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Review. Precision Viticulture. Research topics, challenges and opportunities in site-specific vineyard management

J. Arnó[1]*, J. A. Martínez-Casasnovas[2], M. Ribes-Dasi[1] and J. R. Rosell[1]

[1] *Departamento de Ingeniería Agroforestal*
[2] *Departamento de Medio Ambiente y Ciencias del Suelo. Universidad de Lleida. Rovira Roure, 191. 25198 Lleida. Spain*

Abstract

Precision Viticulture (PV) is a concept that is beginning to have an impact on the wine-growing sector. Its practical implementation is dependant on various technological developments: crop sensors and yield monitors, local and remote sensors, Global Positioning Systems (GPS), VRA (Variable-Rate Application) equipment and machinery, Geographic Information Systems (GIS) and systems for data analysis and interpretation. This paper reviews a number of research lines related to PV. These areas of research have focused on four very specific fields: 1) quantification and evaluation of within-field variability, 2) delineation of zones of differential treatment at parcel level, based on the analysis and interpretation of this variability, 3) development of Variable-Rate Technologies (VRT) and, finally, 4) evaluation of the opportunities for site-specific vineyard management. Research in these fields should allow winegrowers and enologists to know and understand why yield variability exists within the same parcel, what the causes of this variability are, how the yield and its quality are interrelated and, if spatial variability exists, whether site-specific vineyard management is justifiable on a technical and economic basis.

Additional key words: grape yield maps, local and remote sensors, selective vintage, within-field variability, yield monitor, zonal management.

Resumen

Revisión. Viticultura de precisión. Líneas de investigación, retos y oportunidades del manejo sitio-específico en viña

La Viticultura de Precisión (VP) es un concepto que empieza a tener un cierto impacto en el sector vitivinícola. Su implementación práctica está ligada al desarrollo de cierta tecnología: sensores y monitores de cosecha, sensores locales y remotos, Sistemas de Posicionamiento Global (SPG), equipos y maquinaria de aplicación variable, Sistemas de Información Geográfica (SIG) y sistemas para el análisis y la interpretación de la información. En este trabajo se ha llevado a cabo una revisión de las diferentes líneas de investigación relacionadas con la VP. Dichas áreas de investigación se han centrado en cuatro ámbitos muy concretos: 1) cuantificación y evaluación de la variabilidad intraparcelaria, 2) delimitación a nivel de parcela de zonas de tratamiento diferencial, en base al análisis y la interpretación de dicha variabilidad, 3) desarrollo de tecnologías para la actuación variable en campo (*variable-rate technologies*, VRT) y, finalmente, 4) evaluación de la oportunidad del manejo sitio-específico en viticultura. La investigación en estos ámbitos debe permitir a viticultores y enólogos conocer y comprender por qué la cosecha varía dentro de una misma parcela, cúales son las causas de dicha variación, cómo están interrelacionadas la cosecha y su calidad y, ante la existencia de variabilidad espacial, si está justificado técnica y económicamente el manejo diferencial de los viñedos.

Palabras clave adicionales: manejo zonal, mapas de vendimia, monitor de cosecha, sensores locales y remotos, variabilidad intraparcelaria, vendimia selectiva.

* Corresponding author: jarno@eagrof.udl.es
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J. Arnó is member of the SEA.

Abbreviations used: DGPS (differential GPS), DSS (decision-support systems), ECa (apparent electrical conductivity), GIS (geographic information systems), GPS (global positioning systems), GVI (green vegetation index), LAI (leaf area index), LBS (Landwirtschaftliches BUS-System), LIDAR (light detection and ranging), NDVI (normalized difference vegetation index), PA (Precision Agriculture), PCD (plant cell density), PV (Precision Viticulture), PVR (photosynthetic vigour ratio), RTKGPS (Real-Time Kinematic GPS), SSCM (site-specific crop management), VRA (variable-rate application), VRT (variable-rate technologies).

Introduction

The application of Precision Agriculture (PA) techniques in viticulture is relatively recent. In 1999, results began to be published from projects initiated in Australia (Bramley and Proffitt, 1999) and USA (Wample *et al*., 1999) in the wake of the appearance on the market of yield sensors and monitors. These are installable in grape harvesters and allow more detailed measurement of within-field variability. As a result, variable-rate application (VRA) of inputs and selective harvesting at parcel level have become productive strategies which can provide significant benefits for winegrowers. The most relevant aspects which need to be taken into consideration include efficient use of inputs, differentiation of various grape qualities at grape harvest time, yield prediction and greater precision and efficiency of samplings conducted at parcel level (Bramley, 2001b; Bramley and Lamb, 2003; Martínez-Casasnovas and Bordes, 2005).

There are several reasons to justify the suitability of the vineyard for PA. As grapevines grow in lines and with a fixed planting distance, the sampling points can be applied to individual vines which are georeferenceable and, if data collection is carried out year after year, historical series of important value for crop management can be obtained. In addition, its perennial nature suggests that yield spatial variation will maintain some behavioural pattern from one year to the next, an essential characteristic if the aim is to carry out some type of differential action (site-specific management) within the parcel. The growing interest in questions related to grape quality has undoubtedly aroused the greatest expectations in the field of PV. Indeed, the possibility of being able to differentiate between zones of different quality within the same parcel is one of the priority aims of PV.

Precision Viticulture is a concept that is beginning to have an impact on the wine-growing sector, not only in Australia, Argentina, Chile, South Africa or USA but also in Spain and other European countries (France and Portugal in particular). The main objective of PV coincides, in essence, with the generic objectives of PA: the appropriate management of the inherent variability of crops, an increase in economic benefits and a reduction of environmental impact (Blackmore, 1999; Sudduth, 1999). Adaptation of the latest scientific and technological developments, and examination of economic criteria for market competitiveness, have given rise to more pragmatic and modern approaches as well as to the growing prominence in viticulture of countries such as Australia, Chile and South Africa (Sotés, 2004). Indeed, much of the leading research in PV is carried out in these countries. Given the numerous possible subject matters for research in PV, this review paper has focused on four very specific fields: 1) quantification and evaluation of within-field variability, 2) delineation at parcel level of zones of differential treatment, based on the analysis and interpretation of this variability, 3) development of Variable-Rate Technologies (VRT) and, finally, 4) evaluation of the opportunities for site-specific vineyard management.

What type of variability are we referring to and how can it be measured? How can this variability be analysed and interpreted? What is the available technology? Is the application of PA advisable, from an environmental and economic point of view, in viticulture? Below, we look at the most relevant results from the research undertaken in PV and some of the possible answers to the above questions.

Evaluation of spatial variability in winegrape production systems: data sampling and acquisition

Viticultural practices have traditionally been conducted in a uniform manner. In other words, the work involved in soil maintenance or pruning has been applied with equal intensity regardless of the exact location within the parcel, and similarly the use of fertilizers and crop protection products has been applied in identical doses. However, the grape yield usually displays considerable spatial variation within the same parcel. There is, therefore, certain discordance between the uniformity of actions taken at parcel level and the differential yield obtained. Spatial variation, which can be attributed to physical environmental factors (soil, topography, climate), undoubtedly conditions to a significant degree the differential response of the crop, which is reflected in the spatial variability of the yield (Sort and Ubalde, 2005). Doubts appear when we wish to understand, for example, the exact causes that gave rise to this variability or the possible interactions between factors pertaining to the physical environment and factors pertaining to the crop. It is precisely here that PV can offer some answers based on the sampling and subsequent analysis of within-field variability.

The first yield sensors and monitors began to be used in USA (Wample *et al*., 1999) and Australia in

1999 (Bramley and Proffitt, 1999). These devices have a relatively simple design, but are able to supply reliable and geo-referenced values for the grape harvest. For example, the system initially marketed by the Australian company «Farmscan» (Bentley, WA, Australia) basically comprises a set of load cells installed on the grape discharge arm of the grape harvester. By measuring grape weight and other required parameters (such as the displacement speed and position of the harvester), the yield monitor calculates production in tonnes per hectare at different sites in the parcel. Data storage memory cards and specific software for the acquisition and simple manipulation of yield maps also form part of yield monitoring technology.

The interest generated by this type of technology, initially in Australia and subsequently in France and Spain, has given rise to a number of different research studies. The most immediate objectives have been the acquisition of yield maps (through the formulation of standardised protocols) and an analysis of the spatial variability of the winegrape yield (Fig. 1). Bramley *et al*. (2000, 2003), Bramley (2001a), Bramley and Williams (2001), Bramley and Lamb (2003), Bramley and Hamilton (2004) and Taylor (2004), are a few of the most important references from Australian research. Prominent studies in Europe include the work of Tisseyre *et al*. (2001), Arnó *et al*. (2005a,b) and Arnó (2008). In this respect, a Spanish leading vinery company and a research group of the Politechnical University of Madrid have been recently working in the development of quality sensors and a yield monitor to increase the level of information at harvesting to improve the management of the crop and for selective harvesting (Bastida and Ruiz, 2006).

Bramley and Hamilton (2004), two of the most important researchers in the field of Precision Viticulture in Australia, affirm that successful implementation of PV will only be feasible given certain conditions: a) if the spatial variation of the yield is repeated with a certain degree of stability year after year; b) if the causes that give rise to the variability are identified; and, of fundamental importance, c) if these causes can be dealt with on a differential basis (site-specific management) within the parcel. Plant (2001) informs us of the multitude of factors that can bring about spatial variability of the yield. In this sense, the importance of the soil is clear. In vineyard farming the spatial variation of the yield seems to be mostly influenced by the physical properties of the soil as opposed to its chemical qualities (Bramley and Lamb, 2003). Other factors that can affect grape yield include topography and the nutritional status of the vines (Arnó *et al*., 2005a; Sort and Ubalde, 2005), as well as the possible effects of adverse parameters or the health status of the crop (Zhang *et al*., 2002).

Given all of the above, it is clear that soil and crop sampling is required in order to determine the factors that affect the wine harvest. However, if manual sampling is the chosen option (sample collection and subsequent laboratory analysis) data acquisition at high spatial resolution is prohibitive both in terms of cost and time. The solution has necessarily been to work on the development of local sensors that can take continuous readings of the parcels (on-the-go sensors), supplying the values of certain soil properties (mainly soil moisture content), temperature or solar radiation (Montero *et al*., 2007), and/or the vegetative structure of the crop (Sudduth, 1999). Used for all types of crops, these high capability sensors are able to sample large areas as they can be attached to tractors or other self-propelled equipment, supplying information at high spatial resolution and relatively low cost.

As for soil characterization, electric and electromagnetic sensors have been mostly used so far, though

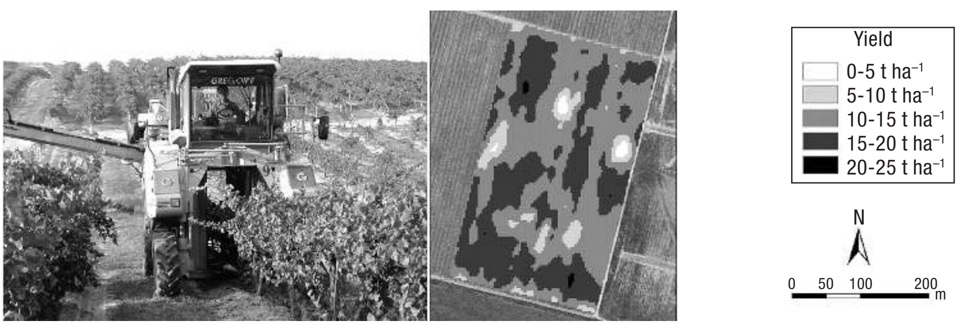

Figure 1. Grape harvester with yield monitor and resulting grape yield map of a parcel in Raimat (Lleida), year 2002.

research has been conducted on soil sensors based on optical and radiometric principles, as well as on mechanical, acoustic, pneumatic and electrochemical principles (Adamchuk *et al*., 2004). Electromagnetic induction sensors, which measure the apparent soil electrical conductivity (EC_a), have been much used in PV. The most well-known example of such sensor is the «EM-38» (Geonics Ltd, Mississanga, Ontario, Canada) and, as electrical resistivity sensors, the «Veris 3100» (Veris Technologies Inc., Salina KS, USA) and the ARP system (Geocarta Ltd., France). Additionally, the use of Global Positioning Systems (GPS) has enabled soil EC_a to be measured over a larger number of points, with considerable spatial resolution being achieved. The suitability of this type of sensors in PV has been recognised by a good number of researchers (Ormesher, 2001; Proffitt and Hamilton, 2001; Bramley and Lamb, 2003). There is a lot of interest in the potential use of EC_a measurement, as it is a parameter which has a good correlation to soil texture, water retention capability, organic material content, salinity and soil depth (Corwin and Lesch, 2005; Samouëlian *et al*., 2005).

The use of this type of sensor is also interesting because they allow delineation of homogenous areas within the parcel (or possible areas for differential management), based on the detection of soil differences and map construction of electrical resistivity/conductivity. Finally (Corwin and Plant, 2005), the greatest agronomical potential use of EC_a measurement lies in the acquisition of spatial information that can optimize soil sampling, and the subsequent identification of the causes that affect yield and/or quality variability. Other soil sensors, which are still in the development stage, include sensors for detection of organic matter content and detection of levels of particular nutrients, humidity sensors and soil depth sensors.

In relation to crop sensors, Zhang *et al*. (2002) point out various possibilities. However, the fundamental use of local crop sensors in PV can be narrowed down to the radiometric sensors «GreenSeeker» (NTech Industries Inc., Ukiah, CA, USA) (Goutouly *et al*., 2006; Tardáguila *et al*., 2008) and «CropCircle» (Holland Scientific Inc., Lincoln, Nebraska, USA), and the video based image analysis system «GrapeSense» (Lincoln Ventures Ltd., Hamilton, New Zealand) (Praat *et al*., 2004).

The use of remote sensing (satellite and digital aerial photographic images) comprises another interesting field of research in PV. Spectral vegetation indices (or crop vigour indices) are constructed from information obtained from multispectral images (spectral reflectances at different wavelengths, specifically in the blue, B, green, G, red, R and near infrared, NIR, bands). Indices used in PV include the PCD (Plant Cell Density), cited by Bramley *et al*. (2003), the PVR (Photosynthetic Vigour Ratio) (Arkun *et al*., 2000; Bramley and Lamb, 2003) and the most commonly used index in PV by far, the NDVI (Normalized Difference Vegetation Index) (Arkun *et al*., 2000; Hall *et al*., 2002; Dobrowski *et al*., 2003; Johnson *et al*., 2003). The PCD is calculated as the ratio of near infrared to red reflectance (NIR/R), the PVR as the ratio of green to red reflectance (G/R), and the NDVI by the combination of near infrared and red reflectances (NIR-R/NIR+R). Finally, the GVI (Green Vegetation Index, based on an algorithm developed by Digital Globe, Earthmap Solutions) is another of the indices that have been proposed (Ortega and Esser, 2005).

Correlation of these indices with certain structural or physiological characteristics of the vine is, in general, satisfactory. Thus for example, the LAI (Leaf Area Index), the presence of nutritional deficiencies, the water stress status or the health disorder status (incidence of pests or diseases) can be inferred based on calculation of the NDVI (Montero *et al*., 1999; Arkun *et al*., 2000; Johnson *et al*., 2003; Ortega-Farias *et al*., 2003; Acevedo-Opazo *et al*., 2008) or other narrow-band hyperspectral vegetation indices sensitive to chlorophyll content (Zarco-Tejada *et al*., 2005; Martín *et al*., 2007). Specifically, the high reflectivity which a vigorous and healthy grapevine plant presents in the near infrared band in comparison to one of poor vigour or subject to adverse conditions (water stress) enables detection of these differences (Lamb, 2001). Thus, the use of this remote information enables differentiation, within the vineyard parcels, of areas of different vigour (the more vigorous or denser vines produce a higher reflection of solar light in the near infrared band and a lower reflectance in the red band).

Interest in estimation of vine vigour (or leaf density), through the use of local or remote sensors, is due to the influence it has on grape yield and quality. It has been shown in red varieties in Australia (Lamb, 2001), that vines with greater vigour and/or leaf density produce a higher quantity of grapes (yield) but of lower quality, in accordance with the lower concentration of phenolic compounds and colour in the pulp. In Spain, at the wine farm of Raimat (Lleida), information obtained from multispectral images has been used to estimate crop vigour and to forecast yield (Martínez-Casasnovas

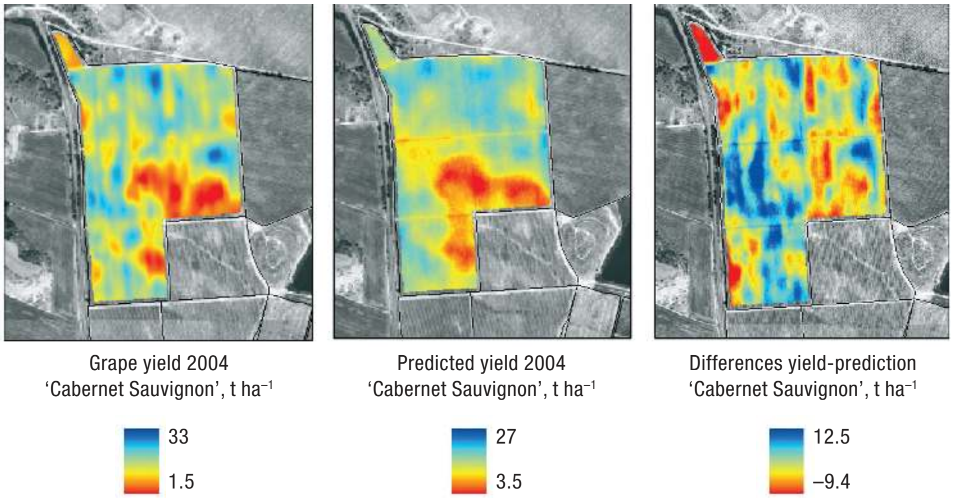

Figure 2. Comparison of the 2004 yield map of a parcel of 'Cabernet Sauvignon' (left) with the map obtained from a prediction model using the NDVI (normalized difference vegetation index) from a QuickBird-2 multispectral image acquired one month before harvesting (centre) (R^2 = 0.72). The map on the right shows the differences between the two maps (Martínez-Casasnovas and Bordes, 2005).

and Bordes, 2005) (Fig. 2). However, full understanding of the vine-production-quality interrelation requires more research into the linkages between, for instance, remote sensed vegetation indices and vine-production-quality parameters (Johnson *et al*., 1996, 2001, 2003; Arkun *et al*., 2000; Hall *et al*., 2002, 2003, 2008; Best *et al*., 2005).

The information that has to be collected is varied (McBratney and Whelan, 2001): yield, quality, physical and chemical properties of the soil, terrain, crop, weeds, pests and diseases. Analysis of the information basically has to comprise an analysis of the spatial variability, because it is precisely management of the variability and not the technology employed what is the essential characteristic which defines Precision Agriculture (Viticulture) (Blackmore, 1999).

Decision-support systems for analysing within-field variability: data analysis and interpretation

There is no doubt that, in the wake of the appearance of grape harvest monitoring systems and of local and remote sensors to measure soil and/or crop properties, the acquisition of significant amounts of data at parcel level has become possible. However, the analysis and management of such data inevitably depends on the prior application of geostatistical methods.

Geostatistics, based on what is called, «the theory of regionalised variables», is basically a probabilistic method of spatial interpolation. Final construction of the map corresponding to parcel level is made possible, based on estimation with error at non-sampled points, using the spatial variability structure of the sampled data (variogram) and an interpolation method (kriging). This type of information, which can be obtained for different properties and for successive years, opens new and interesting possibilities in agronomic crop analysis and management.

Mapping of the variables sampled on site, using geostatistical methods and one reference grid (raster map or surface map), is a recommendable measure (Plant, 2001). There are different spatial interpolation methods (kriging). Several authors have conducted comparative studies, discussions and applications of these methods in the context of PA. Some considerations of interest with respect to yield map construction by kriging can be found in Whelan *et al*. (1996), Bramley and Williams (2001) and in Taylor *et al*. (2007).

Map acquisition (of the grape harvest, soil depth, etc.) constitutes the first link in this type of data analysis. In general, maps constructed at parcel level usually display clear spatial variability. In Australia, Bramley and Hamilton (2004) have described variation ranges of the grape harvest with yields ten times higher in some specific areas of the parcel (the most productive) than those of least production. On the other hand, some interesting results have discussed by Taylor *et al*.

(2005) when comparing the spatial structure of yield variation in Australian and European (France and Spain) winegrape production systems.

Analysis of spatial variability is important for two reasons. From the perspective of PV, it allows the identification of areas or zones of different productive potential within the parcel and an evaluation of the opportunity for their differential management. From the perspective of viticultural experimentation, analysis of parcel spatial variability allows better interpretation of the results of «classical» experimental designs (Bramley *et al*., 2005a).

For zone delineation of a parcel, information about the yield variation pattern is a very interesting starting point (Sudduth, 1999). On other occasions, zoning within the parcel (within-field zoning) is based on several parameters, such as yield, parcel elevation and soil EC (Fraisse *et al*., 2001). In fact, the aim is to identify the areas that reveal similar productive potential and which, therefore, can be uniformly managed (McBratney and Whelan, 2001). These areas, called management zones, normally differ between them in terms of soil properties, slope and microclimate (on the line of the French idea of «wine terroir»). The use of cluster analysis is the recommended classification methodology to allow zoning at parcel level (Bramley and Hamilton, 2004; Taylor *et al*., 2007). Through an iterative process this procedure enables the clustering of values interpolated from the maps into homogenous groups (classes) in relation to the variables chosen for the analysis. It is possible to preset the number of groups (hard *k*-means algorithm or fuzzy *k*-means algorithm), and delineation of 2 to 5 classes is the general recommendation (Fraisse *et al*., 2001; Bramley and Hamilton, 2004). The final goal is to zone the parcel taking into consideration the classes provided by cluster analysis.

Zones of differential crop management within a parcel can vary with the input that is applied. In other words, zoning which optimises nitrogen fertilizing can be different to that which should be used for selective vintage. Likewise, elimination of excessive details of spatial variation should allow delineation of compact and average sized areas, simplifying within-field variation and lessening the requirements for variable-rate machinery (Zhang *et al*., 2002).

Verification of the stability of the spatial distribution patterns of the grape harvest over a number of campaigns has also attracted the interest of Australian and European research in PV. Studies conducted by Proffitt and Hamilton (2001), Bramley and Lamb (2003), Bramley and Hamilton (2004) and Tisseyre *et al*. (2007, 2008) have shown that grape yield is variable within the same parcel, and that this variability is maintained from one campaign to the next following a clearly defined spatial distribution pattern, even when there have been significant differences in total grape yield between consecutive years. With this in mind, Bramley and Hamilton (2004) advocate the adoption of Precision Viticulture based on zoned management of parcels. The use of normalised yield maps for several years (zero mean and unit variance) is the method proposed by Shearer (2001), so that year-to-year yield differences do not have an influence on map interpretation and subsequent zoning of the parcel. As an example, Figure 3 shows the reclassified yield map (class map) obtained from the sum of normalised yields of 2002, 2003 and 2004 in a parcel at Raimat (Lleida) (Arnó *et al*., 2005a).

Geographic Information Systems (GIS) are an important element in the management of data generated by PV. However, information stored in the GIS should be treated in conjunction with other software applications that make data interpretation and appropriate management-taking decisions possible (McBratney and Whelan, 2001). While some authors (Runquist *et al*., 2001) have proposed the development of GIS specifically conceived for PA and their application at parcel level, the fact is that current practices in PV have to make use of advanced data analysis and geostatistical analysis software. In the last few years GIS for PA (PAGIS) have become available. These are programs that are relatively easy to use and which allow yield monitor data manipulation and appropriate file specification for variable-rate equipment and machinery. However (McBratney and Whelan, 2001), the routines they use are too simple and it is difficult to guarantee suitable interpretation and management decision-taking. The development of Decision-Support Systems (DSS) in PV undoubtedly remains a pending assignment. Precision Agriculture (Viticulture) can be basically described as an example of the conversion of data into decisions (McBratney and Whelan, 2001).

Engineering technologies for variability management: the use of Variable-Rate Technologies (VRT)

Practical implementation of PV is linked to the development of certain technologies (Cook and Bramley,

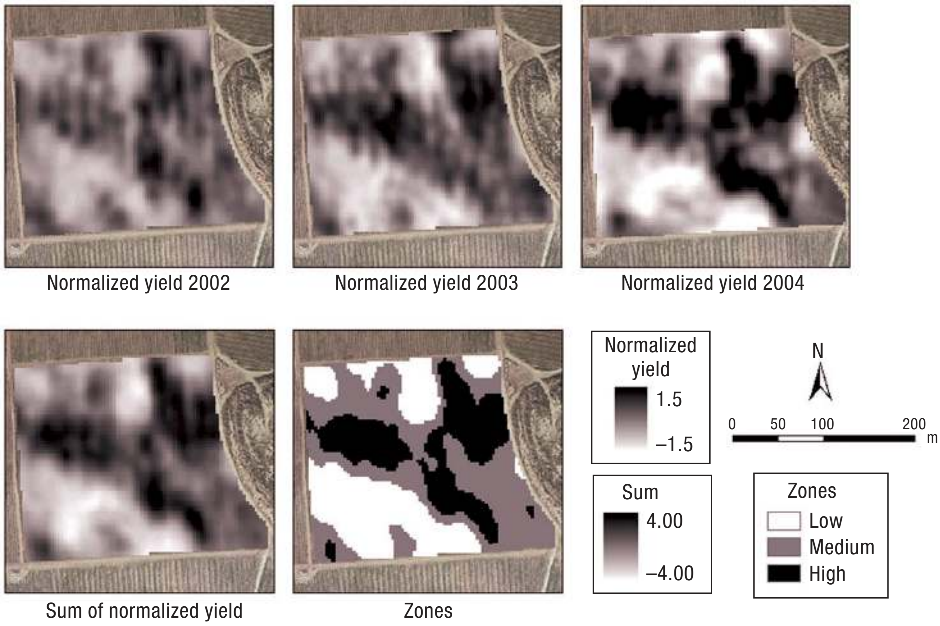

Figure 3. Sum of normalized yield maps and classified management map.

1998): GPS and differential GPS (DGPS), crop sensors and monitors, local and remote sensors, VRA equipment and machinery, GIS and systems for data analysis and interpretation.

GPS systems supply spatial coordinates for sampling and subsequent information mapping (measurement of spatial variability). Another more recent use of GPS has been the detailed topographic mapping of parcels through RTK (real-time kinematic) GPS (Sudduth, 1999). Positioning systems via satellite are of fundamental importance for variable rate crop input application machinery. The simultaneous development of electronic communication standards (Landwirtschaftliches BUS-System-LBS) in agricultural machinery has likewise facilitated the connection and interchangeability between tractor and farming implements (Auernhammer, 2001). Significant efforts have been made to develop international standards to regulate communication and information exchange protocols between sensors, actuators and software programmes of different manufacturers (Zhang *et al*., 2002).

Research conducted in the field of Variable-Rate Technology (VRT) has also been noteworthy. As a result of the work of agricultural machinery companies and research centres, the VRA of fertilizers, crop protection products and seeds is a well established possibility (Sudduth, 1999). A considerable number of researchers in vineyard farming have conducted studies on optimisation of phytosanitary treatments. Variable dose rate, based on electronic characterisation of the vegetation together with the use of proportional spray equipment, is one of the lines of research that has achieved important advances (Escolà *et al*., 2007; Gil *et al*., 2007).

A number of commercially available systems now accept digital application maps in conjunction with a GPS (Blackmore, 1999). The ultimate aim is to abandon the inflexibility associated with the idea of a parcel as the minimum territorial unit, and to move on to work with subparcels or zones which are delineated and treated differentially in accordance with their particular productive and/or qualitative characteristics. In short, Site-Specific Crop Management (SSCM) refers to crop management at a lower spatial scale than that of the parcel (Plant, 2001).

Opportunities for site-specific vineyard management: the evaluation of cost/benefit ratio

In contrast to «uniform» application of fertilizers and crop protection products, PA allows treatments to be carried out with variation of the amounts applied within the same parcel. In this way, fertilizers and pesticides are only used where and when they are necessary and in the appropriate amounts for each site. With this consideration in mind, it is easy to accept the

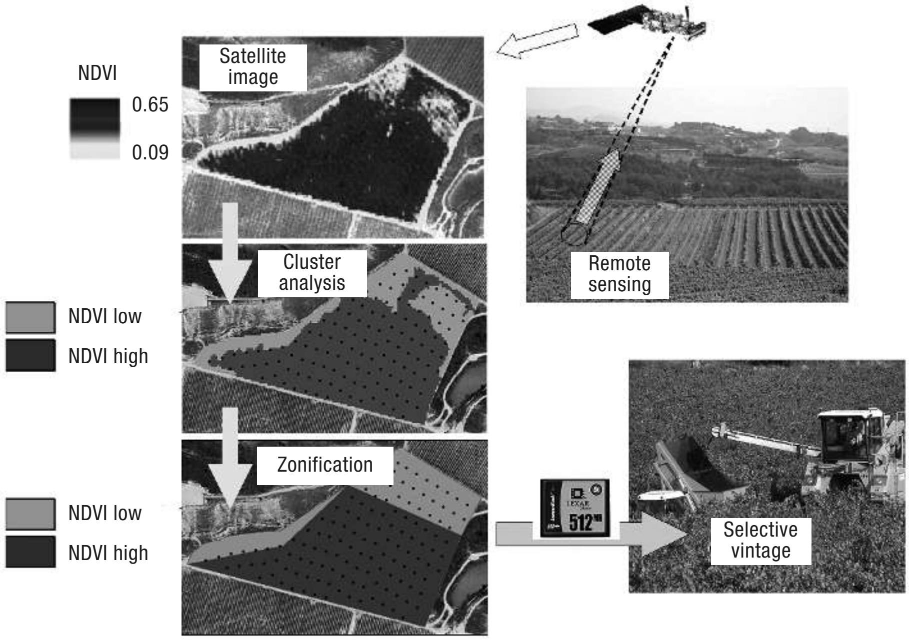

Figure 4. The «cycle» of selective vintage with the aid of multispectral images: remote sensing data acquired ± 2 weeks from veraison is converted to NDVI maps that are classified in different zones, which are characterised according to their grape quality parameters and are transferred to the harvester monitor for selective vintage.

idea that PA can bring clear environmental advantages. Limitation (adaptation) of the applied fertilizer level in accordance with the productive potential (response) of the different zones of a parcel (with the consequent reduction in contamination due to losses of N) (Bongiovanni and Lowenberg-Deboer, 2004) and the reduction in the use and spray drift of pesticides (Giles and Downey, 2003), are clear examples of the possible contribution of PA to greater sustainability of agricultural production processes.

Several authors have looked at economic evaluations of PA (Ancev *et al.*, 2005; McBratney *et al.*, 2005). The results in terms of the cost-benefit relation are still not conclusive for some plants (Plant, 2001). However, the advantages that PV can confer seem to be much clearer (Proffitt and Hamilton, 2001; Ortega *et al.*, 2003; Bramley *et al.*, 2005b).

For the grapegrowers, PV improves the use of productive factors (water, fertilizers, crop protection products), reducing costs and minimizing the environmental impact. Even the design and planting of new parcels can be more appropriately planned by examining their spatial variability. Selective vintage and pricing by product quality are other possibilities offered by PV.

For the winemakers, PV improves the logistics of the winery, based on better programming of the grape harvest and improved yield forecast. Selective harvesting of the grape, based on criteria of quality and/or market expectations, is a technique of undoubted interest for the industry. In experiments conducted in Australia, Bramley *et al*. (2003, 2005b) managed to divide a parcel into zones through the use of an aerial photograph taken during the stage of grape véraison [the stage during which the greatest correlation between the image and the parameters of yield and colour is obtained (Lamb, 2001)]. From the Plant Cell Density (PCD) index, subsequent analysis of the image enabled differentiation of two zones of different vigour, but also of different quality. The zone with the higher PCD index, of greater vigour and yield, produced a wine with an overall lower quality. The advantage of selective vintage lay, therefore, in the greater economic benefit obtained when harvesting the two zones and processing the grapes separately.

The use of vigour maps (drawn up via remote detection) for grape quality zoning is the method currently used by larger-sized companies. Some of the first experiments performed in Spain in the field of selective vintage (Agelet, 2007; Arnó *et al.*, 2007), show within-field variability of certain parameters of quality and, what is more important, the possibility of dividing parcels into zones of different quality based on the use of information supplied by a high-resolution satellite image (Quickbird-2) (Fig. 4).

Bramley and Lamb (2003) estimate that the additional cost which adoption of this type of technology entails, for a five-year period, can amount to between 0.5% and 2% of the perceived yield value. These results have helped to spread the idea that the best prospects for PA in Spain lie in so called high-return crops, as is the case of the grape for winemaking (Valero, 2004).

However, adoption of PA (or PV) in Spain and other countries considered pioneers in this technology has so far been limited. In Australia, for example, Lamb *et al*. (2008) emphasise as possible causes of the slight impact of PA (or PV), the cost of the technologies involved and the general reluctance of farmers to adopt technological changes. Cook and Bramley (1998) and Lamb *et al*. (2008) coincide when pointing out that the void that exists between researcher and farmer has to some extent brought about the distancing (distrust) of the productive sector. If we add the fact that commissioning these new technologies and providing professional advice requires knowledge and skills that very few agents and/or consultants are currently able to offer, then the present stalemate is easy to understand. There seems to be no easy solution at hand. Many farmers have developed a preconceived idea that PA techniques are only possible for large farms. This idea has been endorsed by many agricultural technicians and advisors, and it is very possibly this conservative attitude that is holding back the introduction of PA (PV). It is also true that the development of new technologies has been due more to the initiative of companies than to real demand from farmers and that the greater capacity offered by PA for parcel data acquisition has often exceeded our capacity to understand and usefully apply all that information (Lamb *et al*., 2008).

Future directions of Precision Viticulture

In reality, research into PV is still in its infancy, and to date relatively little has been published in this field. Current and future research into PA (PV) have a number of different priorities (McBratney *et al*., 2005): environmental economics, production quality assessment methods and new technologies for crop monitoring.

In relation to the last of the above, of particular interest is the development of real-time vegetation management systems, through integrated sensors and models which detect and manage particular properties of interest of the vegetation. In France, for example (Tisseyre *et al*., 2001), gravimetric determination of yield has been tested with some success using load cells on grape harvesters, as well as the implementation of sensors to measure grape must pH and grade by refractometry. Spatial monitoring of vines using on-board sensors for grape harvesters has also showed a growing interest in Spain (Bastida and Ruiz, 2006). In Australia, however, researchers seem more preoccupied with identifying the causes of within-field variability (Bramley and Lamb, 2003) and the differential management of factors which would enable an optimum balance to be reached between yield, quality and leaf area of the vines (600 g of grape m^{-2} of leaf area, equivalent to 1.6 kg $vine^{-1}$). Defining zones for differential treatment (site-specific management) is another question which arouses maximum interest in both, Australia and Europe.

However, the study of spatial variability has to be complemented by analysis of seasonal variation (for example, for input adjustment and optimisation during the cycle, based on crop monitoring over a period of time) (McBratney *et al*., 2005). At the same time, zoned management should not be restricted solely to parcel level. It is expedient that delineation of zones susceptible to site-specific management be extended to the whole of the wine-growing farm. Identification of a reduced number of management zones, but at larger scale (in other words, that cover all the farm), is one of the aspects that has to be considered in the future. A dilemma has arisen in viticulture over variability management at regional level («terroir») and variability management at parcel level. Finally, the formulation of an Opportunity Index, along the lines proposed by McBratney *et al*. (2000) and Pringle *et al*. (2003) to assess the suitability of site-specific management, should be investigated in more detail for the particular conditions of viticulture in Spain.

Clearly, Spanish research in PV is very recent, but hopeful. Besides the interesting research of the University of La Rioja (field practices for cost reduction) and the University of Castilla-La Mancha (cordless sensors networks to assess the spatial variability of vines), the Cénit-Deméter is a Spanish consortium that groups several vinery companies, universities and research centres. The main goal of Deméter project is to generate enough scientific and technological knowledge (including PV strategies) that allows grapegrowers and winemakers addressing the challenges raised by the Climatic Change.

Conclusions

Grape yield maps are of fundamental importance for the development of PV. The parcels with greatest opportunities for PV are those which reveal a high degree of yield variation and a strong spatial structure in that variation. A high degree of variation will mean higher VRA of inputs and, therefore, greater economic and environmental benefit in comparison with uniform management. A strong spatial structure is also desirable, as the variable-rate machinery will operate more efficiently when the areas for differential treatment are larger and are defined clearly and regularly. However, decision-taking remains the cornerstone of Precision Viticulture. The parameters and methods used for zoning, the variables to be sampled on site or the actions to be adopted in each zone, are some examples of the decisions that have to be taken and on which the success or failure of the proposed site-specific management will depend. The difficulty which analysis and interpretation of variability faces, due to the lack of functional tools for decision-taking, serves to explain the difficulty faced so far for a rapid and widespread adoption of Precision Viticulture.

Site-specific management in viticulture is still in an initial phase of adoption among grapegrowers and winemakers, at least in Europe. Predicting the future of Precision Viticulture and of the extensive range of innovative technologies that have been appearing over the last 15 or 20 years is difficult. Nonetheless, a greater presence of site-specific crop management is to be hoped for, even if it is only on the basis of the use of some of the technologies that have been mentioned here. The obvious question is: Why can not the vine be one of those crops?

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