relationships between vegetative indices (usually NDVI) and LAI with both airborne (Nemani et al., 2001, Dobrowski et al., 2002) and satellite-borne (Montero et al., 1999, Johnson et al., 2003) sensors. The relationships appear to be insensitive to trellis type and vine spacing (Nemani et al., 2001) however the LAI of the vineyards was relatively low. Johnson et al. (2003) warn that this linear trend may not hold in higher LAI vineyards and NDVI saturation could occur in unpruned or minimally pruned vineyards. Dobrowski et al. (2002) in comparing NDVI and RVI as predictors of canopy leaf area in Vertical Shoot Positioned (VSP) vines, found that the NDVI response was curvilinear over a wide range of leaf areas and concluded that the RVI was preferable as its response was linear over the same leaf area range. The popularity of no- and minimally-pruned vines in Australia may require an independent study to see if the NDVI/RVI-LAI relationships observed in the USA hold true for Australian viticulture. As well as LAI and vigour, vegetative indices have also been correlated to a variety of other canopy parameters such as pruning weights (Johnson et al., 1996, 1998, Dobrowski, 2000), canopy density (Dobrowski, 2002) and canopy transmission (Johnson et al., 1998).

Mapping canopy properties using remote sensors has the advantage that there is less error in measurement compared with traditional canopy measurements (Nemani et al., 2001). The level of detail in a remotely sense imagery is usually greater than that of interpolated ground measurements. There are however disadvantages to the use of remote sensors. If imagery from multiple dates is used then sensor calibration, soil colour (moisture), sun angle and viewing geometry must be considered as
potential error sources (Nemani et al., 2001). VSP vineyards are problematic as the canopy width (~0.5m) is very narrow in relation to the interrow spacing (~2.5m) thus the spectral response is often dominated by the background characteristics such as groundcover, soil colour or shading (Dobrowski et al., 2002, Johnson, 2003). This may result in a “linearizing” effect and reduced sensitivity of the vegetative index to canopy changes (Dobrowski et al., 2002). Variable background cover will also create error in the image if a mixed pixel approach, such as that proposed by Lamb et al. (2001), is used (Johnson, 2003).

In their 1998 paper, the observed relationship between NDVI and vine growth parameters led Johnson et al. to attempt a differential harvesting strategy in the 1997 vintage based on the NDVI response in a 3ha block of chardonnay. The block was subdivided into areas of low, moderate and high vigour and a variety of vine and grape characteristics measured within each subblock. The subblocks were harvested on different days according to the grape characteristics and fermented individually so that the resultant wine could be evaluated and compared. The high vigour subblock produced an inferior (District, varietal) wine compared to the moderate and low vigour subblocks. The low and moderate vigour wines were significantly different (P<0.05) but both were classed as reserve quality wines. In the 2002 vintage a similar experiment was trialled in Western Australia using plant cell density im-

Figure 3.7: Visual representation of the mixed pixel approach advocated by Lamb et al., 2001 (adapted from Hall et al., 2002).

Despite pixels falling at different locations the same combined vine signature is obtained if pixel size is compatible with vine spacing.

Figure 3.8: Examples of different vegetative indices derived from an aerial NIR image of a vineyard near Cowra. Images are (from the top left clockwise) Colour (B,G,R), NDVI, Plant Cell Density (PCD), Photosynthetic Vigour Ratio (PVR), Plant Pigment Ratio (PPR) and False Colour (B,G,NIR).
ages in Cabernet Sauvignon (Bramley et al., 2003). In this trial, separation of the vineyard into high and low vigour area produced two different wine styles with a 50% price mark up on the superior wine. However, like Johnson et al. (1998) there was no attempt to quantify the vegetative index-wine quality relationship. The methods employed by Johnson et al. (1998) and Bramley et al. (2003) are quite simplistic and only look at relative differences in vegetative indices. However this approach has been adopted by several large wine companies in Australia and the USA and it is now common practice in many vineyards to attempt to segregate blocks prior to harvest (Carothers, 2000, Smith, 2003). Results from this commercial utilisation are rarely reported and concerns have been raised in Chile where segregation of blocks into harvest zones using NDVI has produced mixed results over a variety of blocks (Ortega and Esser, 2003). Ortega and Esser (2003) observe that harvest segregation using imagery is best suited to blocks containing strongly contrasting soil. In areas with low soil variation statistical differences in grape quality are not observed although yield differences generally are.

Vigour and quality/quantity mapping are not the only applications of remote sensing in viticulture. High resolution (<1m) mapping can be used for vine row definition (Hall et al., 2002, Bobillet et al., 2003) and vine mapping (Hall et al., 2003) as well as identification of missing vines (gaps) (Arkun et al., 2001). Even slightly coarser resolution (2-3m) can be used for vine identification if the dimensions of the block are known (Gillgren et al., 2003). Hyperspectral high resolution imagery has been used to identify varietal misplantings to avoided unintended grape mixing at harvest (Arkun et al., 2001). While this service was offered in the early 2000s to Australian growers, a lack of response has seen it removed from the market. With the exception of premium blocks, the remote identification of misplantings appears to be of little interest to producers.

Investigations into the use of remotely sensed images for the detection of disease in vineyards, particularly phylloxera, have been occurring sporadically in the USA for 20 years. In 1983, Wildman et al. first reported the use of multispectral aerial photographs taken between 1977 to 1980 to identify and characterise the spread of phylloxera within a Californian vineyard. Analysis of the tempo-

Figure 3.9: Relative vegetation index images from a 12 acre phylloxera infested vineyard near Oakville, Ca. for 1993 (left), 1994 (middle) and a relative vegetation difference image (right). Green areas indicate high vegetative matter and brown low. In the difference image the red and yellow areas indicate where relative vegetation has declined between the years - primarily due to an increased phylloxera population (Adapted from Johnson et al., 1996).
ral images and the patterns of infection also allowed the researchers to identify a secondary disease in the vineyard that was not as aggressive as the phylloxera. Following on from this work a variety of reports (Johnson et al., 1996, Lobitz et al., 1996, Salute et al., 194) have been produced from a Grapevine Remote sensing Analysis of Phyloxera Early Stress (GRAPES) collaboration between NASA, Californian Universities and Mondavi vineyards. Again images from two seasons, 1993 and 1994, were converted into relative vegetation index and combined to determine the spread of the phylloxera (Figure 3.9). This information, together with ground-truthing was useful for evaluating the ability of particular fields to cope with phylloxera stress and prioritising replanting decisions (Johnson et al., 1996).

3.4.3.2 Remote Sensing - RADAR/LIDAR

No reported studies on the use of RADAR (RAdio Detection and Ranging) or LIDAR (LIght Detection and Ranging) sensors in vineyards was found. RADAR may offer some advantages over optical sensors as it is not limited by cloud cover or atmospheric pollutants.

3.4.4 Proximal sensing

As well as remote sensing, a lot of information is collected by proximal sensors. Proximal sensors are located generally within 1-5 metres of the object being measured and are terrestrially mounted. The most common proximal sensors in use in precision agriculture are yield monitors (discussed previously §3.2.2) and soil sensors. However a wide variety of other sensors have and are being applied in viticulture.

3.4.4.1 Soil Sensors

Soil sensors, in particular apparent soil electrical conductivity (ECa) sensors, are probably the most commonly used proximal sensors in viticulture. Numerous studies (Luck, 2002, Lund et al., 2002, Bobert et al., 2001, Dabas et al., 2001, Dalgaard et al., 2001, Gilbertsson, 2001, Nehmdahl and Grieve, 2001, Luck and Eisenreich, 2001, Clark et al., 2000, Hartsock et al., 2000, Lund, 2000 and Drummond et al., 2000) have been presented at International Precision Agriculture conferences on the application and usefulness of proximal soil ECa measurements. Soil ECa is affected by soil moisture, clay percentage, clay type, the ionic concentration of the soil matrix, bulk density and soil temperature (Dabas et al., 2001). Of these, the first four variables are the most influential on the ECa.

Figure 3.10: The Veris 3100 EC cart in a vineyard near Cowra NSW (left) and using a ground penetrating radar (GPR) to map soil in a vineyard (right) (courtesy of S. Hubbard, Lawrence Berkeley National Lab, Ca., USA.).
measurement. The strong effect of variation in the ionic concentration of the soil solution has been used to identify areas of salinity and sodicity with proximal soil conductivity sensors (Williams and Baker, 1982). Soil is rarely, if ever, uniform thus the qualifier “apparent” is used as the electrical conductivity value is assumed for a uniform soil (Dabas et al., 2003). Soil ECa data is a highly sought after data layer in a production system as it permits a quantification and mapping of soil properties with limited soil sampling (Luck and Eisenreich, 2001).

In vineyards the soil ECa is usually measured using electro-magnetic induction (EMI) prior to vineyard design to gain additional information about soil variation (Ormesher, 2001). EMI instruments operate by establishing an electro-magnetic (EM) field. This EM field penetrates the soil producing a secondary EM field. The strength of the secondary field is measured by the EMI instrument and the ratio of the two fields converted to an ECa reading. A variety of EMI instruments are available that measure the soil ECa to different depths. For vineyard soil surveys, shallower readings (~1m) are generally more applicable to crop production hence a preference for instruments such as the Geonics EM38. Commercially there are a number of contractors who will provide ECa mapping for vineyards.

In established vineyards ECa mapping is generally done with EMI instruments however some contractors prefer to use contact soil resistivity sensors, for example the Veris 3100 Cart (Fig. 3.10) or MuCEP (Multi-Depth Soil Imaging System). This is because the EMI instruments produce a magnetic field that radiates above as well as below ground and the presence of metallic objects will influence the strength of the secondary EM field. Vineyards are full of metal, principally wire but also sometimes posts, thus there is some debate over how applicable EMI instruments are in established vineyards. Evans (1998) however has mapped established vineyards with the EM38 instrument. By keeping to the middle of the row and limiting depth to ~1-1.2m Evans argues that the wire trellis does not influence the EM fields. Soil resistivity sensors operate by injecting a direct electrical current (DC) into the soil and measuring the resulting voltage to determine electrical resistivity (1/conductivity). By varying the spacing between electrodes, generally disc coulters, different depths of measurement can be obtained (Luck and Eisenreich, 2001).

In comparing EMI and DC instruments Dabas et al. (2001) preferred the latter instruments as the...
calibration is more stable and less sensitive to error from soil heterogeneity. This is in part due to the fact that DC instruments provide absolute measurements of resistivity and do not require calibration (Luck and Eisenreich, 2001). The pattern of soil EC$_a$ with both methods however has been shown to be relatively stable over large areas (Lund et al., 1999, Short, 2000). By having more than two sets of electrodes many DC instruments are also able to provide multiple depth measurements in a single pass (Lund, 2000). The principle advantage of EMI is the ease of use of instrumentation and the cost. These factors are probably a result of the widespread use of EMI over the past 20 years. As DC instruments become more excepted it is likely that their user friendliness will increase and the cost decrease. The main draw back to the DC sensors are problems when the soil exhibits a high contact resistance, that is when it is either very dry or frozen (Dabas and Tabbagh, 2003; Luck and Eisenreich, 2001).

Despite the widespread use of soil EC$_a$ sensors, particularly Geonics EM38, in vineyard design there are very few published reports on the use of these sensors in viticulture. Evans (1998) has shown that mapping EC$_a$ to various depths, with appropriate calibration, is useful in determining the amount and location of salt in a saline affected vineyard. EM38 measurements have been used to determine the relative soil depth in terra rossa soils in the Coonawarra region of South Australia (Bramley, 2001). However the unique nature of these soils, a weathered soil with a sharp boundary to limestone parent material, means this application of EM38 is probably only valid on this soil type.

No comparisons of the effectiveness of EMI vs DC instruments on prospective or established vineyards were found in the literature. Such a study, particularly in established vineyards, would be of interest to see if the presence of wire in the vineyard is effecting the EM field.

Grote et al. (2004) have shown that ground penetrating radar (GPR) can be used as an alternative to soil EC$_a$ sensors to proximally estimate soil moisture. Their studies on topsoil (0-10cm) moisture have shown a strong correlation between GPR estimations and gravimetric measurements although the relationship becomes less stable in very dry soils. By varying the frequency of the radar signal multi-depth estimations of soil moisture may be possible. As a result studies into the estimation of topsoil soil moisture in vineyards have been undertaken in California (Hubbard et al., 2003). Results are promising but still preliminary.

3.4.4.2 Canopy sensors.

As mentioned previously the use of remote sensing on vineyards with narrow canopy management, such as vertical shoot positioning, may be problematic due to the large percentage of background signal in the image (Dobrowski et al., 2002). To avoid this experiments have been established to map canopy properties from a tractor using digital images to determine canopy porosity (Praat and Irie, 2003, Bruno Tisseyre, ENSAM, Montpellier pers. comm.). Tractor based mapping would be extremely useful as vineyard management frequently requires the traversing of tractors along rows. By mounting sensors on tractors, information could be gathered with no time-cost and at different stages of vine development.

In preliminary studies, strong visual correlations existed between aerial infrared images and the raw proximally sensed camera data (Praat and Irie, 2003). However the similarities have yet to be quan-
CHAPTER III  NEW TECHNOLOGIES FOR AUSTRALIAN VITICULTURE

3.4.3 Vineyard Management

Several record keeping programs specifically designed for viticultural management have been developed over the past 5 years (Rofe, 2001). The majority of these have originated from, and are designed for, the North American market and in general have a strong product tracking, winery quality assurance and sales management slant. Two programs that do cater for vineyard management are Vintners Advantage from MIS (www.miscorp.com) and PC-Blend from Blend Winery Software. A summary of their capabilities is given in Table 3.2. None of these currently offer site-specific mapping capabilities and are essentially bookkeeping services for on-vineyard management.

In Australia the dominant viticulture decision support software has been AusVit, a joint collaboration between Charles Sturt University, Departments of Agriculture in NSW, VIC and WA and the University of Adelaide. The aim of AusVit is to assist overall management by providing information and recommendations about pests and diseases. Its main goal is to minimise the use of chemicals in vineyards to a sustainable and highly efficient level (http://www.csu.edu.au/research/rpegwr/ausvit). The other viticulture specific software available in Australia is PAM Ultracrop - Viticulture Specific Version from Fairport Technologies. This is an adapted version of the PAM QA Plus system that allows site-specific mapping and analysis. At the end of 2003 Fairport Technologies and the CRCV...
# New Technologies for Australian Viticulture

**CHAPTER III**

Precision Viticulture and Digital Terroirs: Investigations into the application of information technology in Australian vineyards

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<td>N</td>
<td>N</td>
<td>N</td>
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</table>

Table 3.2: Functionality of existing software for aiding decision making in vineyards (and wineries). Y = Yes, N = No, P = Possible (usually with an add-on) and missing values indicates uncertainty.
announced a joint project to amalgamate PAM and AusVit. The new program is due in early 2004 and should provide AusVit with some site-specific capabilities. The current capabilities of Pam Ultracrop - VSV and AusVit are also listed in Table 3.2.

3.5.2 Product Tracking

The issue of product marketability and traceability is becoming an important part of maximising on-farm profitability. In general agricultural profit margins are decreasing and economics of scale are increasing. To survive, growers need to increase the scale and efficiency of their enterprises and/or the quality of their product. Many growers are now realising that the bidirectional flow of information along supply chain lines can help maximise product quality. Information flow allows the grower to better understand the consumers’ demand but also allows the consumer access to information on the production system behind the commodity. By selling information with their crop, growers are able to command a premium (Taylor et al., 2003).

Examples of the flow of information along supply chains are becoming more common however they are not being reported in the scientific literature. In Australian viticulture the outstanding example is Banrock Station. They have been actively marketing their “brand” wines into European markets with the logo “Fine Wine Good Earth” to promote their “clean and green” image (www.banrockstation.com). By pursuing conservation farming methods and then conveying this information through to the consumer they are able to command a premium for their wines. In general Australian wines are considered to be “clean and green” by Europeans. However with the threat of salinity and general degrading of agricultural land in Australia the ability to demonstrate that our viticulture has a low environmental footprint may be crucial in maintaining overseas market share (Reedman, 2001).

The technologies to track product through supply chain systems, for example radio frequency identification (RFID) tags and barcode scanners are already developed for the service industry. Their application to horticultural production is still in its infancy but shows great promise (Praat et al., 2003). To my knowledge there has been little site-specific application of these technologies in viticulture. However product tracking and marketing software is freely available, for example Oenolog, Wine Production Management, The Winemakers database, PC-Blend and Breckenridge Winery Management Software (Coggan, 2000). Again these programs are primarily North American driven to provide quality assurance within the wine making process, however the opportunities for information flow are starting to be exploited (Coggan, 2000).

3.6 Information Providers for Australian Viticulture

There are a wide variety information and service providers that are currently supporting the movement to precision viticulture. Table 3.3 provides an indication of who the major information gatherers and distributors are. It is by no means an exhaustive list and no recommendation on information or service quality is implied.

3.7 Summation and Future Research

There is no doubt that the global interest in Precision Viticulture technologies is very high. The intensive nature of viticultural production appears well suited to the application of new and emerg-
ing technologies. The opportunities and money available in viticulture will ensure that private companies continue to develop and market new products. However, as with the broadacre industries, most of the technology to date has been aimed at measuring production variability rather than trying to understand and respond to the variability. Although it is still young, the precision viticultural industry in Australia has seen service providers come and go because their service is tailored to a specific sensor or information and not to growers needs.

Growers are collecting spatial information on their production system. The next step is to turn this information into decisions. Growers need to adopt on-vineyard experimentation to determine the site- or zone-specific responses within their production systems. New and existing DSS also need to be adapted to operate site-specifically once this information is available.

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Table 3.3: Table of Australian spatial information suppliers for viticulture
3.8 References


CHAPTER III NEW TECHNOLOGIES FOR AUSTRALIAN VITICULTURE

Investigations into the application of information technology in Australian vineyards


**CHAPTER III**  
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**Investigations into the application of information technology in Australian vineyards**

- **Precision Viticulture and Digital Terroirs:** Investigations into the application of information technology in Australian vineyards, GSA Annual Meeting, Seattle, WA, 2003.
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