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Analysis of vineyard differential management zones and relation to vine development, grape maturity and quality

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Abstract

The objective of research was to analyse the potential of Normalized Difference Vegetation Index (NDVI) maps from satellite images, yield maps and grapevine fertility and load variables to delineate zones with different wine grape properties for selective harvesting. Two vineyard blocks located in NE Spain (Cabernet Sauvignon and Syrah) were analysed. The NDVI was computed from a Quickbird-2 multi-spectral image at veraison (July 2005). Yield data was acquired by means of a yield monitor during September 2005. Other variables, such as the number of buds, number of shoots, number of wine grape clusters and weight of 100 berries were sampled in a 10 rows × 5 vines pattern and used as input variables, in combination with the NDVI, to define the clusters as alternative to yield maps. Two days prior to the harvesting, grape samples were taken. The analysed variables were probable alcoholic degree, pH of the juice, total acidity, total phenolics, colour, anthocyanins and tannins. The input variables, alone or in combination, were clustered (2 and 3 Clusters) by using the ISODATA algorithm, and an analysis of variance and a multiple rang test were performed. The results show that the zones derived from the NDVI maps are more effective to differentiate grape maturity and quality variables than the zones derived from the yield maps. The inclusion of other grapevine fertility and load variables did not improve the results.

Additional key words: cluster analysis; differential management zones; NDVI; precision viticulture; selective harvesting; yield maps.

Resumen

Análisis de zonas de manejo diferencial en viñedo y relación con el desarrollo de la viña, madurez y calidad de la uva

El objetivo de la investigación fue analizar el potencial de mapas del índice de vegetación de la diferencia normalizada (NDVI) a partir de imágenes de satélite, mapas de cosecha y variables de fertilidad y carga de las cepas para delinear zonas de manejo con diferentes propiedades de madurez y calidad de la uva. Se estudiaron dos parcelas localizadas en el NE de España (Cabernet Sauvignon y Syrah). El NDVI fue derivado de una imagen multiespectral Quickbird-2 adquirida en el envero (julio 2005). Los datos de cosecha fueron obtenidos por medio de un monitor de rendimiento en septiembre de 2005. Otras variables, tales como el número de yemas, número de sarmientos, número de racimos y peso de 100 bayas fueron muestreados en un marco de 10 filas × 5 cepas. Estas variables fueron usadas, en combinación con el NDVI, para definir los aglomerados (*clusters*) como alternativa a los derivados de los mapas de cosecha. Dos días antes de la vendimia se muestreó la uva. Las propiedades analizadas fueron el grado alcohólico probable, el pH del mosto, la acidez total, los polifenoles totales, el color, los antocianos y los taninos. Las variables de entrada, solas o en combinación, fueron aglomeradas (2 y 3 aglomerados) por medio del algoritmo ISODATA, llevando a cabo después un análisis de varianza y de rangos múltiples. Los resultados muestran que las zonas derivadas de los mapas de NDVI son más efectivos para diferenciar uvas con diferentes propiedades de madurez y calidad que no las zonas derivadas de los mapas de cosecha. La inclusión de otras variables de fertilidad y carga de las cepas no mejoró los resultados.

Palabras clave adicionales: análisis de aglomerados; mapas de cosecha; NDVI; vendimia selectiva; viticultura de precisión; zonas de manejo diferencial.

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Abbreviations used: ANOVA (analysis of variance); CV (coefficient of variation); ISODATA (iterative self-organizing data analysis); NDVI (normalized difference vegetation index); NIR (near infrared); PA (precision agriculture); PV (precision viticulture); SD (standard deviation); VESPER (variogram estimation and spatial prediction plus error); WG (number of wine grape clusters); 100B (weight of 100 berries).

Introduction

Vineyard variability is a known phenomenon of which viticulturists are generally aware, understanding that vine performance varies within their vineyards (Bramley & Hamilton, 2004; Bramley *et al.,* 2011). The development of the spatial information technologies tools in the last decades and the advent of grape yield sensors and monitors has allowed obtaining information on vine performance as well as soil variability across the vineyard fields (Proffitt & Malcolm, 2005; Proffitt *et al.,* 2006). Then, the opportunity of the analysis of vineyard spatial variability is important from the perspective of Precision Viticulture (PV), since it allows the identification of zones of different productive potential within the parcel and an evaluation of the opportunity for their differential management (Bramley*,* 2005; Arno *et al.,* 2009).

The system of differential management has been referred to as zonal vineyard management (Bramley, 2005). Several examples of this approach improving the uniformity of fruits delivered to the winery have been already demonstrated. For example, experiences to improve labour at pruning, to forecast yield or to apply cultural practices differentially, as for example irrigation water, with distinct amounts in different management zones along the growing season, have been reported (Proffitt & Pearse, 2004; Martinez-Casasnovas & Bordes, 2005; Proffit & Malcolm, 2005; Martinez-Casasnovas *et al.,* 2009). Nevertheless, the major number of experiences has been addressed to selective harvesting, since the attempt to diminish within-field yield variability is difficult because it is mainly related to soil property differences, which are difficult to change (Proffitt & Malcolm, 2005). Fruit quality has also shown to be variable. Its patterns of spatial variation tend to follow those for yield, although not necessarily in the same rank order (Bramley & Hamilton 2004, 2007). Because of that, selective harvesting only based on intra-field yield variability may not correspond with wine grapes of significant different qualities (Hall *et al.,* 2003). This makes interesting to analyse relationships between wine grape quality properties and other spatial variables that could influence grape yield and quality, helping in the delineation of management zones.

In this respect, some studies point out the importance to know in detail the spatial variability of chemical and physical soil properties for the successful adoption of PV (Bramley *et al.*, 2011). Most of the effort in soil analysis goes into assessment of fertilisation and soil amelioration prior to vineyard establishment, being based on the results of few samples because of the high cost of soil analysis. This has been partially overcome, according to some experiments, by the use of the apparent soil electrical conductivity (EC_a) measurement, as parameter that shows good correlations to reference soil properties (Corwin & Lesch, 2005; Samouëlian *et al.,* 2005; Bramley *et al.,* 2011; Rodriguez-Perez *et al.,* 2011). Nevertheless, although topographical conditions and soil variation have been recognized to be influencing grape growth and the sensory and chemical characteristics of the wines derived from them (Bramley *et al.,* 2011), we can still observe a relative lack of emphasis placed on this area by viticulturists, and soil information is not usually used for management zone delineation.

Vine vegetation development has been also recognised as a factor related to wine grape quality (Hall *et al.,* 2002; Cortell *et al.,* 2005). It can be determined by field measures on selected vines (*e.g.* trunk cross-sectional area, average shoot length, and leaf chlorophyll (Cortell *et al.,* 2005), or by means of optical remote sensing (Rouse *et al.,* 1973; Myneni *et al.,* 1995; Lamb *et al.,* 2004). To measure the continuous spatial variability of vine vigour, optical remote sensing provides a synoptic view of grapevine photosynthetically-active biomass over entire vineyards and appear to be a management tool of enormous potential with red grape varieties, especially if the canopy architecture can be linked to production of phenolics and colour in ripe grapes (Lamb *et al.,* 2004). Other authors have considered the possibility of substituting the information obtained from remote sensing (satellite or aerial images) by optical proximal sensors computing vegetation indexes and ultrasonic sensors to identify areas presenting critical vegetation conditions (Mazzetto *et al.,* 2010), or have experimented with reflection radiometers to characterize spectral features of vineyards (da Silva & Ducati, 2009).

The most used indices from remote sensing data in PV have been the PCD (plant cell density) (Hall *et al.,* 2002; Proffitt & Malcolm, 2005), calculated as the ratio between the near infrared to red reflectance; the PRV (photosynthetic vigour ratio), calculated as the ratio between green to red reflectance; and the NDVI (normalized difference vegetation index), calculated by the combination of near infrared and red reflectances (NIR-R/NIR + R) (Rouse *et al.,* 1973). In some cases, these vigour indices have been used in combination with other vegetative vine variables to predict the spatial variability of yield (Martinez-Casasnovas & Bordes, 2005; Taylor *et al.,* 2010), in combination with yield to help in the delineation of uniform management zones to improve irrigation (Proffitt & Malcolm, 2005; Martinez-Casasnovas *et al.,* 2009), or to delineate management zones for selective harvesting (Johnson *et al.,* 2001; Bramley *et al.,* 2011). However, the use of these indices in PV is becoming to have some criticisms because, as well as it happens with yield spatial variability and grape quality, the spatial variation pattern of these indices is not necessarily the same as the variation of grape quality (Bramley, 2005). Other vine variables determining the vine crop load should be taken into account, together with vegetation vigour indices, to delineate consistent management zones for selective harvesting (Santesteban & Royo, 2006; Santesteban *et al.,* 2008). In this respect, these authors propose to complement zoning based on NDVI with vine load variables such as bunch number per vine or berry weight per bunch, since vine load determines grape quality for vines with similar vegetation development and hydric stress.

At the moment, vegetation indexes from detailed remote sensing data (satellite or aerial images) constitute the main source of data that is used in PV for delineation of differential management zones as alternative to yield maps. On the other hand, and in the absence of detailed soil data, other vine variables (*e.g.* determining the vine crop load) should be taken into account to improve management zone delineation. In this respect, the present research shows a case study in which the objective was to analyse the potential of NDVI (derived from high resolution satellite images), alone or together with other wine grape fertility and load variables, and yield maps acquired by means of yield monitors, in order to establish zones with different grapes maturity and quality variables.

Material and methods

Study area

The case study was conducted in two vineyard fields located in Raimat (Costers del Segre Denomination of Origin, Lleida, NE Spain; 291910 E, 4615070N, 270 m, UTM 31 T). This is a semi-arid area with continental Mediterranean climate and a total annual precipitation between 300-400 mm. The fields are planted in a 3 × 2 m pattern with Cabernet Sauvignon (5 ha, T system formation, sprinkle irrigation, planted in 1986) and Syrah (2.35 ha, Vertical Shoot Position formation, drip partial root drying irrigation, planted in 2002). The viticulturist maintains an herbaceous ground cover between the rows of vines. Soils in these fields are classified as Fluventic Haploxerepts, Calcic Haploxerepts and Typic Haploxerepts (Soil Survey Staff, 2006). The Typic Haploxerepts may present a paralithic contact within the first 50 cm, which could represent a limitation for vine development. Both vineyards are on gentle slopes (2-7%) and south faced terrain.

Data acquisition and analysis

The research was carried out with data collected during the 2005 campaign. First, a Quickbird-2 multispectral image was acquired on 13-07-2005, date within the range of ±2 weeks the moment of veraison, which has been referred to be the optimal time for image acquisition in PV applications (Lamb *et al.*, 2004). The spatial resolution of the multi-spectral image was 2.8 m. The image was corrected for atmospheric scattering by applying the COST model proposed by Chavez (1996). Digital values were converted to reflectance according to the radiance conversion of Quickbird-2 data technical note (Krause, 2003). After this process, the images were projected to the European Datum 1950 and the UTM 31n coordinate system. The projected images were then ortho-rectified based on: a) a set of ground control points collected from a 0.5-m resolution ortho-photo, and b) a 5-m resolution digital elevation model, both produced by the Cartographic Institute of Catalonia. The NDVI was computed according to Eq. 1 (Rouse *et al.*, 1973) (Fig. 1).

$$NDVI = \frac{\varphi_{NIR} - \varphi_{RED}}{\varphi_{NIR} + \varphi_{RED}} \qquad [1]$$

where φ_{NIR} and φ_{RED} are the spectral reflectance measurements acquired in the near-infrared (760-900 nm) and red (630-690 nm), respectively for the case of Quickbird-2. These spectral reflectances are themselves ratios of the incoming radiation that is reflected in each spectral band individually, hence they take on values between 0.0 and 1.0. By design, the NDVI itself thus varies between –1.0 and +1.0. NDVI values in the 2.8 pixel size of the Quickbird-2 image were influenced by the herbaceous cover between the vine rows maintained by the viticulturist. This, however, did not significantly influence the use of this index in NDVI

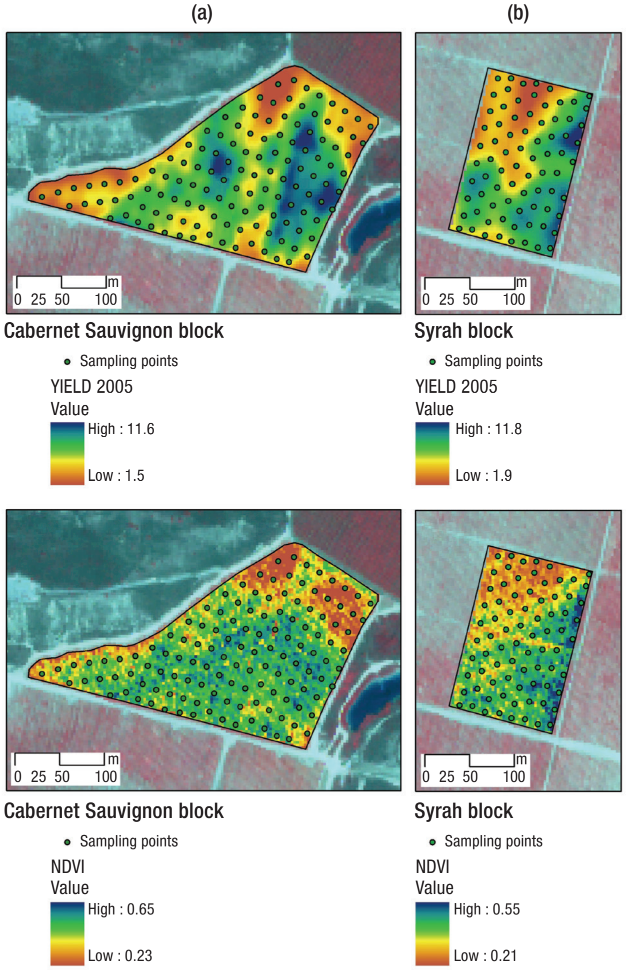

Figure 1. Yield and NDVI maps of the Cabernet Sauvignon (a) and Syrah (b) blocks for the 2005 vintage.

zoning since, according to field observations, the change of vigour of the herbaceous vegetation was coincident in the space with the changes of vine vegetation vigour.

Yield data was acquired by means of a Canlink 3000 Farmscan monitor (Bentley, WA, Australia) during September 2005. The system basically consists of a set of load cells installed on the grape discharge arm of the grape harvester. By measuring grape weight and other required variables, such as the harvester speed and position of the harvester, the yield monitor calculates the production in Mg ha^{-1} at different locations in the parcel (Arno *et al.,* 2005, 2009). The monitor was programmed to weight the grapes at 3 second intervals. From these data, a yield map was produced following the protocol of Bramley & Williams (2001). Data refinement involved normalising the data ($\mu = 0$, $s = 1$) after removal of data records with zero yield or GPS errors, and then removing records for which the Normalized yield was greater or less than ± 3 standard deviations from the mean. The resulting yield data were used to interpolate 3 m grid by local block kriging (10 m × 10 m blocks) using VESPER (Minasny *et al.,* 2005) (Fig. 1).

Along the vegetative cycle of the year, and in a 10 rows × 5 vine pattern (sample density of 30 samples ha^{-1}, see location of sampling points in Fig. 1), the following grapevine fertility and load variables were measured (per lineal meter): number of buds, number of shoots, number of wine grape clusters. The sample density was similar to that proposed by Bramley (2005), who suggested that it enables production of robust maps of vine variation. The sample vines were georeferenced using a Trimble Geo-explorer XT, which has sub-metric precision after differential corrections in post-processing. Two days prior to the harvesting, and in the same sampling pattern, samples of wine grape clusters were collected to determine the weight of 100 berries. The collected grapes were kept in a portable cool box till they reached the laboratory where they were processed. The analysed variables were, for grape maturity: pH of the juice, total acidity (expressed as g H_2SO_4 L^{-1}) and probable alcoholic degree of the juice (º Baumé); and for grape quality variables: total grape phenolics (expressed as absorbance at 420 nm), colour (expressed as sum of the absorbance at 420 nm, 520 nm and 620 nm), anthocyanins (mg g^{-1}) and tannins (mg g^{-1}). For the preparation of the samples the methods proposed in Iland *et al.* (2004) were applied.

The samples of the grapevine fertility and load variables were interpolated to the 3 m grid previously established by global kriging using VESPER (Minasny *et al.,* 2005). Several semivariogram models were applied (spherical, exponential and lineal with threshold). The model that was selected for each variable was the one minimizing the Sum of Squared Error, the Akaike Index Criterion and the Root Mean Square Error.

NDVI, grapevine fertility/load variables and yield maps were clustered using the ISODATA algorithm implemented in Image Analyst for ArcGIS 9.3. The ISODATA is a *k*-means algorithm that uses minimum Euclidean distance to assign a cluster to each candidate pixel in an iterative process (Jensen, 1996), removing redundant clusters or clusters to which not enough samples are assigned. In the present case study the target clusters (zones) were two or three, according to previous experiences of definition of management zones in different study areas (Bramley & Hamilton, 2004; Arno *et al.,* 2005; Proffitt & Malcolm, 2005). The clusters were created according to the following combination of input variables: a) NDVI, b) Yield, c) NDVI, number of wine grape clusters and weight of 100 berries, d) NDVI, number of buds, number of shoots, number of wine grape clusters and weight of 100 berries.

The georeferenced vines, where grape samples were taken, were converted to a point shapefile layer using ArcGIS.9.3. Then, the previously identified zones were assigned to the sample points according to their spatial location. All the data relative to sample points were held in a table that was statistically analysed using the SAS software. An ANOVA test and a Duncan multiple rang analysis were applied to the classified samples to analyse the separation of means and determine significant differences between them. For each vineyard block, the results were summarized according to the number of variables differentiated in each group of clusters. From these data, the global number of predicted variables was compared to the potential number of cases and a χ^2 test was performed to determine significant differences between blocks.

Results

Summarized statistics of the sampled variables

Table 1 presents the basic statistics of the sampled variables in the case study vineyard blocks. Yield is the variable with the highest coefficients of variation (30.1 and 32.2%, respectively), which indicate a potential for PV applications as zonal management or selective harvesting (Bramley & Hamilton, 2004). Grapevine fertility and load variables, such as the number of buds, number of shoots, number of wine grape clusters and the weight of 100 berries also show intra-field variation but in a different rank order than yield. It is closer to the coefficients of variation of the NDVI than to the yield.

Regarding wine grape maturity and quality characteristics, colour, anthocyanins, tannins, total acidity and total phenolics are the properties with higher variability in both vineyard blocks, with maximum CV values of 24.5% and 28.1% in the case of juice colour. Probable alcoholic degree and juice pH are the most homogeneous variables, with CV between 3.9% and 9.9%.

Relationships between NDVI and yield variation zones and vineyard performance

Using the maps of the NDVI, yield and grapevine fertility and load variables, four types of clusters were created according to the combination of input variables described in the “Data acquisition and analysis” section. Here the results of the multiple rang analysis between NDVI or yield zones (defined by means of clustering) are presented. Tables 2 and 3 present these

Table 1. Basic statistics of the sampled variables in the vineyard blocks of the case study: Cabernet Sauvignon and Syrah

Variable	Cabernet Sauvignon (n = 128)		Syrah (n = 77)	
	mean ± SD	CV%	mean ± SD	CV%
NDVI	0.5 ± 0.07	13.1	0.4 ± 0.07	19.0
Yield (Mg ha^{-1})	6.9 ± 2.1	30.1	6.9 ± 2.2	32.2
Buds (No. m^{-1})	7.9 ± 1.0	12.6	9.6 ± 0.6	6.6
Canes (No. m^{-1})	7.6 ± 0.9	11.8	11.6 ± 0.5	4.3
Grapevine clusters (No. m^{-1})	11.0 ± 1.6	14.5	11.3 ± 2.2	19.5
Weight of 100 berries (g)	138.6 ± 19.6	14.1	177.9 ± 23.4	13.2
° Baumé	14.3 ± 0.9	6.8	14.9 ± 1.5	9.9
pH	4.2 ± 0.1	4.0	3.8 ± 0.1	3.9
Total acidity (g H_2SO_4 L^{-1})	2.9 ± 0.5	15.3	3.6 ± 0.4	11.6
Total phenolics (au)	12.0 ± 1.9	15.7	12.8 ± 1.9	14.7
Colour (au)	4.2 ± 1.0	24.5	5.2 ± 1.4	28.1
Anthocyanins (mg g^{-1})	0.66 ± 0.17	25.7	0.81 ± 0.05	26.2
Tannins (mg g^{-1})	0.18 ± 0.04	22.2	0.23 ± 0.05	21.7

n: number of samples. SD: standard deviation. au: absorbance units.

Table 2. Multiple rang analysis in zones defined by the NDVI: Cabernet Sauvignon block (CS) and Syrah block (Sy)

	Clusters	NDVI	Yield (Mg ha^{-1})	° B	pH	Total acidity (g H_2SO_4 L^{-1})	Total phenolics (au)	Anthocyanins (mg g^{-1})	Tannins (mg g^{-1})	Colour (au)	100-berries weight (g)	Buds m^{-1}	Shoots m^{-1}	Wine grape clusters m^{-1}
CS-2C	Cluster 1	0.44	5.65	14.55	3.84	2.72	12.93	0.73	0.20	4.63	128.18	7.83	7.71	10.84
	n = 48	A	A	B	B	A	B	B	B	B	A	A	A	A
	Cluster 2	0.54	7.79	14.11	3.72	3.13	11.44	0.62	0.17	3.92	144.91	7.92	7.56	11.14
	n = 80	B	B	A	A	B	A	A	A	A	B	A	A	A
CS-3C	Cluster 1	0.41	5.41	14.04	3.87	2.67	13.41	0.76	0.21	4.87	123.81	7.62	7.56	10.48
	n = 22	A	A	A	B	A	C	B	C	B	A	A	A	A
	Cluster 2	0.50	6.36	14.77	3.77	2.83	12.28	0.69	0.19	4.39	135.45	7.93	7.80	11.21
	n = 42	B	A	B	A	A	B	B	B	B	B	A	A	A
	Cluster 3	0.55	7.94	14.03	3.72	3.17	11.33	0.60	0.16	3.81	145.82	7.97	7.52	11.08
	n = 64	C	B	A	A	B	A	A	A	A	C	A	A	A
Sy-2C	Cluster 1	0.32	5.56	15.90	3.87	3.44	14.01	0.89	0.25	5.75	165.95	9.90	11.90	10.02
	n = 40	A	A	B	B	A	B	B	B	B	A	B	B	A
	Cluster 2	0.43	8.29	14.00	3.74	3.70	11.58	0.71	0.19	4.51	190.91	9.27	11.35	12.72
	n = 37	B	B	A	A	B	A	A	A	A	B	A	A	B
Sy-3C	Cluster 1	0.30	4.98	16.34	3.88	3.42	14.41	0.92	0.26	5.95	159.74	9.99	12.11	9.64
	n = 27	A	A	C	B	A	C	B	C	C	A	B	B	A
	Cluster 2	0.39	7.20	14.65	3.78	3.59	12.74	0.82	0.22	5.23	184.62	9.49	11.35	11.76
	n = 29	B	B	B	A	AB	B	B	B	B	B	A	A	B
	Cluster 3	0.45	8.85	13.71	3.75	3.70	10.96	0.63	0.17	4.04	192.14	9.23	11.41	12.86
	n = 21	C	C	A	A	B	A	A	A	A	B	A	A	C

C: Clusters; n = number of samples. au: absorbance units. The data in the columns correspond to the mean of the samples in each cluster. The letter indicates statistical differences between clusters with a p–value < 0.05.

results for the Cabernet Sauvignon and Syrah blocks (NDVI and yield based clusters, respectively). In these tables, NDVI or yield zones as referred to as clusters. Then, in the case of two clusters (zones), cluster 1 corresponds with the low NDVI or yield zone values and cluster 2 the high NDVI or yield zone values. In the case of three clusters, cluster 2 corresponds with the medium NDVI or yield zone values while cluster 3 with the high NDVI or yield zone values. The results for the clusters created with the NDVI, number of wine grape clusters and weight of 100 berries; and with the NDVI, number of buds, number of shoots, number of wine grape clusters and weight of 100 berries, were summarized in Table 4.

First, a direct relationship between NDVI zones and yield is observed in both vineyard blocks, with significant separation of yield means in NDVI zones and vice-versa when considering the analysis of two clusters (Fig. 2). In the case of three clusters, only the Syrah block, with higher intra-field variability of vegetation development, presented statistical significant differences.

In the case of the relationship between NDVI or yield with the number of buds, number of shoots, number of wine grape clusters and weight of 100 berries, indicative of grapevine fertility and load, only the weight of 100 berries showed a good relationship either in two zones or three zones in the Cabernet Sauvignon block, but only in two zones the Syrah block. The number of wine grape clusters in the Syrah block was another variable showing a direct relationship with NDVI (2 or 3 zones) and yield (only 2 zones).

The results of multiple rang analysis in wine grape maturity variables with respect NDVI and yield in both blocks (Tables 2 and 3), reveal a better performance of zones derived from the NDVI maps than from the yield data. The probable alcoholic degree in the Cabernet Sauvignon block, that presents a similar CV as the Syrah block (< 10%), is the only variable that does not present a clear differentiation either in the NDVI or yield zones. Nevertheless, in the Cabernet Sauvignon block there is a trend towards an increase of the probable alcoholic degree of the wine grapes with lower yields. In the case of NDVI zones this trend is not confirmed, probably due to the effect of the irrigation system (sprinkle irrigation) in the development of spontaneous vegetation (weeds)

Table 3. Multiple rang analysis in zones defined by the yield: Cabernet Sauvignon (CS) and Syrah blocks (Sy)

Clusters		Yield (Mg ha^{-1})	NDVI	° B	pH	Total acidity (g H_2SO_4 L^{-1})	Total phenolics (au)	Anthocyanins (mg g^{-1})	Tannins (mg g^{-1})	Colour (au)	100-berries weight (g)	Buds m^{-1}	Shoots m^{-1}	Wine grape clusters m^{-1}
CS-2C	Cluster 1	5.00	0.47	14.50	3.79	2.82	12.66	0.71	0.19	4.55	130.87	7.85	7.73	11.07
	n = 55	A	A	B	A	A	B	B	B	B	A	A	A	A
	Cluster 2	8.48	0.53	14.10	3.74	3.09	11.50	0.61	0.17	3.91	144.49	7.91	7.53	10.99
	n = 73	B	B	A	A	B	A	A	A	A	B	A	A	B
CS-3C	Cluster 1	4.01	0.44	14.51	3.85	2.66	13.22	0.74	0.20	4.75	126.88	7.56	7.63	10.38
	n = 27	A	A	B	B	A	C	C	C	C	A	A	A	A
	Cluster 2	6.75	0.52	14.37	3.74	3.03	11.97	0.66	0.18	4.23	137.72	7.89	7.51	11.07
	n = 62	B	B	B	A	B	B	B	B	B	B	AB	A	AB
	Cluster 3	9.24	0.54	13.96	3.75	3.10	11.20	0.58	0.16	3.72	148.23	8.10	7.78	11.39
	n = 39	C	B	A	A	B	A	A	A	A	C	B	A	B
Sy-2C	Cluster 1	4.91	0.33	15.76	3.85	3.53	13.96	0.89	0.25	5.75	165.48	9.73	11.87	10.03
	n = 37	A	A	B	B	A	B	B	B	B	A	A	B	A
	Cluster 2	8.69	0.41	14.27	3.76	3.59	11.80	0.72	0.20	4.61	189.47	9.47	11.42	12.51
	n = 40	B	B	A	A	A	A	A	A	A	B	A	A	B
Sy-3C	Cluster 1	4.42	0.31	15.99	3.87	3.52	14.32	0.90	0.25	5.80	158.35	9.86	12.02	9.91
	n = 28	A	A	B	B	A	C	B	B	B	A	B	B	A
	Cluster 2	7.11	0.38	14.70	3.79	3.63	12.46	0.78	0.22	5.00	187.61	9.40	11.40	11.73
	n = 23	B	B	A	AB	A	B	AB	A	A	B	A	A	B
	Cluster 3	9.30	0.43	14.16	3.75	3.54	11.58	0.72	0.20	4.61	189.65	9.48	11.42	12.47
	n = 26	C	C	A	A	A	A	A	A	A	B	A	A	B

C: Clusters; n = number of samples. au: absorbance units. The data in the columns correspond to the mean of the samples in each cluster. The letter indicates statistical differences between clusters with a p–value < 0.05.

Table 4. Frequency data of the grapevine fertility/load and wine grape maturity/quality variables with differentiation in the multiple rang analysis test per type of zone definition: Cabernet Sauvignon block / Syrah block

Zone variables[1]	Grapevine fertility / load (4 variables)		Wine grape maturity (3 variables)		Wine grape quality (4 variables)		Total	Accuracy (%)
	2 clusters	3 clusters	2 clusters	3 clusters	2 clusters	3 clusters		
NDVI	1 / 2	0 / 1	3 / 3	0 / 1	4 / 4	2 / 3	10 / 14	45.5 / 63.6
Yield	1 / 2	1 / 0	2 / 2	1 / 0	4 / 4	4 / 0	13 / 8	59.1 / 36.4
NDVI, WG clusters, 100B	0 / 2	0 / 2	3 / 2	0 / 0	4 / 4	3 / 1	10 / 11	45.5 / 50.0
NDVI, Buds, Shoots, WG clusters, 100B	0 / 2	0 / 2	3 / 3	0 / 0	4 / 4	1 / 3	8 / 14	36.4 / 63.6
Total	2 / 8	1 / 5	11 / 10	1 / 1	16 / 16	10 / 7	41 / 47	
Global accuracy (%)								46.6 / 53.0

[1] WG: number of wine grape clusters; 100B: weight of 100 berries.

between the vine rows that, to some extent, influences the NDVI value of vines. In the Syrah block, with drip irrigation and less development of spontaneous vegetation between the rows, there are significant differences of probable alcoholic degree in either the NDVI or yield zones, except in the case of 3-yield zones, in which there is not a clear differentiation between the moderate and high yield zones. In relation to juice pH, although it presents the lowest CV among the tested variables (Table 1), it shows significant differentiation in both vineyard blocks, in particular in the 2-NDVI zones (Table 2). In the case of 3-NDVI or 3-yield zones, the moderate/medium zone shows an ambiguous behaviour, being either grouped with the low or the high NDVI or yield zones. However, there is a trend of the pH values towards an increase as the NDVI values or yield decrease.

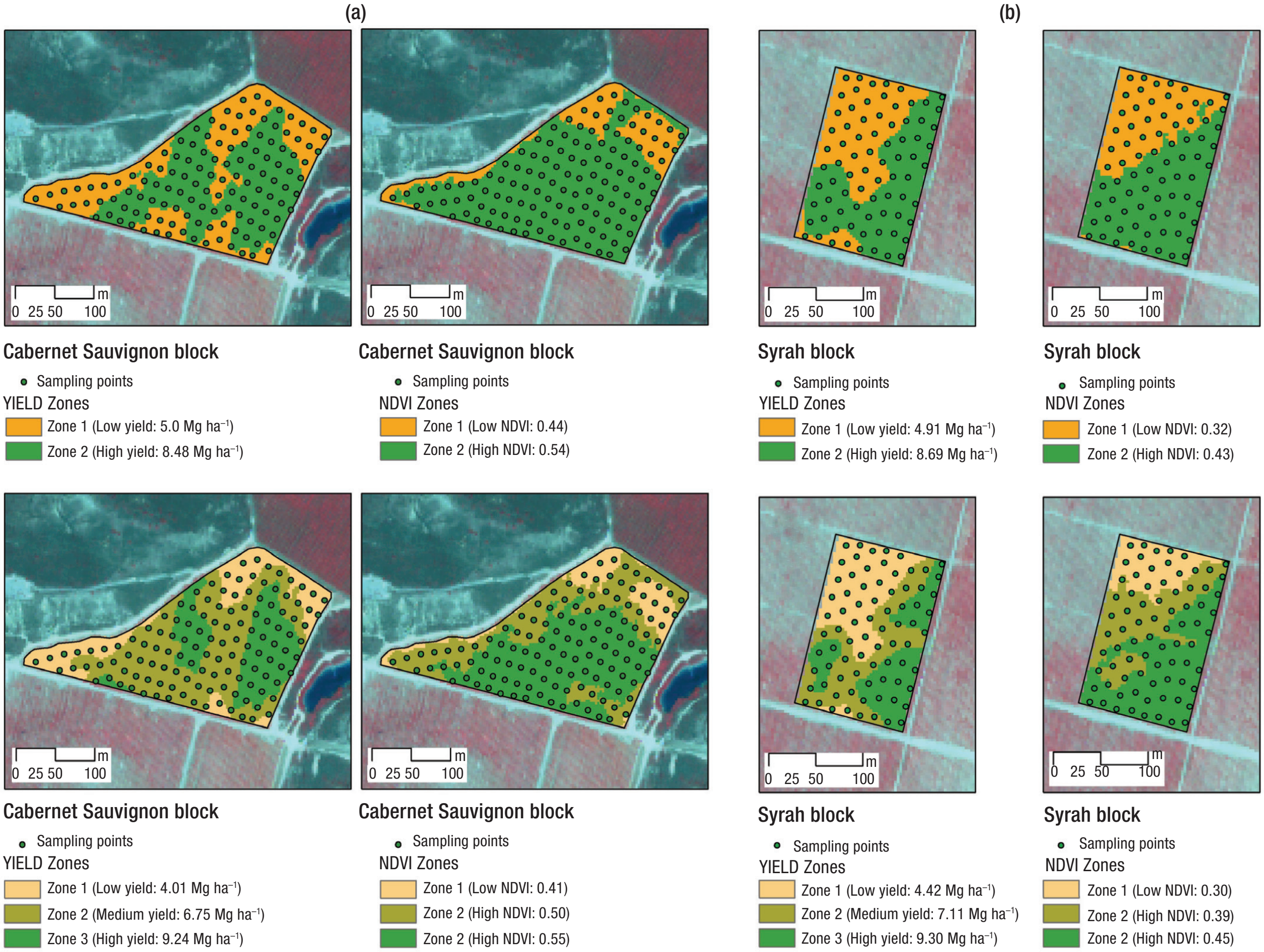

Figure 2. Yield and NDVI zones created with the algorithm ISODATA for the Cabernet Sauvignon block (a) and the Syrah block (b). Upper part: two Yield or NDVI zones; lower part: three Yield or NDVI zones. See statistical data in Tables 2 and 3. The numbers between brackets correspond to the average values in each zone.

Total acidity, although it shows a positive trend with respect the increase of NDVI and yield, it presents variety differences. This property shows clear differentiation (either in 2-zones or 3-zones) in the NDVI clusters in the Cabernet Sauvignon block but not in the Syrah block. In this last block total acidity is differentiated in the two extreme NDVI zones, with the medium-NDVI zone being ambiguous. In summary, NDVI performs better than yield as variable to establish zones with respect total acidity in both blocks since yield zones only differentiated juice acidity in 2-zones in the Cabernet Sauvignon block but not in the Syrah.

Grape quality variables (total phenolics, colour, anthocyanins and tannins) are the properties that present the best performance in the defined zones from NDVI or yield clusters. In all cases the relationships are inverse, which indicates that low vigour or low yield zones are the ones presenting the highest contents of phenolics and the highest values of absorbance units for colour, anthocyanins and tannins in the grape juice. In the case of juice colour, however, the differentiation is not as clear as in the phenolics. For both varieties, the differentiation of colour performs better in 2-zones than in 3-zones, being the moderate/medium NDVI or yield zone always ambiguous.

Frequency analysis and best zone definition criteria

Which variable or group of input variables for cluster (zone) definition is the optimal to differentiate zones for grapevine fertility/load and grape maturity/quality variables? To answer this question a frequency analysis of the number of these variables that presented significant differences in the multiple rang analysis for either 2-zones or 3-zones, and per grapevine variety, was done. The results are summarized in Table 4 for the Cabernet Sauvignon and the Syrah blocks.

If compared with the potential number of positive cases in which the analysed grapevine and wine grape variables could have been differentiated in one block for all types of zone definition (88 positive cases in total), the global accuracy of the differentiation of those variables analysed is moderate: 46.6-53.4% in the Cabernet Sauvignon and Syrah blocks respectively. The results significantly improve if the accuracy is measured per number of zones defined: 65.9-77.3% in the case of differentiation in 2-zones against 29.5-30.0% in 3-zones (for Cabernet Sauvignon and Syrah blocks respectively).

Differentiation by yield clusters performed better in the Cabernet Sauvignon block (59.1%), but in the Syrah block differentiation in NDVI clusters was better (63.6% of the cases). Another relevant result was the fact that the use of variables for cluster definition such as the number of buds, number of shoots, number of wine grape clusters or weight of 100 berries, did not improve the results obtained either with the clustering of NDVI or yield alone. These results do not corroborate the suggestions pointed out by Martinez-Casasnovas & Bordes (2005) or Santesteban *et al.* (2008), who proposed that the mapping of crop load (*e.g.* number of bunches per vine and number of berries per bunch), together with NDVI maps, could help or improve the delineation of management zones corresponding with more differentiated grape qualities.

A deeper analysis of the frequency data per group of grapevine and wine grape variables indicates that, in the case of 2-zones, the wine grape maturity and quality were much better differentiated than grapevine fertility and load variables. This occurred in both vineyard blocks, with better results in the Syrah block due to the moderate performance of the grapevine fertility and load variables (50.0% of the cases with respect 12.5% in the Cabernet Sauvignon block). Per number of zones defined, and in the case of 2-zones, NDVI is the variable that performed better: 72.7-81.8% of the grapevine and wine grape variables were differentiated respectively in the Cabernet Sauvignon and Syrah blocks.

Finally, regarding the analysis in 2-zones, the χ^2 test carried out to compare the performance of the blocks with respect the potential positive cases, indicates that the null hypothesis (the observed frequency distribution is similar to the potential distribution) can be rejected in the case of the Cabernet Sauvignon field with a $p < 0.05$ ($\chi^2 = 12.83$ with respect $\chi^2_{p = 0.05} = 12.59$), but not in the case of the Syrah block. This indicates a general better performance of the grapevine and wine grape parameter differentiation in the Syrah block with respect the Cabernet Sauvignon block.

As mentioned above, the differentiation of the analysed variables in 3-zones produced poorer results than in 2-zones. Wine grape quality variables were the ones that obtained moderate results: 43.8-62.5% of differentiation respectively in the Syrah and Cabernet Sauvignon blocks. Other variables yielded accuracies between 6.3 to 31.3%, which confirms the worse performance of differentiating 3-zones instead of 2-zones for differential management.

Discussion

The present results in two vineyard blocks of the north-east Spain confirm some previous knowledge in PV that has been experienced in other world viticulture regions. The values of the basic statistics of the sampled variables are within the range of variability also found by Bramley (2005) in Cabernet varieties in Australia, who observed more homogeneity in properties as probable alcoholic degree or pH than acidity, colour or phenolics content. These results point out to a poor correspondence between yield or NDVI zones and variables as the probable alcoholic degree or pH. However, the NDVI coefficient of variation (13.1-19%) is of the same rank order than total acidity, colour or phenolics, which could result in a good correspondence of those variables with the NDVI or the NDVI together with load variables derived clusters. Nonetheless, there are controversial results by other researchers who found poor relations of grape wine maturity and quality variables with either NDVI or yield, *e.g.* Acevedo-Opazo *et al.* (2008) in southern France or Santesteban *et al.* (2008) in Navarra (Spain), who state that the NDVI has a good correlation with the vegetative development of vines but wine grape quality is affected by other agronomic factors such as soil properties, water availability or climate characteristics.

Regarding the relationship between vigour indices, such as NDVI, and yield, there was not ambiguity in the relation between NDVI zones and yield or yield zones and NDVI, as it was the cases reported by Johnson *et al.* (2001) or Bramley (2005). However, ambiguity in the medium/moderate-vigour or yield zone has been observed with some grapevine fertility and load and/or wine grape quality variables such as the probable alcoholic degree, pH, total acidity or colour. The results also reveal that differentiation of those variables in 2-zones is better than in 3-zones, with boundaries of medium/moderate-vigour or yield zone either needing adjustment (or the entire zone be incorporated into the remaining zones). According to PV experiences in wineries of NE Spain, the differentiation in two vigour or yield zones is the option that is preferred because of a) the occasional ambiguity to classify the medium/moderate-vigour or yield zone and b) from the logistic point of view, selective harvesting of 3-zones is more difficult to handle by the cellar than harvesting in 2-zones.

The results agree with the observations in Australian vineyards (Sunraysia region of north-west Victoria planted with Ruby Cabernet and Coonawarra region in south-east of South Australia planted with Cabernet Sauvignon) (Bramley, 2005), who found a lack of relationship between probable alcoholic degree in some red grape varieties and yield zones (2 zones) but good correspondence between pH and yield zones, in spite of pH was the property with the lowest CV. Other experiences in different Australian vineyards (Padthaway region of South Australia planted with Syrah and Sunraysia region of north-west Victoria which was planted with Cabernet Sauvignon) have given different results, confirming differentiation of probable alcoholic degree and management zones delineated from NDVI and yield data (Bramley & Hamilton, 2007). Variety differences with respect the relation between total acidity and yield zones were also reported by Bramley (2005) in Australian vineyards. In this experience, Ruby Cabernet wine grapes did not show either a stable correspondence or a clear trend with respect yield zones in most of the analysed years, while Cabernet Sauvignon wine grapes shown statistical differentiation in 3-yield zones. In another experience (Bramley & Hamilton, 2007), total acidity presented a relationship with zones delineated from NDVI and yield, although not in all analysed years for the Syrah variety. Similar results were found by Bramley (2005) and Bramley & Hamilton (2007) with respect the correlation between vigour and colour and phenolics, enhancing the importance of these properties, and colour in particular, as quality index of the wine grape juice and hence of the wine quality. Anthocyanins and tannins differentiated in both blocks when considering 2 zones but performed different in 3 zones. In this case (3 zones), anthocyanins and tannins presented significant differences in the 3 zones when defined on the basis of yield for the Cabernet Sauvignon block, but not in the Syrah block. Tannins, however, presented significant differences in 3 zones for NDVI-clusters in both blocks.

Delineation of management zones has been mainly based on yield maps produced from data acquired by means of yield monitors on harvester machines or from remote sensing vigour indices. However, due to the controversial results of the performance of wine grape maturity and or quality with respect those management zones, as pointed out by Bramley & Hamilton (2004), Bramley (2005), Arno *et al.* (2009), Santesteban *et al.* (2008), the present research has considered other vegetative and load variables to create the potential zones for differential management. These have been combined with the NDVI as input variables for the delineation of management zones as an alternative to yield maps. The results, after considering those variables (number of buds, number of shoots, number of wine grape clusters or weight of 100 berries), did not improve with respect the ones obtained either with the clustering of NDVI or yield alone In addition to the variables considered for cluster definition in the present research, and according to other different experiences in vineyards (Bramley & Lamb, 2003; Bramley *et al.,* 2011), variation in soil properties appears to be a key driver of vineyard variability, suggesting that careful soil management could promote greater control over variation in grape yield and quality. PA demands a much greater focus on the characterisation of soil and crop heterogeneity than has occurred hitherto, which means that greater numbers of samples need to be analysed to have a realistic representation of soil variability (Arno *et al.,* 2005; Bramley & Janik, 2005). Although alternatives to traditional detailed soil surveys exist and have been used to estimate some key soil properties (*e.g.* midi infrared technology, Bramley & Janik 2005; electromagnetic induction based devices, Bramley, 2005; Bramley *et al.,* 2011), most viticulturists and winemakers are not, at present, disposed to invest in such technology or in high density sampling of soils for their detailed characterisation.

Then, in the absence of operational on-the-go sensors to map wine grape maturity and/or quality, methods based on vegetation indices from remote sensing data and/or yield maps from yield monitors seem to be the most extended methods to delineate management zones for different purposes in PV. Of those, the construction of yield maps from yield data monitors is not free of problems, in particular in the case of large vineyards fields in which different harvesters are used at time. Those problems are lack of data in some vine rows because of bad functioning of yield monitor or inexperience of harvester drivers to handle the yield monitor; different calibration of yield monitors on board of different harvesters, etc. It makes that, a priori, we can not be totally sure that we will have good yield data of the entire fields to interpolate yield maps for zoning purposes. Therefore, and according to the results of the present research and the above reasoning, the use of zones based on NDVI maps acquired at the moment of veraison, rather than on yield maps or in combination with other grapevine variables, seems the best option. This also allows the creation of zones for differential management before the harvest of the same vintage of the NDVI map, which improves timing of the decision making about selective harvesting.

As conclusion, the present research confirms in vineyards of the north-east Spain some previous knowledge in PV in other world viticulture regions. The relationship between vigour indices, as the NDVI, and yield is confirmed without ambiguity in the two analysed vineyard blocks. Zones defined from NDVI maps at the moment of veraison have correlated better with wine grape maturity and quality variables than zones defined from yield maps. In this respect, two management zones are recommended in front of three, since the results of the multiple rang and the frequency analysis show that medium vigour/yield cluster is not different from high or low vigour/yield clusters and it would reduce complexity in the handle of wine grapes in the cellars. Also, the inclusion of grapevine variables such as the number of buds, number of shoots, number of wine grape clusters or weight of 100 berries, in combination with the NDVI (variables that can be acquired before harvesting) to define the management zones, did not improve the number of grapevine fertility and load or wine grape maturity and quality variables that can be differentiated in the zones defined by NDVI or yield alone. Finally, on the absence of an operational on-the-go quality sensor technology, and based on the present and previous experience, NDVI maps from detailed multi-spectral images are at present the most economical and best alternative to delineate vineyard management units for different purposes in PV. However, the opportunity exists for better viticultural and enological management decisions if other factors that influence yield and, above all, fruit quality are considered.

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