Geospatial Tools and Techniques for Vineyard Management in the Twenty-First Century

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Abstract

Tools and techniques to monitor and map the environment are now very well developed and widely used in practice. One area in which information technology has been increasingly and successfully applied over the past 20 years is in agricultural and horticultural applications. A specialised area of application of horticulture is Precision Viticulture (PV), a subject that has been increasingly documented in the USA and Australia. Precision Viticulture is now a very well developed approach to vineyard monitoring, mapping and management, and one that has been successfully demonstrated through many studies and practical applications leading to greatly improved efficiency and effectiveness in the day-to-day operation of the vineyard and, ultimately, improved fruit quantity, quality and wine production. This has been particularly true for the larger commercial vineyards with both the financial resources to utilise such technologies and operating over relatively large areas of grapevines. This chapter seeks to provide an up-to-date overview of the role of some of the geospatial and associated technologies in Precision Viticulture (PV).

Introduction

Tools and techniques to monitor and map the environment are now very well developed and widely used in practice. Remote sensing, in the form of aerial photography and a range of airborne sensors, and more recently satellite imagery, has provided an effective way to gather data and information about the environment at many different spatial, spectral, temporal and radiometric resolutions. Digital mapping and cartography, and latterly Geographical Information Systems (GIS), have also provided the means to map and visualise the environment at a variety of different scales, to create environmental databases and to analyse and integrate a wide range of spatial and temporal datasets. Global Positioning Systems (GPS), and more recently the associated mobile technologies such as the Personal Digital Assistant (PDA) and mobile GIS software, have provided the capability to gather, process and display information whilst working in a field environment. Small microprocessors have also yielded miniature environmental sensors that can be deployed in arrays and wireless networks to gather multiple sources of environmental data at a number of locations. Software developments, too, have provided the basis to model the environment, to generate

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visual scenarios and to visualise both data and information with the added benefit of being able to undertake exploratory and interactive studies of the environmental data collected. The Internet now offers rapid access to information in a variety of different forms, and integrated applications of these technologies have provided the means to create Decision Support and Planning Systems (DSS).

One area in which information technology has been increasingly and successfully widely applied over the past 20 years is in agricultural and horticultural applications at the farm level. Both are by their very nature spatial (Smith and Whigham 1999). Precision agriculture and precision horticulture utilise geospatial technologies, including remote sensing (Liaghat and Balasundram 2010) for data collection, positioning, analysis, display, visualisation and communication for the monitoring, mapping and management of a wide range of agricultural and horticultural crops from alfalfa and corn to fruit and nut orchards and tomato crops (http://www.vineview.com).

A specialised area in horticultural applications is Precision Viticulture (PV), a subject that has been increasingly well documented in the USA and Australia and most recently in a volume by Proffit et al. (2006). To date, however, Precision Viticulture (PV) has been somewhat slower to develop than its counterpart in agriculture as the nature of the grapevine and its management are very different from most other crops, being a row-spaced canopy, and implementation of management techniques is generally different and considered somewhat more difficult. Furthermore, viticultural tradition has probably delayed or restricted the implementation of such novel tools and techniques in most European vineyards as compared to the widespread use and development of PV in the New World countries of North America, Australia and New Zealand. Lamb et al. (2008) also argue that there is still a very large knowledge gap between developers and users of IT-based tools and techniques in this field which is partly responsible for the slow uptake of these technologies in practice.

However, Precision Viticulture (PV) is now a very well-documented approach to vineyard monitoring, mapping and management, and one that has been successfully demonstrated through many studies and practical applications leading to greatly improved efficiency and effectiveness in the day to day operation of the vineyard and ultimately the impact upon improved fruit quantity, quality and wine production (Ryerson et al. 2008; Fraigneau 2009). This has been particularly true for the larger commercial vineyards with both the financial resources to utilise such technologies and operating over relatively large areas of grapevines.

This chapter seeks to provide an up-to-date overview of the role of some of the geospatial and associated technologies in Precision Viticulture (PV). Although remote sensing typically forms a major part of Precision Viticulture (PV), as evidenced by the number of publications in this field, a separate chapter in this volume by Johnson et al. covers this aspect of vineyard monitoring and management in more detail than will be considered here. In this chapter, therefore, only minimal coverage will be given to remote sensing, aiming only to touch upon the more specialised remote sensing tools and techniques that will complement those discussed elsewhere in the book. This chapter also aims to highlight some of the more affordable geospatial technologies and techniques that are now currently available for use in the smaller scale vineyard as opposed to solely focusing on the larger commercial-scale vineyard.

Precision Viticulture

Precision Viticulture (PV) is generally considered to be the application of one or more of the geospatial technologies and other related devices, tools and techniques that use spatial location for the purposes of collecting, processing, analysing and visualising environmental data collected in a vineyard. It is considered to be a cyclical process by Bramley (2001) involving observation and data collection, e.g. using remote sensing and mapping, data interpretation and evaluation with the aid of a GIS, and finally, implementation of a management plan. Such information is used for management of the vines, the vineyard, and decision making and planning in the context of vineyard management.

As discussed by Proffit et al. (2006), there is now a wide range of computer-based monitoring and management tools that offer the potential to improve the availability of up-to-date data and information collection, processing, analysis and visualisation to assist in the management of a vineyard. In practice, precision viticulture (PV) provides researchers and winegrowers with a suite of tools to measure and manage the vineyard. However, it should be noted that not all of these tools and techniques can be directly utilised yet by the vineyard manager as their use is still constrained by costs, expertise and familiarity with the different IT technologies, and a general awareness and acceptance of the potential benefits. Indeed, even in the USA and Australia many of the tools and techniques available still often require the expertise and equipment of specialist technology companies to carry out the analysis and visualisation in the data into information pathway.

PV is also considered to be an approach to wine production based on recognition of the fact that the productivity of vineyards and individual blocks within a vineyard can be inherently variable over space and time because of differences in topography, soils, soil moisture, slope and aspect, plant health and vigour, microclimate and the management practices (Proffit et al. 2006). Variability in the environment ultimately leads to variability in grape yield (quantity) and quality and ultimately table grape and wine production. Vineyard management with the aid of PV is therefore considered to be a targeted approach rather than one that will be implemented uniformly over all areas within the vineyard. It therefore seeks to help a vineyard manager gain increased control over an inherently variable production system so that any given management decision has an increased chance of delivering the desired or expected outcomes (Bramley 2001).

The Geospatial Technologies

The geospatial technologies typically include Global Positioning Systems (GPS) and mobile Geographical Information Systems (GIS) for data collection and mapping; remote sensing for monitoring and mapping; desktop GIS for spatial data processing, analysis, modelling and mapping and environmental databases for data storage and retrieval. Today this suite of tools would also consider including modelling, simulation and geovisualisation software tools as well as the use of the Internet, e.g. website and web access, online GIS, mapping and geovisualisation.

As discussed in the chapter by Johnson et al. (this volume), remote sensing, ranging from aerial photography to numerous airborne and satellite sensors, has provided the means to gather up-to-date imagery, data and information about vineyards. Through visual photo-interpretation, and more often now the use of Digital Image Processing (DIP) software for electronic image enhancement and classification, a considerable amount of useful information about a vineyard environment, both canopy and surroundings such as the soil and cover crop, e.g. phenological status, plant vigour, soil moisture and health/disease, can be relatively easily and repeatedly extracted from the remotely sensed image data. Attempts to automate the process for some regularly required information have perfected the information extraction technology to the stage where the imagery can be uploaded and processed online to extract key information which can be used in decision making and planning, e.g. Normalised Difference Vegetation Index (NDVI), an approach similar in many ways to the convenience of taking digital image storage media from a digital camera to the supermarket or pharmacy to process, enhance and print the photographs. This has been particularly successful where regular daily or weekly overflights of imagery are used for real time monitoring, and rapid processing of the data yields much needed information for planning and decision making.

In recent years, the Internet and Google Earth (GE) have provided the capability for improved access to online information by a wider audience. For vineyards, data and information collected using field-based data acquisition systems and low-cost wireless networks can be displayed against background image and terrain information in GE. This opens up many new opportunities to display and share spatial information, to communicate spatial information to a wider audience and to form the basis for constructing local (geospatial-based) information systems for a vineyard without the need for a desktop GIS or knowledge on how to use it.

The following sections of this chapter provide a brief overview of some of the recent developments in the geospatial and related technologies and their applications to vineyard management. Space is also given to ground-based measurements that now benefit from the convenience of spatial or locational information provided by a GPS and a GIS.

Remote Sensing

As stated earlier in this chapter, the application of remote sensing to vineyard monitoring and management is more than adequately covered elsewhere in a separate chapter in this volume. This section will therefore seek only: (a) to cover some of the less well-known examples of platforms and sensors that have been used, (b) to consider some additional aspects of remote sensing for data collection and processing through the use of digital image processing software for information extraction and (c) to integrate remotely sensed data with other sources of spatial information in a GIS environment. Furthermore, these examples will focus specifically on their use in the smaller, non-commercial vineyard.

Airborne Imagery

Aircraft have been widely used for a number of years to capture airborne imagery of vineyards, e.g. Wassenaar et al. (2000), Lamb et al. (2002), Hall et al. (2002), Da Costa et al. (2007), Pitcher-Campbell et al. (2001), Chanussot et al. (2005), Delenne et al. (2010), Ryerson (1974), and Brown (2008). In the beginning, the most useful imagery was either true colour or colour infrared (CIR) aerial photography (Hall et al. 2002). A number of well-known studies by Wildman (1979, 1981, 1987), for example, promoted the use of CIR photography for monitoring outbreaks of phylloxera disease and the phenological status of vineyards. With the advent of digital aerial photography and imagery for monitoring and management purposes, processing data into information has become much faster with the aid of Digital Image Processing (DIP) software, many of which are now available for the vineyard manager, being cheaper and easier to use.

Other remote sensing studies have made use of airborne video (Grierson and Bolt 1995) and high resolution multi-spectral airborne imagery (Hall et al. 2002; Da Costa et al. 2007; Johnson and Lobitz No date) to provide detailed descriptions of vines in a vineyard, information about plant vigour, the identification of dead vines (Chanussot et al. 2005) and biomass, together with ground measurements to define plant water restriction zones within a vineyard, e.g. Acevedo-Opazo et al. (2008). Others have made use of SAR (Burini et al. 2008). Some researchers have made use of CASI hyperspectral imagery, e.g. Hall et al. (2002) and Zarco-Tejada et al. (2005), and Lidar imagery of vineyards to derive information about the vegetation surface and the terrain (Fig. 13.1). Thermal information has also been used on a number of occasions; for example, Jia et al. (2006) used thermal imagery from the Airborne Hyperspectral System (AHS) airborne platform (to complement ground imagery and ASTER satellite imagery) to estimate sensible and latent heat fluxes.

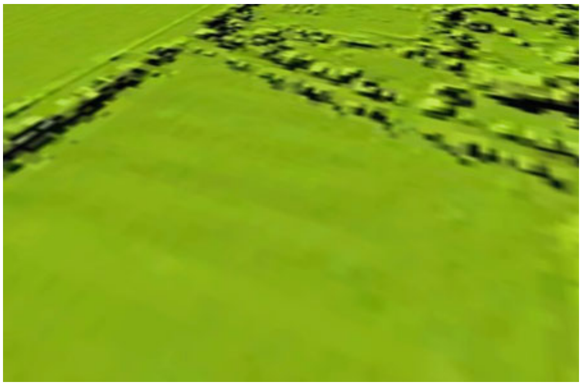

Fig. 13.1 Airborne imagery of a vineyard

Lidar, like all other sensors, provides unique information about the environment that cannot be obtained from any other source. The advantage of this particular source of imagery is the information that it contains about the local variations in vineyard terrain, e.g. hollows and ridges that can be useful when trying to identify potential cold spots and air drainage problems and barriers in a vineyard, but, moreover, valuable information about the vegetation canopy structure can also be obtained (Dubayah et al. 2000). The resolution of such data is also significantly greater than can be obtained from most published topographic contour maps. In addition, Digital Elevation Models (DEM) or Digital Terrain Models (DTM) can be used to explore the relationship between topography and other variables, e.g. soils, soil moisture and drainage. DEMs can also be overlaid with other remotely sensed imagery and digital map data from a GIS to provide a semi-realistic visualisation of the vineyard. In the UK, Lidar imagery is currently being used by some vineyard managers to aid in monitoring and management of the vineyard (Meadowgrove Vineyard, UK).

Remotely sensed imagery from many different sources is often used together and each source is complementary. Most GIS can also handle remotely sensed data as a layer within the GIS and, more often than not, many different sources of geospatial data are integrated as part of the vineyard management task.

But, despite the wealth of imagery and image data now available there are still some potential limitations to its wider use, particularly by the smaller vineyard with limited financial resources and technical expertise. Image acquisition can be expensive particularly if it is

Fig. 13.2 Large-scale model airborne platform

to be acquired, purchased and used on a regular basis. Furthermore, image processing and information extraction still requires expertise, and whilst fairly low-cost software can now be purchased, e.g. Adobe Photoshop and Idrisi from Clark Labs, the learning curve can be quite steep for the vineyard manager, and the expertise and facilities of a commercial company may therefore be required to generate the information needed. This, too, will incur a significant cost for the small vineyard with limited resources.

Small-Scale Airborne Platforms

Though not often taken seriously as a platform for capturing remotely sensed imagery for environmental applications in the past, large-scale model airborne platforms, e.g. fixed wing (aircraft) and rotary wing (helicopters) have, on a number of occasions, been considered as a low-cost alternative to capturing imagery flown by larger-scale platforms (*see* http://www.spaceref.com/news/viewpr.html?pid=12357). With recent technology developments such platforms, therefore, provide a powerful basis to gather data and information that can be tied into a vineyard GIS database and in-situ data collection on the ground.

There are now a wide range of small-scale platforms available to anyone considering the acquisition of low-cost aerial remotely sensed imagery. These include kites, model aircraft, balloons, helicopters, Unmanned Aerial Vehicles (UAVs) and microlights (Johnson et al. 2003a, b; Johnson and Herwitz 2004; Berni et al. 2009). Far from being 'toys,' many of these airborne platforms can now be equipped with traditional but lightweight SLR and digital cameras as well as video cameras for the collection of panchromatic, true colour and colour infrared photography and video footage. Additionally multi-spectral imagery can easily be captured through repeated overflights of the vineyard with the aid of camera filters, or more recently through the use of on-board hyperspectral systems. Some of the so called model platforms are also large enough to carry multiple payloads and now even make use of wireless transmission for real-time data capture (http://www.uav-applications.org/projects/vineyards_1.html). Johnson et al. (2003a, b), Johnson and Herwitz (2004) and Berni et al. (2009) have all used UAVs and lightweight sensors to collect multispectral and thermal imagery of vineyards

Whilst the photography acquired can then be manually interpreted using the techniques of aerial photo-interpretation, Digital Image Processing (DIP) software, much of it now low-cost, can also be used to geo-correct and mosaic the photographic prints or images together as the basis for onscreen interpretation and the mapping of thematic information for input to a GIS. DIP software has considerable potential for the small scale vineyard, allowing the vineyard manager to overfly a vineyard on a regular basis for monitoring and mapping (Fig. 13.2).

These smaller platforms offer a relatively low-cost and flexible means for the frequent capture of airborne imagery to both monitor and map a small vineyard whilst the larger ones can be used for larger area coverage. The lower cost of PCs and accompanying hardware, e.g. storage media, scanners, printers and software, also provides an opportunity for the small vineyard to be able to capture, store, process and map the data on a regular basis in-house.

Satellite Imagery

A number of authors have, over the years, considered and evaluated the role of different sources of satellite imagery for the monitoring of vineyards (Philipson et al. 1980; Minden 1982; Trolier et al. 1989; Chelli et al. 2005). Ducati and Da Silva (2006) used ASTER data for Precision Viticulture. Brancorado et al. (2006) used IKONOS data for vineyard studies in Italy. Early examples of satellite imagery and data often had relatively limited use for vineyard monitoring because of the relatively low spatial and limited spectral resolutions of the data. However, greater success has since been achieved with the newer and higher resolution satellite sensors that now also provide a much better combination of spectral, spatial, temporal and radiometric resolutions for monitoring vineyards and vine plants.

For the most part, however, many of these studies have often been, and still are largely experimental academic research, in terms of their being widely applicable to different locations on a repetitive basis. Some have been more successful and usable than others. Practical use of the image data has also been constrained by the success with which it is possible to extract information about the vine canopy on a reliable and regular basis. Establishing the relationship between the image and the ground information of interest has frequently been quite difficult because of the complexity of the cause-effect relationship between the remote sensing signal and the vegetation and/or ground surface which is also complicated by the intervening atmosphere.

One of the most successful outcomes of image analysis has been the generation of Normalised Difference Vegetation Index (NDVI) maps from imagery, and it has been possible to produce relative and normalised NDVI maps and change detection maps from image analysis on a regular basis (http://www.vineview.com). This provides the basis for providing the information that can be used to develop a management plan, fertiliser strategy, a cultivation and harvest plan to facilitate frost protection, pruning, irrigation and replanting decisions. This information also provides the basis for problem identification, practice improvement, precision application, sampling, harvest planning and profit improvement (http://www.grayhawk-imaging.com).

However, not all information extraction has been so straightforward. A great deal of effort and energy, for example, has been put into academic plant canopy modelling studies, e.g. Suits (1983), Verhoef and Bunnik (1976), Smith (1982), Jaquemoud and Baret (1990) and Jacquemoud et al. (2009), to model the spectral reflectance of plant canopies, and more specifically vine canopies (a row canopy). These studies have formed the basis for extending our knowledge and understanding of the reflectance and emittance characteristics of a vine canopy. Inversion models have also been developed to extract information about the canopy from image data. Recently statistical reconstructions of vine canopies have been explored to assist in more accurately characterising and simulating vine structure and canopy light interception and transmittance (Louarn et al. 2007).

Geographic Information Systems (GIS)

Geographic Information Systems (GIS) are frequently defined as computer-based software and hardware to collect, store, manipulate, analyse and display map and image-based data (Burrough 1986). Today there are many examples of GIS software available for various computer platforms including the desktop, laptop, and even Personal Digital Assistant (PDA) platforms. Ranging from simple field data collection-based software to mapping toolboxes, advanced spatial analysis systems and increasingly sophisticated display and geovisualisation software tools, GIS has become more widely available, easier to use and more affordable over time. Today, GIS software suitable for use in a vineyard environment can be purchased for around $600–$1,000, and there are also many freely available systems that are also perfectly adequate for most purposes.

Commonly available GIS software packages include free open source software such as MapWindow (http://www.mapwindow.org/), GeoDa (http://geodacenter.asu.edu/), TNT-Lite (http://www.microimages.com/

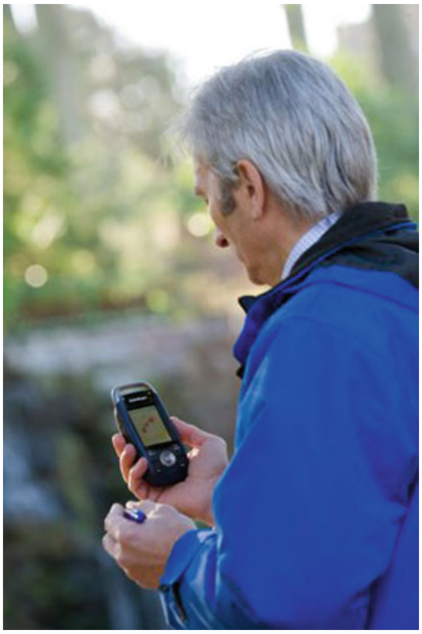

Fig. 13.3 Mobile GIS device

tntlite/) and GRASS (http://grass.itc.it/), to low-cost mapping software, e.g. MapViewer (http://www.goldensoftware.com/) and the more costly and sophisticated spatial analysis software, e.g. Global Mapper (http://www.globalmapper.com/), Manifold (http://www.manifold.net), ClarkLabs Idrisi (http://www.clarklabs.org) and ESRI's ArcExplorer, ArcView and ArcGIS (http://www.esri.com). Some of the software packages available also include powerful integrated digital image processing tools, e.g. Idrisi Taiga, thereby providing the capability for the vineyard manager to enhance, analyse and classify remotely sensed images on site.

Plugin Global Positioning System (GPS) units and various options also allow locational data to be added to the base maps in a GIS, whilst mobile GIS software such as ESRI's ArcPad (http://www.esri.com) and PocketGIS (http://www.pocket.co.uk/) (Fig. 13.3) provide the means to log positional information in the field together with point, line, or area (polygon) feature attributes in the form of, for example, digital photographs and field sketches.

GIS, coupled with Global Positioning Systems, a wide range of environmental sensors (see later in this chapter), increasingly powerful PDAs with field mobility and image processing capabilities, therefore, provide a powerful and relatively low cost suite of easy-to-use tools with which to collect spatial data and to process it into information which can then be used as the basis for decision making and planning.

Many vineyards, particularly those operating on a commercial scale, now make use of GIS in one form or another to map the attributes of the vineyard, from defining and plotting the vineyard boundary, row positions and blocks to the inclusion of the vineyard infrastructure, e.g. access routes and buildings (Merenlender 2000). Over a relatively short period of time vineyard managers can quickly and easily build a detailed spatial database containing a temporal record of the vineyard that can be further analysed using GIS-based spatial analysis techniques to help monitor and map spatial patterns over time, e.g. soil moisture, drainage, phenology, disease and biomass. GIS is also a powerful modelling tool that can be used to integrate data to better understand the relationships between grapevine growth and environmental variables (Castel et al. 2007).

Coupled with image analysis tools, GIS, therefore, provides a comprehensive and integrated spatial data and information toolbox to capture, store, analyse and visualise vineyard data. Dainelli et al. (2005) describe some of the different ways in which very high resolution remotely sensed imagery and GIS has been used to study site variability in Europe, e.g. the Bacchus Project. Reductions in the cost of hardware and software now means that such technology is even more widely available to the smaller vineyards to aid in utilising the tools of PV for day to day management. Furthermore, nearly all GIS and image processing software now comes with tutorials plus data and web-based support to assist in reducing the learning-curve needed to become familiar with the tools, techniques and systems. Better user-interfaces and more user-friendly hardware and software have also considerably aided in the use of off-the-shelf systems helping the non-specialist to make use of sophisticated technology and techniques without the need to be an expert in the field.

Global Positioning Systems (GPS)

A fundamental part of PV is to have an accurate spatial location of features at any one time within a vineyard. Various different types of Global Positioning Systems (GPS) are now widely available to give locational positions of varying accuracies for any individual, feature, or object on the Earth's surface. These systems use satellites to provide a 3D position: longitude, latitude and elevation.

Fig. 13.4 GPS unit

GPS technology has become increasingly sophisticated and accurate, as well as lower in cost. Whilst single, non-differential, GPS receivers probably have limited use in a vineyard for data collection with accuracies that are inadequate for mapping vineyards. Differential GPS (DGPS) provides a positioning accuracy of 2 m or better. Although more costly, Real Time Kinematic (RTK) Differential GPS, using a local base station with known reference coordinates, offers the sort of accuracy (2 cm) that is required for the accurate mapping of vineyard features, as well as for mounting on planting and harvesting vehicles to provide the basis for the navigational control of post and trellis erection, vine planting and other management systems such as fertiliser application and spraying and grape picking (Tisseyre et al. 2007), as well as the capture of photographic and other attribute data about the canopy.

GPS are clearly at the heart of the practice of vineyard spatial data collection and mapping (Fig. 13.4) and a growing number of devices incorporate GPS to provide a spatial location for each measurement required. The data collected can now be plugged directly into a GIS thereby making the process of data collection and mapping much more direct than was possible in the past.

Visualisation

Many GIS software packages now come with 3D visualisation capabilities. This allows for the display of terrain and surfaces in the form of Digital Terrain Models (DTM) or Digital Elevation Models (DEM), and Digital Surface Models (DSM). Whilst some topographic information is available to purchase for vineyard terrain, GIS toolboxes now allow one to generate DTMs from Lidar and contoured map data. More sophisticated (and expensive!) toolboxes that come with image processing software systems, e.g. Erdas Imagine (http://www.erdas.com/) and soft photogrammetry software, e.g. BAESocetSet (http://www.bae-systems.com) allow one to derive detailed DTMs from stereoscopic aerial imagery. The task is not, however, trivial and it is more usual to purchase the data.

Aerial photography and satellite imagery, together with map layers from a GIS, can then easily be overlaid on a DTM (usually with some vertical exaggeration, e.g. 3X) to create a semi-realistic view of the vineyard site, and often providing a new perspective of the site for the vineyard manager, and one that can be examined from any view angle. Some GIS software also allows one to fly through the landscape using predefined flight lines and to capture the flight in the form of a video file, which can be used for the purposes of communication or for scientific visualisation. Draping other map layers over the DTM also provides the possibility to examine relationships between the terrain slope, aspect, soils, illumination and accessibility.

In Niagara, Canada, Duncan (2007) has also developed a new type of vineyard management system which involves the collection of GPS data linked to a database containing coordinates, production yields, soil analysis, a digital photograph and vine health data. Using this information, GIS maps showing slope, aspect, contours, wind patterns and cold air pooling are created to study the effects of vineyard topography. An integral part of this study involves the integration of 3D imaging, visualisation and GIS technologies to generate a realistic 3D map and fly-throughs.

Internet and Google Earth

A related development of the benefits of using geovisualisation in vineyard management is the use of Google Earth for terrain and information visualisation. The Internet or World Wide Web (WWW) offers the vineyard manager a number of possibilities in relation to vineyard monitoring and management. This includes access to vineyard information through websites, e.g. local information systems for a vineyard and winery and online mapping or GIS systems allowing thematic

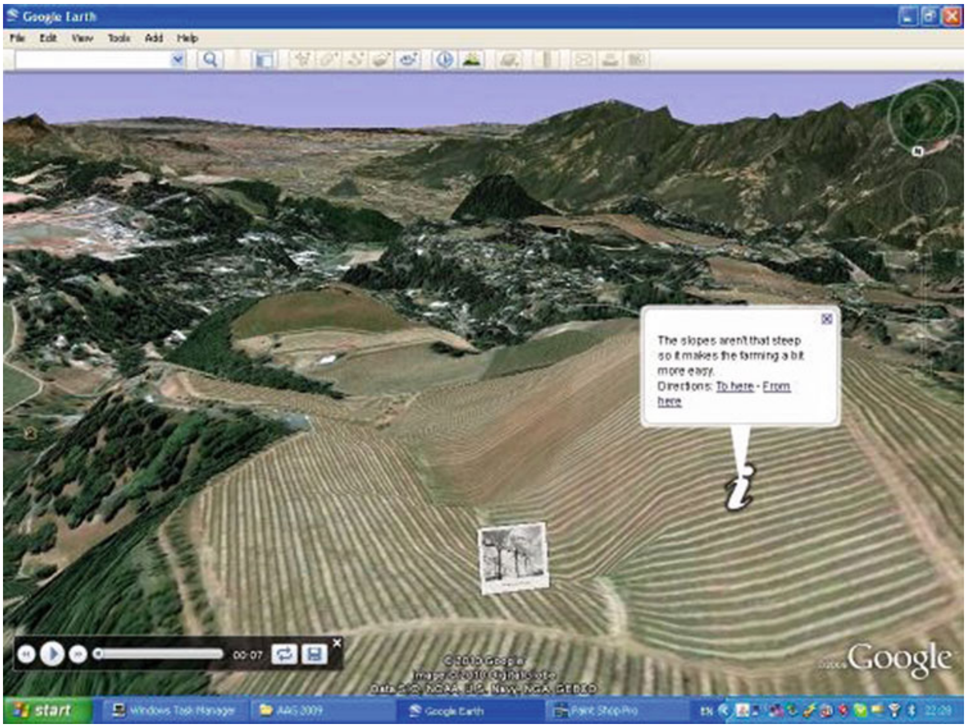

Fig. 13.5 Google Earth

layers to be accessed and displayed (much as they would be in a desktop GIS), as well as the capability to monitor vineyard information from wireless sensor networks placed around the vineyard. An example of the use of the web and GIS is the Catalan Viticultural Register (Lloret and Jurado 2004).

Smart networks allow data to be captured, recorded and displayed or visualised in a graphic format on the web in Google Earth and accessible in the vineyard office providing a wide range of local environmental information about the vineyard, e.g. temperature, soil moisture and humidity which can be logged and displayed (Tongrod et al. 2009; Baggio 2005).

Combined with data captured with the aid of a GPS, the Internet can now also be used to add spatial data and information to Google Earth (GE) (http://earth.google.co.uk/). With the advent of publicly available geographical software applications, such as Google Earth (GE), NASA's Worldwind (http://worldwind.arc.nasa.gov) and Microsoft's Virtual Earth (http://www.viawindowslive.com/VirtualEarth.aspx), there are now opportunities to visualise GIS and image data within this software. Google Earth in particular has become very popular and can be used as the basis to construct a simple Local Information System, virtual fieldtrips or tours and even fly-throughs using the 3D terrain viewing capability.

With the aid of a combination of utility software, e.g. MapWindow, Sketchup (http://sketchup.google.com/) and Shape2Earth (http://shape2earth.com/), it is possible to add GIS data to the GE view, thereby creating a Local Information System (LIS) and Virtual Reality field environment (Green 2009). This information can then be displayed and shared as well as included with more general vineyard information systems. There are already a number of examples where Local Information Systems have been created for a vineyard providing access to information about the vineyard sufficient for a virtual tour of the vineyard and including more detailed and specific layers about various aspects of the vineyard (Fig. 13.5). There are now also many low-cost or free software utilities that can be used to assist in the preparation of a visualisation for a viticultural landscape.

In the context of geovisualisation, Mike Bobbitt Associates (http://www.mikebobbitt.com) have used various software tools to illustrate vine row illumination and the sunlit and shadow areas of the canopy and

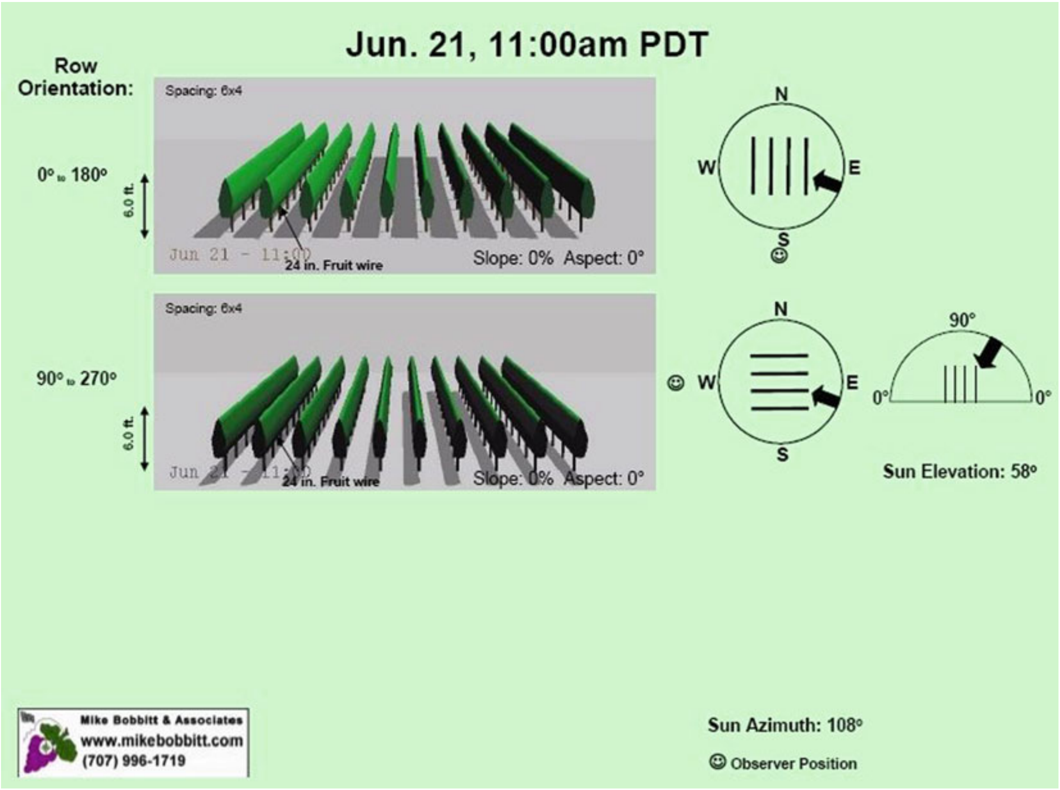

Fig. 13.6 Modelling vine row illumination and sunlit and shadow areas of a vine canopy (Mike Bobbit Associates)

the area in between the rows, and the effects of equipment side slope and row orientation (Fig. 13.6). Other examples displayed on their website include interactive maps that show the vineyard block map, a 3D view of the vineyard and a regional map showing the AVA (American Viticultural Area) boundaries. These combine GIS-based maps with GE views of the vineyard and have the potential to be very powerful communication tools

Developments in Ground-Based Monitoring and Measurement

Traditionally, ground-based measurements have always been part of vineyard management to provide the data and information needed to manage the crop. As already discussed, PV has enhanced our ability to do this more quickly and efficiently with the assistance of a range of new tools and techniques such as remotely sensed imagery, GPS and GIS. Aside from the ease with which it is now possible to collect data more quickly than in the past and more frequently, ground-based data collection is also essential to provide the information necessary for management as well as to assist in the calibration of any remotely acquired data and information.

Over time, the ground-based devices available for collecting such data have also evolved from the once relatively crude and home-crafted DIY tools devised for measuring leaf angles, leaf area and solar radiation to much more sophisticated and accurate devices available off-the-shelf and out of the box, e.g. a range of electronic and digital sensors, light metres and leaf area metres.

Today such field-based equipment is also far more finely tuned to the needs of vineyard management than was the case in the past, being smaller, more portable and catering to the information needs of the commercial vineyard, as well as being commercially available. Such equipment is also cheaper (though not always necessarily affordable if several devices are needed), is designed to collect data more quickly, and includes the capability to capture locational information, thereby allowing it to be plotted, along with many other variables, on a map and correlated with other spatial information. Advances in battery power have also helped to make the equipment more practical in the field, and improved interfaces mean that the operational learning curve is much shorter.

Essential to the practice of PV is reliance on a detailed knowledge of the growth stages of grapevines (phenology) in order to provide a guide for when certain measurements need to be carried out. For example, the vine growth stages described by Coombe and Dry (2004) and the photographs of Institut Francais de la Vigne et du Vin (www.vignevin-sudouest.com) are often cited. Knowledge of grapevine phenology is essential, for example, to help develop a model for the estimation of potential grape yield and quality. Differential GPS, for example, can be used to show the differences in the phenology of the vineyard by recording the location versus the observation that may be based on visual comparison with the reference information or a photographic record (Mariani et al. 2007).

This section of the chapter briefly describes some of the most commonly found examples of ground-based measurement tools often included in the realm of Precision Viticulture that can help to provide the means to generate a more complete picture of all the important variables that are needed to provide the vineyard manager with the basis for a more informed decision-making process.

Field-Based Wireless Sensors and Sensor Networks

Our ability to design and produce ever smaller and lower-cost micro-processor-based sensors and to overcome some of the battery and power management constraints of the past has now enabled vineyard managers to purchase and deploy comprehensive sensor networks in vineyards. Many of these utilise power saving and wireless radio technology; these are generally referred to as Wireless Sensor Networks (WSN) (Morais et al. 2008).

Sensor arrays provide the opportunity to monitor key information of interest to vineyard management. These sensors include the monitoring of soil properties such as moisture and temperature, humidity, wind speed and incoming and outgoing spectral radiation. They have the potential to improve the quantity and quality of products produced by a vineyard using sensors that monitor environmental, climatic and physiological parameters (Morais et al. 2008), and can help to understand vineyard variability to allow appropriate management practices to be implemented (Matese et al. 2009). The design of optimum wireless sensors for such purposes is discussed by Morais et al. (2008), Agrosense (2008).

Wireless networks also provide the means to gather data in real time, and to assist in the identification of areas of disease and the application of fungicides. They can measure temperature, wind speed, humidity, light, wind direction and leaf wetness, all in the form of a so-called weather chip (Fig. 13.7) (McCauley 2006). Practically, such information can be used throughout the growing season to help in the timing of irrigation and fungicide applications (Morais et al. 2008).

Providing the means to capture and display vineyard information in real-time can be a bonus for the vineyard manager who can then monitor the environmental variables from the office computer and, if appropriate and useful, to place such information onto a map of the vineyard. This sort of capability is probably even more important in the larger vineyard than the small one where it is not practically possible to visit all areas within the vineyard on a regular basis.

There are now many examples of such sensors available on the market, and the decreasing costs have significantly impacted upon the frequency and regularity of vineyard monitoring capability. Using sensors costing as little as $50.00 per unit (Hobo data loggers and wireless sensors: http://www.onsetcomp.com/) in a wireless network allows a vineyard to be monitored at any time interval desired, the data being fed back wirelessly to a desktop computer in the manager's office (Dering 2007), and transformed into information in the form of graphs and maps, plotted on a GIS map, or overlaid on Google Earth. Coupled with information from remotely sensed imagery, GPS and GIS, such sensors provide the modern vineyard manager with a wealth of information that can easily be integrated in a GIS to aid in management, planning and decision making.

Hemispherical Photography

Hemispherical photography (making use of a camera with a fish-eye lens) has been used for sometime to capture information about the distribution of leaves within a plant or tree canopy and radiation in numerous

Fig. 13.7 Wireless-based data collection

agricultural and horticultural crops. Photography can be taken from above, within and below the canopy to provide information about the canopy or the light regime within the canopy.

Whilst visual analysis and analysis and interpretation of the photography was once quite a time consuming task, a number of computer-based software products have since enabled faster and more accurate analysis of the images. One of the first was a public domain programme CANOPY developed by Rich (1989) that allowed capture of the images, separation of the canopy foliage from the canopy gaps, and calculation of measures of the canopy architecture and geometry and light penetration. An example focusing on a vine canopy in Vineland, Ontario, in Canada is shown in Fig. 13.8.

Fig. 13.8 Hemispherical photograph of a vine canopy

Today the traditional camera/film combination has been replaced by the HemiView System hardware and software produced by Delta-T Devices (www.delta-t.co.uk). HemiView is a software package designed to analyse hemispherical photographs, and can be used to predict radiation levels above and below a canopy, as well as the direct and diffuse components of the incoming radiation. A significant development has been the digital camera option HEMI-DIG that allows for the capture and transfer of digital hemispherical imagery for input to the HemiView software. Along with the camera there is also available a specially designed Nikon fisheye lens and a self-levelling camera mount. Outputs from HemiView include information on sky geometry, gap fraction, leaf area index, solar radiation, site factors, time-series and sunflecks.

Yield Monitoring and Yield Mapping

Winegrowers usually require a measurement of the grape crop yield. Several yield monitoring systems have been developed for this purpose. Tisseyre et al. (2007) mention a number of these. One such system comprises an apparatus which measures the quantity of grapes harvested with a DGPS recording the coordinates. An advantage of yield monitoring systems is that they are non-intrusive (Proffit et al. 2006). The sonic beam system uses ultrasonic sensors to measure the volume of grapes passing along the discharge conveyor. An alternative is the gravimetric yield-monitoring system that weighs the grapes passing across load cells below the discharge conveyor belt of the harvester. The yield monitors can record about 2,000 measurements per hectare with an average speed of 3 km/h (Tisseyre et al. 2007). From both the yield and coordinates data collected, it is then possible to generate yield maps for the vineyard, typically the product of GIS software, as described by Bramley and Williams (2001). The cost and operation of the specialised equipment, however, means that such technology is largely confined to large vineyards and wineries in Australia, Spain, or California. In France, by comparison, this kind of management is still not in widespread in use.

Selective Harvesting

Whilst grape yield maps have their uses, and are frequently a product of PV, they are not always considered particularly useful when it comes to undertaking vineyard management in an environment which is considered very variable. Tisseyre and McBratney (2008) therefore proposed the development of a Technical Opportunity Index (TOI) to see if it was possible to develop Site Specific Management (SSM) from a yield map and on this basis, for example, to determine selective treatments and harvesting within the vineyard. This method seeks to extend the capability of GIS to provide a Decision Support System (DSS) to aid the vineyard manager based on whether the observed variation within a field is manageable for some proposed field operation (p. 112).

Canopy Measurements

Characterising the vine canopy can be useful to estimate productivity, based on the canopy architecture and density (Schultz et al. 2001). Whilst some canopy measurements can be derived from aerial photography and satellite imagery, as mentioned earlier in this chapter, other ground-based systems using remote sensing monitoring systems, have been developed to assess and map canopy properties. Measurements of the canopy often include leaf area and Leaf Area Index (LAI) which are often made by destructive sampling of the leaves in the vine canopy and with the aid of statistically established correlations estimating the number of leaves and finally the leaf area. Leaf area measurements are usually achieved with the aid of a leaf area metre, and besides being a destructive sampling method, are costly and time consuming.

Today many of the canopy measurement systems are based on digital imaging systems which allow the measurement of several canopy parameters such as canopy height and canopy porosity (gap fraction). Such equipment can usually be mounted on typical vineyard machinery, e.g. a tractor otherwise used for trimming and spraying. Measurements can then be carried out several times during the season to assist in better management of the vineyard (Tisseyre et al. 2007; Polo et al. 2009).

Canopy density can also be measured with handheld apparatus such as a ceptometer, e.g. the AccuPAR Model LP-80 (http://www.decagon.com/canopy/accuparlp80/) that records Photosynthetically Active Radiation (PAR) and Leaf Area Index (LAI). Measurements made in real-time can be stored on the device. Vineyard leaf area is a key determinant of grape characteristics and wine quality established through relationships between NDVI and LAI (Johnson et al. 2001; 2003a, b).

Tuohy (2005) and Bramley et al. (2007) describe a new sensor developed in New Zealand called Grapesense (Grapesense Brochure, (no date)), a video-based image analysis system designed specifically to measure canopy density and porosity for monitoring and mapping of canopy size and growth. The video camera equipment is mounted on a tractor and uses a pink or magenta screen placed behind the vine row of interest to provide a measurement of canopy porosity.

Work by Goutouly et al. (2006) has also led to the development of alternatives to NDVI derived from airborne or spaceborne sensors using ground-based methods. An active sensor, known as Greenseeker, has been developed to measure NDVI which is sensitive to porosity variations of the canopy, and can also be used to establish the growth and vigour of the vine.

Pruning Weight

Strong relationships between leaf area and pruning weight have been identified by Johnson et al. (2003a, b). Others such as Dobrowski et al. (2003) have found good relationships between pruning weight and Ratio Vegetation Indices (RVI) derived from aerial photographs. The measurement of pruning weight is relatively simple and relies on weighing the vine canes cut after pruning to estimate vine vigour. This involves the use of a simple top-load scale combined with the GPS co-ordinates of the sample weighed. The relationship between pruning weights and RVI is also easier than collecting canopy density data. This can be useful early in the season when it would be possible to identify areas on an aerial photograph where pruning weights are expected to be low which would potentially mean insufficient vegetation to ripen the fruit. Action could then be taken to undertake crop thinning or apply Nitrogen to boost growth.

Trunk Diameter Measurements

The diameter of the trunk of a vine plant can easily be measured with either a vernier or a digital calliper. The former provides 1/10 mm accuracy for daily monitoring whilst the latter provides 1/100 mm accuracy. Trunk circumference measurements are a useful measure because they show a strong correlation with vine vigour.

An electronic device known as a dendrometer can also be used to measure trunk diameter. An accuracy of 1/100 mm can be achieved and the device can be used in wireless mode. Matching the measurements to certain growth stages can be helpful when establishing the correlation between trunk diameter and grapevine water status (Selles et al. 2007). There is also a good relationship between average Maximum Daily Trunk Growth (MDG) and average Berry Growth Rate (BGR) from fruit set to veraison, leading to a bigger berry size being obtained at harvest. However, the cost of such a device usually means that only a few will be deployed in the vineyard.

Stem Water Potential (SWP), usually measured at midday, can also be correlated with irrigation treatments. SWP is also correlated to BGR from fruit set to veraison. However, MDG is more related to soil water content than SWP. Therefore MDG and SWP can be used as a tool for irrigation scheduling in vineyards.

Light Within the Canopy

Aside from the hemispherical photography often used for canopy radiation measurement, there are many other sensors that have been developed over the years for measuring incoming and outgoing radiation and hence reflectance or albedo. In the past, monitoring light above, within and below the canopy was undertaken using a range of directional and hemispherical sensors including solar trackers and directional and hemispherical radiometers. The use of spectral filters allowed for the collection of Photosynthetically Active Region PAR and NIR reflectance.

Today these sensors have been modernised and replaced by more portable and easy to use sensors. Delta-T Devices (www.delta-t.co.uk), for example, provides a range of PAR (Photosynthetically Active Region) PAR sensors, sunshine sensors which can be attached to data loggers, including a device known as a SunScan Probe Canopy Analysis System which can be used to acquire PAR interception and Leaf Area Index (LAI). The latter can also be hooked up to a portable data collection terminal. Such sensors can also be attached to a probe so that they can be inserted in the canopy at different heights to establish the extinction of radiation within the vine canopy.

Soil Measurements

Soil type and soil properties, e.g. moisture, are often quite variable across a vineyard site. The variability of soil can be established through conductivity measurements (or its reverse, resistivity). Conductivity correlated with several soil parameters, and these can therefore be mapped. Two types of equipment are used: an ElectroMagnetic Induction (EMI) sensor, and an electrical resistivity sensor. Different models are available to measure conductivity to different soil depths, e.g. from 0 to 75 cm, 25–120 cm and up to 3 m (Tisseyre et al. 2007). Care needs to be used when operating the device as metal objects such as trellis structures in the vineyard can influence the readings, and frequent calibration is often needed. Ideally the measurements have to be made at the following vine growth stages: budburst, shoots (10 cm), flowering or post-harvest.

The electrical sensitivity sensor is used in PV for a one dimensional survey known as Vertical Electrical Sounding (VES). The measurement points are the same as with the EMI. In some cases, the sensors can be pulled behind a quad bike to speed up the time taken to complete a survey (Bramley 2001; Samouelian et al. 2005).

The result of such surveys is the production of soil conductivity or resistivity maps that can be correlated with other soil properties such as solid constituents, water content, cation exchange capacity (CEC), pore fluid composition or soil temperature (Samouelian et al. 2005). Such maps reveal the spatial patterns of soil conductivity and therefore soil properties within the vineyard and can be used within a GIS for correlation with other thematic layers. This information can provide a useful tool to help zone the vineyard into high and low vigour zones.

Soil temperatures measured at different depths and during different growth stages can be used to monitor the influence of temperature on grape maturity. Soil temperature sensors can be placed at different depths, e.g. 10, 50 and 80 cm (Burgos et al. 2007). High soil temperatures at 10 cm depth appear to be correlated with the maturity of grapes. Moreover, the number of days between bud and flowering, and between flowering and veraison decreases when the soil temperature is warmer, and the maturity of the grapes is accelerated. Measurement of soil temperatures and their correlations can help wine growers when they establish their vineyard revealing that the soil environment plays a major role in the development of the vine. However, the relationship between soil moisture and temperature still needs to be better understood so as to be able to predict how the wine *terroirs* will respond to future predictions about global warming and climate change.

Other Sensors

Other sources of information are also important to the vineyard manager. At present there are still no harvester-mounted or hand-held sensors specifically designed to measure quality parameters such as Baume and Brix, pH, titratable acidity (TA) and anthocyanins or phenolics (Tisseyre et al. 2007). However, near-infrared (NIR) spectroscopy can be used to find out the composition of the grapes. A NIR spectrometer can collect very accurate measurements compared to reference methods (Tuohy 2005), and the correlations between NIR measurements and reference methods are very good for Brix, pH, and TA.

Mechanical Tools

Variable Rate Technology (VRT) has not been used widely in viticulture to date because Decision Support Systems (DSS), which allow one to decide how much input to apply at a location, are not well developed. Nevertheless, where the technology has been applied, albeit in a simple way, it has been found to have a direct financial benefit. One of the main applications of VRT mentioned by Tisseyre et al. (2007) is for weeding operations. VRT weeding systems have been commercially available since 2003 and are used to selectively apply herbicides to the vineyard. Detection of the weeds by an optical sensor is the basis for the application of the spray. It has been found that this technology can save up to 75% in the use of herbicides (Tisseyre and Taylor 2005). A similar system, Weedseeker, can also be used on discontinuous vertical canopies to apply fungicides. This also reduces the use of chemical products as the spray is only applied to the canopy and not the gaps (Fig. 13.9).

Current Research and Future Developments

There are a number of sensor developments in the pipeline for vineyards. These include yield, soil property and sprayer sensors. A number of yield sensors are now under development in various parts of the world for placement on grape harvesters. Soil property sensors such as the apparent Electrical Conductivity (EC) are being developed. Tisseyre et al. (2007) mention the Time Domain Reflectometry (TDR) sensor for mobile apparatus. This sensor uses radar. The dielectric reading from the sensor is converted to water saturation providing reliable and accurate soil moisture monitoring capability. It can be used either vertically or horizontally. A new mobile 'on-the-go' soil sensor

Fig. 13.9 Weedseeker

is also mentioned by Tisseyre et al. (2007). Others sensors being developed include soil ion sensors (mainly nitrogen and potassium sensors) and near infrared and mid-infrared sensing systems. Finally, ground penetrating radar and gamma radiometrics are being trialled in vineyards to determine their potential role. Spraying sensors are also being developed that will measure the flow or pesticides from vineyard sprayers (Gil et al. 2007; Llorens et al. 2010).

Summary and Conclusions

Whilst vineyard management has always relied upon the collection of data about the vine canopy, the terrain and the environment, the tools and techniques developed in the context of PV have facilitated greater knowledge and understanding of the vineyard environment and its management for wine production. The tools and techniques now used in PV are quite wide ranging and can provide very accurate information about all aspects of the vineyard. For the most part, yield sensors, vigour maps using indices such as NDVI or PCD or soil sensing surveys are most widely used. Other measurements such as pruning weight and trunk diameter can also be made in relation to spatial location.

However, whilst it is clear that there are many tools and techniques now available, most are still only used in the larger commercial vineyards that have the financial resources and the expertise to hand to justify the use of expensive and high-tech devices and systems. Although some of the cheaper kits are now in use in smaller vineyards, many vineyards are in any case physically just too small to practically make use of the technology, let alone afford it. As noted by Lamb et al. (2008), there are also other factors that limit the widespread use of the technologies ranging from a reluctance to adopt the technology, justification of the costs versus benefits and the expertise needed to make use of the many different tools and techniques, some of which still need to be simplified to encourage their operational use, and accompanied by opportunities for training.

But, as can be seen from the quantity of information now available in the form of journal papers, web pages and factsheets, together with books on precision agriculture and Precision Viticulture, it should not be long before people are more aware of the role and value of PV in vineyard monitoring and management.

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