NEW TECHNOLOGIES AND METHODOLOGIES FOR SITE-SPECIFIC VITICULTURE

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Abstract

Aims: This paper makes a brief overview of the tools and methods that have already been released or are currently under development to assess production variability in vineyards. It also reviews the main results published to date on the amount of variability observed in both yield (quantity) and grape quality at a within-field scale and some implications that the nature of the variation has for site-specific management.

Methods and results: This paper is a review that presents the main experimental results from a recent assessment of the within-field variability of the main parameters in grape production : yield, sugar content, pH, vigour and also vine water status and its link with harvest quality. Information on the spatial structure of production variation is of importance as it provides an idea of how site-specific management may be applied to a particular field. Finally, one of the key points in viticulture is the assessment of the vine water restriction and its variability, over both time and space.

Conclusion: The collection of high-resolution spatial information on crop production is now possible in viticulture. This information includes measurements of the local environment, including soil, canopy growth and the final quantity and quality of production. These new technologies and methodologies will allow growers and viticulturists to consider new management methods, more efficient experimental designs and provide a better understanding of the vine production system.

Significance and impact of study: Precision viticulture tools and methods offer great opportunities in perennial cultivations, like winegrapes. Nevertheless, there are also challenges facing the viticulture industry before widespread adoption of such technologies will occur.

Key words: Sensors, spatial variability, precision viticulture, temporal stability, water restriction

Résumé

Objectif : Ce document fait un rapide état de l'art sur les techniques existantes ou en cours de développement permettant d'appréhender la variabilité spatiale des principaux paramètres en viticulture. Il fait également un état de l'art sur les principaux ordres de grandeur rencontrés dans plusieurs vignobles du monde en matière de variabilité spatiale (amplitude de variation, coefficient de variation) pour les principaux paramètres.

Méthodes and résultats : Ce document présente les principaux résultats obtenus dans le domaine de la viticulture de précision. Il montre qu'au niveau intra-parcellaire, les principaux paramètres de production tels que le rendement, le sucre, le pH, la vigueur et l'état hydrique des plantes présentent une grande variabilité. Dans ce cas, une information importante est la structure spatiale de la variabilité afin de déterminer s'il est possible ou non de gérer les variations observées. Un des paramètres clés pour comprendre la variabilité spatiale de la qualité de la vendange est la contrainte hydrique et sa variabilité tant spatiale que temporelle.

Conclusion : La mesure de paramètres localisés géographiquement en ligne, grâce à des capteurs embarqués sur machine ou grâce à des images aériennes, ne présente plus d'obstacle majeur en viticulture. À court terme, la mesure spatialisée à haute résolution et systématique de paramètres sur la plante et le sol va donc devenir une réalité en viticulture. Ces sources d'information permettent d'accéder à une connaissance fine des systèmes de production qu'il était difficile d'appréhender avec des systèmes de mesure classiques.

Signification et impact de l'étude : Cette étude montre que les outils et méthodes relatifs à la viticulture de précision sont très pertinents pour aider à la gestion de cultures pérennes comme la vigne. Elle met aussi en évidence les défis techniques et sociaux qui sont à relever par la filière avant d'envisager une adoption massive de ces outils et méthodes.

Mots clés : *Vitis vinifera*, variabilité spatiale, viticulture de précision, cartographie, stabilité temporelle

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INTRODUCTION

Over the last fifteen years, many new technologies have been developed for, or adapted to, agricultural use. Examples of these include: low-cost positioning systems, such as the Global Positioning System with the new European EGNOS differential correction, proximal biomass and Leaf Area Index (LAI) sensors mounted on-board agricultural machinery, geophysical sensors to measure soil properties and low-cost, reliable devices to store and exchange/share the information. Combined, these new technologies produce a large amount of affordable high resolution information and have lead to the development of fine-scale or site-specific agricultural management that is often termed Precision Agriculture (PA).

The development and adoption of PA technologies and methodologies to viticulture (termed Precision Viticulture or PV) is more recent. Despite the relative infancy of PV, many PV research projects already exist in practically all the significant wine production areas of the world; including, France (Tisseyre *et al.*, 2005b, Goutouly and Gaudillière, 2006, Bobillet *et al.*, 2005), Spain (Arno *et al.*, 2005), U.S.A (Johnson *et al.*, 2003), Chile (Ortega-Farias *et al.*, 2003, Ortega *et al.*, 2003, Best *et al.*, 2005), South Africa (Strever, 2004), New Zealand (Pratt *et al.*, 2004) and Australia where the adoption of PV seems to be most advanced (Lamb *et al.*, 2004, Bramley and Hamilton, 2004, Taylor *et al.*, 2005b).

Some of these research projects are aimed at developing or utilising sensing systems, such as biomass or leaf area index sensors, yield sensors and quality sensors, to provide information at a resolution never before achieved in viticulture. Other projects are aimed at developing methods to quantify the within vineyard variability observed and data processing tools to assist wine growers and viticulturists to manipulate, analyse and make decisions from such information. Ultimately, combining the technologies and methodologies will allow winegrowers to improve and optimise production systems by taking into account technical and economical aspects of management as well as environmental issues at an intra-parcel (sub-block) level. An example of such an improvement is the possibility of adopting site-specific management to optimize fertilizer application or water use efficiency in irrigated vineyards.

The first section of this paper will present a brief review of real-time sensing systems that are, or will soon be, commercially available. The second section will present some current PV case studies illustrating how the information from these sensors can be used to improve production. The third section of this paper will focus on some methodologies being developed to characterize the spatial variability of winegrape yield and the difference and importance of the magnitude and spatial structure of variation. Finally, some experimental results on the assessment of the within-field variability of the plant-water status and its link with harvest quality will be presented.

NEW TECHNOLOGIES IN VITICULTURE

1. Geo-referencing

In precision viticulture, the ability to geolocate information, equipment or people within vineyards is critical. Nowadays geolocation is usually done with Global Navigation Satellite Systems (GNSS), of which the US Department of Defence's Global Positioning System (GPS) is the most ubiquitous. There are various GNSS receivers available depending on the accuracy of geolocation required. Geolocation in viticulture usually requires a Differential GPS (DGPS) receiver that provides a positional accuracy of around 1 m. For vine planting, where more precision is required, a Real Time Kinematic (RTK) GPS receiver with a positioning accuracy of ~2 cm may be used to guide the planting machine (Wagner Pflanzen Technik, Friedelsheim, Germany).

In Europe, the adoption of DGPS technology by growers should increase drastically with the establishment of the the low cost EGNOS (European Geostationary Navigation Overlay Service). Since June 2006 this service has provided a free differential correction which allows a positioning accuracy of around 2 m (European Space Agency, 2007). The impending commissioning of new GNSS, for example GALLILEO by the European Space Agency, and the rejuvenation should provide more competition, decrease cost and further facilitate the uptake of satellite positioning technology.

For some practical purposes, geolocation can be achieved in vineyards without a satellite-based positioning system. Vineyards rows and vine numbers along rows can be mapped and used to georeference vineyard measurements, particularly hand measurements such as vine circumference or grape quality (Best *et al.*, 2005; Taylor *et al.*, 2005b).

2. Yield monitoring

Yield sensors for mechanical grape harvesters are now available. Three systems have been commercialised: the HarvestMaster Sensor System HM570 (Juniper System Inc., UT, USA), the Canlink Grape Yield Monitor 3000GRM (Farmscan, Bentley, WA, Australia) and the Advanced Technology Viticulture (ATV) system (Advanced Technology Viticulture, Joslin, SA, Australia). All these systems are suitable for retrofitting to grape harvesters without tanks. The HM570 system is based on a volumetric measurement of the yield travelling along the discharge conveyor belt. The 3000GRM and ATV systems utilise a load cell system located underneath the discharge conveyor belt to measure the mass of yield moving across the conveyor.

To our knowledge, three other yield sensors are under development. One by the Pellenc company (Pellenc S.A., Pertuis, France) specially designed to fit the Pellenc grape harvesters with onboard storage capacity (Bourely, 1999). Another yield sensor, also specifically designed to fit harvesters with onboard storage capacity, is currently being developed within the framework of an interreg European project (Corea project). A third system is under development in Australia in collaboration with the Precision Viticulture Research Group at the University of New England (Dr. David Lamb, University of New England, pers. comm.).

Whatever the advantages and the disadvantages of the different monitoring systems, growers have (or will soon have) the opportunity to map the yield of their vineyards with a resolution never before achieved. Figure 1 shows a yield map obtained with the Pellenc prototype on a 1 ha field of Grenache located in Provence (France). The monitoring system allows the acquisition of more than 2000 yield measurements ha^{-1}, with an average speed of 3 km h^{-1}. It is difficult to determine how widespread the adoption of the yield monitoring systems has been. However, it has been predominantly large companies that have invested in such systems (Taylor *et al.*, 2005b), mainly in Australia, but also in California and Spain (Bernd Kleinlagel, Advanced Viticulture Technologies, Australia, *pers. comm.*).

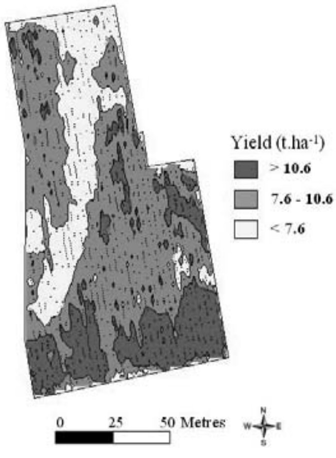


Figure 1 - Example of a winegrape yield map (1 ha Grenache variety).

The map was interpolated from raw yield measurements collected with a yield monitoring system mounted on a grape harvester positioned with DGPS. The raw points are shown as black dots in the figure. (source: Pellenc S.A./ agro-Montpellier, Vi-tis project)

3. In vineyard quality monitoring

To our knowledge, there are still no real-time harvester-mounted or hand-held sensors commercially available to assess grape quality, such as °Brix, titratable acidity, pH, phenolic. The Pellenc company has developed a sugar sensor, based on refractometry, for use on Pellenc grape harvesters. This system is able to provide maps of sugar content with a high resolution but is not commercially available nor capable of being retro-fitted to other makes of harvesters.

Significant progress in quality monitoring is expected with visible and Near Infra-Red (Vis-NIR) spectrometry technology. The Cemagref of Montpellier is currently developing a hand spectrometer to assess the sugar content and acidity in whole grapes/bunches (Crochon, Cemagref-Montpellier, *pers. comm.*). Considerable work on desktop applications of NIR spectroscopy to measure grape and wine quality has been done (Dambergs *et al.*, 2003, Cozzolino *et al.*, 2004) and a research project to again convert this to a field-based instrument is under way in Australia (Dr. Christo Liebenberg, University of Central Queensland, *pers. comm.*)

4. Canopy and vigour monitoring

Two main options are currently being used to monitor vine canopy and vigour:

- remote sensing systems, and

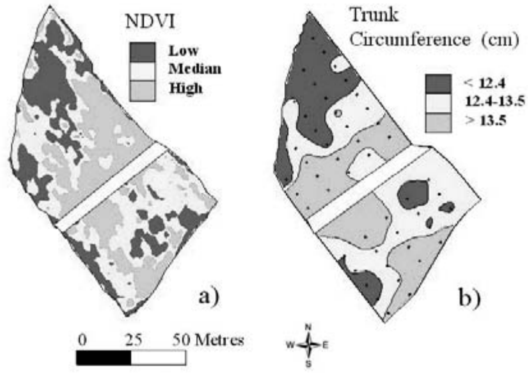
- ground-based monitoring systems.

a - Remote sensing systems

Remote sensing is currently dominated by either aerial- or satellite-mounted multispectral (Blue, Green, Red and Near Infra-Red wavelengths) sensors due to cost and operability. The preferred image resolution for PV is generally around 3 m^2 per pixel. This corresponds with the interrow width at densities between 3,000 and 4,000 vines ha^{-1}. At this resolution the image pixel is a "mixed pixel", that includes reflectance from the vines and the soil. However the relative contribution of the canopy and background signal is constant regardless of where the pixel is located in reference to the vine rows (Lamb *et al.*, 2001; Hall *et al.*, 2002). Coarser resolution imagery tends to omit relevant detail. Finer resolution imagery has been shown to be effective however requires more detailed processing (Hall *et al.*, 2003).

Aerial/satellite images are generally processed to produce vegetative indices, such as Normalised Difference Vegetative Index (NDVI) or Plant Cell Density (PCD) on a per pixel basis. These indices are often used as an estimate of vine vigour. In viticulture, vigour generally refers to the vine (shoot) growth rate whereas in remote sensing, vigour is viewed as a combination of plant biomass (vine size) and photosynthetic activity termed the 'photosynthetically active biomass' (PAB) (Bramley, 2001). The indices computed from remote sensing are related to vigour since vigorous vines are characterised by larger and denser canopies than vines of lower vigour. Many authors have shown relationships between NDVI and vine parameters including Leaf Area Index (LAI) (Johnson *et al.*, 2003), annual pruning weight (Dobrowski *et al.*, 2003) or other vine parameters (Lamb *et al.*, 2004) at a within vineyard level. The use of remote sensing data often constitutes a relevant and low cost information source to perform vigour zoning at a within-field level. This explains why imagery is currently used in Chile (Best *et al.*, 2005), California (Scholasch *et al.*, 2005) and Australia (Lamb *et al.*, 2001; Hall *et al.*, 2002; Proffitt and Pearse, 2004; Lamb *et al.*, 2004; Hinze and Hamilton, 2004; Bramley *et al.* 2005b) to assess vigour zoning.

In order to illustrate the relevance of NDVI information, figure 2 shows two maps from the same vineyard (1.2 ha of Syrah vines in southern France - INRA Pech-Rouge). For both maps, each class corresponds to 33 % of the data. Figure 2a presents a NDVI map with 3 classes derived from a multispectral aerial image with 1 m^2 pixels. Figure 2b presents a vigour map based on 3 classes of trunk circumference (49 measurements on the field). Visually both maps present similar spatial patterns. This experiment was conducted on 11 different vineyards in the same area and similar results were obtained from 10 of the vineyards. It is interesting to note that trunk circumference integrates information on vine vigour since the vine was planted. Zones derived from trunk circumference measurements can be considered as time stable in non-irrigated vineyards.



A 1.2 ha vineyard of Syrah grapes in the Clape Massif, Southern France. a) shows a 3 class NDVI map derived from 1 m resolution aerial imagery. b) shows a 3 class map of trunk circumference (cm) created by inverse weighting distance interpolation. The actual measurements points are shown as black dots in the figure (n = 49) (source : Agro-Montpellier/Inra Pech-Rouge)

Applications of NDVI exist in cool climate viticulture however, due to the higher plantation density (> 6,000 ha^{-1}) and the vertical positioning of the shoots producing narrow canopies, background noise (soil or grass) constitutes a large proportion of the pixel information in these images and the “mixed pixel” approach is less effective. As a result, images tend to require a higher spatial resolution to permit the segregation of the vine and background response. To analyse these images, the vine reponse needs to be separated from the background signal using row recognition algorithms (e.g. Bobillet *et al.*, 2005; Hall *et al.*, 2003). In the future, hyper-spectral imagery will provide significant additional information on the canopy. Hyperspectral imagery may also help discriminate the canopy from the background using the additional spectral information. Very high resolution imagery (pixels of < 0.5 m^2) can also be used to derive additional morphological information, for example, canopy thickness measurements and missing vines counts (Robbez-Masson and Foltete, 2005) at a within vineyard scale. Other research has been conducted to illustrate the use of super-spectral imagery (18 wavebands) (Hall *et al.*, 2002) to measure small inter-varietal differences in the spectral signature of the vine canopy of Cabernet-Sauvignon, Malbec and Shiraz.

Few investigations are currently being performed using multi-temporal imagery at scales larger than field size. Montero *et al.* (1999) has used temporal imagery at a regional scale to monitor vine growth and the change in vine cover. From this work the authors concluded that the growth behaviour of vine is limited by the water availability which is mostly likely linked to the above ground biomass production. The Phylloxera and Grape Industry Board of South Australia has also spent 3 years imaging all vineyards in South Australia to identify any infestations of phylloxera. Infestations could not be directly identified from the imagery, however the location of areas of poor vigour could be identified and subsequently ground-truthed for the pest.

b- Ground-based monitoring systems

Ground-based monitoring systems have also been developed to assess and to map canopy properties. Such systems avoid the problems associated with mixed pixels of soil, grass and vine canopy from remotely sensed images, especially in vertically trained canopies. Most of these systems are based on a digital imaging system which allows the measurement of several parameters such as canopy height and canopy porosity (Praat *et al.*, 2004, Tisseyre *et al.*, 1999 and Souchon *et al.*, 2001). These systems are designed to be mounted on existing vineyard machinery. By mounting sensors on tractors, canopy measurements can be taken during general vineyard operations such as trimming or spraying. This should provide more timely temporal data on canopy development during the season and thus more opportunity to micro-manage production. The sensors can also be used to take side-on or overhead images of the canopy to gain more information on canopy development.

5. Soil Monitoring

To date, real-time on-the-go soil sensing for PA has generally been performed using previously well established geophysical methods. Among these, sensors based on the electro-magnetic properties of soil have been most successfully applied to agriculture. These technologies give a measurement of the apparent soil electrical conductivity (ECa), which can be collected on mobile platforms. ECa is strongly correlated with various soil properties (Corwin and Lesch, 2005; Samouellian *et al.*, 2005).

Three types of ECa sensors are available : (i) Electrical Resistivity (ER) sensors, that utilise invasive electrodes (ii), non-invasive Electromagnetic Induction (EMI or EM) sensors and (iii) time domain reflectometry (TDR) sensors. Invasive ER and non-invasive EM are the most popular sensors as they have been widely commercialised. The commercial development of a TDR sensor for use on a mobile apparatus has not yet occurred but is being undertaken (Jantscke *et al.*, 2006).

The purpose of ER surveys is to determine the resistivity (and thus conductivity) from a given soil volume. Artificially generated direct electric currents are applied to the soil and the resulting potential differences are measured. Potential differences patterns provide information on the form of subsurface heterogeneities and their electrical properties (Samouellian *et al.*, 2005). Commercial examples of ER sensors include the Automatic Resistivity Profiling device (ARP), which was formerly Mucep, (Geocarta Ltd., Paris, France) and the Veris 3100 (Veris technologies, Salina Kansas, USA).

The principle of EMI sensors is to firstly generate a primary magnetic field that induces very small currents in the soil which in turn generate a secondary magnetic field. This secondary magnetic field is measured by a receiver coil in the sensor. Sensors are designed so that the secondary and primary magnetic field are linearly proportional to soil conductivity. (see Corwin and Lesch, 2005 for more technical details). Commercial examples of EMI sensors include the EM-31 and the EM-38 soil conductivity meters (Geonics Ltd, Mississauga, Ont., Canada).

The depth of exploration of the soil profile is proportional (for homogeneous material) to the distance between probes for ER sensors and to the distance between the transmitting and sensing coils for EM sensors. Both these technologies (ER and EM) are largely used in viticulture. Barbeau *et al.* (2005) used ER to compare the effect of rows with or without grass cover on soil water distribution. Taylor (2004), Best *et al.* (2005), Bramley (2005) have used ECa information to delineate within-field soil zones.

Since ER and EM sensors effectively measure electrical conductivities, the presence of metal, such as steel post or trellis wire, may influence the values. The degree of distortion caused by metallic objects in vineyards is the subject of current research. For the EM38 sensor, Lamb *et al.* (2005) showed that steel posts and wires have a significant effect on the values of ECa and a change in trellising structure introduces artefacts in ECa maps. Nevertheless, Lamb *et al.* (2005) showed that the EM38 was still useful for delineating soil zones in established vineyards when the row spacing was large enough (2.5-3 m) however, extreme care must be exercised by an operator to ensure that the EM sensor remains mid-row throughout the survey to minimise error from the trellis.

Figure 3 shows a map of ECa derived from 49 measurements from an ER sensor for the same vineyard shown in figure 2. Figure 3 shows similar spatial patterns to the trunk circumference and NDVI maps in figure 2. This indicates that vigour variability may be temporally stable and dependent on soil variability, highlighting the potential of ECa surveys for zoning purposes.

The predominant problem with geophysical sensors is that the signal tends to integrate several soil properties. In the case of ECa sensors the ECa value is dependent on the soil moisture content, soil clay content, soil clay mineralogy, cation exchange capacity, soil bulk density and soil temperature (Dabas *et al.*, 2001). While this signal

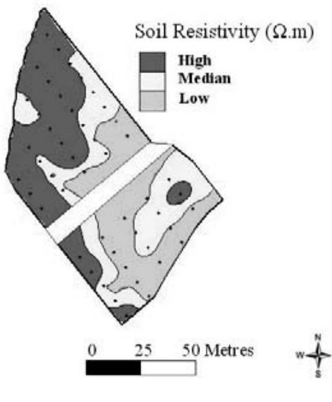


Figure 3 - A map showing 3 classes of soil electrical resistivity (ohm.m) for the vineyard described in figure 2.

The map was interpolated from 49 point measurements shown as black dots in the figure (source : Agro-Montpellier/Inra Pech-Rouge) can be decomposed to extract individual soil properties it often requires multiple sensors to be run simultaneously and/or temporally. At the moment research in the USA (Lund and Adamchuk, 2006) and Australia (Raphael Viscarra Rossel, Australian Centre for Precision Agriculture, pers comm.) is being conducted to construct new mobile on-the-go soil sensors to directly measure soil properties. A real-time commercial pH sensor (Veris Technology, Salinas, Kansas) and a prototype lime requirement platform (Viscarra Rossel *et al.*, 2005) have already been built. Further research into soil ion sensors, particularly nitrogen and potassium sensors (Lund and Adamchuk, 2006), Near-InfraRed (Viscarra Rossel *et al.*, 2006) and Mid-Infrared (McCarty *et al.*, 2002) sensing systems is being undertaken. There are also several other established geophysical sensors available that are being trialled in viticulture including ground penetrating radar (Hubbard *et al.*, 2003) and gamma radiometrics (Mark Baigent, Baigent Technologies, WA, Australia, *pers. comm.*). These new technologies do not respond to the same soil properties as ECa sensors and should therefore provide additional information on soil variability, particularly soil texture information.

When conducting an on-the-go soil survey it is common practice to also record elevation data from a carrier-phase GPS receiver. This permits the generation of a digital elevation model of the vineyard and the derivation of secondary and tertiary terrain attributes such as aspect, slope, curvature and wetness indices.

6. Vine water status monitoring

Many authors (Champagnol, 1984; Seguin, 1983; Dry and Loveys, 1998; Ojeda *et al.*, 2005) have shown that changes in vine water status have an effect on canopy vigour, grape yield and quality. Zoning the vineyards on the basis of vine water status should therefore provide a relevant decision support tool for canopy management. However such a zoning requires the assessment of plant water status with a high spatial and temporal resolution.

Research is currently being undertaken to develop sensors to allow the assessment of vine water status from the temperature of the canopy. Most of these sensors are based on infrared thermography (Stoll and Jones, 2005; Grant and Chaves, 2005; Alves *et al.*, 2005). Unfortunately these technologies remain very expensive and currently require very specific calibration procedures. An alternative approach would be to assess the spatial variability of the plant water status using ancillary information that are related to moisture availability and easy to measure at high spatial resolutions, for example, remotely sensed imagery, machinery-mounted canopy, yield sensors and soil ECa sensors. These ancillary data could provide the basic information required to characterize the within vineyard variability of the soil and the vine and define zones of homogeneous vine water status and/or water availability during the growing and ripening period (Tisseyre *et al.*, 2005a; Taylor, 2004).

7. Variable rate technology

To date, there have only been a few applications of Variable Rate Technology (VRT) documented in vineyards principally due to (a) a lack of decision support systems (DSS) to decide how inputs should be varied and (b) the presence of healthy profit margins in many countries that negates the need to improve production efficiency. As a result VRT applications currently focus on very simple decisions which lead to a direct fiscal benefit. In other agricultural industries, such as grains, variable rate controllers and machinery is well developed and this equipment can be readily adapted to viticulture applications when DSS are developed.

In Europe, the main opportunities for VRT occur with chemical applications. A VRT weeding system (Weedseeker, Avidor Ltd, Villars Sainte Croix, Switzerland) was commercially released in 2003 to selectively apply herbicides. This system is based on an optical sensor which measures reflectance at two wavebands (Green and Near Infra-Red). The computation of an index using these two wavebands allows the system to detect the presence of green weeds in the interrow or underneath the vine canopy and activate the application of herbicide. This systems allows savings of up to 75 % of herbicides (Chambre d'agriculture de l'Aude, 2005). The Weedseeker system has also been used to perform early fungicide applications on discontinuous vertical canopies. In this case, the sensing system avoids chemical application on canopy 'holes', leading to a significant saving of chemicals and also minimising the loss of chemical to the environment. Significant research has also been performed to adjust the amount of chemical applied according to the density and the porosity of the canopy (optidose) (Raynal, 2004). As profit margins decrease and the opportunity and support for site-specific management increases then VRT adoption should increase. Apart from Weedseeker, there are several other optical sensors commercially available to assist with differential chemical applications and are readily adaptable to horticultural and grain cropping systems.

HOW CAN THE INFORMATION BE USED?

The technologies described in the previous section provide accurate spatial information on the production system. These new information sources will provide growers with opportunities to improve in decision making process and the efficiency of production systems. Without the correct decision support then the information is essential just a pretty map and of no value to the grower. Research into developing decision support systems (DSS) has lagged behind technological development and is usually the 'bottleneck' point which impedes the adoption of PV (and PA in general). There are various stages in the production system where increased production efficiencies can be gained through the use of DSS. These include:

a) On-vineyard experimentation: The systematic acquisition of large amounts of spatial data (yield, vigour, soil and elevation) allow scientists to design experiments that take into account the underlying spatial variability and analyse the results accordingly. In viticulture, Bramley *et al.* (2005a) have already designed within-block experiments using airborne imagery or yield maps from previous years. They showed that considerable increase in knowledge about the production system can be gained from such experiments. Research is currently on-going in both viticulture (Bramley *et al.*, 2005a) and broadacre crops (Whelan and Taylor, 2005) to better understand how VRT can be used to design experiments that maximise the return of useful information while minimising the risk to the grower of any production loss from the experimentation.

b) Product traceability: PV technologies provide an opportunity to systematically record all production information spatially. In addition to the sensors discussed above, basic machine operations can be recorded (operating times, area covered, speed) as well as the output from any activity (such as spray flow rate, revolutions of pruning blades, etc.). This data can be automatically collected and digitally stored and provides production information in order to guarantee compliance with specific labels (for example organic wine, low environmental footprint contracts, specific origin, quality label) or conform to policy constraints such as European regulation 852-2004 on herbicides and chemicals. To our knowledge such applications of auditing technologies in viticulture are still in their infancy but show great promise. Systems to locate sprayers by DGPS and to monitor the main parameters of the sprayer (flow rate, tank level, speed) are already released (Farmscan, Bentley, WA, Australia) or are under development (De Rudnicki *et al.*, 2005). Such systems show great promise as chemical traceability remains difficult between the growers and the wineries/cooperatives. These systems allow the growers to prove that the amount of chemical and the date of spray comply with regulations. From a production perspective it also allows producers to verify that chemical applications were properly performed (i.e. no missing rows or double spraying of rows). A European life project (Aware project) involving researchers, growers, cooperatives and software companies is currently underway to apply these technologies (DGPS and sprayers) at a catchment scale near the city of Neffies (Languedoc-Roussillon, France).

c) Differential management: The collection of spatial datasets naturally provides growers with the opportunity to use differential management techniques to minimise the variability in either or both yield and quality, or to take advantage of its variability in order to improve grape/wine quality. There are several ways differential management may be implemented.

i) Target sampling: Understanding the underlying variability allows viticulturists/growers to design targeted sampling schemes to get a better assessment of grape yield and quality. Yield and quality assessment of vineyards is a key point for wineries or cooperatives to manage the wine making process. It is well known that the vineyard assessment of yield and quality (based on classical sampling procedures) is not accurate enough in a significant proportion of cases and may differ from winery assessment by up to 20 % (J. Rousseau, Institut Coopératif du vin, *pers. comm.*). Target sampling schemes that take into account the underlying spatial variability, based on airborne imagery or yield maps of previous years, provide a better assessment of crop production before harvest (Tisseyre *et al.*, 2005b).

ii) Differential harvest: Vegetative indices derived from canopy imagery (either ground-, aerial- or satellite-platforms) have been used to identify areas of different 'vigour' within blocks. The grape quality within these different vigour zones has been tested (using a targeted sampling scheme) and the results used to form differential harvesting strategies. This approach has been successfully adopted in South America (Best *et al.*, 2005) and Australia (Bramley *et al.*, 2005b). The two approaches currently being used are to either pick the block on the same day and segregate the different zones into different bins (and into different quality wines) or pick the different zones on different days when maturity and quality within each zone is considered optimum. Reports from Australia (Bramley *et al.*, 2005b, Hinze and Hamilton, 2004; Profitt and Pearse, 2004) show that differential harvesting is feasible and the extra profit gained easily offsets the extra cost of imagery acquisition, data analysis and differential harvesting.

iii) Other differential vineyard management: Vineyard operations such as differential canopy management, differential spraying, differential fertilisation, differential fruit or leaf removal, are also possible. However, for most of these applications there is a lack of decision support, especially to define application rates, according to the spatial information provided by canopy imagery or other monitoring systems. Moreover, for canopy management at the moment it is difficult to assess the extra cost of the information acquisition and analysis, the cost of any differential management and the benefits gained. This area of research is probably more relevant in high value cool-climate viticulture where canopy management is paramount.

WITHIN-FIELD VARIABILITY IN VITICULTURE

To justify implementation of differential management, there must be a certain level of coherent spatial variability in the production system. If variability is not present, then the null hypothesis of precision agriculture is correct and current uniform management practices are preferable (Whelan and McBratney, 2000). This section aims at presenting some results on the within block (parcelle) yield variability observed in viticulture in the context of both the magnitude and spatial coherence of the yield variability.

Recent work by Taylor *et al.* (2005a) presented a study on the within-field yield variability in viticulture. This study was based on the yield measured on 146 blocks. Yield data was sourced from three research institutions; Agro-Montpellier, Montpellier-France, the Co-operative Research Centre for Viticulture (CRCV)/CSIRO Land and Water, Adelaide, Australia and the Australian Centre for Precision Agriculture, Sydney, Australia. Three different grape yield monitors were used in the collection of data. These were the HarvestMaster HM570 (HarvestMaster ; Utah, USA), the Farmscan Canlink system (Farmscan, WA, Australia) and the Grape Yield Monitor under development by Pellenc S.A. (France). Yield data were obtained in different countries: Australia (several locations), France and Spain. Sampling rate varied depending on the speed of the machine, however in all the cases it was higher than 1,000 yield measurement.ha^{-1}.

1. Non-spatial measurements of variation

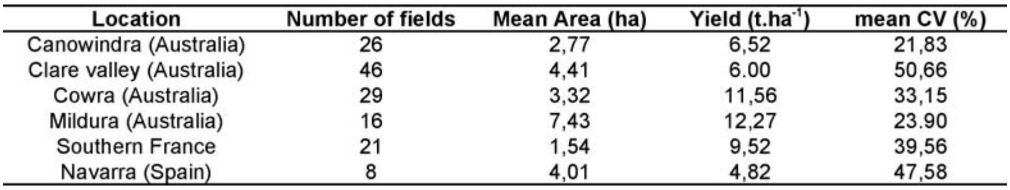
Table 1 shows that the within-field variability of the yield assessed with the coefficient of variation (CV) is large whatever the location. The CV varies from 20 % to 50 % depending on the location. The mean yield results show significant variability regardless of location or variety (full results not shown in this paper see Taylor *et al.* (2005a)). Similar coefficients of variation in yield were observed in other studies where yield samples was hand picked and measured at different sites within the field (Arno *et al.*, 2005, Ortega *et al.*, 2003).

Because of the lack of quality monitoring systems, there are only a few studies dealing with the within-field variability of grape quality and these are generally limited in size. However, published data on grape quality (Bramley, 2005; Taylor *et al.*, 2002; Ortega *et al.*, 2003;, Arno *et al.*, 2005, Ojeda *et al.* 2005, Tisseyre *et al.*, 2005b) highlight a significant within-field variability in various quality parameters. For hand picked samples, with a sample density varying from 15 to 50 measurement.ha-1, CVs from 3 to 10 % were observed in sugar content (°Brix), from 3.5 to 4.2 % for pH, from 1 to 21.6 % for anthocyanins and from 7.3 to 15.4 % for total titratable acidity. CVs for quality parameters are lower than for yield, but considering the units, they correspond at harvest to a large amount of variation in quality (Ojeda *et al.* 2005). Depending on the wine-making process and the grape price of the vintage, even small variations in quality may justify the adoption of differential management and/or harvest (Bramley *et al.*, 2005b).

2. Spatial structure of the within-field variability in viticulture

Non-spatial statistics, such as mean, variance and the coefficient of variation, are useful to characterise the amount of variation which occurs across a field. Nevertheless, these statistics are non-spatial and not designed to quantify spatial variation. Knowing whether it is possible to switch to site-specific management requires the spatial variability to be properly quantified. Pringle *et al.* (2003) proposed the use of geo-statistical techniques to assess such information, including variogram parameters (nugget variance (c0), sill variance (c0+c1) and range (a)) and derived spatial statistics, such as the areal coefficient of variation (CVa) and Spatial Structure statistic (S). The c0 value estimates the amount of variance at a lag distance of 0 m and is a function of stochastic effects and measurement error. The c1 value estimates the amount of auto-correlated variance in these data and contributes with c0 to define the sill (c0 + c1) or the total amount of variance in these data. The range defines the distance over which data are auto-correlated i.e. the distance at which the sill is reached. The derivation of the CVa and S statistics is more complex (interested readers

Table 1 - Location and summary statistics of within-field yield variation on 146 fields and several part of the world (from Taylor *et al.*, 2005a)



Location	Number of fields	Mean Area (ha)	Yield (t.ha^{-1})	mean CV (%)
Canowindra (Australia)	26	2,77	6,52	21,83
Clare valley (Australia)	46	4,41	6.00	50,66
Cowra (Australia)	29	3,32	11,56	33,15
Mildura (Australia)	16	7,43	12,27	23.90
Southern France	21	1,54	9,52	39,56
Navarra (Spain)	8	4,01	4,82	47,58

are directed to Pringle *et al.* (2003) for full details). The CVa attempts to adjust the CV statistic to a standard area to allow comparison between different sized fields. The concept of the S statistic is illustrated in figure 4 using three hypothetical fields. The three fields in figure 4 are of equal area, have the same mean yield, the same yield variance and the data arranged on a regular grid.

- Field (a): no spatial structure is exhibited and data appear as white noise. Values are intimately mixed which makes differential management of the field very difficult. This corresponds to the case where very different values are observed from one vine to another.

- Field (b): exhibits some patchy spatial structure but the patches are generally small and there is no broad trend in the data. It is intermediary in spatial behaviour between fields (a) and (c).

-Field (c): exhibits a strong spatial distribution in distinct patterns. In this case, the spatial structure promotes differential management in obvious zones. NB. there is still some small-scale stochastic variability in the data, however this variability is overshadowed by the spatially organised variation in the data.

In terms of variability, each of these three fields exhibits exactly the same coefficient of variation (CV), however, the within-field spatial structure of the data is significantly different between fields. This highlights the problem of relying on non-spatial statistics with spatial data sets.

To our knowledge, in viticulture, only Taylor *et al.* (2005a) have undertaken a detailed study of the within-field variability using geo-statistical techniques. This work was conducted on a significant data base of yield data (presented in the previous section table 1). The results of this study highlighted the presence of a spatial structure in almost all the blocks regardless of variety, location and training system effects. The study also highlighted significant trends on the data:

- In Australia, the within-field variability presented larger spatial patterns than in Europe (mean variogram range was twice that of France and Spain). This difference may be explained by larger field sizes in Australia,

- The spatial structure statistic (S) was predominantly due to variance explained by a quartic trend surface for European fields i.e there was often a strong trend within European fields.

- The magnitude of yield variation (assessed with CVa) was larger in Europe than in Australia.

The authors hypothesised that the larger CVa in European vineyards results from:

- The lack of irrigation which may increase the yield difference between zones of different soil condition. Variation in soil moisture availability may be emphasized in non-irrigated vineyards.

- The fact that traditional European vineyards are often designed around social constraints such as communal land, heritage locations and buildings rather than pure technical constraints such as soil type, soil moisture availability and slope.

The authors also hypothesised that in European conditions, the proportion of the variability explained by a trend surface may be due to the practice of planting on hill slopes, thus increasing the heterogeneity of the underlying soil. These hypothesis would required further work on a larger database to be validated. Nevertheless, results obtained by Taylor *et al.* (2005a) show that there is manageable yield variability regardless of location, but the opportunity for management is driven by different factors in different locations.

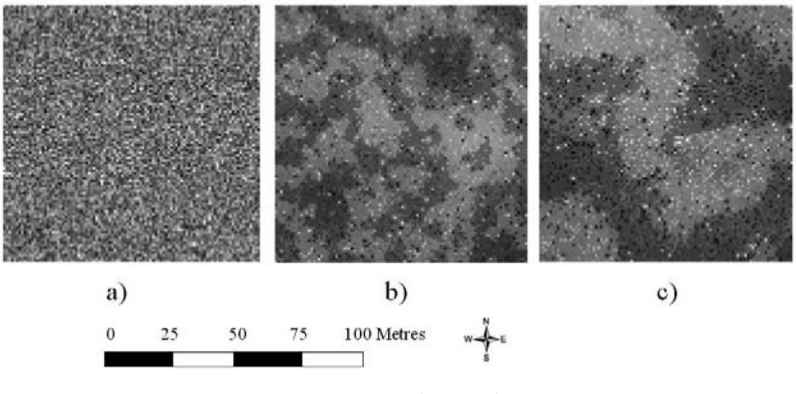


Figure 4 - Three hypothetical fields of yield distribution all with the same mean and variance but with different spatial organisation of the within-field variability.
The field area is 1 ha. a) shows no spatial structure, b) exhibits some spatial structure and c) exhibits a strong trend in yield variation.

TEMPORAL STABILITY OF THE WITHIN-FIELD VARIABILITY

The temporal stability of the within-field spatial patterns also needs to be considered. Indeed, temporal stability determines to what extent the within-field variability of the previous year constitutes a relevant decision tool to manage the vineyard in subsequent years. In other words, to what extent yield, ºBrix or vigour maps from previous years can be used to determine differential management of the canopy, crop inputs and harvest in the current year. This topic requires long term experiments and only a few studies are currently underway to research this topic.

Published work (Bramley and Hamilton, 2004: Tisseyre *et al.*, 2001) examining yield and vigour maps from consecutive several years have reported that there is temporal stability in within-field patterns. According to these authors, this result was expected given the perennial nature of vines. However although the spatial patterns were consistent there was considerable variability in the mean annual yield of the fields. This temporal variability may be due to year effects of climate or management. However, at a within-field level, zones of high yield (or high vigour) are observed at the same locations in the vineyard over time. Similar behaviour was observed for low yield (and low vigour) zones. These conclusions were observed on both irrigated (Bramley and Hamilton, 2004) and non-irrigated (Tisseyre *et al.*, 2001) vineyards. These results highlight the relevance of yield maps and vigour maps from previous years as a decision support tool for future management. Indeed if such information is temporally stable it may be used by the grower to consider differential vigour management (fertilisation, irrigation, canopy management) and to define optimal target sampling, in order to assess more accurately, yield and quality at harvest.

Recent work by Ojeda *et al.* (2005) has confirmed these observations and shown that zoning based on the plant water status is also temporally stable. Ojeda *et al.* (2005) based their zoning on predawn leaf water potentials at 48 sites in a non-irrigated 1.2 ha Syrah block. Measurements were taken at 13 different dates over two years. Results of this experiment showed that regardless of the year, or the stage of production, high vine water restriction always occurred at the same sites in the field. Similar results were observed for low vine water restriction. Figure 5 shows a map resulting from a cluster analysis of the 13 different dates on this experimental field. It highlights zones which systematically present very high, high, moderate and low water constraints. Figure 5b shows the predawn plant water potential (mean of the zones) for 8 dates between flowering and harvest over the year 2003. It is interesting to note that each zone has a unique plant water restriction path, highlighting the potential of a such a zoning for differential management or timing of management. It is also interesting to compare the clustering result with figures 2 and 3 from the same field. Tisseyre *et al.* (2005a) showed that the plant water restriction zoning was strongly linked with yield, annual vigour (assessed from the weight of wood), trunk circumference (Figure 2a) and soil resistivity (Figure 3a). These results confirmed the temporal stability of vigour and yield within-field variability and shows that variability is strongly linked with vine water status variability and soil variability (mainly soil water availability). These results are interesting since they also confirm the relevance

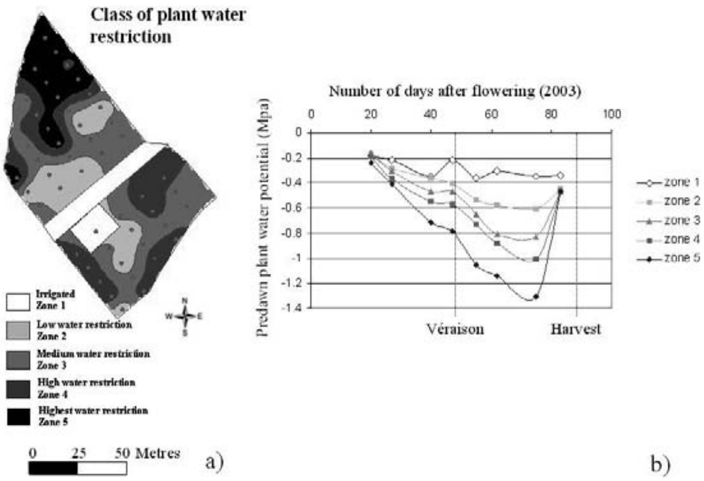


Figure 5 - a) Map of 5 zones derived from a cluster analysis of vine water status from 48 sites within the vineyard measured at 13 different dates in 2003 and 2004.
The vineyard is the same vineyard described in Figure 2. b) Plot of the change in mean predawn plant water potential (Mpa) for each derived zone (in Fig. 5(a)) between flowering and harvest in 2003.

of an airborne imagery and an ECa soil survey in determining potential management zones.

The quality of grapes (ºBrix, pH, total titratable acidity, phenols, anthocyanins) at harvest however does not exhibit the same temporal stability of yield and vigour parameters. Results obtained in Southern France (INRA Pech-Rouge-Gruissan) on two non-irrigated blocks, one with 30 sites measured over 6 years (unpublished results) and another with 48 sites measured over 2 years (Ojeda *et al.*, 2005), showed that the temporal stability of grape quality was not obvious. Similar experiments were carried out by Bramley (2005) on two irrigated blocks in South Australia, one over 4 years and the other over 3 years. Bramley (2005), showed consistent temporally stable patterns for each quality attribute (sugar content, pH, total titratable acidity, phenols) at both sites. However Bramley (2005) drew attention to the fact that while the patterns of variation in quality attributes tended to follow those for yield, the individual quality attributes were not necessarily in the same rank order. The inference is that in irrigated vineyards, quality data could potentially be used to derive differential management and harvest strategies in subsequent years but within-season sampling of zones is needed for decision making relating to 'total' fruit quality. In non-irrigated vineyards the usefulness of quality data from previous years is uncertain in assisting with future differential management strategies

The recent work by Ojeda *et al.* (2005) may explain the differences in the amount of temporal stability of quality zones observed between irrigated and non-irrigated conditions. Based on plant water restriction zones (Figure 5a.), Ojeda *et al.* (2005) showed that the grape quality at harvest largely depended on the vine water status of the zones. In non-irrigated conditions, this is strongly dependent on the climate (particularly rainfall) of a year and on the soil available water-holding capacity (AWC). Climate may exhibit high temporal variability (but low spatial variability) whilst AWC is temporally stable but often highly spatially variable. The interaction of these two factors in non-irrigated situations will produce highly variable spatio-temporal quality patterns. In irrigated vineyards the hypothesis is that irrigation, by allowing better management of AWC, could constitute a significant tool to minimise the temporal variability in grape quality induced by climate variability. Thus with a uniform irrigation strategy quality variability should follow available soil moisture variability. While data on AWC has not been published for the work of Bramley (2005), his assertion that quality zones can be predicted from yield/vigour zones, which have been linked to AWC, lends some support to this hypothesis. If AWC variability is a determinant of quality variability then differential irrigation should be a significant tool to minimise the amount of within-field variation in quality. Currently the lack of real-time quality sensors to collect high resolution grape quality means that zoning on quality data is both time-consuming and expensive (Bramley, 2005). Therefore surrogate data sets to derive zones are needed. High resolution soil data together with imagery may constitutes relevant data layers for the identification of zones for differential irrigation.

CONCLUSION

The goal of this paper was to make a brief review of sensing systems, methods and tools dedicated to Precision Viticulture (PV). In a relatively short time, technologies and methodologies to collect and analyse high resolution data on vine characteristics, soil and environment properties, grape yield and grape quality has become a reality. These information sources provide accurate spatial information about variability in viticulture production systems. These new technologies and methodologies will allow growers and viticulturists to consider new management methods, more efficient experimental designs and provide a better understanding of the vine production system. The first section of this paper has provided an overview of some of the technologies available and some examples on how the information may be used using current precision viticultural case studies.

This paper has also focused on some methodological aspects to characterize spatial variability in production systems. From a database of yield measurements from several blocks in very different locations, it was shown that yield exhibits within-field variability. The occurrence of this spatially organised yield variability is driven by variability in soil and environmental parameters, particularly water availability. Managing this variability could constitute a significant challenge for vine growers. On less extended investigations, it has also been shown that some parameters, such as yield and canopy vigour, present a significant temporal as well as spatial stability. Conversely, temporal stability was not observed on grape quality in non-irrigated vineyards negating the potential use of quality maps from previous years as a decision tool to manage the quality in years to come.

PA tools and methods offer great opportunities in perennial cultivations, like winegrapes. Nevertheless, there are also challenges facing the viticulture industry before widespread adoption of such technologies will occur. The first challenge is to start making sensible decisions from the output of these technologies i.e. to improve production efficiencies a greater understanding of how the output from these sensors relates to the physiology of the vine is required. The main challenge for PV is the ability to provide the methods, skills, training, and advice to make the system work. The challenges are:

- for researchers to provide effective tools and methodologies to process the data,

- for universities to provide graduates with sufficient skills,

- for cooperatives and wineries to be able to provide the services to manage the information.

This challenge is particularly important for traditional or "old world" production systems (such as France) where the viticulture industry is characterised by a high number of winegrowers and a large diversity in grower perceptions as well as their skills in information technology.

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