Are precision agriculture tools and methods relevant at the whole vineyard scale ?

L.G. Santesteban, Serge Guillaume, J.B. Royo, Bruno Tisseyre

Are precision agriculture tools and methods relevant at the whole-vineyard scale?

L.G. Santesteban[1], S. Guillaume[2], J.B. Royo[1], B. Tisseyre[2]
[1]*Departamento de Producción Agraria, Universidad Pública de Navarra, Campus de Arrosadia, 31006 Pamplona, Spain Phone : +34-948-169718. Fax : +34-948-169732*
[2]*UMR ITAP, Montpellier SupAgro/Cemagref, bat 21, 2 place Viala, 34060 Montpellier, France. Phone : +33-499-61-23-35. Fax : +33-499-61-24-36*

Abstract

Precision viticulture has been applied to date mainly at the field level, for which the ability of high resolution data to match within-field variability has been already shown. However, to be fully operational, it should also be applicable at the whole-vineyard scale. The aim of this study was to analyze whether it is possible to use precision viticulture tools to define meaningful management zones at the whole-vineyard scale.
Experiments were carried out in year 2008 on 90 ha planted of cv. Tempranillo from a vineyard with a total area of 140 ha in Spain. A three-level classification was established at both scales using NDVI, elevation and soil apparent conductivity data. The agronomic significance of these classes was tested comparing the vegetative growth, yield, carbon discrimination isotopic ratio and berry quality observed at each class. The analysis of high resolution information has been proved to be relevant in order to define whole vineyard classes with agronomic implications, the spatial variability of the vineyard being structured.

Key words : *Vitis vinifera* L., NDVI, within vineyard variability, precision viticulture.

Introduction

In the last decade, there has been an important increase in applying precision agriculture to viticulture. Since the earliest studies in the 1990s, there have been significant improvements in both the spatial resolution of remotely obtained information, currently of the order of centimetres (Hall *et al.*, 2010) and in the mathematical analyses performed with the information acquired (Pedroso *et al.*, 2010, Paoli *et al.*, 2007).
To date, precision agriculture tools and methods have been mainly applied at the field level, and much research has highlighted the ability of high resolution data to match within field variability at this scale (Acevedo-Opazo *et al.*, 2008a, Acevedo-Opazo *et al.*, 2008b), and the potential benefits of its management according to the obtained zoning (Bramley *et al.*, 2004, Taylor, 2004, Arnó *et al.*, 2009). The field level corresponds to a production unit that has the same age, variety and rootstock, and is usually managed uniformly in terms of fertilization, pruning, irrigation, etc. In precision agriculture, this scale of work is interesting since it only needs to take into account a few factors causing spatial variability (mainly soil composition and water availability) and allows the identification of within field zones where the plant response differs according to these factors.
However, to be fully operational, precision viticulture principles should be also applicable at a larger scale, i.e. the whole-vineyard scale, which encompasses all the fields managed by the same grower. This scale is also interesting, since most growers

focus their management on a multi-field scale, and decisions need to be made for each field of the whole vineyard. Applying precision viticulture tools and methods at this scale may provide relevant information on the whole vineyard variability that could also be helpful to the grower in order to consider differential management for each field.
At the field level, precision viticulture (PV) technology highlights micro-scale variability which is mainly due to environmental factors (Bramley and Hamilton, 2007). As the area considered increases, new variability sources are likely to appear. The analysis of the spatial variability at this scale may help to highlight some phenomena that were not identifiable at a smaller scale. This scale of analysis may be of interest to propose a typology of fields which may receive on average the same treatment.
Therefore, PV suitability needs to be checked at this scale. The aim of this study was to analyze whether it is possible to define meaningful management zones at the whole vineyard scale using precision viticulture tools. The originality of this approach is that a specific experiment was designed on a large vineyard, spread over a whole catchment area. In order to analyze properly the relevance of the spatial variability, this study has focused on a vineyard planted with the same variety and a homogeneous training system.

Material and Methods

Experimental site

Experiments were carried out in year 2008 on a 140 ha commercial vineyard located in Olite, Southern Navarre, Spain (42°25'4"N, 1°40'48"W, WGS84, 340 m asl), under semi-arid climatic conditions. Since among the 140 ha of the vineyard, most of the area (90 ha) is planted with cv. 'Tempranillo', experiments focused on this variety. Except for one field, most of the fields planted with cv. 'Tempranillo' had the same planting density.

Auxiliary information

a. NDVI information

Multispectral Airborne images of 30 cm. resolution were provided and processed by Geosys–Spain company (Leica ADS40 sensor). Two images were provided: one acquired in 2007 and another in 2008. Both images had the same characteristics and were acquired in August, shortly after veraison, once vegetative growth had stopped. Assuming temporal stability of the spatial variability of vigour (Tisseyre *et al.*, 2008), the image of 2007 was used to define the sampling of additional data, whereas the image of 2008 was used for the analysis of these additional data in relation to NDVI values (see next sections). The 30 cm image pixels were aggregated into 3 m pixels, which approximates the "mixed pixel" row spacing approach of Lamb *et al.*, (2004), using the methodology outlined in Acevedo-Opazo et al. (2008a).

b. Soil and elevation data

Based on the spatial analysis of the NDVI measured in 2007, a sampling grid was defined at the whole-vineyard scale. This sampling grid was dedicated to acquiring additional auxiliary data in 2008. The distance between samples was defined according to the NDVI semi-variogram. It was defined to take into account 75% of the NDVI spatial variability (25 % of the semi-variogram sill). The practical range of the semi-variogram corresponding to 25% of the sill was 31 m (Fig. 1). A 30x30 m grid was then defined over the whole vineyard, leading to the establishment of 256 sampling points. Soil apparent electrical conductivity (EC_a) measurements were made over all the sample sites of the grid using a handheld EM38 (Geonics Ltd, Ontario, Canada) in March 2008. The same grid was used to create a digital terrain model from elevation data obtained on all the sampling points with a laser Tachymeter (TPS 1001, Leica, Heerbrugg, Switzerland).

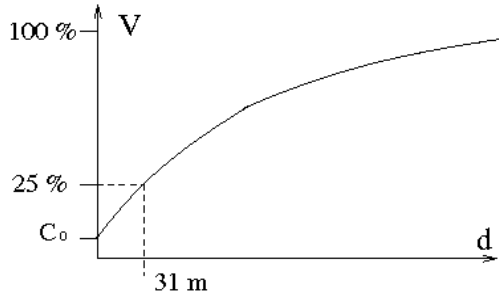

Figure 1: Semi-variogram of the NDVI over the whole vineyard and distance corresponding to the sampling grid.

Plant information

Plant measurements were performed at 64 out of the 256 sampling points. These 64 points were defined expertly on the basis of the NDVI values measured in 2007. Their locations have been defined to take into account the full range of variation of NDVI assuming that this would estimate the diversity of plant vigour and the resulting responses of the plant in terms of yield and quality over the whole vineyard. At each sampling point, 10 adjacent vines were marked. Trunk cross-sectional area (TCSA) and the sum of cross-sectional basal area of all the shoots of each vine (SCSA) were measured at flowering and veraison. Berry size and composition were determined at three times (10 days before veraison, 10 days after veraison and harvest) in 200-berry samples by measuring berry weight and, after crushing, sugar content, titratable acidity (TA) and pH. 10 days after veraison and at harvest, malic and tartaric acid were measured enzymatically (Easychem, Systea s.p.a., Italy). Yeast assimilable nitrogen (YAN) was estimated following the procedure described by Aerny (1996) and anthocyanin content estimated according to the methodology described by Glories and Augustin (1993). At harvest, yield and bunch number per plant were measured.

Plant water status was estimated indirectly through the measurement of the carbon isotope ratio in berries, known to be a good integrator of cumulative water status (Van Leeuwen *et al.*, 2009, Santesteban *et al.*, 2009). At each sampling point, 50-berry samples were taken at the same times defined above for quality measurements, dried and grounded into a fine homogeneous powder, and 2 mg samples were analyzed for $\delta^{13}C$ using an Elemental analyzer (NC2500, Carlo Erba Reagents, Rodano, Italy) coupled to Isotopic Mass Spectrometer (Thermoquest Delta Plus, ThermoFinnigan, Bremen, Germany). Carbon isotopic ratio was expressed as $\delta^{13}C = [(Rs - Rb)/Rb] *1000$, where Rs is the ratio $^{13}C/^{12}C$ of the sample and Rb is the $^{13}C/^{12}C$ of the PDB (Pee Dee Belemnite) standard (0.0112372).

Data analysis

a. Classification and class validation

The classification has been implemented to consider management classes. As proposed by Bramley and Hamilton (2007), three variables were used in the classification process, two of them describing the environment of the plant (elevation and soil apparent conductivity), and the third one corresponding to the response of the plant (NDVI). The classification was run at whole-vineyard scale. It was performed using a non-supervised approach: hierarchical ascendant classification. Classification was stopped at three classes assuming three management classes were enough to take into account the spatial variability. The validation of the correspondence between the classes established and the observed plant behaviour was performed through one-way Anova. Variance homogeneity was tested prior to analysis using Levene´s test, and mean separation according to Tukey-Kramer´s test, well-suited for unbalanced data sets (Sahai *et al.*, 2004). All these analyses were performed using SPSS v.17 (SPSS Inc).

b. Mapping

Data mapping was performed using GvSIG (v1.1, Generalitat Valenciana, Spain) by importing X, Y and data for each field and each variable. Data interpolation was performed using 3Dfield software (Version 2.9.0.0, Copyright 1998-2007, Vladimir Galouchko, Russia). The interpolation method used in this study was based on a deterministic function (inverse distance weighting). For most variables, three classes of values were considered to build the maps; low, medium and high, that corresponded to 0-33%, 33-67% and 67-100% percentiles.

Results

Results of the classification

Figure 2 shows the three different classes obtained at the whole-vineyard scale. It also summarizes the main characteristics of the whole vineyard on the basis of elevation, NDVI and ECa values. Class 1 includes locations of high NDVI with low to medium ECa and, mainly, with the highest elevations. Class 3 corresponds to locations of low NDVI values characterized by high ECa and low elevation. Class 2 is an intermediate class between class 1 and 3 with medium NDVI and medium ECa values. Maps in Figure 2 show a clear relation between elevation, soil and vigour. Note that this relationship would have been very difficult to identify if the study had focused on the scale of a single field. The results presented in Figure 2 show, for this vineyard, the opportunity to work on a larger scale instead of the within-field scale. In this case, elevation is a critical variable that seems to determine the soil properties and the level of vine vigour at the whole vineyard level.

Agronomic validation of the clusters at whole vineyard scale

The validation of the agronomic interest of the classes established has to be performed by analyzing the class distributions of vineyard and grape characteristics. The location of the sampling points using year 2007 NDVI, resulted in quite an uneven distribution, 13 belonging to class 1, 43 to class 2 and 8 to class 3.

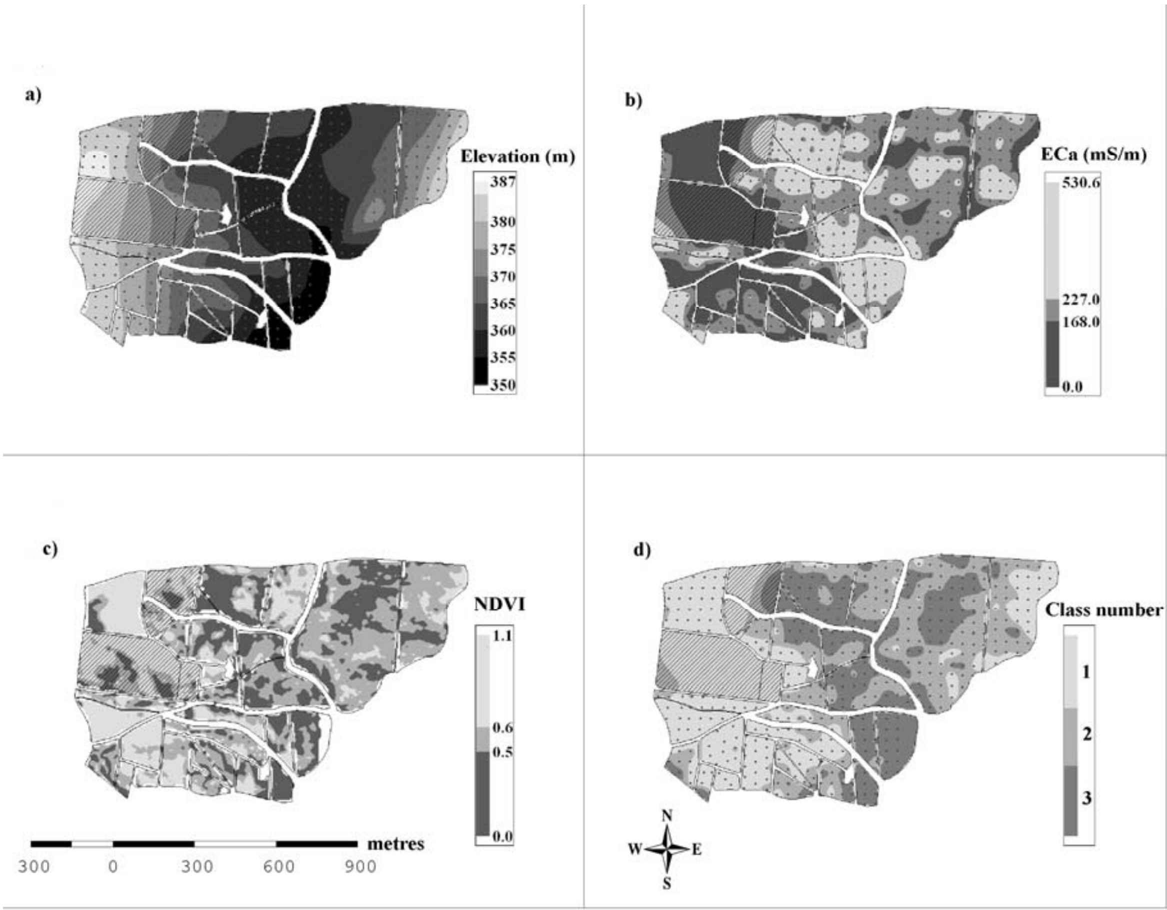

Figure 2: Maps of the whole vineyard showing (a) the whole vineyard variability for elevation, (b) soil apparent conductivity (ECa), (c) NDVI and (d) the resulting clusters after hierarchical ascendant classification.

There was certain correspondence between trunk size and vineyard shoot growth on the one hand and the established classes on the other hand (Table 1), the lowest vigour being found for class 3 and the highest for class 1. This ranking is illustrated by the monotonic behaviour of the values in Table 1. Classification also showed a good correspondence with berry carbon isotope discrimination and with berry yeast available nitrogen content (Table 1), which indicates that the established classes are related to two of the main factors that determine vineyard behaviour in semi-arid areas: water and nitrogen availability (Coombe et al., 2005).

Table 1: Correspondence of the classification established at whole vineyard scale with vine vegetative growth, berry carbon isotopic discrimination ratio and berry nitrogen content.

Class	TCSA (cm^2)	SCSA (mm^2)	$\delta^{13}C$ (‰) ver-10	ver+10	harvest	YAN ($mg\ L^{-1}$)
1	8.70 a	985.0 a	-25.53 c	-23.74 b	-23.80 b	327.8 c
2	5.31 b	809.0 a	-24.60 b	-23.00 ab	-23.05 ab	228.2 b
3	3.03 c	580.0 b	-23.43 a	-22.41 a	-22.09 a	191.2 a
P	*0.000*	*0.002*	*0.001*	*0.025*	*0.005*	*0.002*

TCSA: Trunk cross-sectional area; SCSA: sum of shoot cross-sectional area; ver-10: 10 days before veraison; ver+10: 10 days after veraison; YAN: yeast available nitrogen in berries at harvest. Values followed by different letters indicate significant differences according to Tukey-Kramer´s test

Yield was also higher for class 1, in spite of there being no differences in fruit load either expressed as cluster number or berry number per vine (Table 2). Differences in yield were caused mainly by greater berry size, observed at the three stages of berry development analysed (Table 2).

Table 2: Correspondence of the classification established at (a) within-field level and (b) whole vineyard scale with yield, fruit load and berry weight.

Class	Yield (kg vine^{-1})	Cluster number	Berry number	Berry weight (g) ver-10	Berry weight (g) ver+10	Berry weight (g) harvest	Berry number SCSA^{-1}
1	2.21 a	12.26	1213	0.68 b	1.57 c	1.65 b	1.23 c
2	1.96 a	12.78	1239	0.63 ab	1.33 b	1.52 ab	1.53 b
3	1.45 b	11.10	1034	0.56 a	1.16 a	1.32 a	1.78 a
P	*0.073*	*0.515*	*0.554*	*0.081*	*0.013*	*0.044*	*0.008*

ver-10: 10 days before veraison; ver+10: 10 days after veraison; SCSA: sum of shoot cross-sectional area. Values followed by different letters indicate significant differences according to Tukey-Kramer´s test

Concerning berry quality, there was no clear correspondence between the classes defined and most berry composition parameters. There is no monotonic relation between the values and the classes as shown in Table 3. No further clear trends could be observed.

Table 3: Correspondence of the classification established at whole vineyard scale with berry composition at harvest

Class	TSS (°Brix)	pH	TA (g Atart L^{-1})	TartA (g L^{-1})	MalA (g L^{-1})	TAnt (mg L^{-1})	EAnt (mg L^{-1})	TP (mg L^{-1})
1	21.92	3.96	3.73 b	3.82	4.22	1008.5	455.7 a	1091.9
2	20.97	3.96	3.75 b	3.52	4.14	921.4	381.7 b	1087.6
3	21.22	3.91	4.32 a	4.24	3.70	964.2	410.0 b	1035.6
P	*0.216*	*0.877*	*0.048*	*0.129*	*0.406*	*0.384*	*0.015*	*0.505*

TSS: total soluble solids; TA: titratable acidity; TartA: tartaric acid; MalA: malic acid; TAnt: total anthocyanins; EAnt: extractable anthocyanins; TP: total phenolics. Values followed by different letters indicate significant differences according to Tukey-Kramer´s test

Discussion

The analysis of high resolution information has been proved to be relevant in order to define vineyard classes with agronomic relevance. The spatial variability of the vineyard being structured, the classes correspond more or less to patterns or zones. In this particular area, the zones with higher NDVI, lower ECa and higher elevation had higher vigour, berry size and yield (Tables 2 and 3), as a consequence of a better water and nutritional status throughout the season as shown by the lower carbon isotope discriminating ratio and the higher nitrogen levels in berries. Water status has been already shown to be the most relevant factor determining vine yield and berry size in this region (Santesteban and Royo, 2006), and nitrogen is also known to significantly affect shoot and berry growth (Bell and Henschke, 2005). Carbon isotope discriminating ratio in berries has proved to be a very interesting tool to integrate plant water status during berry development and should be used in any research dealing with precision viticulture or modelling in areas where water limitations occur.

A clear correspondence was not found between grape composition and the defined zoning (Table 4). This result is in agreement with experiments carried out under similar conditions in terms of significant water restriction (Acevedo-Opazo *et al.*, 2008a, Ojeda *et al.*, 2005). Lack of correspondence between berry composition and zoning is due to the complexity of the processes that affect berry composition: despite the zoning proposed in this study indirectly integrates some the factors that affect berry composition (shoot growth, water status, nitrogen level), it does not take into account some other factors, such as fruit load, that also affect berry composition (Keller et al., 2008).

The zoning obtained can be relevant to deal with some important aspects of vineyard management. Elevation is a critical variable that seems to determine the soil properties, the water availability and the level of vine vigour. This general trend was hardly visible at the field scale. The zones obtained could be used to redefine the irrigation blocks, apply nutrients much more rationally and perform some differential vineyard operations (e.g.: pruning, cluster thinning, leaf pulling, etc). Since the spatial variability is quite structured, these changes are feasible and could improve the whole vineyard performance.

Ideally, site specific management should be considered according to the validated zones. However, practically, variable rate application may be hardly possible at the within-field level for some operations because machinery is not available or because facilities were designed at the field level (irrigation). These results show that data obtained at high resolution can be used as a first approach to choose some operations (pruning, thinning or even irrigation) where rate of application can vary according to the field considered. Figure 3 shows an example of field classification based on the zones validated. Each field was assigned the label of the most common class in the field. Figure 3 can be seen as a simplification of Figure 2. Once the fields are labelled, the same operation can be applied to all the fields of the same class. Obviously, the labelling process could be improved by taking into account other available data

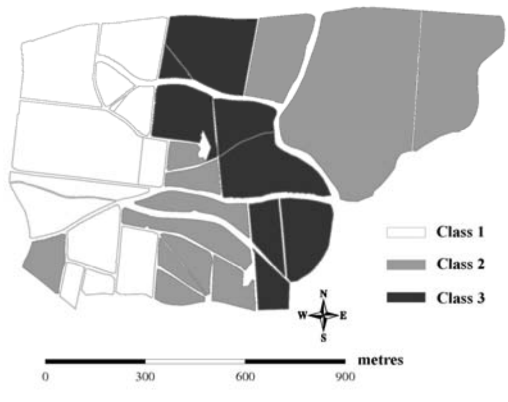

Figure 3: Field classification based on within-field class occurrence. Field was assigned the class corresponding to the majority class of measurement sites.

As a first approach, class 1 could correspond to fields where nitrogen applications should be avoided; water availability reduced by the introduction of a cover crop; and Regulated Deficit Irrigation strategies held in order to moderate shoot growth and fertility. On the contrary, great attention would need to be paid to class 3 fields, mainly with regards to irrigation, that should probably be based on short high frequency applications to minimize water stress.

Besides, in these fields, it would also be interesting to consider a decrease in bud load in order to avoid overloading those vines, and fruit thinning should be applied in those years for which cluster number was considered to be too high. Lastly, class 2 fields should be managed following an intermediate strategy. Apart from that, this classification could also be considered to segregate fields in to groups with different wine-style vocation, some being probably more suitable for rosé and young red wines and others having a greater potential to obtain aged wines, which also would guide vineyard managers to adapt field management to the grape specifications required for each style of wine.

Therefore, from a practical point of view, this scale of decision could be relevant for operations that can barely vary at the within-field level. The management of within-field variability could be seen as a way to manage "residual" spatial variability. This variability could be managed by other operations that can be varied at the within-field level.

Conclusion

The study showed that precision viticulture tools and methods can be applied and may be useful at the whole vineyard scale. The analysis of the spatial variability at this scale (catchment scale) may reveal a general trend of variation that is barely visible at the within-field level. This scale of analysis may be the support necessary to decide specific managements at the field level. However, since the experiments were performed at a vineyard spread over a whole catchment with contiguous fields (which results in some continuity in spatial variation and makes data interpretation much easier) similar in terms of age, variety and training system (which limits the variability of NDVI values), other experiments must be carried out in order to test the relevance of such an approach under a more sparse spatial distribution of the fields or under a large diversity of training systems, variety and age of plantation, circumstances usually found when dealing with co-operatives and smallholders.

Acknowledgements: The authors would like to thank Michel Murua and all the staff in Pagos de Araiz winery for their valuable co-operation. This work has been funded by Verdtech Nuevo Campo, Adena & Fundación Caja Rural del Sur, as part of the ECOSAT project, and by Fundación Fuentes Dutor.

References

Acevedo-Opazo, C., Tisseyre, B., Guillaume, S. and Ojeda, H. 2008a. The potential of high spatial resolution information to define within-vineyard zones related to vine water status. *Precision Agriculture* 9, 285-302.

Acevedo-Opazo, C., Tisseyre, B., Ojeda, H., Ortega, S. and Guillaume, S. 2008b. Is it possible to assess the spatial variability of vine water status? *Journal International des Sciences de la Vigne et du Vin* 42, 203-220.

Aerny, J. (1996) Composés azotés des moûts et des vins. *Revue Suisse de Viticulture, Arboriculture et Horticulture* **28**, 161-165.

Arnó, J., Martinez-Casasnovas, J.A., Ribes-Dasi, M. and Rosell, J.R. 2009. Review. Precision Viticulture. Research topics, challenges and opportunities in site-specific vineyard management. *Spanish Journal of Agricultural Research* **7,** 779-790.

Bell, S.J. and Henschke, P.A. 2005. Implications of nitrogen nutrition for grapes, fermentation and wine. *Australian Journal of Grape and Wine Research* **11,** 242-295.

Bramley, R.G.V. and Hamilton, R.P. 2004. Understanding variability in winegrape production systems 1. Within vineyard variation in yield over several vintages. *Australian Journal of Grape and Wine Research* **10,** 32-45.

Bramley, R.G.V. and Hamilton, R.P. 2007. Terroir and precision viticulture: Are they compatible? *Journal International des Sciences de la Vigne et du Vin* **41,** 1-8.

Coombe, B. G., Dry, P. R. and Anderson, C. J. (2005) Viticulture. Ed. Winetitles, Adelaide, Australia.

Glories, Y. and Augustin, M. 1993. Maturité phénolique du raisin, conséquences technologiques: application aux millésimes 1991 et 1992. In *Journée technique du C.I.V.B.: Actes du colloque* Bordeaux.

Hall, A., Lamb, D.W., Holzapfel, B.P. and Louis, J.P. 2010. Within-season temporal variation in correlations between vineyard canopy and winegrape composition and yield. *Precision Agriculture* **12,** 1-15.

Keller, M., Smithyman, R.P. and Mills, L.J. 2008. Interactive effects of deficit irrigation and crop load on Cabernet Sauvignon in an arid climate. *American Journal of Enology and Viticulture* **59,** 221-234.

Lamb, D.W., Weedon, M.M. and Bramley, R.G.V. 2004. Using remote sensing to predict grape phenolics and colour at harvest in a Cabernet Sauvignon vineyard. *Australian Journal of Grape and Wine Research* **10,** 46-54.

Ojeda, H., Carrillo, N., Deis, L., Tisseyre, B., Heywang, M. and Carbonneau, A. 2005. Precision viticulture and water status II: Quantitative and qualitative performance of different within field zones, defined from water potential mapping. In: *Proceedings of 14th GESCO Congress*. Geisenheim, Germany, pp. 741-748.

Paoli, J.N., Strauss, O., Tisseyre, B., Roger, J.M. and Guillaume, S. 2007. Spatial data fusion for qualitative estimation of fuzzy request zones: Application on precision viticulture. *Fuzzy Sets and Systems* **158,** 535-554.

Pedroso, M., Taylor, J., Tisseyre, B., Charnomordic, B. and Guillaume, S. 2010. A segmentation algorithm for the delineation of agricultural management zones. *Computers and Electronics in Agriculture* **70,** 199-208.

Sahai, H. and Ojeda, M. M. (2004) Analysis of variance for random models: theory, methods, applications, and data analysis. Ed. Birkhäuser, Boston.

Santesteban, L.G., Miranda, C. and Royo, J.B. 2009. Interest of berry carbon isotope composition as an integrator of vineyard water status in semi-arid areas. In *16th International GiESCO Symposium*. Davis, California, pp. 223-226.

Santesteban, L.G. and Royo, J.B. 2006. Water status, leaf area and fruit load influence on berry weight and sugar accumulation of cv. 'Tempranillo' under semiarid conditions. *Scientia Horticulturae* **109,** 60-65.

Taylor, J.A. 2004. Digital Terroirs and Precision Viticulture. Investigations into the application of information technology in Australian vineyards. Ph.D Thesis. The University of Sydney

Tisseyre B., Mazzoni C., Fonta H., 2008. Whithin-field temporal stability of some parameters in viticulture: potential toward a site specific management. *Journal International des Sciences de la Vigne et du Vin* **42,** 27-39.

Van Leeuwen, C., Tregoat, O., Chone, X., Bois, B., Pernet, D. and Gaudillere, J.P. 2009. Vine water status is a key factor in grape ripening and vintage quality for red Bordeaux wine. *Journal International des Sciences de la Vigne et du Vin* **43,** 121-134.