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

L. G. Santesteban · S. Guillaume · J. B. Royo · B. Tisseyre

Abstract Precision viticulture (PV) has been mainly applied at the field level, for which the ability of high resolution data to match within-field variability has been already shown. However, the interest of PV for grape growers would be greater if its principles could also apply at a larger scale, as most growers still focus their management on a multi-field scale, not considering each field as an isolated unit. The aim of this study was to analyse whether it is possible and relevant to use PV tools to define meaningful management zones at the whole-vineyard scale. The study was carried out on a 90-ha vineyard made of 27 contiguous fields. The spatial variability of vine vigour, estimated with the Normalized Difference Vegetation Index (NDVI), was analysed at within-field and whole-vineyard scales. The spatial variability of the vigour was significant and spatially organized whatever the considered scale. Besides, vineyard spatial variability was characterised using information on environmental factors (soil apparent conductivity and elevation) and vine response (yield, vigour and grape composition). At both scales, NDVI and measured environmental factors were used to establish a three-level classification, whose agronomic significance was tested comparing the vine response observed for each class. The analysis of high resolution information allowed the definition of classes with agronomic and oenological implications, although there was not a straightforward correspondence between the classes defined and quality. Analysing the variability at the whole-vineyard scale highlighted a trend of spatial variation associated to elevation that was hardly visible at the within-field level.

Keywords *Vitis vinifera* L. · NDVI · Within-vineyard variability · Precision viticulture

L. G. Santesteban · J. B. Royo
Departamento de Producción Agraria, Universidad Pública de Navarra, Campus de Arrosadia, 31006 Pamplona, Spain

S. Guillaume · B. Tisseyre (✉)
UMR ITAP, Montpellier SupAgro/Cemagref, Bat 21, 2 Place Viala, 34060 Montpellier, France
e-mail: tisseyre@supagro.inra.fr

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Introduction

A significant increase in applying precision agriculture to viticulture has occurred in the last decade: at the research level, the number of research works published has increased to 20 papers in 2011; whereas at the commercial level many companies now offer Precision viticulture (PV) services in countries with a progressive wine industry. Since the earliest studies in the 1990s, there have been significant improvements in both the spatial resolution of remotely obtained information, currently in the order of metres (Hall et al. 2011; Acevedo-Opazo et al. 2008a, 2010; Bramley and Hamilton 2004), and in the mathematical analyses performed with the information acquired (Tisseyre and McBratney 2008; Pedroso et al. 2010; Paoli et al. 2007). Precision agriculture (PA) tools and methods have been mainly applied at the field level, and much research has highlighted the ability of high resolution information obtained from airborne imagery and soil electrical properties maps to match within-field variability at this scale (Acevedo-Opazo et al. 2008a, b), and the potential benefits of its management according to the obtained zoning (Bramley et al. 2005; Taylor 2004; Arnó et al. 2009). The field level corresponds to a production unit having the same age, variety and rootstock, and is usually managed uniformly in terms of fertilization, pruning, irrigation, etc. In PA 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) (Bramley and Hamilton 2007), and allows the identification of within-field zones where the plant response differs according to these factors.

However, interest in PV for grape growers would be greater if its principles could also apply at a larger scale encompassing all the properties managed by the same grower or the same company within a contiguous location. Most growers focus their management on a multi-field scale, not necessarily considering each field as an isolated unit: sometimes several fields may share management decisions, and other times certain areas of a field may need to be managed separately. Moreover, from a pragmatic point of view, if we consider that, except for few ‘boutique’producers, the minimum average fermentation tank size is not smaller than 25 t, and that field size in European vineyards is frequently smaller than 3 ha, it would make no sense to apply PA at the within-field scale in order to consider selective harvesting. Therefore, it is necessary to evaluate the performance of PA tools at a multi-field or at a whole-vineyard scale. Unfortunately, there is little information on how PA works at these scales: Johnson et al. (2003) demonstrated, working at two locations that accounted for 800 ha of vineyards, that leaf area can be relatively well estimated ($R^2 = 0.73$) from multispectral satellite imagery. Bramley (2003) successfully combined information on yield, soil apparent conductivity and elevation to delineate salinity/sodicity zones at a whole-vineyard scale (24 ha). Bramley et al. (2011) have more recently evaluated the feasibility and profitability of applying PV tools to delineate selective harvesting policies considering altogether two nearby sites that comprised a total area of about 25 ha, showing that PA can increase the net benefit not only for small producers or for large, well-resourced companies, but also for producers geared to large scale production.

The main reason that may cause PV to work differently at within-field and multi-field or whole-vineyard scales is that, as the area considered increases, the possibility of the concurrence of new sources of variation also increases. Thus, at the field level, PV technology highlights micro-scale variability which is mainly due to variations in soil depth and in its chemical and physical properties (Bramley and Hamilton 2007), whereas when the area considered increases, variability sources, linked, for instance, to elevation, to slope or to slope aspect are more likely to appear. The analysis of the spatial variability at the whole-vineyard scale may help to highlight some phenomena that were not identifiable at a smaller scale. Therefore, the interpretation of the variability of a single field may be facilitated by the analysis of variation of the adjacent fields.

Taking into account the above-mentioned considerations, the suitability of PV needs to be validated at the whole-vineyard scale. The aim of this study was to analyse whether it is possible to define meaningful management zones at this scale using PV tools. The originality of this approach is that a specific study was designed on a large vineyard spread over a whole catchment area to analyse the spatial variability at two different scales: (i) micro-scale (within-field) and (ii) meso-scale (whole-vineyard, which encompasses all the fields). To avoid terminological misunderstandings, in the following document we will use the term "field" to refer to the management unit, usually planted with the same variety, training system and subjected to the same management practices (also referred to by some authors as block) and the term "whole-vineyard" to designate the entire property, owned by a grower or a company, usually made up of multiple fields (also termed as ranch or farm by growers). We focused, as a first approach, on a vineyard planted with the same variety and a homogeneous training system to better analyse the relevance of the spatial variability at both scales, avoiding further sources of variation that may occur as a result of differences in variety and training system (Tisseyre et al. 2011; Lamb et al. 2005).

Materials and methods

Site description

This study was carried out in year 2008 on a commercial vineyard made of 27 contiguous fields (Fig. 1) located in Olite, Southern Navarre, Spain (42°25′4″N, 1°40′48″W, WGS84, 340 m asl), under semiarid climatic conditions. Most of the vineyard area (90 ha) was planted with the *Vitis vinifera* L. cultivar Tempranillo (65 % of the total) and therefore the study focused on this cultivar. Vine spacing was 2.5 m between rows and 1.1 m between vines within a row, except for one fields (vineyard designation P51) which had 3.0 m between rows and 1.4 m between vines. With one exception (P50-A), all fields were planted in 2003. All fields were 6 years old at the time of the study (2008). Management of all fields was relatively uniform in terms of tillage, fertilization and irrigation. All fields were mechanically tilled between the rows and chemically-weeded under the rows, fertilization consisted mainly on the yearly application of 40, 20 and 80 units of N, P and K, respectively. Concerning irrigation, vines were irrigated, as a general rule, once a week from mid-June (anthesis) until early-September (1–2 weeks before harvest). The amount of water supplied was, as an average, 32 L per vine and week, which corresponds to a deficit irrigation strategy due to structural limitations in water supply.

Auxiliary information

Multispectral airborne images of 30-cm resolution were provided and processed by Geosys–Spain Company (sensor ADS40, Leica Geosystems, St. Gallen, Switzerland). 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 (i.e.: onset of fruit ripening stage, marked by a change in the colour of the berries), once vegetative growth had stopped. Assuming temporal stability of the spatial variability of vigour (Kazmiersky et al. 2011), 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 the

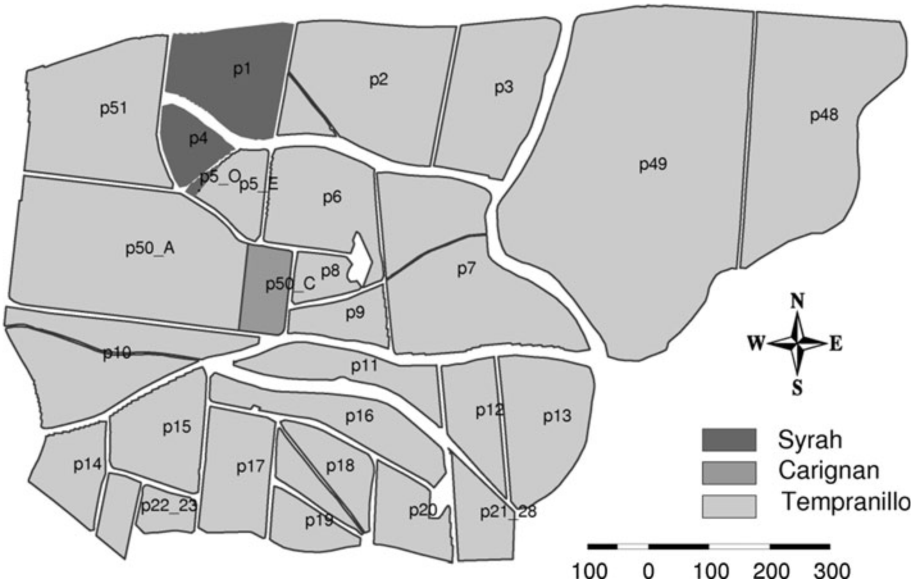

Fig. 1 Map of the whole-vineyard showing the variety as well as the name of the fields

Normalized Difference Vegetation Index (NDVI) (Rouse et al. 1973) values (see next sections).

Images were processed to have a vegetation index (NDVI) widely known to vary proportionally to plant vigour (Acevedo-Opazo et al. 2008a; Hall et al. 2003). Given the spatial resolution of the images, it would have been possible to apply a segmentation algorithm to extract the NDVI values corresponding specifically to the vines (Hall et al. 2003). However, in absence of inter-row cover grass on all the fields, hypothetical effects of a non-vine signal were assumed limited and the approach which approximates the "mixed pixel" row spacing (Lamb et al. 2004) was used. The 30-cm image pixels were aggregated into 3-m pixels using the methodology outlined in Acevedo-Opazo et al. (2008a). The spectral regions contained in the images were: blue (445–520 nm), green (510–600 nm), red (632–695 nm) and near-infrared (757–853 nm). The NDVI was derived for each image and Matlab 7.0 software (Mathworks, Natick, Mass, USA) was used for image processing and analysis.

Spatial analysis of the NDVI

For each field and for the whole-vineyard, NDVI values were used to compute classical statistics like mean and standard deviation. To summarize how the variability was distributed, geo-statistical information was also derived at the two scales. This information is based on the variogram and its related parameters (nugget effect C_0, sill C_1 and range r), and the trend. Two indices were then derived from the variogram and the trend: Cambardella Index (I_c) (Cambardella and Karlen 1999) and Opportunity Index (O_i) (Pringle et al. 2003).

Cambardella Index estimates the proportion of total variance which is erratic (not spatially organized) (Eq. 1).

$$I_c = \frac{C_0}{C_0 + C_1} \times 100 \quad (1)$$

where C_0 is the "nugget" variance of the adjusted variogram (estimated variance at $h = 0$) and C_1 is the estimate of the spatial structural variance. In condition of stationarity, $C_0 + C_1$ estimates the variance of the area. According to Cambardella and Karlen (1999), I_c gives a good indication on how the data are arranged spatially, namely: $I_c < 25$: strong spatial dependence and small erratic variance; $25 < I_c < 75$: moderate spatial dependence; and $I_c > 75$: random spatial distribution.

In addition to the Cambardella Index, the Opportunity Index (O_i) for site specific management as introduced by Pringle et al. (2003) was also computed using NDVI values. In this study, the O_i was used to select the fields most likely to be managed site specifically. O_i is conditional on two components (Eq. 2): (i) *M* the magnitude of variation presents in the NDVI map and (ii) *S* the spatial structure of NDVI values relative to the minimum area (*m*) within which variable rate controllers can reliably operate. Any particular choice was made on the type of operation. The parameter *m* was therefore considered with an area of 10 m^2 for all the fields and for the whole-vineyard.

$$O_i = M \times S \quad (2)$$

where *M* is the magnitude of data variation, and *S* is the spatial structure of data variation.

In Eq. (2), the magnitude of field variation (*M*) is assessed by the areal Coefficient of Variation (CV_a). The spatial structure of field variation (*S*) is assessed by the proportion of total variance explained by a trend surface of field data and the integral scale of the trend surface residual. Pringle et al. (2003) showed that O_i was reasonably successful in ranking fields from the most suitable to the least suitable for site-specific management.

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, which was dedicated to acquiring additional auxiliary data in 2008. The distance between samples was defined according to the NDVI semi-variogram, 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. 2). A 30 × 30 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 across all the sample sites of the grid using a handheld ground conductivity meter (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).

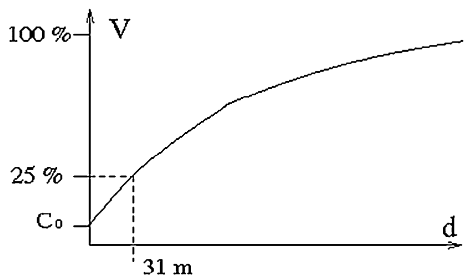

Fig. 2 Semi-variogram of the NDVI over the whole-vineyard and distance corresponding to the sampling grid

Plant information

Plant measurements were taken at 64 of the 256 sampling sites. Four vineyards were excluded from these measurements as they were either planted with a different grape cultivars (P1, P4 and P50-C) or planted in a different year (P50-A). The number and location of the 64 sites dedicated to plant measurements were defined according to several criteria: (i) 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 vine in terms of yield and quality over the whole-vineyard, (ii) labour availability to acquire all of the measurements on the entire vineyard in one day and optimization of travel time between sites, and (iii) information given by the technicians at the winery.

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 anthesis and veraison. Berry size and composition were determined three times during the growing season (10 days before veraison, 10 days after veraison and at harvest) using 200-berry samples. Berry weight was measured and then, after crushing, total soluble solids determined with a temperature compensating bench refractometer (RFM840, Bellingham-Stanley Ltd, UK), pH by directly submerging the electrode into must at room temperature and expressed as proton concentration. Afterwards, 20 mL of filtered must were titrated with NaOH 0.25 mol L^{-1} up to pH 8.1 with a pH-Burette 24 auto-titrator (Crison, Barcelona, Spain), results expressed as equivalent g TarA L^{-1}. At harvest and 10 days after veraison, malic and tartaric acid were measured enzymatically (Easychem, Systea s.p.a., Italy) and anthocyanin content estimated according to the methodology described by Glories and Augustin (1993). Yeast available nitrogen (YAN, mg L^{-1}) was calculated following the method described by Aerny (1996) with slight modifications: 20 mL of must were titrated up to pH 8.1, then 8 mL of methanol-stabilized 35–40 % (w/w) formaldehyde previously adjusted to pH 8.1 added to block the primary amine function promoting proton release from the amino acids and, after settling for 10 min, titrated with NaOH 0.05 mol L^{-1} up to 8.1. Yield and bunch number per vine were also measured at harvest.

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 described above for quality measurements, dried and ground into a fine homogeneous powder. Three 2-mg samples were analyzed for $\delta^{13}C$ using an elemental analyser (NC2500, Carlo Erba Reagents, Rodano, Italy) coupled to Isotopic Mass Spectrometer (Thermoquest Delta Plus, ThermoFinnigan, Bremen, Germany). Carbon isotopic ratio was expressed as $\delta^{13}C = [(Rs - Rb)/Rb] \times 1\,000$, 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

Classification and class validation

The classification has been implemented to consider management classes. Three variables were used in the classification process, as proposed by Bramley and Hamilton (2007); 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). Concerning geomorphological data, we considered elevation as the most relevant variable (instead of slope or slope aspect) as previous conversations with vineyard's manager and preliminary data analyses suggested it as such. Taking into account that the cultural practices were relatively similar across all the fields since the planting year, they were assumed to have no major effect on NDVI values. The classification was run at two scales: (i) field level, where only data belonging to the considered field were taken into account providing within-field classes, and (ii) whole-vineyard scale. The classification was performed using a non-supervised approach: Ward's clustering (WHC). In this study, WHC was preferred over the most commonly used *k* means clustering because it better allowed highlighting how the data fit with the expected number of classes. Especially, it was possible to check the presence of potential outliers in the merging process. At each spatial scale, after checking the relevance of the resulting classes (especially the presence of possible outliers), it was decided to make three management classes.

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 and Ojeda 2004). All these analyses were performed using SPSS v.17 (SPSS Inc., Chicago, USA).

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 3-Dfield 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

Analysis of the spatial variability at different scales

Table 1 includes the classical statistical and geo-statistical indices calculated from NDVI values for each field and for the whole-vineyard. Table 1 shows that within-field variability was significant, with an average standard deviation of 25 %. Cambardella Index (I_C) values were relatively low ($I_C < 30$, except for fields P9, P14, P18 and P4), indicating that for more than 80 % of the fields, the variability was spatially structured. Regarding the Site Specific Opportunity Index (O_i), 75 % of the fields showed a significant value ($O_i > 10$). To select at which field implement site specific management, Pringle et al. (2003) did not advocate for an absolute threshold for O_i values, but proposed to use a threshold value based on the distribution of observed values (i.e.: median). In this study, we considered a very high threshold corresponding to the upper quartile. Considering this arbitrary threshold, 6 fields were very well suited to precision agriculture tools and methods to manage within-field variability (Table 1). All these fields (P50_A, P49, P51, P21_28, P13 and P48) exhibited large areas and represented almost 50 % of the total area of the vineyard.

Table 1 Classical statistics and geo-statistical indices calculated from NDVI values for each field and the whole-vineyard

Field name	Area (ha)	Mean	Std.	I_c	O_i
P50A	7.7	0.60	0.16	28.7	80.0
P49	17.4	0.46	0.11	27.6	73.8
P51	4.7	0.72	0.16	0.8	70.8
P21_28	3.0	0.42	0.15	26.5	61.0
P13	3.0	0.36	0.15	0.6	60.8
P48	7.5	0.51	0.09	7.2	47.0
P10	4.1	0.66	0.16	26.9	46.0
P7	6.3	0.44	0.09	9.2	44.2
P6	2.9	0.44	0.15	21.7	41.2
P1	2.8	0.59	0.13	2.1	38.0
P12	1.5	0.45	0.16	0.2	37.0
P20	1.4	0.46	0.16	12.0	33.5
P22_23	1.3	0.57	0.19	4.5	30.5
P2	5.3	0.37	0.19	16.9	26.5
P19	0.9	0.49	0.13	0.2	21.2
P11	1.7	0.54	0.13	9.5	18.1
P17	2.2	0.57	0.08	7.6	16.1
P3	3.8	0.57	0.09	29.8	14.8
P8	0.7	0.60	0.12	18.6	12.8
P16	2.3	0.52	0.09	9.3	12.1
P50_C	1.1	0.60	0.10	1.1	11.2
P15	2.3	0.63	0.07	27.2	9.8
P18	1.8	0.47	0.08	40.0	9.5
P9	1.0	0.46	0.12	46.0	8.5
P14	1.4	0.45	0.13	39.0	7.9
P5_E	1.1	0.50	0.09	25.0	6.9
P4	0.9	0.55	0.07	31.9	3.3
Whole-vineyard	90.1	0.51	0.16	17.0	63.4

Fields are ranked according to O_i values

Std standard deviation, I_c Cambardella Index, O_i Opportunity Index for site specific management

Regarding the variability of the NDVI at the whole-vineyard level, an ANOVA revealed that the inter-field variability was statistically significant ($P < 0.01$) compared to the within-field variability (results not shown). At the whole-vineyard scale, the variability of NDVI was highly structured spatially ($I_c = 17$ %), which agrees with the strong spatial structure observed for the majority of the fields. Finally, the O_i ($O_i = 63$) highlights a significant interest to implement a site-specific management strategy at the whole-vineyard level.

The results we obtained based on the analysis of the spatial variability of the NDVI show that, at least for 80 % of the fields, it is interesting to manage the spatial variability either at the within-field or the whole-vineyard level. To compare the feasibility of implementing site-specific management practices at these two scales, two fields (P48 & P49) were selected. These fields were chosen because of (i) their high value of O_i, (ii) the fact that they were next to each other, and (iii) their large area, which accounts for a significant proportion of vineyard area (Fig. 1). In the following sections, these two fields are considered as a single field.

Results of the classification at two different scales

Description of the classes at the two scales

Figure 3 shows classes for fields P48 and P49, as well as maps of auxiliary information, which summarize the main characteristics of the single fields on the basis of elevation, NDVI and ECa values. Class 1 corresponds to locations of high NDVI with low to medium ECa, corresponding mainly to the highest elevations. Class 3 corresponds to locations of low NDVI values characterized by high ECa. Class 2 corresponds to an intermediate between Classes 1 and 3 with medium NDVI and ECa values. Maps in Fig. 3 show a clear relation between soil and vigour on these two fields. The relationship between vigour and altitude was not marked. However, except for particular patterns, locations of high elevation were more vigorous and vice versa.

At the whole-vineyard scale, it is interesting to note that classes had almost the same characteristics and the same spatial organisation as those conducted at the field scale (Fig. 4), Class 1 including locations of high NDVI with low to medium ECa and, mainly, with the highest elevations, Class 3 locations of low NDVI, high ECa and low elevation and Class 2 as intermediate between them. This similarity can be explained by the choice of fields, as they were selected according to their variability and their size. Moreover, considering the magnitude of variation, Figs. 3 and 4 show that it almost encompasses the variability observed at the whole-vineyard scale for all the parameters. It is then logical that the classification process gives similar classes at both scales. Maps in Fig. 4 show a

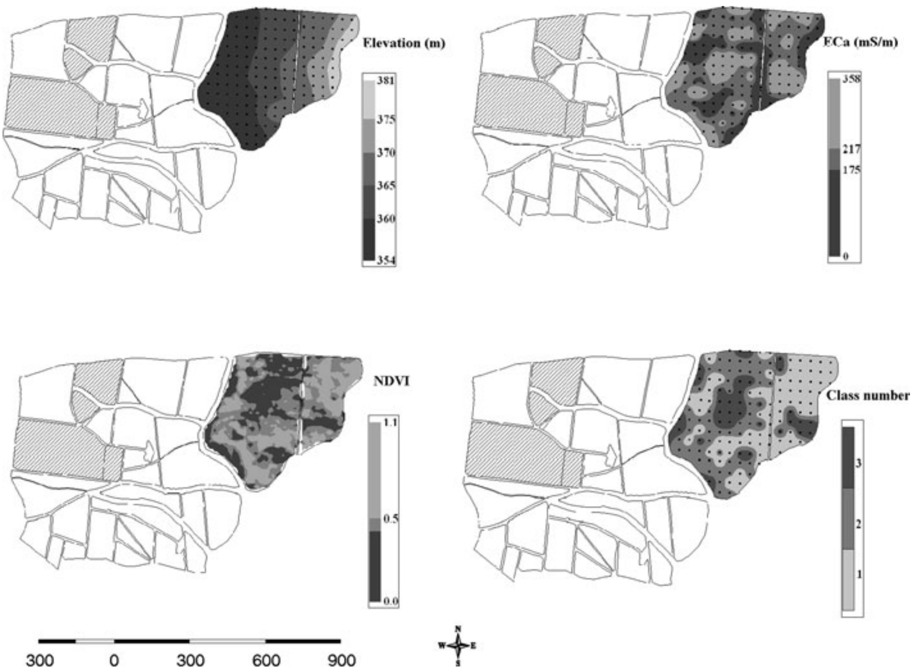

Fig. 3 Maps of single fields P49 and P48 showing the within-field variability of elevation, soil apparent conductivity (ECa), NDVI and the resulting clusters after Ward's clustering

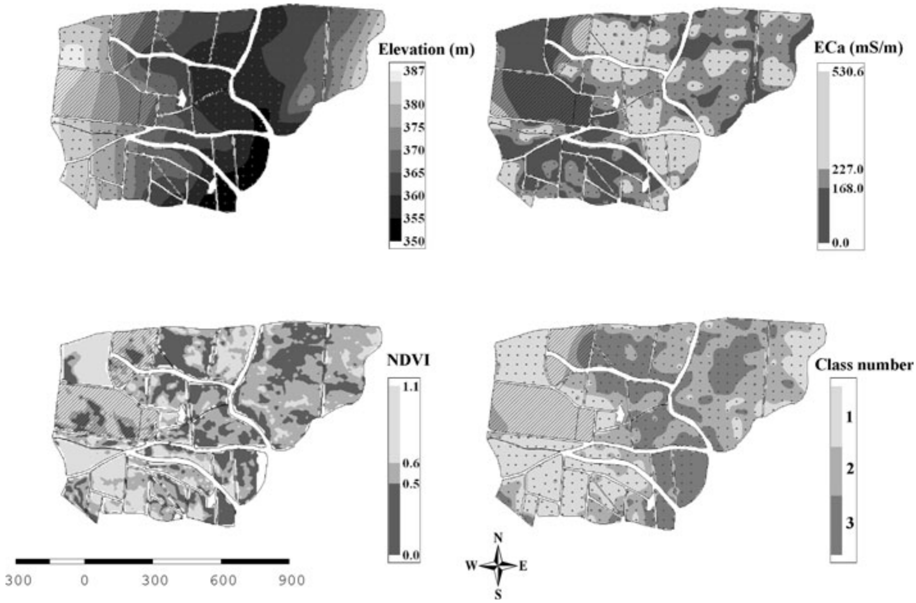

Fig. 4 Maps of the whole-vineyard showing the whole-vineyard variability of elevation, soil apparent conductivity (ECa), NDVI and the resulting clusters after Ward's clustering

clear relation between soil, vigour and elevation. This relationship was hardly visible at the within-field level, but elevation has proven to be a critical variable that determines the soil properties and the level of vine vigour at the whole-vineyard level.

Agronomic validation of the clusters at the two scales

Validation of the agronomic interest of the classes established requires analysing the class distributions of vineyard and grape characteristics. Regarding within-field scale, 14 out of the 64 sampling points were located at P48 & P49, 5 belonging to Classes 1 and 2, and 4 to Class 3. At whole-vineyard scale, the location of the sampling points, performed using year 2007 NDVI, resulted in quite an uneven distribution, 13 belonging to Class 1, 43 to Class 2 and 8 to Class 3.

There was certain correspondence at both scales between trunk size and vineyard shoot growth on the one hand, and the established classes on the other hand (Table 2), 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 2. However, at the within-field level, no significant differences between classes could be found, due to the limited data set available at this scale. Classification at both scales also showed a good correspondence with berry carbon isotope discrimination ratio and with berry yeast available nitrogen content (Table 2), which indicates that the established classes were related to two of the main factors that determine vineyard behaviour in semi-arid areas: water and nitrogen availability. Similarly, this trend was only significant at the whole-vineyard scale.

Yield was also higher for Class 1 at the whole-vineyard scale, in spite of there being no differences in fruit load either expressed as cluster number or berry number per vine (Table 3). Differences in yield at the whole-vineyard scale were caused mainly by greater

Table 2 Correspondence of the classification established at (a) within-field level and (b) whole-vineyard scale with vine vegetative growth, berry carbon isotopic discrimination ratio and berry nitrogen content

Class	TCSA (cm^2)	SCSA (mm^2)	$\delta^{13}C$ (‰)			YAN ($mg\ L^{-1}$)
			ver−10	ver+10	Harvest	
(a) Within-field level (P48& P49)						
1	5.56	818.4	−24.44	−23.07	−23.27	282.1
2	5.27	763.6	−23.99	−22.28	−22.86	216.8
3	4.54	673.9	−23.13	−22.31	−21.95	201.6
P	0.588	0.724	0.33	0.557	0.210	0.339
(b) Whole-vineyard level						
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

Values followed by different letters indicate significant differences according to Tukey–Kramer's test

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

Table 3 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 no $vine^{-1}$	Berry no $vine^{-1}$	Berry weight (g)			Berry number $SCSA^{-1}$
				ver−10	ver+10	Harvest	
(a) Within-field level (P48& P49)							
1	2.50 a	9.40	1482	0.70	1.44 a	1.60	1.81
2	1.47 b	10.78	890	0.68	1.29 ab	1.42	1.17
3	1.46 b	9.80	986	0.57	0.95 b	1.21	1.46
P	0.068	0.897	0.304	0.255	0.087	0.158	0.216
(b) Whole-vineyard level							
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

Values followed by different letters indicate significant differences according to Tukey–Kramer's test

Ver−10 10 days before veraison, *ver+10* 10 days after veraison, *SCSA* sum of shoot cross-sectional area

berry size, observed at the three stages of berry development analysed (Table 3). This trend was also observed at within-field scale, although differences were only significant for berry size at the beginning of the ripening stage (ver+10d) and for yield.

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 4. No further clear trends were observed at neither the within-field nor whole-vineyard scale.

Discussion

The analysis of high resolution information has proven to be relevant at a whole-vineyard scale to define vineyard classes relevant from an agronomic and oenological point of view. The spatial variability of the vineyard was spatially structured and not erratic and the classes corresponded more or less to patterns or zones. In this particular vineyard, the zones with higher NDVI, lower ECa and higher elevation had higher vigour, berry size and yield (Tables 2, 3), as a consequence of a better water and nutritional status throughout the season, as shown by the lower carbon isotope discriminating ratio and by the higher nitrogen levels in berries. Water status has been shown to be the most relevant factor determining vine yield and berry size in this region (Santesteban and Royo 2006), and nitrogen is known to significantly affect shoot and berry growth (Bell and Henschke 2005). The carbon isotope discrimination ratio in the fruit proved to be a valuable tool to integrate plant water status during berry development at a whole-vineyard scale, as the obtained values for this ratio were coherent with the classes established and also with berry weight (Tables 2, 3). As measuring fruit carbon isotopic ratio is relatively inexpensive, we recommend taking this parameter into account for further PV studies or modelling, at least in areas where water limitations occur.

A clear correspondence was not found between grape composition and the zoning defined (Table 4). This result is in agreement with other studies carried out under similar conditions in terms of significant water restriction (Acevedo-Opazo et al. 2008a; Ojeda et al. 2005). The processes that affect berry composition are complex, not driven by one or two factors and, despite the proposed zoning, some are indirectly included (shoot growth, water status, nitrogen level). Some other factors such as fruit load that also affect berry composition and interact with the above-mentioned factors are not taken into account (Keller et al. 2008).

Elevation was a very relevant variable at this vineyard, as it indirectly affects soil water dynamics (more rainfall water available in spring at the lower lying parts) and soil salinity (the lower parts in the vineyard having higher salinity levels). This causes lower lying parts

Table 4 Correspondence of the classification established at (a) within-field level and (b) 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})
(a) Within-field level (P48&P49)								
1	21.30	3.90	4.03	3.62	1.73	805.6	353.6	904.8
2	19.48	3.81	3.92	3.64	2.06	739.7	303.3	920.4
3	18.71	4.13	4.07	3.97	1.90	689.3	316.5	898.2
P	0.119	0.097	0.952	0.810	0.698	0.461	0.501	0.974
(b) Whole-vineyard level								
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

Values followed by different letters indicate significant differences according to Tukey–Kramer's test

TSS total soluble solids, *TA* titratable acidity, *TartA* tartaric acid, *MalA* malic acid, *TAnt* total anthocyanins, *EAnt* extractable anthocyanins, *TP* total phenolics in the vineyard to have moderate growth in spring, when the soil water reservoir is full, but to experience more water stress in summer, as irrigation was only applied moderately. A similar behaviour was observed in one of the few studies that apply PV to a whole-vineyard (Bramley 2003). However, at other vineyards other geomorphologic variables (particularly slope aspect) can be more relevant than elevation, so they should be tested. This would be particularly true at those vineyards where North- and South-facing slopes are frequent, and less likely at vineyards where most slopes are East- and West-facing, as it was the case at this particular site. The incidence of elevation on the agronomic performance was hardly visible at the field scale, but was highlighted at the whole-vineyard scale. The zones obtained at this scale 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.

Site-specific management should be ideally considered according to zones outlined through geostatistical procedures. However, 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). Therefore, an alternative would be to use data obtained at high resolution 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 5 shows an example of field classification based on the zones validated. Each field was labelled according to the most common class in the field. Figure 5 represents a simplification of Fig. 4. Once the fields were labelled, the same operation could be applied to all the fields of the same class. Obviously, the labelling process could be improved by taking into account other available data. As a first approach, some considerations could be made taking into account the production objectives of this winery, shared by many other winegrowers in Navarra that aim at commercializing 3–4 types of wine that range from super-premium to medium-prized quality wines, and to avoid the additional cost of cluster thinning to fit into the legal restrictions in yield imposed at the

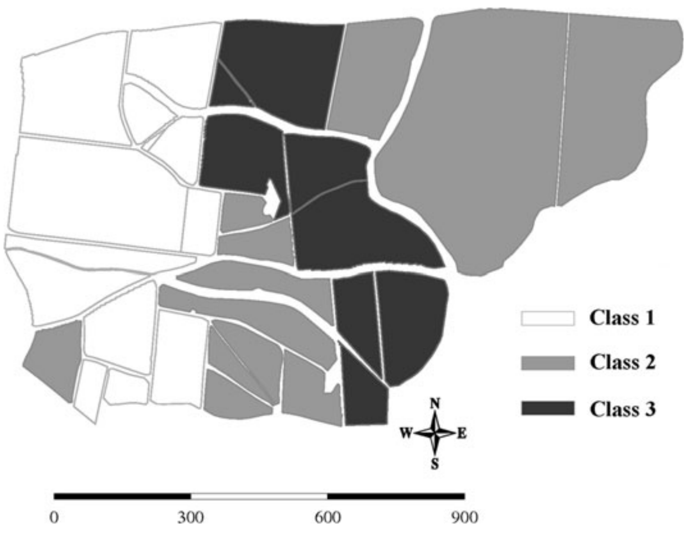

Fig. 5 Field classification based on within-field class occurrence. Fields were assigned the class corresponding to the majority class of the measurement sites

Navarra appellation (<8 t ha^{-1}). Class 1 would 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, whereas, on the contrary, great attention would need to be paid to Class 3 fields, mainly regarding 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 to avoid overloading those vines and fruit thinning applied those years when cluster number is considered to be too high. Lastly, Class 2 fields should be managed following an intermediate strategy. Apart from that, if a multi-block selective harvesting strategy, similar to that proposed in Bramley et al. (2011) is not applied, this classification could also be considered to segregate fields into groups with different wine-style vocation according to the commercial targets of the winery. In that sense, some fields could be more suitable for rosé and young red wines and others may have a greater potential to make wines with aging vocation, 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 method 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. The vineyard in our study presents particular features: (i) it is spread over a whole catchment with contiguous fields, which necessarily results in some continuity in spatial variation and makes data interpretation much easier, (ii) all the fields are nearly the same age, have the same variety and the same training system, which reduces the potential interference environmental factors can have on NDVI estimation (canopy configuration and leaf spectral properties).

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