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Spatial variability in grape yield and quality influenced by soil and crop nutrition characteristics

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Abstract Knowledge of spatial variability of soil fertility and plant nutrition is critical for planning and implementing site-specific vineyard management. To better understand the key drivers behind vineyard variability, yield mapping from 2002 to 2005 and 2007 (the monitor broke down in 2006) was used to identify zones of different productive potential in a Pinot Noir field located in Raimat (Lleida, Spain). Simultaneously, the vineyard field was sampled in 2002, 2003 and 2007, applying three different schemes (depending on the number of target vines in different grape yield zones). The sampling carried out in 2002, which involved different soil, topographic and crop properties (mineral contents in petiole), made it possible to evaluate the influence of these parameters on the grape yield variability. The zones of lowest yield coincided with locations in which the nutritional status of the crop exhibited the lowest values, particularly with respect to petiole contents of calcium and manganese. Sampling systems adopted in 2003 and 2007 (grape quality and soil attributes) confirmed the inverse spatial correlation between grape yield and some grape quality parameters and, more importantly, showed that the percentage of soil carbonates had a great influence on grape quality probably due to the reduced availability of manganese in calcareous soils. Site-specific vineyard management could therefore be considered using two different strategies: variable-rate application of foliar fertilizers to increase the yield in areas with low production and also foliar or soil fertilizers to improve the quality specifications in some areas.

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Introduction

Since the first appearance and commercial use of sensors and yield monitors on grape harvesters, it has been evident that the yield of grapes exhibits significant spatial variability (Bramley and Hamilton 2004). In fact, many winegrowers are fully aware of this variability which affects not only production, but also other parameters related to grape quality (Bramley 2005). As a consequence, it is very difficult to predict grape yield (Martínez-Casasnovas and Bordes 2005) and the quality of the product that actually enters the wine cellar. This also limits the possibility of differentiating between wines that, when sold, may also exhibit significantly different qualities.

Aware of the new technologies and opportunities offered by precision agriculture, the Spanish company Codorníu decided to initiate a precision viticulture project on its Raimat (Lleida) estate in 2001 (Arnó et al. 2005). This involved the acquisition of equipment for grape yield monitoring and its incorporation into one of their self-propelled grape harvesters. In 2002, working in collaboration with the University of Lleida, the company established a work protocol based on three main objectives: obtaining grape yield maps; analysing the spatial variability shown in these maps; and determining the possible influence of certain soil and crop related parameters on observed differences in grape yield. Later, in 2003 and 2007, two additional studies were carried out to assess the spatial relationship between yield, vine parameters, grape and must quality and also some physical and chemical soil properties.

Grape yield and grape quality within a given field are variable. When this spatial variability is large (i.e., when the differences between zones are considerable and the spatial grape yield or quality pattern is not random), site-specific crop management (SSCM) becomes feasible. The ultimate aim is, therefore, to develop a procedure that will allow the implementation of precision viticulture based on the use of variable-rate application maps. As Bramley and Lamb (2003) observed, the possibilities of successfully introducing this type of technology will ultimately be conditioned by the degree to which it is possible to understand the factors responsible for the spatial variability, the temporal stability of this variation, and the possibilities of being able to manage the parameters that are responsible for it.

The influence of soil characteristics on grape yield has already been studied by Bramley (2001) for Australian winegrape production systems. This author showed that variations in soil depth are the major cause of yield variability, with the highest yielding zones frequently being the areas with the deepest soils. This is because water availability in the root zone increases according to effective soil depth (Tardaguila et al. 2011). Soil salinity and clay content (and in particular its location in the soil profile) are two other physical soil properties that have an important influence (Bramley and Lamb 2003).

Quality is also very important in viticulture. Wine quality seems to be influenced by the "terroir": the final expression in the wine of the combined influence of soil, topography, microclimate, grape variety and cultural practices. However, Bramley and Hamilton (2007) confirmed that contrasting wines may derive from different areas within the same, uniformly managed vineyard. This supports the view that 'terroir' is spatially variable at the within-vineyard scale (Bramley et al. 2011). According to Hidalgo (2006), deep calcareous soils with sandy-loam textures and low fertility are the most suitable for vineyards. In contrast, clay soils (with a clay content of higher than 30–40%) give high yields but of less quality (Bramley and Hamilton 2007), producing wines with a low alcohol content which are more acidic and richer in nitrogen. Furthermore, an excess of nitrogen fertilization increases the vigour of vines and yield, but slows down the process of maturation, producing juices with fewer sugars and phenolic compounds. An excess of soil organic matter may also have a negative effect, producing wines that are richer in nitrogen and poorer in flavour. On the other hand, the availability of elements such as iron and manganese in appropriate quantities is very important for producing high quality wines (Bramley et al. 2011).

Another point of interest in viticulture is that quantity is inversely proportional to quality. In Australia, for example, the optimization of wine quality has meant having to limit yield to 6 t ha^{-1} (Bramley and Proffitt 1999). Both yield and quality seem to be basically influenced by soil physical properties and soil fertility (Tardaguila et al. 2011). Bramley (2001) has shown that the K/Mg ratio in the petiole, the yield and the probable alcoholic degree of the juice are all correlated and that the accumulation of sugars depends on there being an appropriate proportion of these two nutrients. The similarity between the pattern of spatial variability of the phenolic content in the grapes and the manganese content in the petiole was also noted by Bramley (2001). However, the existence of some form of spatial covariance between grape yield and grape quality remains a matter for discussion. Bramley and Lamb (2003) pointed out that the structure of the spatial variation of grape quality parameters needs not coincide with the spatial distribution pattern of the yield. In fact, although it has been demonstrated that yield spatial distribution pattern tends to be relatively stable from year to year, the best grape quality zones may not always be the same (Bramley and Hamilton 2004). This may indicate that, in addition to yield maps, any within-field zoning of grape quality may require other crop, soil and/or environmental parameters (Santesteban et al. 2010).

Analysis of the spatial variability of grape yield and quality has been undertaken by researchers into precision viticulture in various countries, including France (Tisseyre et al. 2001; Acevedo-Opazo et al. 2008), Chile (Ortega et al. 2003) and Australia (Bramley and Hamilton 2004; Taylor 2004; Bramley 2005). Within-field variability in grape yield and quality is important for decision making in crop management (Tisseyre et al. 2007, 2008; Hall et al. 2010). The present study has sought to understand the key factors in vineyard variability within the context of Spanish viticulture, with the aim of contributing, along with other similar studies, to improving their management. The objectives of this study were: to analyse spatial variability in yield through field zoning; and to determine the soil and crop factors that affect this variability. The extent to which soil characteristics are related to grape quality attributes is another of the questions raised. The ultimate goal is to establish how grape yield, grape quality, or both, can be improved in the areas with poor characteristics by targeted crop fertilization and/or soil amendment practices.

Materials and methods

Grape yield maps

Grape yield maps for the 2002, 2003, 2004, 2005 and 2007 vintages were obtained for a 5 ha field planted with *Vitis vinifera* of the Pinot Noir cultivar and located in Raimat (Lleida, Spain) (ED50 UTM 31n co-ordinates 291125, 4616275, 275 m.a.s.l.). The field (denoted P30) was planted in 1985 and irrigated using a sprinkler system. The pattern of the plantation was 3.2 m between rows and 2.1 m along the rows.

To obtain the grape yield maps, a Gregoire G-140 SW self-propelled grape harvester (Fig. 1) (Grégoire SAS, Chateaubernard, France) was equipped with a GPS/dGPS receiver, load cells and a Canlink 3000 yield monitor produced by Farmscan (Computronics, Perth, Western Australia).

Using the Farmscan™ Data Manager program (supplied with the Canlink 3000 monitor), data that had been stored by the yield monitor were saved as a text file. The mapping process consisted of editing the initial data for spatial interpolation (kriging) that would convert the point data collected by the yield monitor into data referring to specific surfaces. Spatial interpolation was carried out with version 1.6.3 of the VESPER program for geostatistical analysis (Minasny et al. 2005). As there was a large amount of yield data, the option was kriging in 10 m blocks and projecting interpolated data over a regular 3 m grid. For the interpolation of each point, a local variogram based on a minimum of 150, and a maximum of 200, neighbouring (yield data) points was used. Moreover, the ranges obtained from the interpolated maps, based on local variograms, were very similar to the range of variation for real grape yields as determined by local block kriging (Bramley and Williams 2001).

Sampling of vine, soil and grape quality variables

Samples of the soil and of the crop (analysis of petioles) were taken to study the factors that could influence grape yield and quality. To do this, a regular grid with sampling points (target vines) every 11 rows and 20 vines (about 35.2 × 42 m) was established in 2002. This allowed us to obtain approximately 6.5 samples per hectare. In 2003 and 2007, the

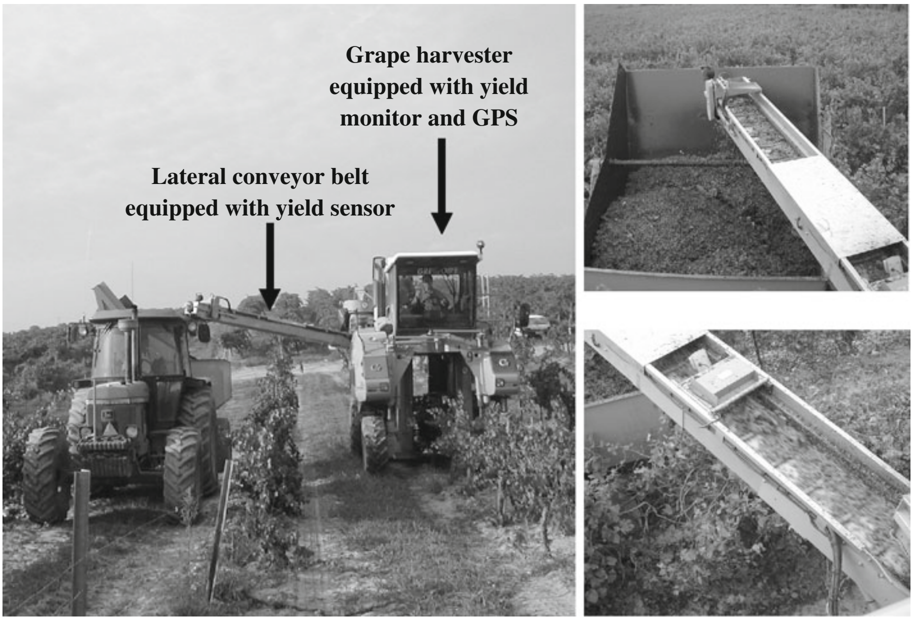

Fig. 1 Grape harvester and tractor + trailer (*left*) and detail of the location of the yield sensor on the lateral discharge conveyor belt (*right*)

sampling density was increased to every 10 rows and 10 vines (grid of 32 × 21 m). Figure 2 shows the study field and the distribution of the sampling points for years 2002, 2003, and 2007. While crop samples were taken in June 2002 (at flowering) and soil data in January 2003, the soil sampling in 2007 was carried out in November and grape quality data for 2003 and 2007 were obtained just a few days before the corresponding vintages. The sampled vines were geo-referenced, taking co-ordinates from the trunks, using a Trimble Geoexplorer XT GPS with an external antenna and differential correction in post-processing using the data provided by the CatNet network of the Cartographic Institute of Catalonia. The sampling density could be considered acceptable in all cases, as the main goal of the research was simply to assess possible interactions between grape yield, quality and soil parameters and not to analyze spatial variability in detail through the construction of appropriate surface (raster) maps.

The sampling carried out in the field was therefore systematic, with the sampling points being distributed using a rectangular grid and providing uniform coverage of the field (Fig. 2). As the spatial correlation scale of the sampled variables and possible zoning of the field were not known in advance, a simple random sample was discarded on the grounds of the potential ineffectiveness of such a measure if the density of the sampling points proved to be unsuitable.

In 2002, data at each point were obtained relating to: the different physical and chemical properties of the soil (texture, pH, electrical conductivity, percentage of $CaCO_3$, organic matter and root depth); properties related to the field topography (elevation and slope), which were obtained from a digital model of the terrain; and mineral contents in petioles (N, P, K, Ca, Mg, Fe, S, Zn, Cu, Mn, B and Na), which effectively provided information relating to the nutritional state of the crop. It is known that petiole sampling is useful for the posterior analysis and diagnosis of the nutritional state of vineyards at field level, although rootstock and variety have a significant influence on the mineral composition of vine leaves. To facilitate the evaluation of root depth, pits were opened at each point. Having taken a single soil core for the whole profile, soil analysis was performed using the following methods: pipette method for soil texture; a 1:2.5 dilution of soil:water for soil

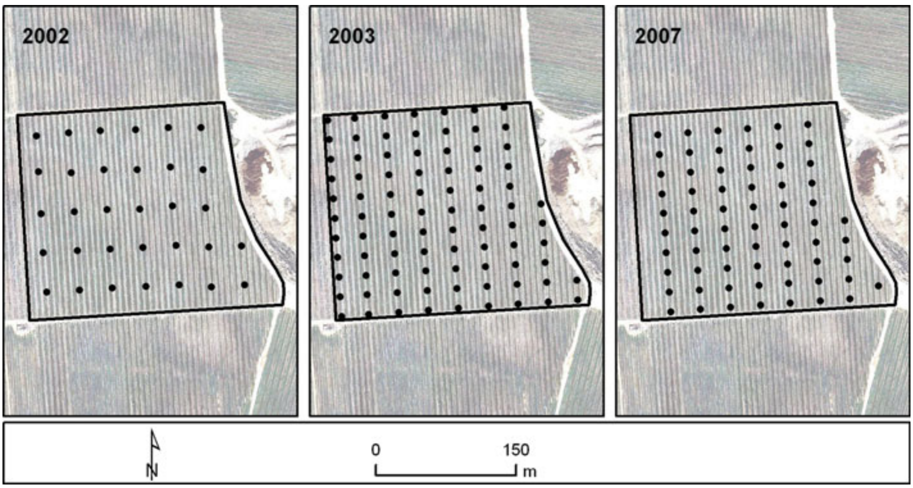

Fig. 2 Distribution of sampling points in field P30 (Pinot Noir). *Left*: 32 sampling points in 2002. *Centre*: 85 sampling points in 2003. *Right*: 66 sampling points in 2007

pH; 1:5 soil:water ratio for conductivity (µS cm^{-1} at 25°C); Walkley–Black dichromate oxidation for organic matter, and gas analysis by reaction with HCl for soil carbonates. Petiole selection consisted of cutting the whole leaf opposite a basal bunch to collect 100 petioles from nine vines around the sampling point. Then, laboratory used dry tissue to determine nutrient levels of grapevine petiole samples. In 2003, the sampling centred on grape quality attributes: probable alcoholic degree, acidity and phenolic content. Finally, the variables sampled in 2007 were also related to grape quality (weight of 100 berries, probable alcoholic degree, total acidity expressed as g H_2SO_4 l^{-1}, anthocyanins, polyphenols and colour of grape juice) and to some soil properties (texture, pH, electrical conductivity, percentage of $CaCO_3$, organic matter, available water retention capacity or AWRC, and soil depth). Like in 2002, soil samples were analyzed following the same methods but having obtained the samples using an auger-hole. As for the grape quality parameters, standard methods were used (Iland et al. 2004).

Cluster analysis of grape yield

The five grape yield maps produced for field P30 (Pinot Noir, Fig. 3) exhibited some visual differences in the patterns of grape yield variation (no data were acquired in some areas in 2005 due to accidental disconnection of the yield monitor). However, reclassified maps into two and three yield classes remained temporally stable for this field (Arno et al. 2011). Therefore, it was hypothesized that conclusions drawn on the basis of a single yield map would be consistent with these different 'yield zones'. As grape yield in field P30 (Pinot Noir) showed the highest degree of variability in 2002 compared to subsequent campaigns (Table 1), interest focused on assessing the possible causes of spatial variation for that particular year. The annual rainfall in 2002 (340 mm) differed from the years 2005

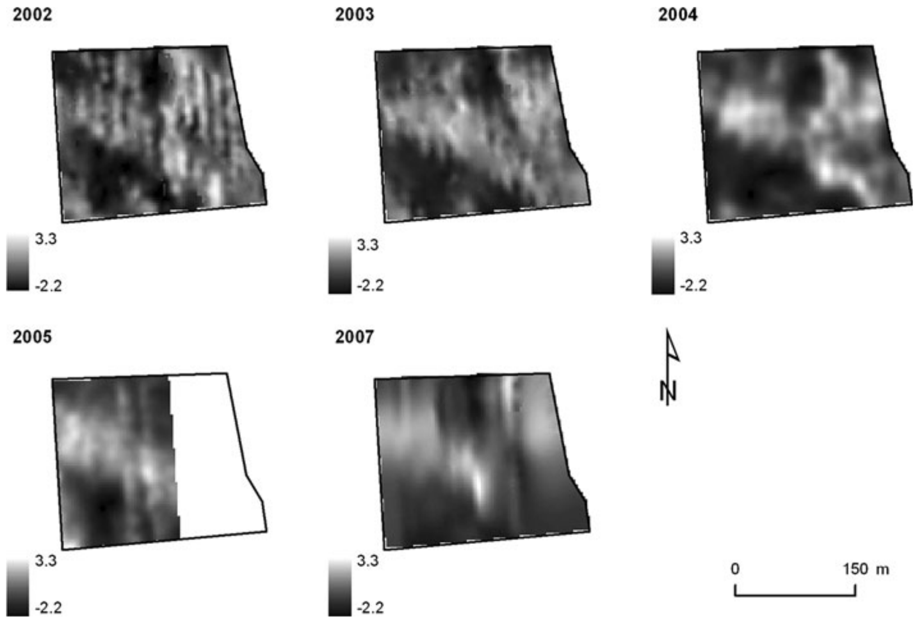

Fig. 3 Grape yield maps for field P30 (Pinot Noir) in which the yield data have been normalised to a mean of zero and a standard deviation of one

Table 1 Descriptive analysis of the values interpolated from yield maps in field P30 (Pinot Noir)

	2002	2003	2004	2005	2007
Mean (t ha^{-1})	9.9	10.3	6.6	5.0	6.3
Minimum (t ha^{-1})	0.1	0.3	1.9	2.4	4.1
Maximum (t ha^{-1})	27.9	22.7	13.1	10.3	8.9
Standard deviation (t ha^{-1})	5.5	4.6	2.7	1.2	0.9
Coefficient of variation, CV (%)	56	45	40	24	15

(292 mm) and 2007 (212 mm), and irrigation and fertilization were then carried out following standard requirements.

To determine the soil and crop variables that could have affected yield variability in 2002, the interpolated grape yield data for this year was classified using cluster analysis, and the *k*-means algorithm. In one case, two groups were established: low yield (L) and high yield (H) and, in another, three groups were created: for low (L), medium (M) and high (H) grape yield. The decision to establish two and three zones (classes) was based on the temporal stability of grape yield maps in field P30 when two and three classes were adopted (Arno et al. 2011). Bramley and Hamilton (2004, 2007) used the *k*-means algorithm with yield data for several different years for within-field zoning. In this study, the algorithm was used with a single variable (grape yield of the 2002 vintage) and each observation (or interpolated point) was assigned to a cluster according to the "distance" between the observation and the centre or average value for the group.

Extraction of yield data to sampling locations

The ArcGIS 9.3 (ESRI, Redlands, CA, USA) was used to assign to each sampling point the average yield within a circular area around of 3 m radius (buffer). The zonal statistics tool of ArcGIS Spatial Analyst was used to overlay the buffer layer over the yield map and to calculate the mean grape yield for each point. Obtaining mean yield data was a prerequisite for knowing the yield level (cluster) corresponding to each sampling point and for carrying out further logistic regression of grape yield (categorical data) on the soil and crop parameters. To avoid performing a regression for each of the sampled variables, factor analysis that considered all the variables sampled in the field (except grape yield) was first applied (Mallarino et al. 1999). The basic idea was to describe the original variables in terms of a smaller number of 'factors' using the following factor analysis model:

$$X_i = a_{i1}F_1 + a_{i2}F_2 + \cdots + a_{im}F_m + e_i \quad (1)$$

where X_i was the *i*th sampled variable; a_{i1}, a_{i2},…, a_{im} were the 'factor loadings' for the *i*th variable; F_1, F_2,…, F_m were *m* uncorrelated common factors, each with mean zero and unit variance; and e_i was a factor specific only to the *i*th variable, with mean zero and uncorrelated with any of the common factors. Thus, it is assumed that each original variable can be expressed as a linear combination of 'factors', plus a residual term that reflects the extent to which the variable is independent of the other variables. Factor analysis procedure involved three stages. First, provisional factor loadings were determined by principal components analysis, limiting to three the number of selected factors (in our case, the number of eigenvalues greater than unity). Once the first three factors had been extracted, the factorial matrix was orthogonally rotated in order to aid its interpretation (Varimax method). The last stage of analysis involved calculating the factor scores (i.e., the values of the factors for each of the sampling points), subsequently used to formulate two different models for grape yield prediction (maps of two or three grape yield classes). To analyse whether the yield response was dichotomous or not (map of two classes), the logistic regression model was:

$$\ln\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1 F_1 + \beta_2 F_2 + \beta_3 F_3 \tag{2}$$

where p was the probability of the grape yield level being low (thus, $1 - p$ would be the probability of the grape yield being high), F_k were the explanatory variables (latent variables resulting from the factor analysis) and β_k were the adjusted parameters in the model. The model is interesting in two ways. As well as allowing calculation of the specific probability of each type of yield, it could also be used to establish the opportunity (odds) of obtaining one type of yield as opposed to another $\left(\frac{p}{1-p}\right)$, and of calculating the odds ratio between both types of yield against changes in the explanatory factors or variables. Finally, the use of a multi-nomial logistic model allowed modelling of the grape yield when the response was polytomous (for low, medium and high grape yields). Specifically, the model used when grape yield had been classified into three classes was:

$$\ln\left(\frac{p_1}{p_3}\right) = \beta_{01} + \beta_{11} F_1 + \beta_{21} F_2 + \beta_{31} F_3 \tag{3}$$

$$\ln\left(\frac{p_2}{p_3}\right) = \beta_{02} + \beta_{12} F_1 + \beta_{22} F_2 + \beta_{32} F_3 \tag{4}$$

where p_1 was the probability of the grape yield level being low, p_2 the probability of being medium, and $p_3 = 1 - p_1 - p_2$ the probability of being high (reference category). Finally, F_k were the factor scores of the latent variables resulting from the factor analysis, and β_{kj} the adjusted parameters in the model.

Analysis of variance (ANOVA) was subsequently used to study the relationship between grape yield and quality in 2003, while the relationship between grape quality and the soil characteristics sampled in 2007 was finally addressed by applying canonical correlation analysis. This statistical procedure (Manly 1994) was used to divide the variables (grape quality and soil properties) into two groups and interest centres based on their inter-relationships. Finding what relationships, if any, existed between these two groups of variables is of considerable viticultural interest.

The univariate model for the ANOVA was:

$$V_{ij} = V_m + \left(C_j - V_m\right) + e_{ij} \tag{5}$$

where V_{ij} was the value of sampled variable V at point i within the yield cluster j, V_m was the average value of V, C_j was the average value of V in cluster j, and e_{ij} was the value of the experimental error. This model allowed testing of significant effects of yield cluster (factor analyzed) on the quality variables sampled in 2003. The analysis was completed by mean separation using Duncan's test.

Concerning the statistical method used in 2007, canonical correlation analysis is a generalization of multiple regression in which several grape quality attributes (Y variables) were simultaneously related to several soil properties (X variables). The approach was to search for a linear combination of X variables, say

$$W_1 = a_{11}X_1 + a_{12}X_2 + \cdots + a_{1p}X_p \tag{6}$$

and a linear combination of Y variables, say

$$V_1 = b_{11}Y_1 + b_{12}Y_2 + \cdots + b_{1q}Y_q \tag{7}$$

so that the correlation between W_1 and V_1 be as large as possible. In practice more than one pair of canonical variables (W_1, V_1) can be obtained, being the minimum value p or q the final number of pairs of variables. In addition, canonical variables were chosen so that the first pair (W_1, V_1) had the highest possible correlation and was therefore the most important; the second pair (W_2, V_2) had the second highest correlation, subject to these variables being uncorrelated with W_1 and V_1, and so on. To avoid interpretation problems (in case X or Y variables were highly correlated), canonical variables that were significant (p value <0.10) were subsequently described by looking at their correlations with the X and Y variables rather than the coefficients a_{ij} and b_{ij}.

The statistical analyses were carried out using the SAS Enterprise Guide (SAS Institute Inc., Cary, NC, USA). Only the factor analysis and logistic regression required a specific program: the SAS 9.1.3 Service Pack 4, respectively employing the *proc factor* and *proc catmod* procedures.

Results and discussion

Spatial variability in grape yield

The grape yield classification for the year 2002 based on the *k*-means algorithm resulted in two clusters (low and high, Fig. 4): consisting of a large area of low production (almost 70% of the total area with an average yield of 7.0 t ha^{-1}) and of a smaller area with a higher level of production (average 16.4 t ha^{-1}). The cluster analysis of yield, made in three groups (low-L, medium-M and high-H), reduced the size of the low grape yield zone in favour of areas classified as having a medium level of yield. The zone of low grape yield (cluster L) now included 40% of the total area and had a mean production of 4.4 t ha^{-1}. The zone of medium production, or cluster M, occupied just over half of the total field area and had a mean production of 12.4 t ha^{-1}. Cluster H (with an average of 20.6 t ha^{-1}) was the most productive area though it occupied only 8.5% of the total surface. In short, the zones of low and medium grape yield represented 91% of the total area of the field. The incidence of areas of high productivity was clearly reduced and such areas were concentrated in the easternmost part of the field.

To determine the possible causes of yield variability, factor analysis was carried out with the (soil, crop and topographic) variables that had been measured at 29 of the 32 points initially sampled in field P30 in 2002. The reduction in the data matrix was the result of eliminating sampling points at which variables with outliers had been detected. The procedure for analysis was limited to the extraction of the first three factors (which explained 59.05% of the variability); the resulting rotated matrix is presented in Table 2.

Factor analysis

Factor 1 included the mineral elements that had shown the greatest linear inter-dependence (correlation matrix, not shown): Mg, Fe, S, B, Zn, Ca and Mn. Copper content was moved to Factor 2, even though it had a high correlation with some of the elements in Factor 1.

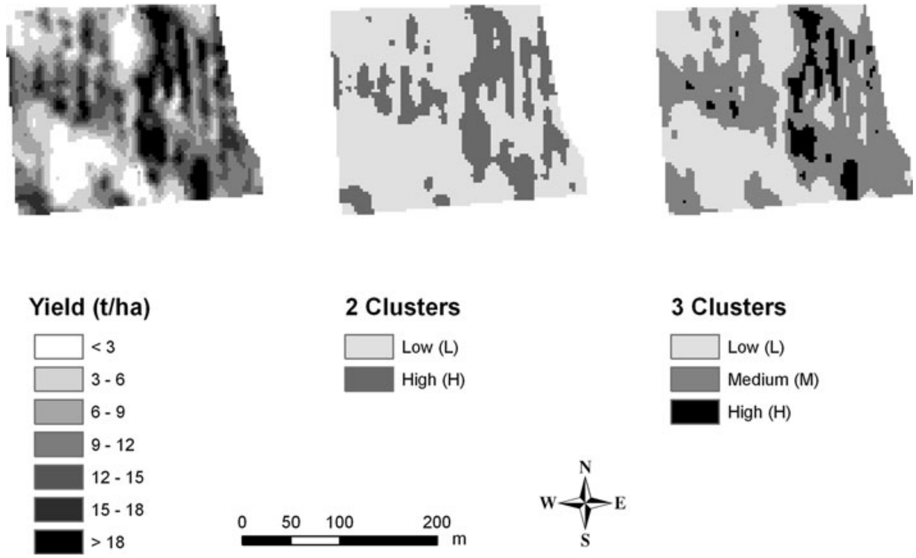

Fig. 4 Grape yield maps for field P30 (Pinot Noir). **a** Original map of grape yield corresponding to the 2002 vintage. **b** Reclassified map based on 2 clusters or levels of yield (low and high). **c** Reclassified map based on 3 clusters or levels of yield (low, medium and high)

Finally, it is important to highlight the presence of N, an essential nutrient for vines, which had previously shown a clear inter-dependence with Zn. In short, Factor 1 encompassed 8 of the 12 mineral elements analyzed in the petioles, the majority of which are very important nutrients in vineyards. Factor 2 could also be considered to relate to the nutritional state of the crop; however, unlike Factor 1, it only included three mineral elements: K, Na and Cu. Focusing exclusively on the number of variables involved, it could therefore be regarded as less important than Factor 1. It is also true that Factor 2 could be linked to the Na content in petiole, probably due to the quality of irrigation water (not tested) and the presence of clay soils and alkaline pH. Finally, the variables with the greatest loads in Factor 3 were: the textural fractions of clay and silt, the percentage of $CaCO_3$ in the soil, the P content per petiole and the elevation of the terrain. Factor 3 could then be considered a factor linked to available water for plants, since the physical characteristics of the soil (texture) and the elevation (presumably associated with shallow soils) affects the water holding capacity of soils and, to some extent, P mobility in soil and its subsequent availability to the crop.

Having obtained scores for factors at each sampling point, a logistic regression model of yield class on factors resulting from the factor analysis was formulated. In view of the complexity that a logistic regression model with a polytomous response (low, medium and high grape yield) and three independent variables (factors 1, 2 and 3) might involve, the approach taken was to include in the model only those factors that showed significant differences with respect to the yield cluster.

Analysis of variance of the factors (Table 3) demonstrated that only Factor 1 was significant ($p = 0.0111$) when grape yield had been previously reclassified on the basis of three clusters (low-L, medium-M and high-H), while in no case were factors significant in the map reclassified on the basis of two clusters. Consequently, a logistic regression model between yield (with three levels of response) and Factor 1 (mineral elements per petiole)

Table 2 Rotated factorial matrix for field P30 (Pinot Noir) in 2002

Variable[a]	Factor 1	Factor 2	Factor 3
Depth (cm)	0.53246	−0.04506	−0.17726
Clay (%)	0.17197	0.25436	**−0.73960**
Silt (%)	−0.24567	0.05083	**0.79921**
pH[b]	0.09424	−0.40293	0.08697
EC (μS cm^{-1})[c]	−0.24328	−0.22389	−0.16370
Carbonates (%)[d]	0.07153	−0.09248	**−0.8421**
om (%)[e]	−0.05050	0.10126	0.37162
N (g kg^{-1})	**0.68453**	−0.16117	−0.13955
P (g kg^{-1})	0.25426	−0.46385	**0.57715**
K (g kg^{-1})	0.17027	**0.82932**	0.34523
Ca (g kg^{-1})	**0.75584**	0.02828	−0.05075
Mg (g kg^{-1})	**0.83832**	0.48047	−0.08639
Fe (mg kg^{-1})	**0.82793**	0.47834	−0.00911
S (g kg^{-1})	**0.76200**	0.38108	−0.14882
Zn (mg kg^{-1})	**0.84571**	0.00930	−0.27482
Cu (mg kg^{-1})	0.56230	**0.69344**	−0.19902
Mn (mg kg^{-1})	**0.81544**	−0.05155	−0.09073
B (mg kg^{-1})	**0.74696**	0.45963	0.28474
Na (mg kg^{-1})	0.18482	**0.80859**	−0.03302
Elevation (m)	−0.27951	−0.43878	**0.56108**
Slope (%)	0.26610	0.06417	−0.02073
Variance (%)	28.52	16.10	14.43

Bold values indicate 'factor loadings' that show a correlation between sampled variables and factors

[a] The sand fraction was not included in the analysis as it could be obtained as a linear combination of clay and silt

[b] pH measured using a 1:2.5 soil:water dilution

[c] *EC* Electrical conductivity (1:5 soil:water ratio)

[d] $CaCO_3$ equivalent

[e] *om* organic matter

Table 3 Effect of grape yield level (cluster) on the factors extracted in field P30 (Pinot Noir)

	2 Clusters (low, high) $p > F$	3 Clusters (low, medium, high) $p > F$
Factor 1	0.8640	0.0111
Factor 2	0.2115	0.1030
Factor 3	0.7522	0.8249

was formulated. The resulting equations and associated probability curves for each yield level are presented in Fig. 5. The probability of obtaining a high yield was small (less than 10%) for the whole range of variation of Factor 1. Therefore, discrimination was most effective among areas of low and medium grape yield.

The probability (p_2) of a medium grape yield increased with increasing values of Factor 1; on the other hand, the probability of a low grape yield ($p1$) diminished with the same

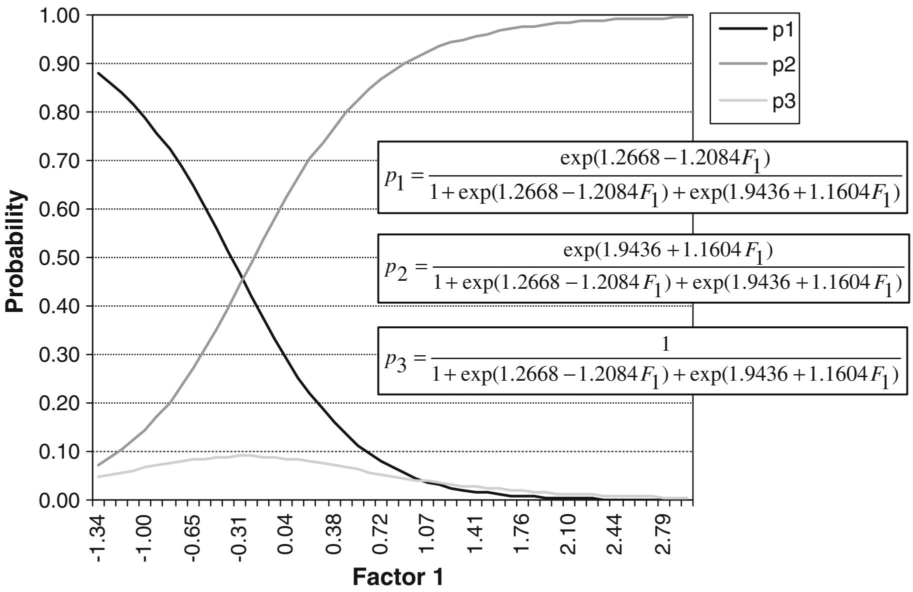

Fig. 5 Logistic regression curves for grape yield level (low-$p1$, medium-$p2$ and high-$p3$) based on Factor 1 (mineral content per petiole). $p1$ is the probability of a low grape yield, $p2$ is that of a medium grape yield, $p3 = 1 - p1 - p2$ is the probability of a high grape yield, and F_1 represents the values of factorial scores of Factor 1

factor. In terms of odds, positive values of Factor 1 ($F1 > 0$) increased the odds of a medium yield, while negative values ($F1 < 0$) tended to increase the odds of a low yield. In fact, the odds between the two yield groups (medium grape yield versus low grape yield) could be calculated through Eq. 8,

$$\frac{p_2}{p_1} = \exp(0.6768 + 2.3688 \cdot F_1). \tag{8}$$

In this way, and for a value of Factor 1 equal to zero ($F1 = 0$), there was twice the probability (1.97) of obtaining a medium grape yield as opposed to a low one. The increase in the amount of Factor 1 in one unit meant that the odds of obtaining a medium grape yield as opposed to a low one multiplied almost 11-fold $\left(\text{odds ratio} = e^{2.3688}\right)$.

Assessing the opportunity for variable crop nutrition

The logistic model results suggested that grape yield was influenced by the nutrition status of the petiole. Therefore, one would expect that variable crop fertilization in this field was warranted given the variable nutritional status of the vines. However, the practical utility of the first model was the main concern. As Factor 1 groups different nutritional elements, it is possible to make a variable-rate application to increase the presence of the mineral contents involved (N, Ca, Mg, Fe, S, Zn, Mn, B) in areas with low yield levels. A potential variant of this approach would be to obtain a model that relates the yield (cluster) to those variables whose communality (variance that is related to the common factors) was essentially explained by Factor 1. Following this logic, calcium (Ca) and manganese (Mn) would have been the only Factor 1 variables that, besides having high correlations with the mentioned factor (0.75584 and 0.81544, respectively, Table 2), also showed practically no correlation with the rest of the factors, although this did not happen for other nutrients. On the other hand, only two of the 29 sampling points in field P30 were associated with a grape yield typified as high. Even so, of the 27 remaining points, 12 were associated with low yield and 15 with medium yield (the grape yield classification map based on three clusters had already predicted a relatively limited presence of areas with a high yield). The logistic regression model had again demonstrated the low incidence of areas with high levels of grape yield in field P30. Having made these considerations, the two simple binary logistic regression models were adjusted to predict the two main grape yield levels (low and medium) observed in this field. Ca was used as an explanatory variable in one of the models, while Mn content was the variable used in the other. In Tables 4 and 5, the two regression models which had been formulated based on the odds of there being a low ($p1$) as opposed to a medium grape yield ($p2$) are shown.

Algebraic treatment of the resulting equations produced the odds of obtaining a medium yield as opposed to a low one, based on levels of Ca (9) and Mn (10) per petiole:

$$\frac{p_2}{p_1} = \exp(-19.1197 + 0.9790 \cdot \mathrm{Ca}) \tag{9}$$

$$\frac{p_2}{p_1} = \exp(-5.8661 + 0.1029 \cdot \mathrm{Mn}), \tag{10}$$

where the goodness of fit was very satisfactory in both models, judging from the results of the Hosmer and Lemeshow contrast (1989) and the respective indices of predictive capacity (0.897 in the case of Ca and 0.908 for Mn).

There was a greater probability of obtaining a medium grape yield as opposed to a low one if the Ca petiole content was above 19.5 g kg^{-1}. Moreover, the odds of obtaining a medium grape yield multiplied seven-fold with a 2.0 g kg^{-1} increase in the amount of Ca present in the grapevine $(\text{odds ratio} = e^{0.9790 \times 2.0})$. In the case of Mn, for a petiole content of 57 mg kg^{-1}, there was an equal probability of obtaining either of the two levels of grape

Table 4 Binary logistic regression parameters for model relating the grape yield (low vs. medium) to amount (g kg^{-1}) of Ca per petiole in field P30 (Pinot Noir)

Term	Coefficient (β)	Standard error	χ^2 wald	$p > \chi^2$	CI 95.0% for β	
					Lower	Higher
Independent	19.1197	8.2066	5.4279	0.0198	3.0350	35.2043
Ca (g kg^{-1})	−0.9790	0.4179	5.4888	0.0191	−1.7979	−0.1600

CI confidence interval

Table 5 Binary logistic regression parameters for model relating the grape yield (low vs. medium) to amount (mg kg^{-1}) of Mn per petiole in field P30 (Pinot Noir)

Term	Coefficient (β)	Standard error	χ^2 wald	$p > \chi^2$	CI 95.0% for β	
					Lower	Higher
Independent	5.8661	2.1747	7.2763	0.0070	1.6038	10.1285
Mn (mg kg^{-1})	−0.1029	0.0390	6.9631	0.0083	−0.1793	−0.0265

CI confidence interval

Table 6 Differences in soil properties and vine nutrient status (petioles at flowering) during season 2002–2003 between the low and medium zones

Yield zone	Root depth (cm)	Organic matter (%)	Clay fraction (%)	Soil pH	Ca (g kg^{-1})	Mn (mg kg^{-1})
Low (L)	49.6 a	0.99 a	48.2 a	8.22 a	1.82 a	46.9 a
Medium (M)	78.1 a	0.91 a	49.1 a	8.36 a	2.19 b	92.4 b

yield. However, the odds of a medium grape yield as opposed to a low one were tripled (odds ratio $= e^{0.1029 \times 10}$) if the content of this nutrient was increased by 10 mg kg^{-1}.

The petiole data obtained probably reflect differences in grape yield caused by soil and topographic parameters. Root depth was lower (although not significant) in areas of low yield (Table 6). This feature combined with a high soil pH may have resulted in a lower availability of some nutrients in the soils with limited depth explored by roots. No deficiencies were detected, but the results were similar to those found by Bramley et al. (2011). The question remains whether this information can be used for management once the vine condition is known (in June). Fertilization by foliar application, either just before flowering or during ripening, is a well-known option in viticulture. However, another possibility is the differential application of fertilizers in the post-harvest period, with the aim of storing nutrients in the plants so that they will have an effect during the following campaign. In this case (field P30, Pinot Noir), the yield patterns were consistent for different years and differential management would be justified according to the extension of the field affected (40% of the total area) and the relative simplicity of spatially delimitating its area.

Soil properties and grape quality: assessing the opportunity for variable soil amendment

The analysis of spatial covariance between grape yield and grape quality was centred on the work carried out in 2003 (Fig. 6). Clustering of the 2003 yield into two different zones made it possible to differentiate between two types of grape quality. Thus, the low yield zone (cluster 1) had a higher sugar content and lower total acidity than the high yield zone. However, no differences were found in total phenolic content (index) contrary to the results obtained by Bramley and Hamilton (2007) and Bramley et al. (2011).

The spatial correlation between the phenolic content of grapes and the Mn content of the petiole has been already studied by Bramley (2001). In 2002, field P30 (Pinot Noir) showed the lowest levels of this nutrient in areas where grape yield was also low. The differential foliar application of Mn in post-harvest in 2002 could therefore have led, in 2003, to an increase in grape yield and, simultaneously, an improvement in grape quality (in this case, in the phenolic content of the grapes). As the nutritional state of vines depends, to a great extent, on soil fertility, the question remains whether grape quality is ultimately influenced by soil characteristics. To investigate the relationships between soil properties and the grape quality parameters sampled in 2007, a canonical correlation analysis was used which assumed the independence of the sampled locations. Of the seven pairs of canonical variables obtained, only the first was significant ($p = 0.0761$, Fig. 7), with a correlation of 0.65, indicating that the colour of grape juice is mainly related to the presence of carbonates in soil. To be more precise (Table 7), the canonical variable V_1 measures both the colour of grape juice and the berries with low weight, and W_1 measures low soil carbonate

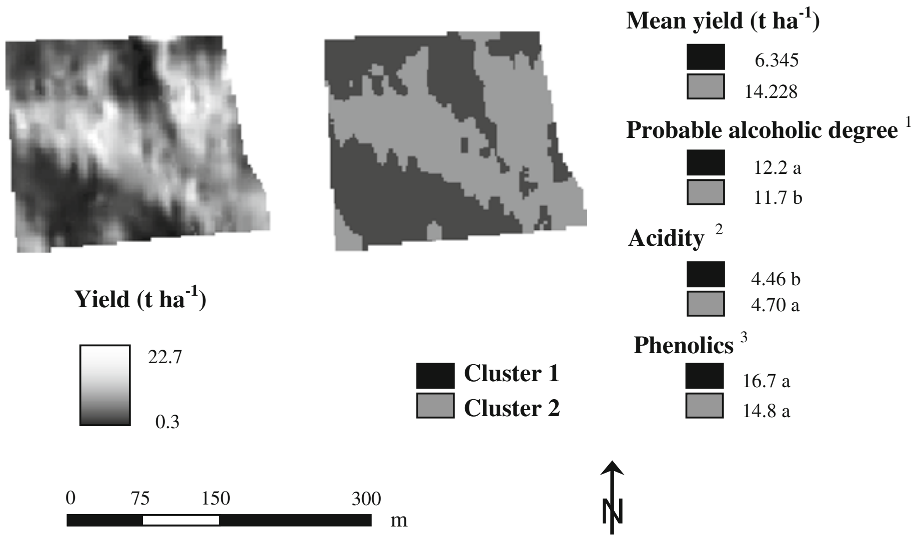

Fig. 6 Grape yield map of the 2003 vintage (P30, Pinot Noir), reclassifying the grape yield map into two clusters (low yield, cluster 1 and high yield, cluster 2) and comparing grape quality parameters. [1] (% vol.). [2] Total acidity expressed as g H_2SO_4 l^{-1}. [3] Measure related to must absorbance at 280 nm

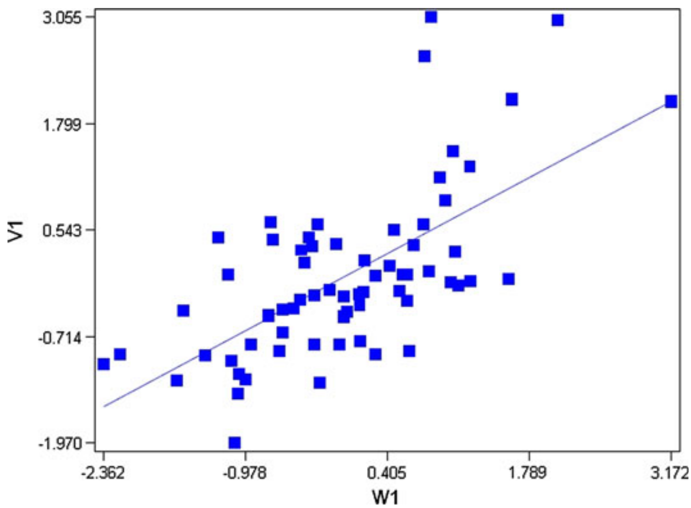

Fig. 7 Canonical correlation between grape quality (V_1) and soil properties (W_1)

content. It therefore appeared that soils with an excessive percentage of carbonates (expressed as %$CaCO_3$) also tended to produce grape juice with poor colour characteristics.

The soils in the study area (Raimat, Spain) have high content of carbonates and, more specifically, soils in field P30 (Pinot Noir) could initially be considered ideal for producing excellent quality wines. However, it is generally accepted that, apart from a delay in grape ripening which tends to produce more acidic wines, soils with an excessive presence of

Table 7 Correlations of sampled variables Y (quality) and X (soil) with the canonical variables V_1 (grape quality attributes) and W_1 (soil characteristics)

Y variables	V_1	X variables	W_1
Weight of 100 berries (g)	−0.4348	Clay (%)	−0.1610
Probable alcoholic degree (% vol.)	0.2327	Sand (%)	−0.0276
Acidity (g H_2SO_4 l^{-1})	−0.2049	Electrical conductivity (dS m^{-1})	0.0880
Anthocyanins (mg $berry^{-1}$)	0.3617	Carbonates (%$CaCO_3$)	−0.7146
Polyphenols (mg $berry^{-1}$)	−0.0905	Organic matter (%)	0.1512
Colour[a] of grape juice	0.8089	AWRC (mm)	0.1918
		Soil depth (cm)	−0.1285

[a] Colour: sum of levels of must absorbance at 420, 520 and 620 nm

carbonates (active lime) can also produce deficiencies in nutrients such as boron and manganese. For instance, Mn deficiency can produce signs of chlorosis early in the season. According to Bramley (2001), restrictions in the availability of Mn to vines (probably caused by calcium carbonate and high soil pH) could explain the low phenolic content in grapes (and, as a consequence, the poorer colour characteristics that are reflected by the canonical variable V_1). This consideration led to the possibility of correcting the probable Mn imbalance and other possible mineral nutrient deficiencies by applying an appropriate variable soil amendment. Furthermore (Bramley et al. 2011), the present results support the view that soil properties (physical and chemical) presumably influence the nutritional status of vines and, therefore, they may ultimately determine some grape quality attributes.

The opportunity of applying variable crop/soil fertilization would therefore seem justified, as both yield and quality are closely related to the nutritional state of the vines. The differential application of soil chelates could be a good option for some nutrients. However, foliar applications are probably the most viable option in field P30 (Pinot Noir) due to, on average in soil, the high total carbonate content (26% $CaCO_3$ equivalent) and alkaline pH (8.0). A foliar application just before flowering with chelating products is an option. But the differential application of foliar fertilizers in post-harvest, before the leaf fall, could be a reasonable strategy to employ when the goal is to accumulate these nutrients in the vines and to thereby influence the vintage of the following campaign.

Conclusions

Within-field variability of grape yield and quality raises important questions concerning whether site-specific crop management could be used in vineyards. In our study, both the magnitude and the spatial structure of this variability seem to make the adoption of some differential management strategies a feasible option. Problems arise, however, when looking for causes of this variability, with the density of the soil and crop sampling being key considerations in this type of research. Data analysis is also important, and multivariate statistical methods are a good choice for easy and accurate interpretation of results.

As well as the soil and crop properties that can influence the variability of grape yield, mineral concentration per petiole (basically relating to N, Ca, Mg, Fe, S, Zn, Mn and B) played the greatest role in differentiating areas of low and high production. Field P30 (Pinot Noir) was variable in topography. However, topographic variables (elevation and slope) did not influence the variation in the grape yield and it could only be ascertained that high values for soil depth (the depth explored by the roots) tended to have a positive influence upon grape production. With regard to grape quality attributes, soil fertility and soil physical and chemical properties are of great importance. In this sense, the presence of soil carbonates in European vineyards probably leads to deficiencies in some mineral nutrients (e.g., Mn), reducing the availability of this micro-element to vines, and affecting the desired level of grape colour in red grapes.

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