New technologies to characterize spatial variability in viticulture

Nouvelles technologies pour caractériser la variabilité spatiale en viticulture

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Abstract: Measurements of parameters spatialy positionned, with on line sensors mounted on classical machinery or airborne imagery is no more a problem in viticulture. In a short time, high resolution data dedicated to the assessment of the vine characteristics, the soil, the harvest, etc. will become a reality. This information sources will allow the wine grower to have a spatial accurate knowledge of the vineyard and its variability. Such an accuracy in monitoring the production system was never achieved until now. This paper makes a brief overview of the tools and methods already released or under development to assess the vineyard variability of the main parameters. This work makes also an overview of the main references in vineyard variability. It presents the main results observed on yield, sugar, TTA, etc. within field variability. For each of these parameters clues on magnitude of variation and coefficient of variation observed at a within field scale are given.
Assessing the within field variability can lead the wine grower to take advantage of this variability by adopting site specific management practices. In that case, information of the spatial structure of the variation is of importance since it gives an idea of how a site specific management is opportune on each field. This work will present the main results obtained in spatial structure assessment in viticulture (focusing on yield). Finally, one of the keypoint in viticulture is the assessment of the plant water restriction and its variability whether over the time or over the space. This work presents main experimental results dedicated to the assessment of the within field variability of the plant water status and its link with harvest quality.

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

Introduction

Over the last five years, many new technologies have been developed and adopted in agriculture: low-cost positioning systems, such as the Global Positionning Systems with the new European EGNOS differential correction, crop measurement devices mounted on-board agricultural machinery and low–cost, reliable devices to store and exchange/share the information. All together, these new technologies produce a large amount of affordable high resolution information and have lead to the development of finer-scale or site-specific agricultural management that is often termed Precision Agriculture (PA)
The development and adoption of the tools and the methods used in Precision Agriculture to viticulture (termed Precision Viticulture or PV) is more recent. However, many developments and research projects already exist in practically all the significant wine production areas of the world e.g. in France (Tisseyre *et al*., 2005b, Goutouly et Gaudillière, 2006, Bobillet *et al*., 2005), in Spain (Arno *et al*., 2005), in California (Johnson *et al*., 2003), in Chile (Ortega-farias *et al*., 2003, Ortega *et al*., 2003, Best *et al*., 2005), in South Africa (Strever, 2004), in New Zealand (Pratt *et al*., 2004) and in Australia where the adoption of precision viticulture seems to be the more advanced (Lamb *et al*., 2004, Bramley and Hamilton, 2004 ; Taylor *et al*., 2005b).
These research projects aim at developing or utilising sensing systems, such as leaf area index, yield and quality sensors, to provide information at a resolution never before achieved in viticulture. They also aim to develop methods to quantify the within vineyard variability observed and data processing tools to assist wine growers and the viticulturists to manipulate, analyse and make decisions from such information. These new

information sources constitute a challenge to producers to improve the management of vineyards and improve wine quality. Precision viticultural technologies and methodologies will allow the winegrowers to opimize the production system by taking into account technical, economical and also environmental issues at an inter-parcel level. An example of such an improvement is the possibility of adopting site-specific management to optimize fertilizer application or water consumption in the case of irrigated vineyards.
In the first section, the goal of this paper is to make a brief review of sensing systems dedicated to precision viticulture whether they are already released or still under development. In the second section this paper will give some examples on how can the information be used using current precision viticultural case studies. The third part of this paper will focus on some methodological aspects to characterize the spatial variability. It also will give some clues on magnitude and spatial structure observed in vineyards (focusing on yield). Finally, this work presents some experimental results on the assessment of the within field variability of the plant-water status and its link with harvest quality.

New technologies in viticulture

Positioning

In precision viticulture, the geolocation of information, machines or people within the vineyard utilises the same technology as precision agriculture. The DGPS (Differential Global Positionning System) is the technology most commonly used. DGPS provides a positional accuracy of around 1 m, which is enough for most mapping applications. However for some particular operations more or less accuracy is required and other positionning system may be used. This is the case for vine planting where a Real Time Kinematic (RTK) GPS is used to guide the planting machine (Wagner Pflanzen Technik [1]). RTK-GPS can provide a positioning accuracy of ~2 cm allowing the machine to precisely plant rows.
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, grape quality (Best *et al*., 2005, Taylor *et al*., 2005b).
In Europe, adoption of DGPS technology by the growers may increase drastically with the establishment of the EGNOS (European Geostationary Navigation Overlay Service). This service provides a free differential correction which allows a positionning accuracy around 2 m. The impending commisioning of GALLILEO, a global navigation satellite system, by the European Space Agency should also facilitate the uptake of satellite positioning technology.

Yield monitoring

Yield sensors for mechanical grape harvesters are now commercially available. Two systems have been commercialised; the HarvestMaster Sensor System HM570 (Juniper System Inc., UT, USA) and the Canlink Grape Yield Monitor 3000GRM (Farmscan, Bentley, WA, Australia). Both these systems are suitable for retrofitting to grape harvesters without tanks. The HM570 system is based on a volumetric measurement of the yield over the discharge conveyor belt. The 3000GRM is based on a load cell system also located below the discharge conveyor belt.
To our knowledge, two other yield sensors are under development. One by the Pellenc company (Pellenc S.A., Pertuis, France) specially designed to fit the Pellenc grape harvesters (Bourely, 1999) with onboard storage capacity. Another yield sensor, also specifically designed to fit harvesters with onboard storage capacity, is currently being developped in the framework of an inter-reg European project (Corea porject).
Whatever the advantages and the disadvantages of the different monitoring systems, the point is that growers have (or will soon have) the opportunity to map the yield of their vineyards with a resolution never achieved until now. Figure 1 shows a yield map obtained with the Pellenc prototype on a 1 ha field of Grenache. The yield monitoring system allows the acquisition of more than 2,000 yield measurements ha^{-1} with an average speed machine of 3 $km.h^{-1}$ and a plant density of 4,000 plants ha^{-1}. It is difficult to determine how widespread the adoption of the yield monitoring systems has been however, it seems that it has been mostly large companies that have invested in such systems (Taylor *et al.*, 2005b), mainly in Australia, but also in California and Spain (Kleinlagel, 2004).

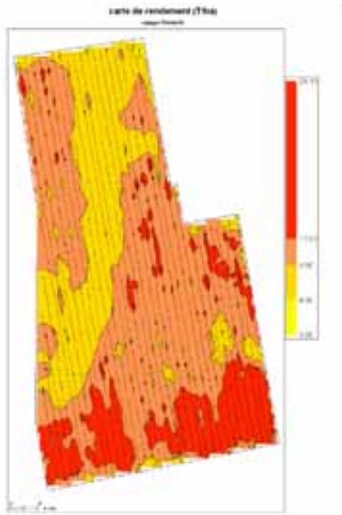


Figure 1 - Example of a yield map (1 ha, Grenache variety) made up from yield monitoring system mounted on a grape harvester positioned with DGPS
source : Pellenc S.A./ agro-Montpellier, Vi-tis project

Quality monitoring

To our knowledge, there are still no sensors commercially available to assess the grape quality (sugar, titrable acidity, pH, phenolic, etc) for either mechanical grape harvesters or for hand use on-the-go in the vineyard. The Pellenc company has developped a sugar sensor (refractometer) 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.

Significant progress is expected with spectrometry technology. The Cemagref of Montpellier is currently developing a hand spectrometer (the tromblon) that should allow the assessment of the grapes sugar content and acidity. 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 (Christo Liebenberg, Universtiy of Central Queensland, *pers. comm.*)

Canopy monitoring and vigour monitoring

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

- remote sensing data,
- ground-based monitoring systems.

a. Remote sensing data

Remote sensing is currently dominated by multispectral (Blue, Green, Red and Near Infra-Red wavelenghts) sensors due to cost and operability. The image resolution is generally around 3 m² per pixel. This corresponds with the interrow width (densities between 3,000 and 4,000 vines ha^{-1}).

The collected information is a mixed pixel which includes reflectance from the vines and the soil. Images are generally processed to produce indices, such as NDVI (Normalised difference vegetative index) or Plant Cell Density (PCD) on a per pixel basis. These indices are generally used as a vigour assessment. In viticulture, vigour generally refers to the vine growth rate (of the shoots) 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 index computed from remote sensing is related to vigour since vigorous vines are characterised by larger and dense canopies than vines of lower vigour. Many authors have shown relationships between NDVI and Leaf Area Index (Johnson *et al.*, 2003), NDVI and annual pruning weight (Dobrowski *et al.*, 2003) or other vine parameters (Lamb *et al.*, 2004) at a within vineyard level. Use of remote sensing data often constitutes a relevant and low cost information source to perform vigour zoning at a within field level. This explain why imagery is currently used in Chile (Best *et al.*, 2005), in California (Scholasch *et al.*, 2005) in 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.

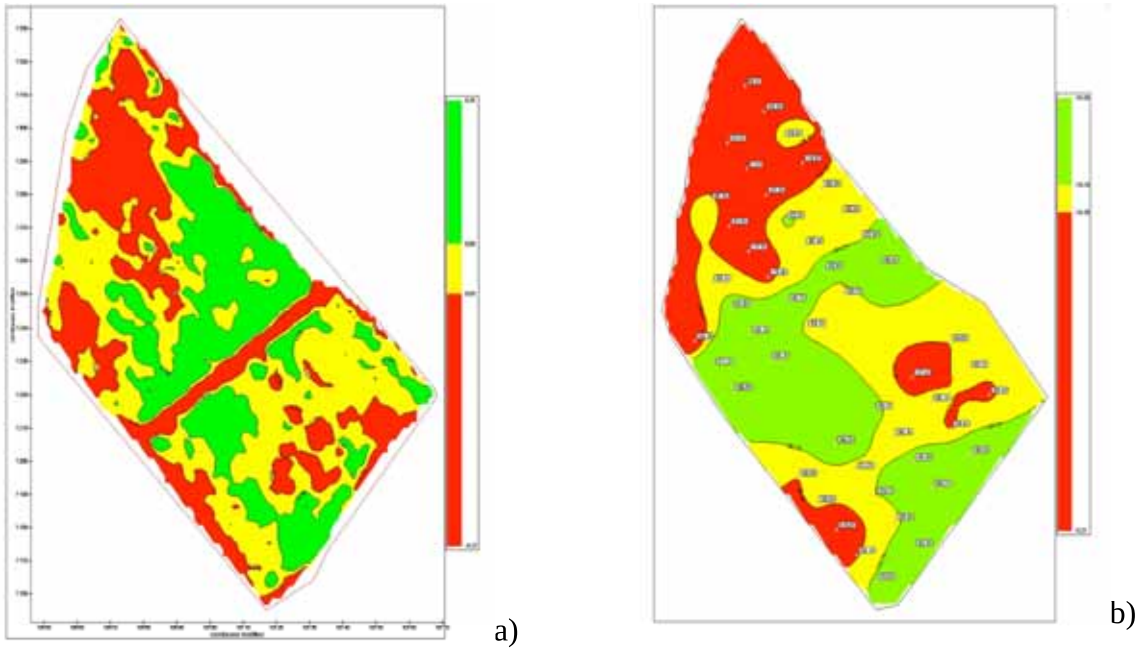


Figure 2 - Vineyard of 1.2 hectares (Syrah variety in the Clape Massif, Southern France, Inra Pech rouge).
a: NDVI map computed from airborne imagery (1 pixel = 1 m.).
b: trunk circumference map (49 measurement points. *source : Agro-Montpellier/Inra Pech-Rouge*

In order to illustrate the relevance of NDVI information, figure 2 shows two maps of the same vineyard (field of 1.2 ha planted with Syrah in southern France-INRA Pech-Rouge). Figure 2a presents a NDVI map with 3 classes of NDVI derived from a multispectral aerial image with $1m^2$ pixels. Figure 2b presents a vigour map based on 3 classes of trunk circumference (49 measurements on the field). Figure 2 shows that both maps present very similar spatial patterns (although coefficient of determination between both information was rather small $r^2=0.62$). This experiment was conducted on 11 different vineyards in the same area. Similar results were obtained for 10 of them. It is also interesting to note that trunk circumference integrates information on vine vigour since the vine was planted. Zones provided by trunk circumference can be considered as time stable on this non-irrigated vineyard.

Few applications of NDVI exists in cooler climates where the vertical positioning of the shoots produces narrow canopies and the background noise (soil or grass) constitutes a large proportion of the collected information by the pixels. In the future, hyper-spectral imagery and high resolution imagery will provide significant additional information on the canopy. It may also provide information to help discriminate the canopy from the background using the additional spectral information or with additional image morphological information. Research is currently being conducted on high resolution images to provide row recognition algorithms (Bobillet *et al.*, 2005, Hall *et al.*, 2003), thickness canopy measurements and missing vines counting (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, CASI) (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 performed on multi-temporal imagery at a within field scale. To our knowledge only Montero *et al*. (1999) has used imagery at a regional scale to monitor vine growth and change in vine cover. This approach gave interesting results since the authors concluded that the growth behaviour of vine is limited by the water availability and this may be mostly likely linked to the above ground biomass production.

Ground based monitoring systems

Ground based monitoring systems have been developed to assess and to map canopy properties. Such systems avoid the problems of background noise due to mixed pixels of soil, grass and vine canopy that are associated with remote sensing technology, especially on vertical training systems. Most of these systems are based on a digital imaging system which allows the measurement of several parameters such as canopy height, canopy porosity (Praat *et al*., 2004; Tisseyre *et al*., 1999; Souchon *et al*., 2001). These systems are designed to be mounted on exisiting machinery and incorporated into existing vineyard management (trimming, spraying, etc.). By mounting these kind of sensors on tractors, canopy measurements can be taken during general vineyard operations using a recording system like a video tape. This should provide more timely and continuous temporal data on canopy development during the season. This may provide more opportunity to micro-manage production.

Soil Monitoring

To date real-time on-the-go soil sensing for precison agriculture has generally been performed using previously well established geophysical methods. The general principle of these geophysical sensors is to non-intrusively collect data on the soil. Among these sensors, those which are based on the electric properties or on electro-magnetic properties of soil have been most successfully applied to agriculture. These technologies give a measurement (apparent soil Electrical Conductivity: EC_a) which is easy to perform on a mobile apparatus and which is strongly correlated with soil material and properties (Corwin and Lesch, 2005 ; Samouellian *et al*., 2005).

Three types of EC_a sensors are available : (i) Electrical Resistivity (ER) sensors that utilise invasive electrodes (ii) no-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 occured.

The purpose of electrical resistivity surveys is to determine the resistivity (or the conductivity) distribution from the sounding 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 of their electrical properties (Samouellian *et al*., 2005). Commercial examples of ER sensors include the Mucep (Geocarta Ltd., France) and the Veris 3100 (Veris technologies, Salina KS).

The principle of electromagnetic induction surveys is to generate a magnetic field arising from an alternative current in a transmitter coil. In the soil, this system induces very small currents which generate a secondary magnetic field. This secondary magnetic field is measured by a receiver coil in the sensor. Sensors are designed in a way that secondary and primary magnetic field are linearly proportional to soil conductivity. (see Corwin and Lesch, 2005 for more technical details). Commercial example of EM 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 transmitting and sensing coils for EM sensors.

Both these technologies (ER or 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) used such soil information to delineate within field soil zones.

Since ER and EM sensors are effectively measuring electrical conductivies the presence of metal, such as steel post or trellis wire, may influence the values and the degree of distorion 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 artefact in ECa maps. Nevertheless, results showed that the EM-38 was still useful for delineating soil zones in established vineyards when the row spacing was large enough (2.5-3 m). Lamb *et al.* (2005) concluded that extreme care must be exercised by an operator to ensure that EM antenna unit remains mid-row throughout the survey.

In order to illustrate the relevance of EC_a measurements on a vineyard, Figure 3 shows two maps of the same vineyard (the same 1.2 ha field of Syrah shown in figure 2). Figure 3b presents a NDVI map with 3 classes of NDVI (same map as in figure 2a). Figure 3a presents a soil resistivity map based on 3 classes of soil resistivity (49 measurements on the field with four probes sounding 2 meters depth). Both maps in figure 3 show similar spatial patterns. This experiment was conducted on 11 different vineyards in the same area. Again similar results were obtained for 10 of them. Refering to figure 2, it is interesting to note that spatial patterns of ECa also present strong similarities with the trunk circumference map. This indicates that vigour variability may often temporal stable and dependent on soil variability, highlighting the relevancy of EC_a surveys for zoning purposes.

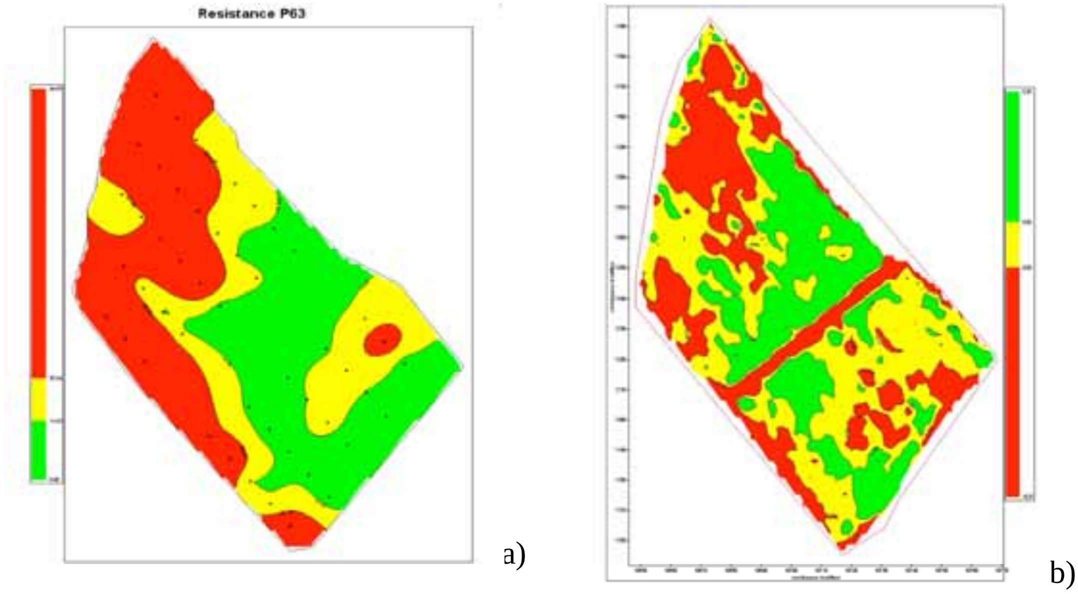


Figure 3 - Vineyard of 1.2 hectare (Syrah variety in the Clape Massif, Southern France, Inra Pech rouge).
a: Résistivity map (ohm.m) on 49 measurement sites.
b : NDVI map computed from airborne imagery (1 pixel = 1 m).
source : Agro-Montpellier/Inra Pech-Rouge

When conducting an on-the-go soil survey it is common practice to also record elevation data from a RTK carrier phase GPS receiver. This permits the generation of a digital elevation model of the vineyard and the derivation of secondary terrain attributes such as aspect, slope, curvature and wetness indices.
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 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 (Adamchuk) and Australia (Raphael Viscarra Rossel, Australian Centre for Precision Agriculture, *pers comm*) is being conducted to construct new mobile on-the-go soil sensors. Real-time commercial pH (Veris) and prototype lime requirement platforms (Viscarra Rossel *et al.*, 2005) have already been built and further research into soil ion sensors, particularly nitrogen and phosphorus sensors, is being continued.

Plant water satus Monitoring

Many authors (Champagnol, 1984; Seguin, 1983; Dry and Loveys, 1998; Ojeda *et al.*, 2005) have showed that changes in grapevine water status have an effect on grape yield, grape vigour and quality. Zoning the vineyards on the water status basis would lead to a relevant decision support tool. 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 plant 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 other information that is easy to measure at high spatial resolution e.g. remote sensing, machinery mounted crop and yield sensors, soil ECa sensors, etc.). These complementary data could provide the basic information required to characterize the within vineyard variability of the soil and the plant and define zones with homogeneous plant water status and/or water availability during the growing and ripening period (Tisseyre *et al.*, 2005a; Taylor, 2004).

Variable rate technology

To date, few application of Variable Rate Technology has been implemented in vineyards principally due to a lack of decision support in deciding how treatments should be varied and healthy profit margins that negate the need to improve production efficiency. This explains that released VRT technologies currently focus on very simple decisions which leads to a direct benefit.

In Europe the main opportunities of VRT deals with chemicals. A VRT weeding system was released in 2003 to selectively apply herbicides (Weedseeker, Avidor Ltd, villars sainte croix, Suizerland). This system is based on an optical sensor which measures reflectance at two wavebands (Green and Near infra red). The computation of an index allows the system to detect the presence of green weeds on the row. The sensor commands the herbicide spray. This systems allows savings of up to 75 % of herbicides (1)(2). This system is also used to perform early fungicide applications on discontinuous vertical canopy. In this case, the sensing system avoids chemical application on canopy « holes », leading to a significant saving of chemicals but also to a more environmentally friendly production system. Significant research has also been performed to adjust the amount of chemicals to apply according to the density and the porosity of the canopy. As profit margins decrease and the opportunity and support for site-specific management increase then VRT adoption will increase.

How can the information be used?

The tools and methods described in the previous section: monitoring systems, geo-referenced information, imagery, etc. provide accurate information on the production system (the spatial accuracy of most of these systems are ~1-2 m). These new information sources will allow the growers to rationalise and to optimize their production system. The information can be used in a decision-making process. There are various stages in the production system where this may be achieved. New practices are expected in different area :

- On-vineyard experimentation : New PV technologies and methodologies already allow the systematic acquisition of huge amount of data (yield, vigour, soil and elevation variation). Moreover, this information allows the scientist to design experiments that take into account the underlying spatial variability or to analyse the results accordingly. In viticulture, Bramley *et al.* (2005a) have already run such experiments using airborne imagery or yield maps of the previous years. They showed that considerable benefit may accrue through considering underlying variability in the analysis.
- Product traceability: PV technologies provide an opportunity to systematically record all production information spatially. In addition to the sensors discussed above, basic machine operations (etc.)can be recorded (operating times, area covered, speed) as well as the output from any activitity (e.g. 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 (e.g. organic wine, low environmental footprint contracts, specific origin, quality label) or conform to policy constraints (e.g. 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. For example, systems to locate sprayer by DGPS and to monitor the main parameters of the sprayer (flow rate, tank level, speed) are already released (Farmscan, Bentley, WA, Australia) or under development (De Rudnicki *et al.*, 2005). Such a system may present great promises because chemical traceability remains difficult from the growers to the wineries or to the cooperatives. They 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 rows sprayed twice). A European life project (Aware project) involving researchers, growers, cooperatives and software companies is currently underway to use these technologies (DGPS/sprayers) on a whole catchement scale (Neffies, Languedoc-Roussillon, France).
- Differential management : The collection of spatial datasets naturally provides growers with the opportunity to use differential management techniques to minimise the variability in their crop or to take advantage of its variability in order, for example, to improve grape/wine quality. There are several ways differential managment can be implemented ;

  <u>Target sampling</u>: Understanding the underlying variability allows viticulturists/growers to design targeted sampling schemes to get a better assessment of grape yield and the quality. Yield and quality assessment of the vineyards is a keypoint for wineries or cooperatives to manage the wine processing. It is well known that vineyard assessment of yield and quality (based on classical sampling procedure) is not accurate enough in a significant proportion of cases and may differ from winery assessment by about 20 % (Rousseau, Institut Coopératif du vin, *pers. Com.*). 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).

  <u>Differential harvest :</u> Vegetative indices derived from canopy imagery (either ground-based, aerial or satellite) 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 a differential harvesting strategy. 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 segregating the different zones into different bins (and into different quality wines) or picking the different zones on different days when maturity and quality within each zone is considered optimum. Independent reports Bramley *et al.* (2005b), Hinze and Hamilton, (2004), Profitt and Pearse, (2004) report that the differentially harvesting was profitable and easily offset the extra cost of imagery acquisition and analysis and harvesting.
Other differential vineyard management can be considered. They concerns differential canopy management, differential spraying, differential fertilisation, differential fruit or leaves removal, etc (Taylor *et al*., 2005b). However, for most of these applications there is a lack of decision support, especially to define management rates according to the spatial information provided by canopy imagery (either ground-based, aerial or satellite) or other monitoring systems. Morevover for canopy management at the moment it is difficult to assess the extra cost of information acquistion and analysis, the cost of differential managment and the benefits gained.

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 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.

Magnitude of variation

Recent works of 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. Table 1 shows a summary of the locations and classical statistics from the study.
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 that significant variability in yield regardlessof the location and also whatever the 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).

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)	mean CV (%)
Canowindra (Australie)	26	2,77	6,52	21,83
Clare valley (Australie)	46	4,41	6	50,66
Cowra (Australie)	29	3,32	11,56	33,15
Mildura (Australie)	16	7,43	12,27	23,9
Southern France	21	1,54	9,52	39,56
Navarra (Spain)	8	4,01	4,82	47,58

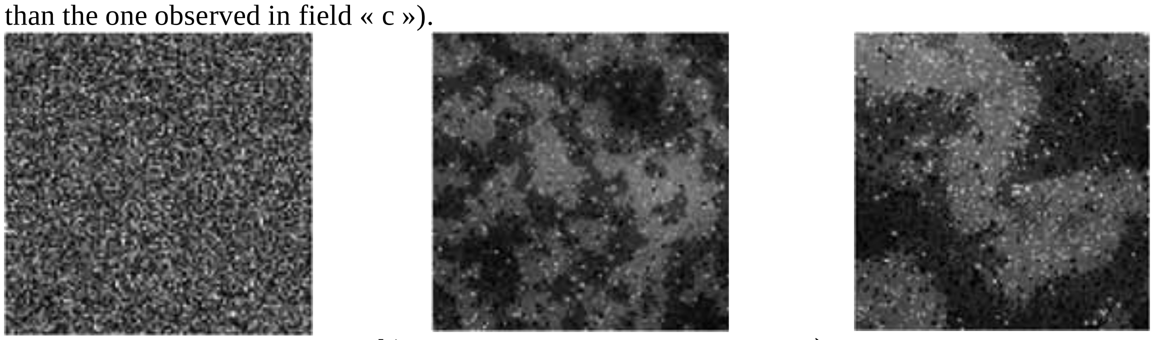
Because of the lack of quality monitoring systems, few works deal with the within field variability of the grapes quality. Published data on the quality (Bramley, 2005; Taylor, 2004; Ortega *et al*., 2003 ; Arno *et al*., 2005; Ojeda *et al*., 2005; Tisseyre *et al*., 2005b) highlighted a significant within field variability in various quality parameter as well. On hand picked samples, with a sample density varying from 15 to

50 measurement per hectares, CVs from 3 to 10 % were observed on sugar (°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 titrable acidity. It seems that CVs for quality parameters are lower than the yield, but considering the units, they correspond at harvest to large amount of variation in quality (Ojeda *et al.*, 2005). Depending on the wine process and the price of the harvest, such amount of variation in quality may justify the adoption of differential managements and especially differential harvest (Bramley *et al*., 2005b).

Spatial structure of the within field variability in viticulture

Indices like the coefficient of variation are usefull to characterise the amount of variation which occurs at the within field level. Nevertheless they are far to be informative enough. Indeed, knowing if it is possible to switch to site specific management requires to qualify the spatial structure of the variability. Pringle *et al*. (2003) proposed to use geo-satistical techniques to assess such information, including variograms parameter (nugget (C0), sill(C1) and range (r)) and its individual components like the areal coefficient of variation (CVa) and Spatial Structure statistic (S). Being a concept more difficult to explain, it is illustrated figure 4. Figure 4 shows an example of the problem on three hypothetical fields. Suppose these fields are of equal area, have the same mean yield, the same yield variance and the data arranged on a regular grid. In terms of variability, each of these three fields exhibits exactely the same coefficient of variation (CV). However, the within-field spatial distributions of the points are characterised by significant difference from a field to another :

- Field « a » : no spatial structure is exhibited. Values are intimately mixed which necessarily lead to a very difficult management of the field. This corresponds to the case where very different yield values are observed from a vine to another.
- Field « c » : a spatial distribution in five main distinct patterns. In that case, the spatial structure leads to a very easy management of the field in obvious zones. Note that an erratic variability is still exhibited by yield data. But this erratic variability may be negligeable compared to the one spatialy organised.
- Field « b » : exhibits intermediary behaviour between fields « a » and « c » (with spatial patterns smaller than the one observed in field « c »).



a) b) c)

Figure 4 - Hypothetical fields of 1 ha with same mean and same variance but with different spatial organisation of the within field variability.

Figure 4 highlights the necessity to drive a more detailed analysis, than classical statistics and indices like the CV, to characterise the within field spatial variability.

To our knowledge, in viticulture only the work of Taylor *et al.* (2005a) has considered 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). Results of this study highlighted the presence a spatial structure on almost all the blocks of the data base, whatever the variety, the location of the block and the training system. This study also highlighted significant trends on the data :

- In Australia, the within field variability observed presented spatial patterns larger 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.
- The magnitude of yield variation (assessed with the areal coefficient of variation CV_a) was larger in Europe than in Australia.

The authors hypothetised that larger CV_a in both France and Spain 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 availibility and slope.

The authors also hypothetised that in European conditions, the proportion of the variability explained by a trend surface may be due to the practice of planting on hillslopes, 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 yield variability has to be considered whatever the location.

Temporal stability of the within field variability

As well as spatial variability the temporal stability of within field variability also needs to be considered. Indeed, temporal stability determines to what extent, the within field variability of the previous year constitues a relevant decision tool to manage the vineyard in the year to come. In other words, to what extent yield, sugar or vigour maps of the previous years can be used to consider differential management of the canopy, crop inputs and harvest. This topic requires long term experiments and very few studies currently exist to enlighten this point.

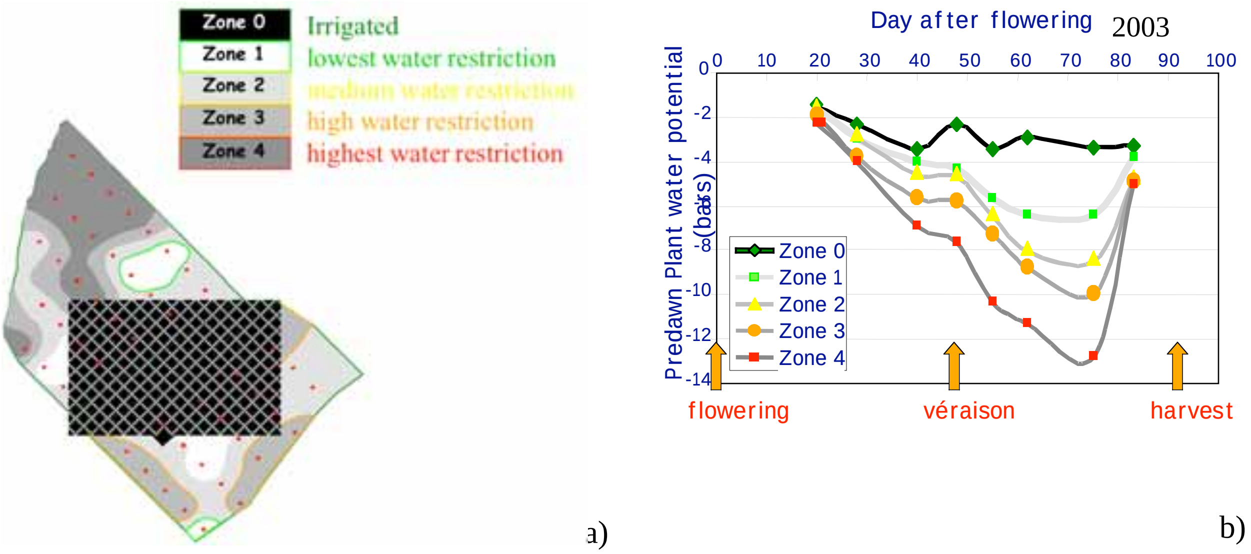


Figure 5 - a) plant water status zoning of block from a clustering (zoning based on 48 measurement sites on the block and 13 dates over 2003 and 2004 - 1.2 hectare vineyard planted of Syrah variety in the Clape Massif, Southern France, Inra Pech rouge). b) Predawn plant water potential (bars-mean of the zones), 8 dates over the year 2003 between flowering and harvest.

Some work (Bramley and Hamilton, 2004 ; Tisseyre *et al.*, 2001) based on yield or vigour maps made up several years in a row on the same field exhibited a certain time stability of the within variability. According to these authors, this result was expected given the perrennial nature of vines.. The studies did exhibited an annual variability in the mean yield of fields. This temporal variability may be due to a year effects on climate or managment. However, at a within field level, zones of high yield (or high vigor) are observed at the same locations in the vineyard over time. Similar behaviour was observed for low yield (and low vigor zones). These conclusions were observed either on irrigated (Bramley and Hamilton, 2004) or on non-irrigated (Tisseyre *et al.*, 2001) vineyards. These results may 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, for example, the mean field yield at harvest.

Recent results of Ojeda *et al*. (2005) confirmed these observations. Ojeda *et al.* (2005) showed that a zoning based on the plant water status (predawn leaf water potential) was also temporally stable. This zoning was based on 48 sites of measurement performed on a non irrigated 1.2 ha Syrah block at 13 different dates over two years. Results of this experiment showed that whatever the date and whatever the year, high plant water restriction was always located at the same sites in the field. Similar results were observed for low plant 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, showing the relevance of a such a zoning. 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) but also with trunk circumference (figure 2a) and soil resistivity (figure 3a). These results confirmed the temporal stability of the vigour and yield within field variability. This spatial variability is strongly linked with plant water status variability and soil variability (and mainly soil water avalaibility). These results are intersting since they also confirm the relevance of a airborne imagery and an EC_a soil survey to make up such a zoning.
Considering the harvest quality (sugar content, pH, total titrable acidity, phenols, anthocyanins). Results obtained in Southern France (INRA Pech-Rouge-Gruissan) on two blocks, one with 30 sites measureed over 6 years (unpublished results) and 48 sites of measurement over 2 years (Ojeda *et al.*, 2005), showed that temporal stability of grape quality was not obvious. These results were obtained on two non-irrigated blocks. A similar experiments was carried out by Bramley (2005) on two irrigated blocks, one over 4 years and the other over 3 years. On this experiment Bramley (2005) observed consistent patterns for each attribute (sugar content, pH, total titrable acidity, phenols) in each year of the study, and with many attributes following the same pattern
Recent work by Ojeda *et al.* (2005) may explain differences observed between irrigated and non irrigated conditions. Based on plant water restriction zones (figure 5a.), they showed that the grape quality at harvest largely depended on the plant water status « path » of the zones. In non irrigated conditions, this « path » depends on the climate of the year and also on the soil water availibility. Zones where moderate water restriction occured in one year presented interesting quality level at harvest. Conversely, the year after, when very high water restriction occurred on the same zone grape quality was poor at harvest. This result largely explains why, on non-irrigated vineyards, grape quality may present weak spatio-temporal stability. Depending on the climate of the year and the soil water availibility, quality can vary from a location to another. This result also hypothetises that irrigation, by allowing the management of the plant water restriction, could constitute a significant tool to minimise the temporal variability in grape quality. It also highlights the relevance of differential irrigation to decide the amount of water supply on a per zone basis. High resolution soil survey with imagery could constitutes a relevant decision tool to make up zones for differential irrigation purposes.
This results showes that depending on the conditions, harvest quality maps of previous year may be irrelevant to consider differential harvest for the year to come.

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 short time, high resolution data dedicated to the assessment of the vine characteristics, the soil, the harvest, etc. will become a reality. These information sources will allow growers to have a spatial accurate knowledge of the vineyard and its variability. Such an accuracy in monitoring the production system has not been possible until now. New technologies in vineyards will necessarily allow the growers and the viticulturists to consider new management methods, more efficient experiments design and a better understanding of the vine production system. This paper gave some gave some examples on how the information may be used using current precision viticultural case studies.
This paper also focused on some methodological aspects to characterize the spatial variability. It also gave some clues on magnitude and spatial structure observed in vineyards (focusing on yield). From a database where yield was monitored on several blocks in very different locations, it was shown that yield present a within field variability. This within variability presented a spatial structure. Occurrence of this spatially organised variability in yield highlights underlying variability due to soil, elevation, water availibility. Managing this variability could constitute a significant challenge for vine growers. On less extended investigations, it was shown that some parameters presented a significant temporal stability. This was mainly the case for yield and canopy vigour. Conversely, such a temporal stability was not observed on grape quality on non-irrigated vineyards. Leading to a difficulty to use quality maps of previous years as a decision tool to manage the quality for the year to come.
This paper shows that Precision Agriculture tools and methods offer great promises to a perennial cultivation, like winegrapes. Nevertheless, big challenges face the viticultural industry before widespread

adoption of such technologies by the growers and the viticulturists will occur. The first challenge, which constitues a real challenge, is to start making sensible decisions from the output of these technologies. To improve production efficiency a greater understanding of how the output from these sensors relates to the physiology of the vine is required. The main challenge for precision viticulture will be on the ability of the producers to provide the methods, the skills, the training, the advices which will make the system work. The challenge is :

- for the researchers, to provide the good dedicated tools and methods to process the data,
- for the universities, to provide the good skills to the students,
- for the cooperatives and wineries, to be able to provide the services to manage the information.

This challenge is particularly of importance for the « old world » where the process has to contend with a high number of winegrowers and a large diversity in grower perceptions as well as their skills in information technology. A challenge we are capable of meeting.

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