APPLICATION OF A VERY DETAILED SOIL SURVEY METHOD IN VITICULTURAL ZONING IN CATALONIA, SPAIN

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Abstract

Aims: The aim of this study was to implement a very detailed soil survey methodology in 1,243 ha of vineyards in Catalonia (Spain) and analyse its suitability for viticultural zoning.

Methods and results: The Soil Taxonomy at series level was used as the basis for classifying soils and delineating soil map units at 1:5,000 scale. A principal component analysis showed that most of the variability of soil properties, which was explained by factors related to water stress, iron chlorosis and vegetative growth, was not reflected exactly in the soil map unit classification. A k-means clustering analysis was proposed in order to group soils according to their potential for vine growing.

Conclusion: A very detailed soil survey method, based on Soil Taxonomy, could be used as a basic map for viticultural zoning, when was directed at the differentiation of zones of distinct suitability for vineyard growing, by means of cluster analysis.

Significance and impact of study: This study showed how very detailed soil maps, which can be difficult to interpret and put into practice, can be valorised as viticultural zoning maps by means of a simple methodology.

Keywords: soil survey, soil classification, viticultural zoning, principal component analysis, cluster analysis.

Résumé

Objectifs : Dans ce travail, une méthodologie très détaillée d'enquête pédologique a été mise en œuvre et son applicabilité sur le zonage viticole a été étudiée sur 1 243 ha de vignes de Catalogne (Espagne).

Méthodes et résultats : La taxonomie des sols a été utilisée comme base pour classifier les sols et tracer des unités cartographiques à l'échelle 1:5000. Une analyse en composantes principales a montré que la variabilité des propriétés des sols, en raison des facteurs liés au stress hydrique, à la chlorose ferrique et à la croissance végétative, ne se reflète pas exactement dans la classification des sols. L'algorithme k-means a été proposé en vue de grouper les sols selon leur potentiel viticole.

Conclusion : Une méthode d'enquête pédologique très détaillée, fondée sur la taxonomie des sols, peut être utilisée comme cartographie de base pour le zonage viticole, dirigé à la différentiation des zones de distincte potentialité pour la croissance de la vigne, au moyen d'une classification.

Signification et impact de l'étude : Cette étude a montré comment des cartes des sols très détaillées, qui peuvent être difficiles à interpréter et à mettre en pratique, peuvent être valorisées comme des cartes de zonage viticole à partir d'une méthodologie simple.

Mots clés : enquête pédologique, classification des sols, zonage viticole, analyse en composantes principales, classification

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INTRODUCTION

During recent years, viticultural zoning studies have increased significantly in relation to the expansion of the international wine market. Viticultural zoning can be defined as the spatial characterisation of zones that produce grapes or wines of similar composition, while enabling operational decisions to be implemented (VAUDOUR, 2003). The aims of viticultural zoning are related to the delimitation of protected viticultural areas, which serve to give added value to wines according to their origin, or the delimitation of homogeneous areas for vineyard management, which can be used to optimize the grape quality (VAUDOUR and SHAW, 2005). There are different methods of viticultural zoning, depending on the factors considered. The simplest methods only consider soil, climate or the interaction between soil and climate (MORLAT, 2001). Then, other factors can be added: variety and viticultural and oenological technology (CARBONNEAU, 2001), and historical and sociological wine-growing factors (VAUDOUR, 2003). Among the various environmental factors and for a specific mesoclimate, soil is the most important factor on viticultural zoning (SOTES and GOMEZ-MIGUEL, 2003), due to its direct effect on vine development and wine quality. The soil properties which have the most influence are the physical ones, namely the properties that control the soil water content (SEGUIN, 1986), due to their direct effect on equilibrium between vegetative vigour and grape production (VAN LEEUWEN and SEGUIN, 1994), and consequently on grape and wine quality (ESTEBAN *et al.*, 2001; TREGOAT *et al.*, 2002; GUROVICH and PAEZ, 2004).

There are several approaches through soil studies which are oriented to viticultural zoning, depending on the number of variables taken into account and whether they are spatialized or not (VAN LEEUWEN *et al.*, 2002). The methods that provide the most information for viticultural zoning are soil survey techniques, since they bring both the knowledge of spatial variability of soil properties and soil classification according to its viticultural potential (VAN LEEUWEN and CHERY, 2001). Moreover, vineyard management maps can be derived from a soil map. Therefore, soil maps are usually used as the basic cartography for zoning studies. There are a great variety of kinds of soil surveys, depending on the levels of information needed (SSS, 1993). These levels of information will condition the methods used for delineating soil map units. In DUTT *et al.* (1981) distinct viticultural regions, at a reconnaissance scale, were determined by considering the soil temperature regime. GÓMEZ-MIGUEL and SOTÉS (2003) carried out the zoning of protected viticultural areas by means of soil surveys at 1:50,000 scale, which were based on the American Soil Taxonomy classification. ASTRUC *et al.* (1980) used a soil map at 1:25,000 scale, and considered as the most important factors the water availability, followed by the presence of carbonates and other chemical components. MORLAT *et al.* (1998) considered as the main property the effective soil depth, since this is directly related to water availability by the roots. Many viticultural zoning studies note the importance of water availability, since this property integrates edaphico-climatic, biological and human factors (DUTEAU, 1981; SOTES and GOMEZ-MIGUEL, 1992; VAN LEEUWEN *et al.*, 2002). The use of polygon-based soil surveys has as its main limitations the size of the soil map unit that can be delineated as a polygon on a paper map, the representation of gradual changes in soil properties as abrupt changes and the manual map production process, which is time-consuming and error-prone (ZHU *et al.*, 2001).

The increase in the power of information technology and tools such as DGPS and remote and proximal sensing, and an increase in the application of precision viticulture in recent years (BRAMLEY and LAMB, 2003; BRAMLEY and JANIK, 2005), have promoted a great development of digital soil maps (McBRATNEY *et al.*, 2003; TAYLOR, 2004) to overcome the limitations of polygon-based soil maps. Digital maps are based on geographic information systems (GIS) data layers, which are relatively fast to obtain and allow the representation of soil properties as a continuum. Generally, the methodologies followed are based on the prediction of soil classes and/or attributes from independent variables (SCULL *et al.*, 2005). Digital soil maps derived from real-time on-the-go sensing technologies, such as electromagnetic induction sensors (DABAS *et al.*, 2001; CORWIN and LESCH, 2005) or ground-penetrating radar (LUNT *et al.*, 2005; PRACILIO *et al.*, 2006), are interesting in viticultural zoning, since they show a high correspondence with vineyard characteristics (TISSEYRE *et al.*; 2006) and moreover, they allow the characterising of within-vineyard soil variability (HALL *et al.*, 2002). TAYLOR and MINASNY (2006) developed a methodology for converting very intensive soil survey data into continuous digital soil maps. These maps were coherent with vineyard knowledge and presented a strong and convincing spatial representation of soil variability within the vineyard. GÓMEZ-MIGUEL and SOTÉS (2001), in order to minimise the cost of high resolution soil surveys, proposed a methodology of viticultural zoning at very detailed scale, which mixed polygon-based mapping techniques based on Soil Taxonomy with very intensive fixed grid soil surveys for some soil properties. The limitations of digital soil maps are the requirement for real soil observations to fit the prediction models, and also, the overfitted models, which predict poorly due to lack of observations and parsimony (McBRATNEY *et al.*, 2003). The use of new technologies can complement and facilitate the application of conventional soil surveys, but these methods remain essential (VAN LEEUWEN *et al.*, 2002): they are necessary for the proper calibration of remote and proximal sensors, for the correct interpretation of sensing data and they are the basis of some technologies.

In this study, the soil map units were delineated as polygons, following the criteria of the Soil Survey Manual (SSS, 1993) and VAN WAMBEKE and FORBES (1986). A polygon-based method was chosen, because it was expected to pass from a farm level management to a block level management (a vineyard plot divided into more homogeneous parts), according to soil properties determined by laboratory analysis. The soil survey methods implemented are based on the Soil Taxonomy classification (SSS, 2006), which is the system used by the official institutions of the study area (PORTA *et al.*, 2009). Soil Taxonomy is a hierarchical classification system which can be used at different levels of information. For some scientists, the hierarchical approximation is conceptually unsatisfactory, since the resulting classes can sort out soils with differences that may not be important for some interpretations or uses (YOUNG and HAMMER, 2000). For instance, YOUNG and HAMMER (2000) found that some Soil Taxonomy classes had no relationship to distributional patterns of soil attributes. In those cases, multivariate statistical analysis can be used in order to find other classifications more adjusted to the natural distribution of soils (AREOLA, 1979; YOUNG and HAMMER, 2000). In this study, similar statistical analyses have been used in order to evaluate whether soil map units defined by Soil Taxonomy sorted out soils with important differences for vine growing.

The aim of this study was to implement a very detailed soil survey methodology in 1,243 ha of vineyards and analyse its suitability for viticultural zoning. More concrete objectives were to (i) carry out a soil survey method at 1:5,000 scale based on Soil Taxonomy classification, (ii) analyse the variability of physicochemical properties of the resulting soil map units by means of Principal Component Analysis, (iii) realise a viticultural zoning proposal, applying to soil map units a k-means clustering method and (iv) analyse the correspondence between cluster classes and Soil Taxonomy classes.

MATERIALS AND METHODS

1. Setting

This study was carried out approximately in 1,243 ha of vineyards in Catalonia (Spain), which are oriented at high quality wine production. These vineyards are located on three distinct main geological units of Catalonia, concretely on the Catalan Coastal Range, the Ebro Basin and the Prepyrenees, approximately between 41° 8' N and 42°13'N and between 0° 38' E and 1° 43' E. The altitude ranges between 200 m and 1,000 m.

The climate type is Mediterranean, characterised by a dry warm season during summer, even though there are differences in temperatures and precipitation according to the altitude and distance to the sea. The mean annual precipitation varies from 520 mm to 650 mm. The annual precipitation has a high interannual variability (from 305 mm to 1110 mm). The mean annual temperature ranges between 12.7 and 14.9 ºC. In terms of viticultural indices, the thermal index of Winkler (WINKLER, 1962) varies from 1,441 ºC (zone II) to 2382 ºC (zone V), and the heliothermal index of Huglin (HUGLIN, 1978) ranges from 1,877 ºC to 2,500 ºC. The viticultural climate (TONIETTO and CARBONNEAU, 2004) ranges between subhumid and moderately dry, between temperate and warm, and between very cold nights and temperate nights. Finally, the soil climate is characterised by a xeric soil moisture regime and a mesic or thermic soil temperature regime (SSS, 1999).

2. Soil survey procedure

The soil survey implemented applied most of the criteria of the Soil Survey Manual of the Department of Agriculture of United States (SSS, 1993) at 1:5,000 scale. When working at agricultural plot level, a very detailed level of information is recommended, with scales higher than 1:15,840 (SSS, 1993) or 1:5,000 (FAO, 1979). GOULET and RIOUX (2006) used a soil survey at 1:10,000 scale, which was capable of differentiating soils and viticultural potential at vine plot level. In France, there are other many works on soil surveys at 1:5,000 scale, for a zoning orientated towards differentiating viticultural potential (for example, COHEN, 1986; GUILLY, 1990). GÓMEZ-MIGUEL and SOTÉS (2001) demonstrated the suitability of the 1:5,000 scale for very detailed viticultural zoning proposals. The method applied in this study delineates soil map units as polygons from soil observations which are selected according to different landforms and lithologies (figure 1). The density of soil observations was 1 observation by cm^2 of map, of which a sixth part corresponded to soil pits and the rest to soil auger holes. The depth of soil profiles was the shallowest of a root-limiting layer or 200 cm. One observation by cm^2 of map was adopted, doubling the density recommended by FAO (1979) and GUNN *et al.* (1988). At 1:5,000 scale, this density resulted in 4 observations by hectare. When applying a ratio of soil pit:soil auger hole 1:5, 0.7 soil pits by hectare were dug. This density of soil pits is higher than that recommended in several works (FAO, 1979; PORTA *et al.* 1999; LEGROS, 1996; VAN LEEUWEN *et al.*, 2002).

For each profile, a detailed field description included site description (location, soil temperature and moisture regime, drainage class, depth to water table, geomorphic information, parent material and surface stoniness) and profile description (horizon depth and genetic denomination (SSS, 1999), soil colour (Munsell charts), mottles, coarse fragments, structure, consistence, cementations, effervescence (hydrochloric acid), roots, pores, cracks, biological and human activity, accumulation of materials and ped and void surface features) (CBDSA, 1983; SCHOENEBERGER *et al.*, 2002; PORTA and LÓPEZ-ACEVEDO, 2005). Moreover, for each horizon, physical and chemical properties were analysed, according to the Soil Survey Laboratory Methods Manual of the Department of Agriculture of United States (USDA, 1996). The selected physical properties were texture (pipette method) and moistures at -33 KPa and -1500 KPa (pressure-plate extraction from disturbed samples). The selected chemical properties were pH (suspension of 1:2.5 soil:water), electrical conductivity (suspension of 1:5 soil:water), organic matter (Walkley-Black), nitrogen (Kjeldahl), calcium carbonate (Bernard calcimeter), active lime (Nijelsohn), gypsum (extracted by acetone), iron (extracted by EDTA), phosphorous (Olsen), cation exchange capacity and exchangeable bases (extracted by ammonium acetate). In some cases, a micromorphological study was undertaken in order to clarify or identify pedogenic processes which were difficult to detect with the naked eye (UBALDE *et al.*, 2005).

When soil profiles were fully characterised, they were classified according to Soil Taxonomy (SSS, 2006). This method of classification is organised at different levels: Order, Suborder, Great Group, Subgroup, Family and Series. The order and suborder levels are defined by soil forming processes and factors. The great groups and subgroups are determined by similarities in kind, arrangement, and degree of expression of pedogenic horizons, soil moisture and temperature regimes, and base status. Conceptually, the Reference Soil Groups of the World Reference Base (FAO/ISSS/ISRIC, 2006) and the Grands Ensembles de Références of the Référentiel Pédologique Français (INRA, 1995), could fit at an intermediate level between order and group level. Family level is defined by chemical and physical properties which affect management. Finally, soil series is the most detailed level, and they are soils that are grouped together because of their similar pedogenesis, soil chemistry and physical properties. Each series consists of soil layers that are similar in colour, texture, structure, pH, consistence, mineral and chemical composition, and arrangement in the profile.

The soil series were used to delineate the soil map units (SMU), following the criteria of VAN WAMBEKE and FORBES (1986). The soil survey party plotted the map unit boundaries onto orthophotographs. These boundaries were determined by means of soil observations, looking for differences in slope gradient, landform, colour, stoniness… When all SMU were delineated, they were listed and codified and the soil map legend could be designed. The resulting soil map was digitised and introduced within a Geographic Information System (GIS). The selected GIS software was ArcGIS (ESRI®).

3. Statistical analysis

As a first step for evaluating whether SMU, which are defined by the Soil Taxonomy classification, differentiated soils with important differences for vineyard growing, an analysis of the variability of physicochemical properties of SMU was carried out. The statistical method selected was a Principal Component Analysis (PCA), which considered the average physicochemical properties of soil series as variables and the SMU as cases. This PCA was performed in STATISTICA®. The soil properties considered were those of the surface horizons (0 – 15/60 cm depth), because in the majority of soils, most of the root system was found within this depth, due to the presence of lithic and paralithic contacts, indurated layers, compacted layers or skeletal layers. Moreover, in the deepest soils, the soil preparation before plantation and ploughing created a change of compactness at 50/60 cm of depth, which favoured horizontal root growth over vertical growth.

The following step was focused on exploring the suitability of the SMU (soil map units) for viticultural zoning purposes. The method selected was cluster analysis, which has previously been used in other studies, in order to find out which soil classifications are best adjusted for concrete uses (AREOLA, 1979; YOUNG and HAMMER, 2000). Cluster analysis has been also used

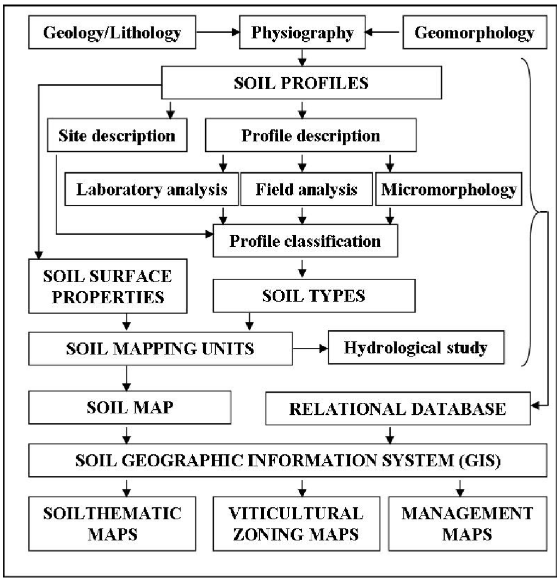

Figure 1 - Flow chart of the vineyard soil mapping methodology (Ubalde *et al.*, 2008).

in the zoning of digital soil maps (TAYLOR and MINASY, 2006). The cluster analysis was realised from average physicochemical data of soil series, using the k-means method in STATISTICA®. This method groups data in k clusters of greatest possible distinction. Initial cluster centres were determined by sorting distances and taking observations at constant intervals. Cases with missing values were deleted. The number of clusters for the final k-means clustering solution was selected by analysing the average distance among clusters. The most appropriate number of clusters was considered to be found when by increasing the cluster number, the average distance among clusters was not substantially reduced. As a result of this analysis, the average of each variable (edaphic property) was presented by each cluster, as well as the p-level of the ANOVA carried out for each variable. It was considered that there were significant differences among variables when p-level < 0.05. We also calculated the percentage of SMU that belonged to a determinate cluster.

Finally, classes formed by cluster analysis were compared with different levels of Soil Taxonomy (order, suborder, group, subgroup and different families), by the Pearson's chi-square test in STATISTICA®. In this analysis, the null hypothesis was the independence (no association) between variables.

RESULTS AND DISCUSSION

1. Soil classification and mapping

The soil series determined during the soil survey belonged to Entisol, Inceptisol, Alfisol and Mollisol orders (SSS, 2006) and 12 different groups, according to a wide variety of soil forming processes and their resulting diagnostic horizons (table 1). Table 1 also shows the approximate correspondence between Soil Taxonomy and the World Reference Base (FAO/ISSS/ISRIC, 2006) and the Référentiel Pédologique (INRA, 1995).

The most frequent soil order was Entisols, which are characterised by little or no evidence of soil formation. The groups described were Xerorthents (shallow soils with a root-limiting layer), Xerofluvents (deep soils, rich in organic matter in depth), Xeropsamments (sandy soils) and Xerarents (soils deeply mixed by earthworks). The second largest order was Inceptisols, which are characterised by being in early stages of soil formation. The groups described were Haploxerepts (soils with incipient accumulations of calcium carbonate and soils with gypsum accumulation) and Calcixerepts (soils with accumulations of calcium carbonate). The next largest order was Alfisols, which are characterised by silicate clay accumulation and a base saturation greater than 50 %. The groups identified were Haploxeralfs (soils with clay accumulation), Palexeralfs (soils with accumulation of clay and calcium carbonate) and Rhodoxeralfs (very rubefacted soils). The last order in importance was Mollisols, which are base-rich soils with a dark coloured surface horizon, due to organic matter accumulation. The groups identified were Haploxerolls (soils with high organic matter content), Calcixerolls (soils with high organic matter content and accumulations of calcium carbonate) and Palexerolls (soils with high organic matter content and cementations of calcium carbonate).

Although soil forming processes were determinant when describing classification between order and subgroup level, the family level was determined by physical and chemical properties which affect soil responses to management and manipulation for use. The properties used were the grain-size composition of the whole soil (including the fine earth and coarse fragments) for particle-size classes, the calcium carbonate content for mineralogy classes, the soil temperature regime for soil temperature classes and thickness of rooting zone for soil depth classes. Families, together with other criteria (differences in texture, arrangement of horizons), give rise to soil series, which are the most detailed level of soil

Table 1 - Soil classification at subgroup level, with their diagnostic horizons

Soil Taxonomy (SSS, 2006)		**DIAGNOSTIC HORIZONS**	**World Reference Base (FAO/ISSS/ISRIC, 2006)**	**Référentiel Pédologique (INRA, 1995)**
Orders	Groups		Reference Soil Groups	Grands Ensembles de Références
Entisols	Xerorthents	Ochric	Leptosols, Regosols	Lithosols, Régosols, Rendosols
	Xerofluvents	Ochric	Fluvisols	Fluviosols, Colluviosols
	Xeropsamments	Ochric	Arenosols	Arénosols
	Xerarents	Ochric, argillic fragments	Anthrosols	Anthroposols
Inceptisols	Haploxerepts	Ochric, calcic, gypsic	Cambisols, Gypsisols	Calcosols, Calcisols
	Calcixerepts	Ochric, calcic, petrocalcic	Calcisols	Calcarisols
Alfisols	Haploxeralfs	Ochric, argillic	Luvisols	Luvisols
	Palexeralfs	Ochric, argillic, calcic	Luvisols	Luvisols
	Rhodoxeralfs	Ochric, argillic, calcic	Luvisols	Luvisols
Mollisols	Haploxerolls	Mollic	Phaeozems	Phaeosols
	Calcixerolls	Mollic, calcic	Kastanozems	Phaeosols
	Palexerolls	Mollic, petrocalcic	Phaeozems	Phaeosols

classification. The consideration of all these variables allowed the differentiation of a high number of soil types, so that in the study area every 3 to 4 soil profiles belonged to one soil series, by average.

Finally, the SMU were delineated from soil series and other properties with influences on soil management (slope, surface stoniness and surface texture). The final number of SMU was approximately double that of the number of soil series. The mean surface of the delineated SMU was 1.4 hectares. This area allowed the use of this soil survey as the base map for block management at vineyard plot level, in spite of not knowing the intrablock variability. This inconvenience can be mitigated by combining this cartography with more intensive sampling for some variables (GÓMEZ-MIGUEL and SOTÉS, 2001; SORT and UBALDE, 2005).

2. Variability of soil properties

Figure 2 shows a Principal Component Analysis (PCA) where variables are mean physicochemical properties of surface horizons (0 – 15/60 cm depth) and cases are soil series. Cases are labelled at subgroup level, in order to see any trend at this level. Factor 1, which explains 28 % of variability, separates sandy soils and gravelly soils from clayey soils and soils with a high capacity for water retention. This factor can be considered the factor of potential for water stress, because it separates soils with low water holding capacity (high contents of

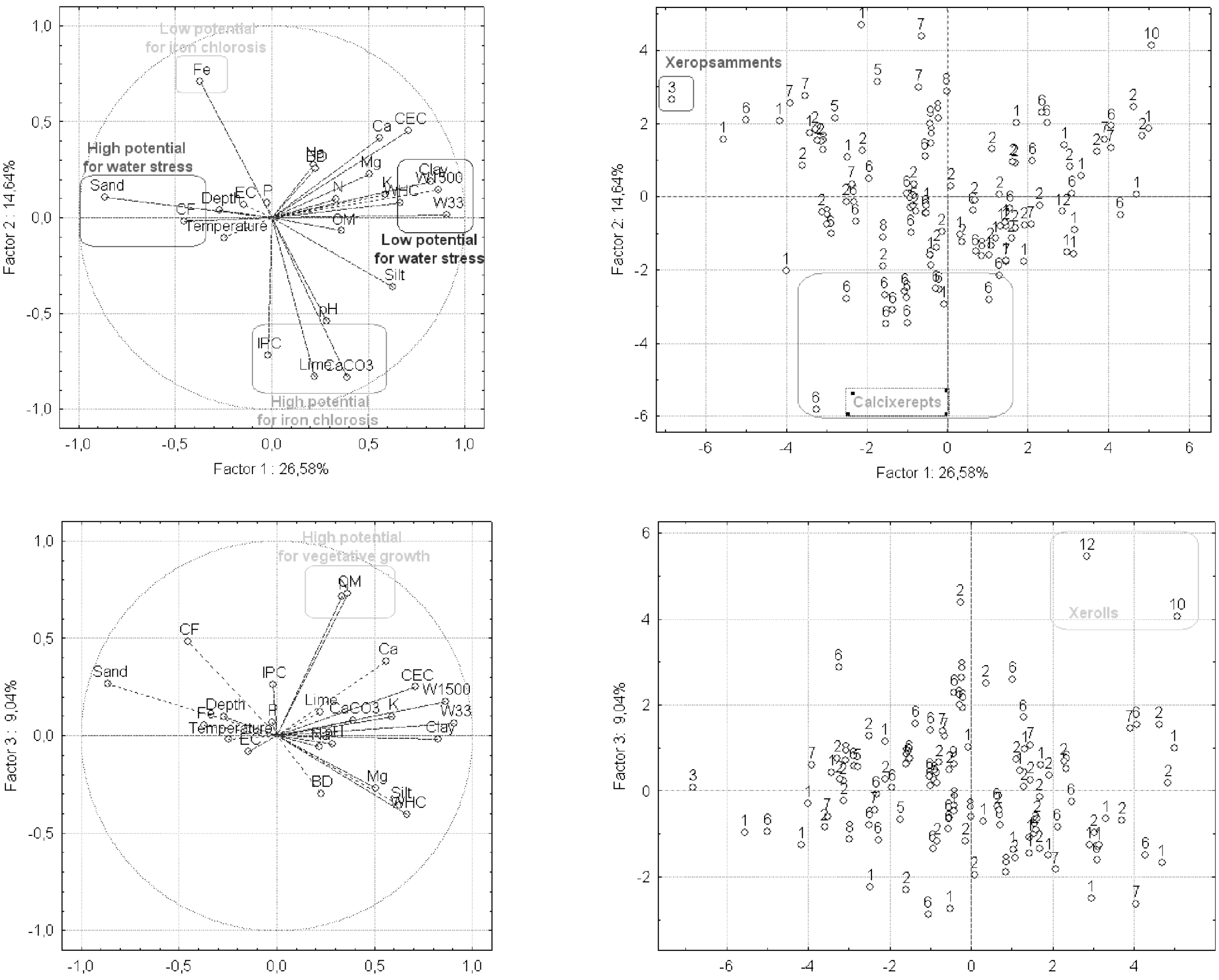

Figure 2 - PCA of physical and chemical surface properties for soil series of the study area.
In the first column there is the projection of variables and in the second column there is the projection of cases. In the first row there is represented factor 1 x factor 2, and the second row represents factor 1 x factor 3.
Legend for variables: OM, organic matter; CEC, cation exchange capacity; EC, electrical conductivity; W1500 and W33, water content at 1500 and 33 KPa, respectively; BD, bulk density; CF, coarse fragments; WHC, water holding capacity; IPC, potential for chlorosis occurrence index; Depth, thickness of rooting zone; Temperature, temperature regime.
Legend for cases: 1, Xerorthents; 2, Xerofluvents; 3, Xeropsamments; 4, Xerarents; 5, Haploxerepts; 6, Calcixerepts; 7, Haploxeralfs; 8, Palexeralfs; 9, Rhodoxeralfs; 10, Haploxerolls; 11, Calcixerolls; 12, Palexerolls.

sand and gravel) from soils with high contents of clay and high capacity of water retention. The only different subgroup is Xeropsamments, which are characterised by high contents of sand. Factor 2, which explains 15 % of variability, separates soils with high contents of carbonates from soils with high contents of iron. This factor can be considered the factor of potential for iron chlorosis occurrence, because it separates soils with high contents of active lime and high iron chlorosis occurrence index from soils with high contents of iron. The only different subgroup is Calcixerepts, which are characterised by carbonate accumulation. The last factor considered, which explains 10 % of variability, separates soils with high contents of organic matter and nitrogen. This factor can be considered the factor of potential for vegetative growth, which is very influenced by N fertility (CHONE *et al.*, 2001). The only different subgroup is Xerolls (Haploxerolls and Palexerolls), which are characterised by important organic matter accumulation. This analysis highlights that physical and chemical properties are not determinant at subgroup level, except to subgroups which are characterized by undergoing soil forming processes with strong consequences on physicochemical properties.

In short, most of the data variability is explained by soil properties which are very important for vineyard growth, because these properties determine soil potential for water stress, iron chlorosis and vegetative growth. When grouping series, it is expected that these properties will be the ones most differentiated within each group. As a result, a zoning realized by grouping series would be useful in viticulture.

3. Viticultural zoning

As shown in previous sections, very detailed soil survey methods give rise to a large number of SMU and, moreover, PCA suggests that Soil Taxonomy series would not be the most suitable classification to shape important edaphic properties for vineyard growing (water stress, iron chlorosis, vegetative growth). In order to reduce SMU number and find a soil classification more adjusted to viticultural zoning proposals, cluster analysis was selected among different statistical analyses, which are used in soil study (COURTNEY and NORTCLIFF, 1977), because this method allows the grouping of data, minimizing within-group variability while maximizing among-group variability (YOUNG and HAMMER, 2000). That is why this methodology is useful not only to simplify SMU, but to maintain most of the data variability. As highlighted in the PCA, this data variability was useful for sorting out soils which are characterized by having very distinct main edaphic properties for vine growing.

Figure 3 represents the inverse relationship between the number of clusters and the average distance among them. The most appropriate number of clusters can be determined by the slope change, which indicates the point where an increase of the number of clusters does not result in a substantial reduction of the distance between clusters. In our case, 8 clusters were selected.

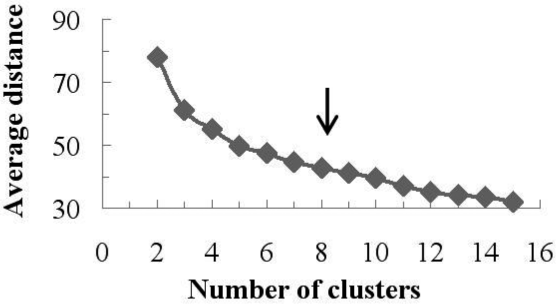

Figure 3 - Estimation of final cluster number according to average distance between clusters.

Averages of soil properties for each cluster are shown in table 2. The significance (*p* level) of among-cluster variability is also shown, and almost all variables present significant differences to 95 % (exceptions are pH, phosphorus, sodium and electrical conductivity). Finally, the importance of each cluster is illustrated with the percentage of SMU included within them. Cluster 4 is the one which encloses the largest number of SMU and cluster 8 the least.

In table 3, soils with properties next to the average of the cluster have been described and an interpretation of implications for vineyard management has been carried out. Obviously, there are soils in the clusters that would be outside of this description. However, most of the soils which come out separately in clusters present properties with different implications for vineyard growing, and consequently for viticultural zoning. For example, an optimal rootstock for each cluster could be suggested according to the different potentials for water stress, iron chlorosis and vegetative growth. Clusters 4 and 5 have been joined in this interpretation, because they do not differ substantially in the soil properties that had more weight in the factors considered in the ACP.

The results of the chi-squared test of independence, which determine if a significant association exists between clusters and different levels of Soil Taxonomy, are shown in table 4. It was ascertained that there were no associations between clusters and the highest levels of Soil Taxonomy (from order to subgroup). However, there is a significant association at family level. The significance is 99% for particle-size class and cation-exchange activity class and 90% for mineralogy class. This association can be explained because physicochemical properties are important when gauging the families, and basically these

Table 2 - Cluster means for soil properties considered, and significance of clusters variability.

Soil properties*	Cluster No. 1	Cluster No. 2	Cluster No. 3	Cluster No. 4	Cluster No. 5	Cluster No. 6	Cluster No. 7	Cluster No. 8	ANOVA signif. p
pH	8.3	8.5	8.3	8.4	8.5	8.3	8.4	8.5	0.460
OM	1.4	1.2	1.7	1.3	1.3	0.8	1.0	0.8	0.024
N	0.09	0.07	0.11	0.07	0.07	0.05	0.06	0.06	0.003
CaCO3	20	35	34	41	44	15	29	25	0.000
Lime	5.5	7.9	6.6	9.5	11.1	4.1	6.9	7.3	0.017
Fe	228.5	99.5	190.7	91.1	80.8	257.7	179.6	247.0	0.000
P	27.1	13.1	18.1	26.7	22.2	21.3	26.9	23.7	0.230
K	272.1	206.1	209.4	240.0	221.0	95.2	179.1	229.1	0.000
Sand	33.9	32.3	35.7	35.2	43.3	56.3	44.1	53.4	0.000
Silt	38.2	41.6	31.9	41.3	37.7	30.0	38.0	31.5	0.025
Clay	26.4	26.1	31.1	22.1	18.0	13.7	17.9	15.1	0.000
CEC	14.7	12.2	18.5	10.3	8.6	9.3	8.0	5.3	0.000
Mg	271.1	281.6	211.2	186.0	178.1	134.0	249.3	234.7	0.016
Na	58.0	60.4	61.3	58.5	48.2	52.2	46.9	53.4	0.105
EC	0.20	0.17	0.21	0.21	0.22	0.19	0.21	0.29	0.522
W33	23.3	22.9	25.3	21.1	19.1	17.2	19.1	16.0	0.000
W1500	11.2	10.6	12.5	9.5	7.8	6.9	7.6	6.3	0.000
WHC	17.7	18.0	18.7	15.9	13.9	11.5	14.9	12.9	0.003
IPC	3	28	16	26	35	3	10	50	0.002
Percent	11.9	12.8	4.6	22.0	14.7	12.8	17.4	3.7	-

* Legend: OM, organic matter (%); Lime, active lime (%); CEC, cation exchange capacity (cmol+/kg); EC, electrical conductivity (dS/m); W1500 and W33, water content at 1500 and 33 KPa, respectively (%); WHC, water holding capacity (mm/10 cm); IPC, iron-chlorosis occurrence index; Percent: Frequency of SMU into each cluster in percentage.

Table 3 - Interpretation of clusters for viticultural zoning.

Cluster	General vineyard soil description	Implications for viticulture
6	Shallow and moderately deep soils, coarse or moderately coarse textures, low or moderate water holding capacity, low calcium carbonate content and very low organic matter content.	High potential for water stress and low potential for iron chlorosis and vegetative growth.
8	Shallow and moderately deep soils, coarse or moderately coarse textures, low or moderate water holding capacity, high calcium carbonate content and very low organic matter content.	High potential for water stress, medium potential for iron chlorosis and low potential for vegetative growth.
7	Moderately deep and deep soils, medium textures, high water holding capacity, high calcium carbonate content and low organic matter content.	Medium potential for water stress, iron chlorosis and vegetative growth.
4 – 5	Moderately deep and deep soils, medium textures, high water holding capacity, very high calcium carbonate content and low organic matter content.	Medium potential for water stress and vegetative growth, high potential for iron chlorosis (cluster 5 > 4).
1	Deep and very deep soils, medium or finer textures, very high water holding capacity, low calcium carbonate content and low organic matter content.	Low potential for water stress and iron chlorosis and high potential for vegetative growth.
2	Deep and very deep soils, medium or finer textures, very high water holding capacity, high calcium carbonate content and low organic matter content.	Low potential for water stress, medium potential for iron chlorosis and high potential for vegetative growth.
3	Deep and very deep soils, medium or finer textures, very high water holding capacity, high calcium carbonate content and medium organic matter content.	Low potential for water stress, medium potential for iron chlorosis and very high potential for vegetative growth.

Table 4 - Pearson's chi-square test of independence between different taxonomy levels and clusters.

Taxonomy level	*Chi*-square	df	p-level
Order	26.9	21	0.176
Suborder	40.4	35	0.245
Group	69.1	63	0.279
Subgroup	29.6	35	0.727
Particle-size class	96.8	63	0.004
Mineralogy class	12.7	7	0.080
Cation-Exchange Activity class	39.0	21	0.010

properties are the ones that were used for cluster determination.

In order to analyse the relationship between different Soil Taxonomy classes and cluster classes, the frequency in which taxa distribute in clusters is shown in figure 4. It is selected a non-significant case (group level), a significant case at 99% (particle-size class) and a significant case at 90% (mineralogy class). Agreeing with the results of PCA, trends are observed at group level for Xeropsamments, Calcixerepts and Xerolls, which present higher frequencies in clusters with higher content of sands (cluster 6), carbonates (cluster 4 and 5) and organic matter (cluster 1 and 3), respectively. On the other hand, clearer trends are observed at family level, consistent with the results of the chi-squared test. With respect to particle-size class family, the sandy and skeletal families are most frequent in clusters with the highest sand contents and the lowest water holding capacity (cluster 5, 6 and 8), loamy families predominate in clusters of medium textures (cluster 4, 5 and 7), silty families are most frequent in the cluster with the highest silt content (cluster 4) and fine and clayey families predominate in clusters with the highest clay contents (cluster 1 and 3). With respect to the mineralogy class family, the carbonatic class presents the highest frequencies in clusters with the most carbonates (cluster 4 and 5) and the mixed class in the clusters with the least carbonates (cluster 1, 6 and 7). So, as in previous studies (YOUNG and HAMMER, 2000), there are some statistically significant associations among cluster groups and Soil Taxonomy families. However, this association is not strong enough to predict accurately the taxonomic classes from cluster memberships, or vice versa.

In figure 5, it is shown a detail of the soil map and other maps related to vineyard crop. As seen before, the use of Soil Taxonomy at series level and 1:5000 scale (Figure 5-A) resulted in a high number of SMU, due to a high sampling density and a high variability of soil forming processes and physicochemical soil properties. Consequently, the SMU average size was 1.4 ha, allowing the use of this information for land management in blocks, for example for fertilization (figure 5-C). However, this large number of SMU difficulted the interpretation of the legend and did not accurately shape the variability of important properties for vineyard growing. The map of cluster classes (figure 5-B) led to a drastic reduction in the number of SMU, while keeping much of the data variability and obtaining a classification closer to soil viticultural potential. This cluster map has a legend that distinguishes polygons according to the potential of water stress, iron chlorosis (figure 5-D) and excess of vigour, and with simple reclassifications, maps of suitability for varieties or root-stocks, sectors of irrigation and other viticultural treatments can be obtained. The main

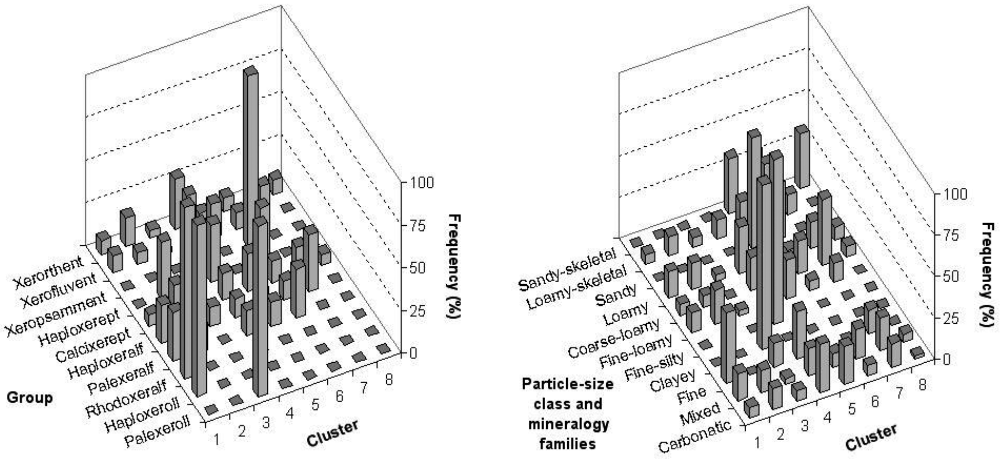

Figure 4 - Frequency of each taxa into each cluster in percentage.

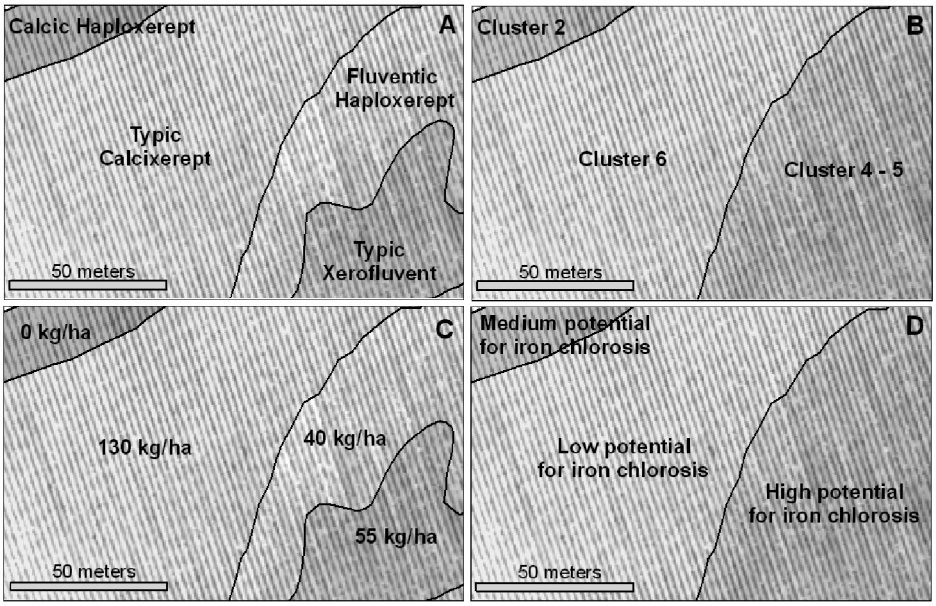

Figure 5 - Detail of (A) the soil map according to Soil Taxonomy, (B) the cluster classes map, (C) the map for block management, concretely for mineral fertilization and (D) the map of potential for vineyard growing, concretely for iron chlorosis.

advantages of this viticultural zoning proposal are its simplicity when carrying out statistical calculations, as well as when transforming these results in georeferenced information. With STATISTICA®, a table in dbf format with the SMU codes and the corresponding clusters can be extracted, and can be attached through ARCGIS® to the soil map. Finally, for obtaining the cluster map, an operation of dissolution of polygons, considering the cluster number as variable, is carried out. On the other hand, this method presents different limitations. One limitation is the consideration only of surface horizons since, although most of the root system is found near the surface, the deep roots can have a great importance when facing water stress in the very dry and warm summers, which are common in the study area. Another limitation is that new soil map units cannot be assigned automatically to the existing cluster classes, since belonging to a cluster class cannot be predicted accurately from taxonomic classes. It should be also remarked that this level of study is merely descriptive, so that with this information the relationships between the soil type and the quality of the wine and the grape cannot be determined. To know these relationships, ecophysiological studies have to be carried out. However, it seems interesting to us to be able to transform, by means of a simple methodology, conventional soil maps which can be difficult to interpret, into viticultural zoning maps, whose map units are determined maximizing the difference in soil properties, which are determining for vineyard production.

CONCLUSIONS

In this study, we present a simple methodology that allows us to get the maximum value from conventional soil maps as base maps for viticultural zoning, directed at the differentiation of zones according their potential for vine development. The chosen scale, 1:5,000, allowed us to divide vine plots into blocks, which could be used for a differentiated viticultural management. On the other hand, the soil classification used, Soil Taxonomy at series level, allowed us to differentiate a great number of soil map units, but in return it showed certain deficiencies when reflecting the variability of important properties for vineyard cropping. As up to 50% of the variability was explained by three factors related to vine development (potential for water stress, iron chlorosis and vegetative growth), we proposed a cluster analysis for facilitating a viticultural interpretation of the soil map, since this analysis allowed us to reduce the number of soil map units and to group soils maximizing the variability among the groups. As a result, this method was suitable to separate soils according their distinct potential for vine growing, in relation to water stress, iron chlorosis and vegetative growth. A limitation of this method was that the relationship between cluster groups and Soil Taxonomy groups was not strong enough to predict accurately cluster membership from taxonomic classes. So new soil map units could not be assigned to existing soil cluster classes.

In short, as a main conclusion of this study, a very detailed polygon-based soil survey method, based on Soil Taxonomy, can be used at very detailed scale as a basic map for block management and also at a smaller scale, by means of cluster analysis, when viticultural zoning is directed at the differentiation of zones of distinct potential for vineyard growing.

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