Oenological significance of vineyard management zones delineated using early grape sampling

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Running title: Delineation of within-vineyard zones using early berry sampling

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Abstract

Early definition of oenologically significant zones within a vineyard is one of the main goals of precision viticulture, as it would allow an increase in profitability through the adaptation of agronomic practices to the specific requirementsof each zone, and/or segregation of the harvest into different batches to produce wines with different qualities. The aim of this work was to evaluate whether early grape sampling is a relevant tool for within-vineyard zone definition. The study was carried out in 2010 and 2011 in a 4.2 ha vineyard, where a grid of 60 sampling points was defined. 300-berry samples were picked from each sampling point after veraison and at harvest,post-veraison information being used to define zones within the vineyard after fuzzy k-means analysis and subsequent application of a zoning procedure that took into account membership degree and neighbourhood criteria. Two variations of the zoning procedure were used, standard (StdZ) and Top (TopZ) zoning. Each was designed to meet different requirements of wineries; StdZ gave the same oenological relevance to all the zones, and TopZ differentiated the zones producing "top class" grapes, minimizing the within-zone variability in the top-class zone. Grape composition obtained at harvest from the zones delineated post-veraison was compared.Zone delineation using post-veraison data was proved to be oenologically relevant, provided sampling is performed once veraison is completed. The two zoning algorithms designed were shown to be suitable for objective zone delineation according to the goals intended for each.

Keywords: early zoning, fuzzy k-means, grape quality, precision viticulture, Vitis vinifera L.

Introduction

During the last decade, a consensus has been reached on the relevance that within-field variability has in viticulture (Bramley and Hamilton 2007; Tisseyre et al. 2007) and on the implications this variability has on grape quality (Bramley et al. 2011a; Martínez-Casasnovas et al. 2012)and on winery profitability (Bramley et al. 2011b; Proffitt and Pearse 2004).

Since most vineyards have been planted not taking sufficiently into account the existing soil variability, one of the most useful purposes of Precision Viticulture is to delineate within-vineyard zones, in order to adapt agronomic practices to the specific

This is a post-peer-review, pre-copyedit version of an article published in Precision Agriculture. The final authenticated version is available online at: https://doi.org/10.1007/s11119-013-9328-3.

requirements in each zone and/or segregate the harvest into different batches that can be used to produce wines with different characteristics. Some early approaches tried to define zones based only on vegetative indices such as NDVI and PCD, which have been shown to correlate well with the annual shoot growth (Hall et al. 2011; Johnson et al. 2003), and yield (Arnó et al. 2011; Bramley and Hamilton 2004). However, the correspondence of these zones with grape composition is not as clear (Lamb et al. 2004; Santesteban et al. 2010). In order to overcome this limitation, some authors have delineated within-vineyard zones using the combination of different information sources such as soil characteristics, elevation and fruit load or yield from previous seasons, the zones being delineated by common clustering methods. This approach has proved to be more satisfactory, although the correspondence between the zones obtained and grape composition, particularly for phenolics, is only moderate (Arnó et al. 2012; Santesteban et al. 2013).

An alternative approach for within-vineyard zone delineation could be based on an early sampling of grapes across the vineyard. This approach would allow yearly establishment of zones of grape potential quality some weeks before harvest. There is not much information available on the temporal stability of grape composition zones within a vineyard: when several seasons are compared, no great stability is observed (Bramley 2005; Tisseyre et al. 2008) although some authors reported coherence between sugar content and acidity from season to season (Baluja et al. 2013; Tagarakis et al. 2013). In contrast, when several sampling dates within a season are compared, a greater degree of stability has been reported in both red (Baluja et al. 2012a, 2012b) and white grapes (Trought and Bramley 2011). Therefore, it would be sensible to test the efficacy of early grape composition measurements to define quality zones, using these parameters alone or in combination with other information sources.

The aims of this work were (i) to evaluate the suitability of grape composition information obtained from samples picked early in the season to define zones with oenological significance at harvest, and (ii) to test two zone delineation algorithms designed to match different winery requirements.

Material and methods

Data acquisition

This study was carried out in a 4.2 ha gobelet-trained cv. ‘Tempranillo’ vineyard located in Leza (42º33’22’’ N, 2º 38’ 07’’W, 572 m asl, Basque Country, Spain) in two consecutive years (2010 and 2011). The vineyard was 17-years old at the beginning of the experiment, with a 2.4 x 1.2 m planting distance and no irrigation system, as this is a traditionally rain-fed vineyard area. This area belongs to Classes II-III in Huglin's classification,(Huglin and Schneider 1998)and the climatic conditions in 2010 and 2011 are summarized in Fig. 1.

NDVI information was obtained from QuickBird satellite images taken shortly after veraison (first half of August) in 2009 (the year prior to the beginning of the experiment), 2010 and 2011. A sampling grid was defined according to the NDVI semi-variogramcalculated with 2009 data in order to take into account (approx.) 75% of the NDVI spatial variability (25% of the semi-variogram sill). As a whole, the defined sampling grid consisted of 60 nodes or sampling points (SP), with a 30 m x 30 m distance between them. At each SP, 15 adjacent plants located in three consecutive rows were marked, and used for the experimental measurements and sampling.

From each SP, 300-berry samples were gathered at two times in the season: post-veraison and harvest. In 2010, post-veraison sampling was performed relatively late (13th Sept, three weeks after the end of veraison), whereas in 2011, sampling was performed when veraison was about to end (>98 % of berry colour change, 16th Aug). Harvest sampling dates were Oct 5th in 2010 and Sept 27th in 2011, two days before the vineyard was harvested by the winery. For each sample, berry weight (BW) and the main composition parameters were determined using standard procedures: after crushing, total soluble solids (TSS) was measured with a temperature compensating refractometer RFM840 (Bellingham-Stanley Ltd., Kent, UK), pH and titratable acidity (TA) using a pH-Burette 24 auto-titrator (Crison, Barcelona, Spain), malic (MalA) and tartaric acid (TarA) concentration was measured enzymatically using an autoanalyzer (Easychem, Systea s.p.a., Italy), whereas yeast assimilable nitrogen (YAN) was estimated following the procedure described by Aerny (1996) with the modifications detailed in Garcia et al. (2011). Phenolic maturity was evaluated after 4 h extraction in two different media (pH=1.0, pH=3.2) following the methodology described in Glories and Augustin (1993) that allows estimating the concentration of total (TAnt) and extractable (EAnt) anthocyanins and of total phenolics (TP). Besides, yield was determined at harvest, by weighing all the clusters from the 15 vines in each SP.

Data analysis

Data analysis was performed in four steps. First, the SP were classified in clusters according to their grape composition measured post-veraison. Secondly, in order to test the temporal stability of grape composition throughout the ripening period, grape composition at harvest was compared to the clusters defined in the previous step.

Afterwards, the results obtained in the previous classification wereused to delineate management zones within the vineyard using two algorithms and, lastly, the oenological significance at harvest of the zones defined early in the season was evaluated.

Clustering of the SP according to early grape composition

Unsupervised clustering was performed using the nine grape composition parameters (Table 1) obtained from veraison samples using the *fuzzy k-means* algorithm. Unsupervised clustering aims at grouping data items into homogeneous clusters according to a proximity criteria defined by a distance function. Cluster analysis is an iterative process that starts with a random set of cluster centers, and each individual is assigned to the cluster with the closest center, then new centers are computed for each cluster based on the points included in the cluster. The type of distance (Euclidian, diagonal or Mahalanobis) used depends on the type of variables studied (McBratney and Moore 1985); in this study, Euclidian distance has been used considering the variables to be independent. The fuzzy version, unlike the classical k-means, in which each data point belongs to one and only one cluster, yields membership degrees (MD) to each cluster. A stopping criterion of 0.0001 was usedto obtain good convergence, which means that the change in membership with an iteration of means calculation was less than 0.0001(Fridgen et al. 2000). Cluster analysis was performed testing fuzzy exponents (m) that ranged between 1 and 2 at 0.1 intervals (McBratney and Moore 1985) considering 2, 3 and 4 as potential number of clusters (C), since greater sub-divisions would not be operative for vineyard management purposes. The optimum value of m for each C was determined using the validity function (Eq. 1):

$$\frac{dj(M,C)}{dm} * C^{0.5} = \sum_{i=1}^{n} \sum_{j=1}^{c} u_{ij}^{m} \log(u_{ij}) d^2(x_i, C_j) \qquad \textbf{(1)}$$

where j denotes the objective function, M denotes the classification result, C is the number of clusters, n is the number of objects in the dataset, u_{ij} is the membership degree of object x_i in cluster C_j, m is the fuzzy exponent, $d(x_i,C_j)$ is the distance between object x_i and cluster C_j. The function obtained was plotted against m, and the m value for which the function showed its maximum value was chosen (Sun et al. 2012).

In order to determine the optimum C, the fuzziness performance index (FPI) and the modified partition entropy (MPE) as defined by McBratney and Moore (1985) were calculated. FPI (constrained in the range $0 \leq \text{FPI} \leq 1$) is a measure of the degree to which different classes share membership, and as FPI increases towards 1, the degree of membership sharing increases. MPE is an indicator of the amount of disorganization created by a specified number of clusters. Like FPI, it is also constrained to values between 0 and 1 (Boydell and McBratney 2002). Therefore, class number was chosen in order to obtain the smaller values for FPI and MPE. All the calculations were performed using FuzME software (Australian Centre for Precision Agriculture, Australia), accessible as freeware.

Evaluation of the temporal stability of grape composition

In order to determine if the differences in grape composition detected after veraison were still observed at harvest, two procedures were used. First, a one-way analysis of variance (ANOVA) was performed, taking the cluster to which each SP was ascribed using post-veraison data with the *fuzzyk-means* procedure as the main factor, and yield, BW and the nine grape composition parameters measured at harvest as dependent variables. 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). In addition, a principal component analysis (PCA) was performed using the 9 grape composition parameters measured at harvest. Then, all the SP, labelled by their respective cluster number,were plotted in the plane defined by the two first principal components to allow a visual evaluation of the group compactness. Allanalyses were performed using SPSS v.19 (IBM SPSS, Chicago, IL, USA).

Delineation of management zones within the vineyard

The results obtained in the previous classification were used to delineate zones within the vineyard. Although most authors use zones defined directly after the classes or clusters obtained with cluster analysis, it must be noticed that these classes are not taking into account spatial considerations and, in particular, neighbourhood criteria. From a practical viticultural point of view, it is sound to includeneighbourhood criteria to define zones, as the variability in vine and grape characteristics is spatially structured (Baluja et al. 2013; Santesteban et al. 2013), and as the zones defined must be as continuous as possible in order to facilitate vineyard management. This is particularly true if we consider that the ascription of each SP to one cluster when *fuzzy k-means* analysis is performed is not a true or false type value, but an ascription with an associated membership degree.

Two different approaches were used for zone delineation in this work. Both approaches consideredneighbourhood criteria and membership degree for zone delineation decision-making. The first one, labelled as Standard Zoning (StdZ) aimed at delineating zones that span relatively compact areas with significant oenological differences between them, giving the same oenological relevance to all the zones. The second approach, denoted as “top-class” zoning (TopZ) intended to differentiate the zones producing “top class" grapes from the rest of the vineyard, minimizing the within-zone variability in the top-class zone. The details of the rules for zone delineation are included in the decision trees represented in Fig. 2. Both procedures were based on the definition of zone cores, to which adjacent points incorporate depending on theirmembership degree (MD) and their neighbourhood to the zone core. Two SP were considered to be neighbouring when connected by an edge according to Delaunay triangulation (Delaunay 1934), and a SP was considered to neighbour a zone core if the latter includes any SP neighbour to the former. Figure 3 shows the Delaunay graph for the vineyard included in this study as generated by the GeoFis software(Guillaume et al. 2012).The process was divided in tothree subsequent steps (Fig. 2). In the first step, zone cores were defined considering those SP ascribed to each cluster with high confidence (high MD), including only those SP whose MDwas over a membership threshold (MT) whose value depended on the number, n, of clusters considered (Eq. 2),.

$$MT = 1.4/n \qquad \textbf{(2)}$$

Once all SP have been visited and zone cores defined, in the second step, neighbourhood and MD criteria were considered to integrate the SP whose MD for the cluster that any neighbouring zone core belonged to was higher than $0.9/n$. This step was applied starting from the SP closest to the centre of the vineyard towards those located near its boundaries.As zone cores grow, all the SP points were visited iteratively until no changes in inclusion into the zone cores were observed. Lastly, in the third step, the remaining points (not integrated in any zone core due to their low MD and/or isolation from similar zone cores) were ascribed to a neighbouring zone core and the definitive zoning was established.

The two zoning methods share these three steps.However, there are two major differences between them (Fig. 2a, b). First, for TopZ, a top-quality cluster was defined and used for the definition of a top-quality zone core. The top-quality cluster was defined as the one whose average grape composition parameters were more satisfactory according to the winery preferences, and the SP not included in the top-quality zone were jointly considered to constitute a non-top-quality zone. Secondly, in StdZ a zone core needed to meet a minimum size criterion, not required for the delineation of zones in TopZ as, in the latter case, it can be interesting for the winery to harvest separately even a small zone in the field. This test on zone size was performed at the end of step 1, once all neighbouring SP have been visited. For graphical representation, class of the SP was interpolated using the 'neighbourhood' command in gvSIG (v1.10, Generalitat Valenciana, Spain)

Evaluation of the oenological significance at harvest of the zones defined post-veraison

In order to determine the oenological significance of the zones defined with the two zoning procedures (StdZ and TopZ), the zones defined with each algorithm were compared for yield, berry weight and grape composition of the grape samples picked from the SP included in each zone at harvest. The evaluation was carried out following a similar procedure to that described above for evaluation of temporal stability between clusters defined by *fuzzy k-means* analysis: (i) a one-way ANOVA considering the zone where each SP was located according to post-veraison data as the main factor, and (ii) a PCA of the SP using the 9 grape composition parameters measured at harvest, SP were plotted according to the two first components and the proximity as well as the compactness of the SP belonging to each zone were visually evaluated. In addition, the coefficient of variation (CV) of yield, berry weight and grape composition parameters within each zone were compared to each other and to the CV of the whole vineyard.

Results and discussion

Fuzzy k-means clustering and within-season temporal stability of grape composition

The grape samples picked both years after veraison included a relatively wide range of grape composition (Table 1), which indicates the existence of within-field variability for these parameters. The degree of ripeness of these samples was different between years, those picked in 2010 being at a more advanced maturity status (greater TSS, pH and anthocyanin content, lower TA) than those collected in 2011, which agrees with the differences in the sampling dates used each year (earlier in 2011). Higher differences were also observed for phenolic components (TAnt, EAnt, TP), theirCV being greater in 2011, which possibly matches the fact that samples were picked earlier that year (at the end of veraison), when the differences in composition between berries are greater due to the asynchronous nature of veraison, which can take 2-3 weeks to complete between parts of the field or even between bunches on the same vine (Keller2010).

Cluster definition was performed using the grape composition parameters obtained in the samples picked post-veraison. In 2010, both indices agreed that the optimum number of clusters was 2; whereas in 2011, the optimum number was 2 according to FPI and 3 according to MPE (Fig. 4). Therefore, both possibilities were explored in the subsequent analyses. In general terms, the FPI and MPE obtained were closer to 1 than to 0, which indicates a moderate degree of disorganization (Boydell and McBratney 2002). For all the runs, the optimum fuzziness exponents ranged between 1.7 and 1.9 depending on the year and number of clusters considered.

The clusters defined with post-veraison data showed significant differences for most grape composition parameters, whatever the year or the number of groups considered (Table 2). The PCA representation also showed clear separation of the clusters in both years (Fig.5). However, when compared with harvest data, the oenological significance of the groups defined post-veraison depended on the year. Thus, in 2010, the differences between clusters were still observed at harvest for all the parameters considered except for MalA and TarA (Table 3) and the clusters defined post-veraison remained relevant on the PCA corresponding to grape composition at harvest(Fig.6). In contrast, in 2011 only some of the grape composition parameters (pH, TA, MalA and YAN) were still different at harvest (Table 3), while the groups overlapped in the PCA representation (Fig.6), resulting in a lack of clear oenological significance.

The fact that the oenological relevance at harvest of the clusters defined post-veraison was dependent on the year is probably caused by the differences in the sampling times.In 2011, samples were picked much earlier in the season, at a time (end of veraison) when the phenological lag between plants can be more important for grape composition than other factors that will become decisive during ripening.In contrast, in 2010, samples were picked later, when grape composition was more homogeneous (Keller, 2010). At veraison, the most rapid changes in grape composition parameters occur, and a delay or an advance of two or three days can be very significant for grape composition. A similar trend was observed by Baluja et al. (2012b): in maps showing the evolution of phenolic compounds in red grapes during the ripening period, these authors observed thatthe earliest sampling datedata didnot match with the spatial patterns in grape composition observed in the subsequent sampling dates. This suggests that when early classification of red grape composition is required, it would be advisable to perform sampling after veraison is completed. This would allow a proper separation of the differences in composition caused by soil and vine characteristicsavoiding interference caused by the asynchrony of veraison between field points due to the asynchrony of veraison.

Post-veraison delineation of zones and evaluation of their oenological significance at harvest

Zoning was performed only with 2010 data since, as mentioned above, post veraison grape composition in 2011 did not match that measured at harvest due to the too early picking of the samples. The zones delineated with the standard (StdZ) and top (TopZ) zoning procedures are represented in Fig.7. In StdZ, zone A covered 1.84 ha, whereas zone B included the remaining 2.36 ha; whereas in TopZ, the part of the vineyard considered as A was smaller (0.98 ha) due to the more strict conditions imposed. The estimated amount of grapes included in zones A and B respectively would be 2.95 and 5.97 Mg with StdZ, and 1.52 and 7.40 Mg with TopZ.

Both zoning algorithms resulted in zones which were significant from an oenological point of view. In PCA analysis, the grapes obtained from the zones defined were relatively well separated at harvest in the PCA (Fig.8), and showed differences for grape composition parameters at harvest except MalA and TarA (Table 4). The coefficients of variation of these parameters were clearly smaller within the zones than in the whole field except for yield, which confirms the usefulness of zoning performed with grape composition data obtained post-veraison. The zones labelled as A showed lower yield, smaller berry size and more favourable composition (greater TSS, TAnt, EAnt and TP) according to specifications for red grape production in that area than the whole field, which would make that zone a candidate for grape segregation in order to obtain top quality wines.

TopZ would allow a better selection of the areas in the field that will yield the best grapes, particularly as the variability in grape composition within Zone A decreases. When the coefficients of variation obtained for Zone A with StdZ and TopZ were compared, lower values were always observed with TopZ. The compactness observed between the points assigned to Zone A in the PCA performed with 2010 harvest composition was greater with TopZ (Fig.8a, b) than with StdZ. Decreasing within-zone variability is very important from an oenological point of view, as the presence of a small proportion of lower quality grapes can reduce significantly the organoleptic quality of the wines far beyond what the calculation of the mathematical average for chemical components can predict (Kontoudakis et al. 2011). Apart from the improvement that TopZ conveyed in terms of decreasing variability in Zone A, it also resulted in more favourable grape composition to produce top quality wine (greater TSS, TAnt, EAnt and TP).

The within-season temporal stability in the within-field spatial variability of grape composition once veraison is well-completed, used jointly with the zone delineation algorithms,would be an interesting tool for a seasonally-targeted zone delineation if confirmed on other varieties and circumstances. Zone delineation based on early grape composition would allow adapting the cultural practices performed late in the season such as cluster thinning (Santesteban et al. 2011; Valdes et al. 2009) to the specific needs of each zone and/or to segregate the harvest in to batches with different quality potential. Thishas also been shown to be economically advantageous under some circumstances (Bramley et al. 2011b; Proffitt and Pearse 2004). The latter is particularly feasible when harvest is performed by hand (as it is in all the goblet-trained vineyards in this area) or if mechanicalmap-based differential harvesting is carried outeither using two bins and two tractors which follow the grape harvester(Bramley et al 2005),or with harvesters that automatically sort the grapes into different hoppers during harvesting as done by Santos et al. (2012) or by the recently developed EnoControl^{TM} system (NewHolland Agriculture, PA, USA).

The zones delineated using early sampling data and the zoning algorithms had a greater oenological significance than those that could be obtained using only a vegetative index (NDVI) (Fig. 9a, b), which in 2010 resulted in significant differences ($P<0.05$) for pH and TP, and in 2011 for TSS, pH, MalA and YAN (Table 5). Similarly, PCA analysis showed a less clear separation of grapes according to their composition at harvest when classes were defined according to NDVI (Fig. 10). However, the approach for zone delineation based on grape sampling, though feasible, can be, to some extent, non-realistic from a winery point of view, as it would require a lot of hand-work in a relatively short period of time.

In order to obtain a cheaper procedure for the definition of zones that are oenologically significant at harvest, grape sampling and analysis at a smaller number of sampling points could be combined with other, faster non-destructive procedures for grape composition based either on fluorescence (Cerovic et al. 2008)or on near infrared spectrometry (Santos et al. 2012) and the zone definition algorithms then applied. Similarly, a stratified sampling procedure could be established taking into account other ancillary information available from that or from earlier seasons (vegetative indices, electrical conductivity maps, grape composition from previous seasons). Due to the complexity of the factors that determine final grape composition (Keller 2010), the inclusion of grape composition information for zone delineation will probably improve the oenological significance of the zones or classes defined using only vegetative indices (Hall et al. 2011; Lamb et al. 2004; Santesteban et al. 2010; Tagarakis et al. 2013) or a combination of these with soil, elevation or fruit load data (Arnó et al. 2012; Baluja et al. 2012a; Santesteban et al. 2013).

The two zoning algorithms designed for zone delineation using the results obtained after *fuzzy k-means* cluster analysis improved the performance of cluster analysis itself, and would be applicable in many viticultural conditions, provided that the requisites for zone core definition and the membership degree thresholds considered were accordingly adjusted.

Moreover, taking into account neighbourhood and membership probabilities for zone delineation conveys two main advantages. First, it allows the definition of more manageable zones from a practical point of view, which will facilitate both decision-making and the instruction-giving processes to the vineyard manager. Secondly, and more relevantly from a methodological point of view, it improves the performance of the zoning process, as it questions and smoothes the boundaries of the zones defined, not wasting a valuable part of the information gathered (i.e.: what the surrounding nodes in the sampling grid are like, and that ascription to one cluster is not a ‘yes or no’ issue).

Conclusion

Within-field grape composition was proved to be temporally stable between post-veraison and harvest under the study conditions, provided post-veraison sampling is performed once veraison is fully completed. This fact, if confirmed under other conditions and varieties, would constitute an interesting tool for early definition of oenologically-significant zones. The zoning algorithms designed also proved to be adequate for sound zone delineation using neighbourhoodand membership probability information. Further research is required to design procedures that allow the combination of several sources of information, obtained with different resolution and sampling strategies, to delineate significant, within-vineyard zones at a reasonable cost.

Acknowledgements

This work was funded by the Dpt. Innovación, Industria & Empleo of the Government of Navarra (MODELVID, Ref: IIM11879.RI.1), by the Centro para el Desarrollo Tecnológico Industrial-CDTI (Ref: IDI-20100729, co-funded by the European Union ERDF as part of the Operational Programme I+D+i Technology Fund 2007-2013) and by Fundación Fuentes Dutor. I.U. The Spanish Ministry of Education funded I.U. stage in SupAgro, Montpellier (EDU/2719/2011). The authors also would like to express their gratitude to the owners and staff in Bodegas Luis Cañas, particularly to M. José Aparicio and Olaya Fernandez, and to Rafael Álvarez (Verdtech Nuevo Campo) for their co-operation and interest.

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Table 1 Descriptive statistics of grape composition observed in post-veraison samples

	Mean		**Range**		**CV**		**Spread**	
	2010	**2011**	**2010**	**2011**	**2010**	**2011**	**2010**	**2011**
TSS (ºBrix)	21.7	15.6	20.2-23.8	14.3-17	3.59	4.47	16.6	17.3
pH	3.34	3.00	3.23-3.48	2.93-3.12	1.61	1.62	7.48	6.34
TA (g AT L^{-1})	5.36	13.7	4.35-6.49	10.9-16.5	9.62	7.90	40.9	40.9
MalA (g L^{-1})	3.60	8.74	3.00-4.20	6.70-11.0	9.65	9.07	33.3	49.2
TarA (g L^{-1})	6.42	8.25	5.90-7.00	7.50-9.40	3.90	5.67	17.1	23.0
YAN (mg L^{-1})	73.9	102.9	49.1-152.3	78.0-145.7	27.5	16.5	139.3	65.1
TAnt (mg L^{-1})	669	177	459-976	79.2-356.5	18.6	33.7	77.3	157
Eant (mg L^{-1})	263	88.7	189-384	38.3-148	14.7	31.0	74.1	123.7
TP (mg L^{-1})	937	837	720-1205	728-972	10.99	7.52	51.7	29.1

Spread, the range divided by the median, expressed as a percentage; CV, Coefficient of variation; TSS, Total Soluble Solids; TA, Titratable Acidity; MalA, Malic Acid concentration; TarA, Tartaric Acid concentration; YAN, Yeast Assimilable Nitrogen; TAnt, Total Anthocyanins; EAnt, Extractable Anthocyanins; TP, Total Phenolics

Table 2 Comparison of the grape composition after veraison in the clusters defined with fuzzy k-means analysis. The number of clusters considered was 2 in 2010 and 2 or 3 for 2011 according to the FPI and MPE indices (see Fig. 2)

	2010			**2011**									
	A	**B**	***P***	**A**	**B**	***P***	**A**		**B**		**C**		***P***
TSS (ºBrix)	22.4	21.2	*<0.001*	16.4	15.3	*<0.001*	16.9	a	15.6	b	15.2	c	*<0.001*
pH	3.39	3.31	*<0.001*	2.98	3.00	*<0.001*	3.07	a	2.98	b	2.99	b	*<0.001*
TA (g AT L^{-1})	4.88	5.68	*<0.001*	12.5	14.3	*<0.001*	11.9	c	13.6	b	14.4	a	*<0.001*
MalA (g L^{-1})	3.28	3.81	*<0.001*	7.99	9.11	*<0.001*	7.76	b	8.65	a	9.18	a	*<0.001*
TarA (g L^{-1})	6.43	6.40	*0.653*	8.01	8.38	*0.003*	7.81	b	8.10	b	8.58	a	*<0.001*
YAN (mg L^{-1})	84.6	65.5	*<0.001*	113.1	97.7	*0.001*	124.5	a	104.7	b	93.2	b	*<0.001*
TAnt (mg L^{-1})	741	619	*<0.001*	233	149	*<0.001*	280	a	187	b	129	c	*<0.001*
Eant (mg L^{-1})	294	242	*<0.001*	113.3	76.4	*<0.001*	127.2	a	98.3	b	64.8	c	*<0.001*
TP (mg L^{-1})	910	937	*<0.001*	824	844	0.248	830	b	816	b	863	a	*0.025*

TSS, Total Soluble Solids; TA, Titratable Acidity; MalA, Malic Acid concentration; TarA, Tartaric Acid concentration; YAN, Yeast Assimilable Nitrogen; TAnt, Total Anthocyanins; EAnt, Extractable Anthocyanins; TP, Total Phenolics. A, B, C grape composition clusters, ordered according to their potential quality for red winemaking; P, statistical significance of ANOVA.

Table 3 Comparison of the grape composition obtained at harvest in the clusters defined with fuzzy k-means analysis. The number of clusters considered was 2 in 2010 and 2 or 3 for 2011 according to the FPI and MPE indices (see Fig.2)

	2010			**2011**									
	A	**B**	***P***	**A**	**B**	***P***	**A**		**B**		**C**		***P***
Yield (kg)	1.57	2.45	*<0.001*	1.22	1.37	*0.116*	0.978	b	1.312	a	1.445	a	*0.001*
BW (g)	1.90	2.04	*<0.001*	1.92	2.12	*0.001*	1.70	b	2.08	a	2.15	a	*<0.001*
TSS (ºBrix)	25.5	24.9	*<0.001*	24.0	24.0	*0.874*	24.0		24.2		23.8		*0.053*
pH	3.53	3.47	*<0.001*	3.56	3.55	*0.715*	3.58	a	3.57	ab	3.53	b	*0.007*
TA (g AT L^{-1})	3.67	3.98	*0.001*	3.45	3.56	*0.248*	3.33	b	3.47	ab	3.64	a	*0.022*
MalA (g L^{-1})	2.70	2.85	*0.054*	1.76	1.93	*0.023*	1.72	b	1.98	a	1.82	ab	*0.015*
TarA (g L^{-1})	6.22	6.22	*0.973*	5.92	5.92	*0.901*	5.93		5.87		5.97		*0.278*
YAN (mg L^{-1})	127	112	*0.002*	113	100	*0.008*	116.0	a	92.4	b	111.4	a	*<0.001*
TAnt (mg L^{-1})	961	854	*<0.001*	946	922	*0.357*	965		943		906		*0.165*
Eant (mg L^{-1})	371	333	*0.001*	351	340	*0.380*	352		353		332		*0.192*
TP (mg L^{-1})	1193	1121	*0.008*	1132	1151	*0.515*	1156		1168		1118		*0.220*

BW, Berry Weight; TSS, Total Soluble Solids; TA, Titratable Acidity; MalA, Malic Acid concentration; TarA, Tartaric Acid concentration; YAN, Yeast Assimilable Nitrogen; TAnt, Total Anthocyanins; EAnt, Extractable Anthocyanins; TP, Total Phenolics. A, B, C grape composition clusters, ordered according to their potential quality for red winemaking; P, statistical significance of ANOVA.

Table 4 Comparison of grape composition at harvest in the zones defined with the two zoning algorithms (StdZ, Standard zoning; TopZ, Top zoning)

	Mean							**CV**				
		StdZ			**TopZ**				**StdZ**		**TopZ**	
	Total	**A**	**B**	***P***	**A**	**B**	***P***	**Total**	**A**	**B**	**A**	**B**
Yield (kg)	2.09	1.60	2.53	*<0.001*	1.56	2.30	*0.008*	45.0	26.0	42.0	24.9	44.2
BW (g)	1.98	1.92	2.04	*0.001*	1.85	2.02	*<0.001*	7.15	8.23	5.26	6.58	5.17
TSS (ºBrix)	25.1	25.5	24.8	*0.001*	25.7	24.9	*<0.001*	2.87	2.25	2.94	1.88	2.68
pH	3.50	3.52	3.47	*<0.001*	3.54	3.48	*<0.001*	1.49	1.35	1.35	1.01	1.45
TA (g AT L^{-1})	3.86	3.71	3.99	*0.002*	3.52	3.97	*<0.001*	9.19	2.79	4.08	6.70	8.17
MalA (g L^{-1})	2.80	2.73	2.85	*0.131*	2.59	2.86	*0.002*	10.5	18.7	10.8	9.39	10.1
TarA (g L^{-1})	6.22	6.18	6.26	*0.191*	6.15	6.25	*0.127*	3.54	2.79	4.08	2.03	3.94
YAN (mg L^{-1})	118	124	114	*0.041*	126	115	*0.051*	15.7	18.7	10.8	16.1	15.5
TAnt (mg L^{-1})	901	945	855	*0.003*	1004	864	*<0.001*	12.5	12.8	11.4	11.6	10.2
EAnt (mg L^{-1})	348	366	332	*0.001*	386	333	*<0.001*	12.3	11.7	11.1	10.4	10.2
TP (mg L^{-1})	1149	1200	1105	*<0.001*	1235	1122	*<0.001*	9.01	8.59	7.60	7.36	8.44

CV, Coefficient of variation; StdZ, Standard zoninig; TopZ, Top Zoning; BW, Berry Weight; TSS, Total Soluble Solids; TA, Titratable Acidity; MalA, Malic Acid concentration; TarA, Tartaric Acid concentration; YAN, Yeast Assimilable Nitrogen; TAnt, Total Anthocyanins; EAnt, Extractable Anthocyanins; TP, Total Phenolics. A, B, C grape composition clusters, ordered according to their potential quality for red winemaking; P, statistical significance of ANOVA.

Table 5 - Comparison of the grape composition obtained at harvest in those points with low and high vigour according to NDVI (Normalized Difference Vegetation Index) values.

	2010			**2011**		
	Low NDVI	**High NDVI**	***P***	**Low NDVI**	**High NDVI**	***P***
Yield (kg)	1.54	1.83	*0.031*	1.37	1.21	*0.122*
BW (g)	1.94	2.03	*0.014*	2.05	2.05	*0.969*
TSS (ºBrix)	25.3	25.0	*0.067*	23.8	24.4	*0.001*
pH	3.51	3.48	*0.006*	3.53	3.60	*<0.001*
TA (g AT L^{-1})	3.78	3.94	*0.094*	3.55	3.47	*0.398*
MalA (g L^{-1})	2.77	2.81	*0.617*	1.78	2.08	*<0.001*
TarA (g L^{-1})	6.22	6.21	*0.778*	5.93	5.89	*0.556*
YAN (mg L^{-1})	118	119	*0.809*	109.1	92.8	*0.001*
TAnt (mg L^{-1})	917	878	*0.201*	921	952	*0.219*
Eant (mg L^{-1})	354	342	*0.312*	337	359	*0.084*
TP (mg L^{-1})	1182	1110	*0.008*	1139	1156	*0.560*

BW, Berry Weight; TSS, Total Soluble Solids; TA, Titratable Acidity; MalA, Malic Acid concentration; TarA, Tartaric Acid concentration; YAN, Yeast Assimilable Nitrogen; TAnt, Total Anthocyanins; EAnt, Extractable Anthocyanins; TP, Total Phenolics. A, B, C grape composition clusters, ordered according to their potential quality for red winemaking; P, statistical significance of ANOVA.

Figure captions

Fig. 1 Monthly mean temperature (T) and accumulated rainfall (R) in 2010, 2011 and in the average year (2001-2011) at the study area.

Fig. 2 Decision trees designed to delineate (a) standard (StdZ) or (b) top quality (TopZ) zones from the clusters defined by *fuzzy k-means* analysis. *SP, Sampling point; MD, Membership degree; MT, Membership Threshold; n, number of cluster.*

Fig. 3 Representation of Delaunay triangulation for the sampling points (SP) defined in the vineyard.

Fig. 4 FPI and MPE values of *fuzzy k-means* analyses considering 2, 3 and 4 clusters performed with 2010 and 2011 grape composition observed post-veraison. *TSS, Total Soluble Solids; TA, Titratable Acidity; MalA, Malic Acid concentration; TarA, Tartaric Acid concentration; YAN, Yeast Assimilable Nitrogen; TAnt, Total Anthocyanins; EAnt, Extractable Anthocyanins; TP, Total Phenolics. A, B, C, grape composition clusters.*

Fig. 5 Results obtained with PCA for post-veraison grape composition, indicating as A, B and C the cluster to which each sampling point was assigned post-veraison. *TSS, Total Soluble Solids; TA, Titratable Acidity; MalA, Malic Acid concentration; TarA, Tartaric Acid concentration; YAN, Yeast Assimilable Nitrogen; TAnt, Total Anthocyanins; EAnt, Extractable Anthocyanins; TP, Total Phenolics. A, B, C, grape composition clusters.*

Fig. 6 Results obtained with PCA for grape composition at harvest, indicating as A, B and C the cluster to which each sampling point was assigned post-veraison.

Fig. 7 Maps of the zones defined using the two zoning algorithms.

Fig. 8 Results obtained with PCA for grape composition at harvest, indicating as A and B the zone where each sampling point was included with each of the zoning algorithms. *TSS, Total Soluble Solids; TA, Titratable Acidity; MalA, Malic Acid concentration; TarA, Tartaric Acid concentration; YAN, Yeast Assimilable Nitrogen; TAnt, Total Anthocyanins; EAnt, Extractable Anthocyanins; TP, Total Phenolics. A, B, grape composition clusters.*

Fig. 9. Maps of zones defined using NDVI data.

Fig 10. Results obtained with PCA for grape composition at harvest, indicating as cluster 1 like high NDVI, 2 medium NDVI and 3 low NDVI.