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Quantifying the effects of soil and climate on grape and wine quality : applicaton in a viticultural zoning based on very detailed soil surveys

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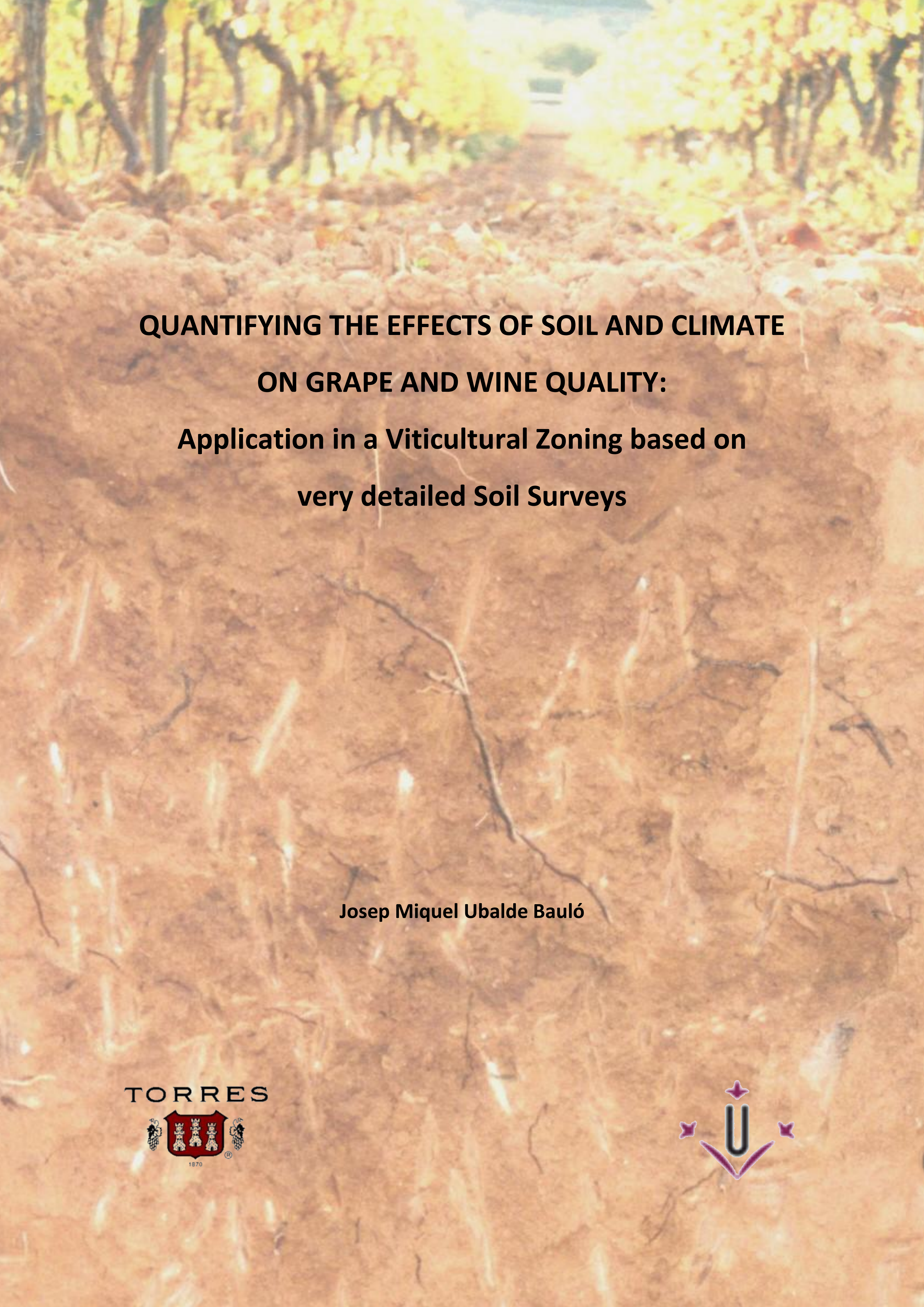

QUANTIFYING THE EFFECTS OF SOIL AND CLIMATE ON GRAPE AND WINE QUALITY:

Application in a Viticultural Zoning based on very detailed Soil Surveys

Josep Miquel Ubalde Bauló

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Thesis submitted in fulfilment of the requirements for the degree of Doctor in Environment and Soil Science in the University of Lleida

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Tu ne quaesieris (scire nefas) quem mihi, quem tibi
finem di dederint, Leuconoe, nec Babylonios
temptaris numeros. Vt melius, quidquid erit, pati!
seu pluris hiemes, seu tribuit Iuppiter ultimam,
quae nunc oppositis debilitat pumicibus mare
Tyrrhenum: sapias, uina liques et spatio breui
spem longam reseces. Dum loquimur, fugerit inuida
aetas: carpe diem, quam minimum credula postero.

Horace (65 - 8 BC)

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Als editors de les revistes que han confiat amb els articles que formen part d’aquesta tesi i als revisors anònims que han fet aportacions que han millorat els resultats finals.

A la meva família i amics, que han estat sempre al meu costat, donant-me suport tant en els bons moments com en els no tant bons.

Josep Miquel Ubalde Bauló
Vilafranca del Penedès, 8 de març de 2010

CONTENTS

ABSTRACT

This study, carried out in vineyards of high quality wine production in Catalonia (Spain), aims to determine the suitability of very detailed soil surveys, based on Soil Taxonomy, for viticultural zoning purposes, and quantifies the effects of soil and climate on grape and wine quality in some representative soil map units. After an introductory chapter, this objective is developed in different chapters. Chapter 2 analyses the suitability of soil map units, determined at a 1:5,000 scale according to Soil Taxonomy classification, to determine important edaphic properties for vineyard growing. A *k*-means clustering analysis is proposed in order to group soils according to their potential for vine growing, since most of the variability of soil properties was not reflected exactly in the soil map unit classification. Chapter 3 discusses the implications of soil forming processes on very detailed soil surveys. The identified soil forming processes had significant effects on soil properties which are important for vineyard growing. However, soil forming processes were not always reflected in soil classification, especially in soils modified by man. Chapter 4 analyses the suitability of Soil Taxonomy to characterize the soil moisture regime for viticultural zoning purposes. A soil moisture regime classification based on cluster analysis was developed, since Soil Taxonomy did not adequately reflect the variability of soil moisture dynamics during vineyard growing. Chapter 5 focuses on the influence of soil and climate on vintage variability. Climate and soil moisture explained 70% of vintage variability and soil properties explained 28% of variability. Generally, climate was the most influential factor on must composition, while soil factor mostly affected yield. Chapter 6 determines the effects of climate and soil on grape ripening and wine quality of Cabernet Sauvignon. Climate and soil had overall a significant effect on grape ripening. These effects of soil and climate can be explained mainly by their influence on vine water availability status. Soil was determining in wine phenolic composition, and related wine tasting characteristics. As a final conclusion, very detailed soil surveys based on Soil Taxonomy are valuable sources of information for viticultural zoning studies, although their implementation can be improved with statistical analysis that considers the variability of soil properties related to grapevine growing. Moreover, although climate explains most of the vintage variability, soil type is decisive in determining the vineyard potential for wine quality.

RESUM

L’objectiu d’aquest estudi, dut a terme en vinyes destinades a la producció de vi de qualitat a Catalunya (Espanya), és determinar si un mapa de sòls molt detallat, basat en la Soil Taxonomy, és apte per estudis de zonificació vitícola i quantificar els efectes del sòl i el clima sobre la qualitat del raïm i del vi, en unitats cartogràfiques representatives. Després d’un capítol introductori, aquest objectiu es desenvolupa en diferents capítols. El capítol 2 analitza l’aptitud d’unitats cartogràfiques de sòls, classificades segons la Soil Taxonomy, per reflectir la variabilitat de propietats edàfiques importants per al cultiu de la vinya. Degut a què aquesta variabilitat no es reflectia exactament en la classificació de les unitats cartogràfiques, es va proposar una anàlisi clúster per agrupar els sòls segons el seu potencial vitícola. En el capítol 3 es discuteixen les implicacions dels processos formadors del sòl en la cartografia de sòls molt detallada. Els processos formadors identificats tenien efectes significatius sobre propietats edàfiques importants per al cultiu de la vinya. Malgrat tot, aquests processos no sempre es reflectien en la classificació dels sòls, especialment en els sòls modificats per l'home. El capítol 4 analitza l’aptitud de la Soil Taxonomy per caracteritzar el règim d'humitat del sòl en estudis de zonificació vitícola. La Soil Taxonomy no reflectia adequadament la variabilitat de la dinàmica de la humitat del sòl durant el desenvolupament de la vinya, pel que es va proposar una classificació dels règims d’humitat del sòl a partir d’una anàlisi clúster. El capítol 5 se centra en la influència del sòl i del clima sobre la variabilitat de la verema. El clima i la humitat del sòl explicaven el 70% de la variabilitat mentre que les propietats del sòl n’explicaven un 28%. En general, el clima va ser el factor més influent en la composició del most, mentre que el sòl afectava sobretot en el rendiment. El capítol 6 determina els efectes del clima i el sòl en la maduració del raïm i la qualitat del vi de Cabernet sauvignon. Tant el clima com el sòl presentaven un efecte significatiu sobre la maduració del raïm. Aquest efecte podria ser explicat per la influència del sòl i el clima sobre la disponibilitat d'aigua per a la vinya. El sòl va ser determinant en la composició fenòlica del vi, i conseqüentment en el tast de vins. Com a conclusió final, els mapes de sòls molt detallats basats en la Soil Taxonomy són una font valuosa d’informació per a estudis de zonificació vitícola, encara que la seva aplicació es pot millorar amb anàlisis estadístiques que considerin la variabilitat de propietats edàfiques determinants per al cultiu de la vinya. D'altra banda, encara que el clima explica la major part de la variabilitat de la verema, el tipus de sòl és decisiu en la determinació del potencial d’una vinya per a la producció de vi de qualitat.

RESUMEN

El objetivo de este estudio, llevado a cabo en viñas destinadas a vino de calidad en Cataluña (España), es determinar si un mapa de suelos muy detallado, basado en la Soil Taxonomy, es apto para estudios de zonificación vitícola y cuantificar los efectos del suelo y el clima sobre la calidad de la uva y del vino, en unidades cartográficas representativas. Tras un capítulo introductorio, este objetivo se desarrolla en diferentes capítulos. El capítulo 2 analiza la aptitud de unidades cartográficas determinadas según la Soil Taxonomy, para reflejar la variabilidad de propiedades edáficas importantes para la vid. Debido a que esta variabilidad no se reflejaba exactamente en la clasificación de las unidades cartográficas, se propuso un análisis cluster para agrupar los suelos según su potencial vitícola. En el capítulo 3 se discuten las implicaciones de los procesos formadores del suelo en la cartografía de suelos. Los procesos formadores identificados tenían efectos significativos sobre propiedades edáficas importantes para la vid. Sin embargo, estos procesos no siempre se reflejaban en la clasificación de los suelos, especialmente en suelos antrópicos. El capítulo 4 analiza la aptitud de la Soil Taxonomy para caracterizar el régimen de humedad del suelo en estudios de zonificación vitícola. La Soil Taxonomy no reflejaba adecuadamente la variabilidad de la humedad del suelo durante el desarrollo de la vid, por lo que se propuso una clasificación de los regímenes de humedad del suelo a partir de un análisis cluster. El capítulo 5 se centra en la influencia del suelo y del clima sobre la variabilidad de la vendimia. El clima y la humedad del suelo explicaban el 70% de la variabilidad y las propiedades del suelo explicaban un 28%. En general, el clima fue el factor más influyente en la composición del mosto, mientras que el suelo afectaba sobretodo en el rendimiento. El capítulo 6 determina los efectos del clima y el suelo en la maduración de la uva y la calidad del vino de Cabernet Sauvignon. Tanto el clima como el suelo presentaban un efecto significativo sobre la maduración de la uva. Este efecto podría ser explicado por la influencia del suelo y el clima sobre la disponibilidad de agua para la viña. El suelo fue determinante en la composición fenólica del vino, y consecuentemente en la cata de vinos. Como conclusión final, los mapas de suelos muy detallados basados en la Soil Taxonomy son una fuente valiosa de información para estudios de zonificación vitícola, aunque su aplicación se puede mejorar con análisis estadísticos que consideren la variabilidad de propiedades edáficas determinantes para el cultivo de la vid. Por otra parte, aunque el clima explica la mayor parte de la variabilidad de la vendimia, el tipo de suelo es decisivo en la determinación del potencial de un viñedo para la producción de vino de calidad.

ACCOUNT

The content of some chapters of this thesis correspond to the following publications:

Chapter 2

Ubalde, J.M.; Sort, X. and Poch, R.M. Application of a very detailed soil survey method in viticultural zoning in Catalonia, Spain. *Journal International des Sciencies de la Vigne et du Vin*, (2009), **43:2**, 55-66.

Chapter 3

Ubalde, J.M.; Sort, X. and Poch R.M. How soil forming processes determine soil-based viticultural zoning at very detailed scale (Catalonia, Spain). *Journal of Soil Science and Plant Nutrition*, (2011), **1**, 100-126.

Chapter 4

Ubalde, J.M.; Sort, X.; Nacci, S. and Poch R.M. Determining soil moisture regimes for viticultural zoning purposes. *Soil Forming Factors and Processes from the Temperate Zone*, (2013), **12:1**, 1-16.

Chapter 5

Ubalde, J.M.; Sort, X.; Poch, R.M. and Porta, M. Influence of edaphoclimatic factors on grape quality in Conca de Barberà vineyards (Catalonia, Spain). *Journal International des Sciencies de la Vigne et du Vin*, (2007)**, 41:1,** 33-41.

Chapter 6

Ubalde, J.M.; Sort, X.; Zayas, A. and Poch, R.M. Effects of soil and climatic conditions on grape ripening and wine quality of Cabernet Sauvignon. *Journal of Wine Research*, (2010), **21:1**, 1-17.

We would like to acknowledge the editors of these journals, who agreed to online publication of this PhD Thesis. Please, use the above references when using concrete information of these chapters.

Chapter 1

GENERAL INTRODUCTION: WHAT IS VITICULTURAL ZONING?

Viticultural zoning can be defined as the spatial characterization of zones that produce grapes or wines of similar composition, while enabling operational decisions to be implemented (Vaudour, 2003).

Viticultural zoning studies have increased significantly over the past 10 years, in relation to the expansion of the international wine market (by 1,777 million litres from 1994 to 2005, according to The Global Wine Statistical Compendium, 1961-2005), especially in the New World countries (Australia and Chile almost tripled production between 1994 and 2005). This increase in wine production has led to a highly competitive market, and wine-producing areas have used product differentiation according to regional origin as a strategy to expand their wine markets. Thus, one of the main viticultural zoning objectives is related to the delimitation of protected viticultural areas. Moreover, the necessity of optimizing product quality and the development of new technologies in precision viticulture, have favoured viticultural zoning studies oriented to the delimitation of homogeneous areas to apply a differentiated management (fertilization, harvesting, diseases,…) or to select the best land for growing vines or a particular cultivar or rootstock (Vaudour and Shaw, 2005).

The viticultural zoning delimitations are usually called ‘terroir’ units. Generally, ‘terroir’ is defined as an entity in space and time, characterized by an interaction between the environmental potential and viticultural and oenological practices, which is significant for grape and wine quality (Vaudour, 2003; Deloire et al., 2005). However, there is no agreement in the scientific community about the definition of the term ‘terroir’, and even now, a group of experts of the OIV (Office International de la Vigne et du Vin) are working on a definition which will be acceptable at international level (Fanet, 2007). This lack of agreement is due to the variability of applications, definitions and methodological approaches followed by different authors and viticultural regions, making international comparisons difficult (Vaudour and Shaw, 2005). Moreover, not all languages supported by the OIV can provide an accurate translation of the term ‘terroir’ and in some countries, particularly in the New World, this term is considered too complex and poorly defined to be useful (Fanet, 2007).

However, scientists from the INRA (Institut National de la Recherche Agronomique, France) and the INAO (Institut National des Appellations d'Origine, France) presented a definition in the 6th International Terroir Congress in 2006 (Casabianca et al., 2006), which served as a draft resolution for the OIV. The definition proposed, known as the 'Declaration of Montpellier', says (Fanet, 2007): "The 'terroir' is a delimited geographical area in which a human community built along its history, a collective knowledge of production, based on an interaction between biological and physical environment, and a set of human factors. Thus, the technical routes used reveal an originality and result in a reputation for original products of this geographical area". Jöel Rochard completed the proposed definition with the sentence: "Terroir also participates of specific landscape characteristics" (Fanet, 2007). The complete definition is close to the definition adopted by UNESCO in 2005.

This definition reflects the importance of the human and historical aspects, as well as the empirical knowledge inherited from history and society. These aspects are accepted by the traditions of European viticulture, but the younger producing countries are not always ready to take account of this human side. As a consequence, they prefer the term 'viticultural zones', which is associated with a relatively simple viticultural characterization, compared to 'terroirs', which require more features and a more cautious approach (Vaudour and Shaw, 2005). These different concepts have led to a broad spectrum of scientific definitions of 'terroir'. The simplest methods only consider soil or climate (Morlat, 1989, 2001). Then, other factors can be added: variety and viticultural and oenological technology (Carbonneau, 2001), and historical and sociological wine-growing factors (Vaudour, 2003).

The environmental factors used in most viticultural zoning studies are climate (Coombe, 1987; Hamilton, 1989) and soil (Rodríguez and García-Rodeja, 1995; Rodríguez, 1996; Fregoni, 1985; Falcetti et al., 1995; Rodríguez et al., 1996; Oliveira, 2001). Often, soil is studied together with climate, because its effects on wine quality are only consistent under the same climatic conditions (Saayman, 1977; Conradie, 1998). Other factors considered are cultivar and rootstock (Pouget, 1978), vine training system (Carbonneau, 1980), productivity (Huglin and Balthazard, 1976), geomorphology and topography (Dumas et al., 1997) and geology (Van Schoor, 2001).

Among the permanent factors in viticultural production, climate is probably the factor with the greatest influence on the suitability of the environment for grapevine growing and wine production (Hidalgo, 1999). The most important climatic variables are temperature, precipitation and solar radiation, but also mesoclimates and microclimates can be decisive.

The temperature is probably the most important parameter, because it affects almost all aspects of vineyard functioning (Coombe, 1987). Temperatures have a fundamental, decisive influence in grape ripening and wine composition (Hidalgo, 1999). The cold limit for viticulture without winter protection can be considered -1ºC of mean temperature for the coldest month (Gladstones, 2000). Spring average minimum temperatures can be used in order to assess frost risk after budbreak (Gladstones, 1992). A minimum of cumulated temperatures during the growing season is necessary to ensure complete ripening for a certain cultivar (Winkler, 1962; Huglin, 1978). Also, cumulated temperatures determine pulp ripening speed and harvesting date (Branas et al., 1946; Huglin, 1978; Duteau, 1990). Night temperatures during the ripening period affect grape phenolic compounds' accumulation and wine aroma and colour (Kliewer and Torres, 1972; Tonietto, 1999; Tonietto and Carbonneau, 2002; Deloire et al., 2003; Deloire et al., 2005). Anthocyanin accumulation can be severely undermined by high diurnal temperatures during the ripening period (Van Leeuwen et al. 2004).

A precipitation between 350 and 600 mm is considered suitable for the production of high quality wine (Hidalgo, 1999). Excessive precipitation leads to a reduction in grape quality, since grape acidity increases, sugar content reduces and grape maturity is retarded, besides which it also favours the appearance of fungal diseases (e.g. mildew). Moreover, wine production and quality can also be damaged in case of insufficient rainfall (Luini et al., 1985). Even in areas with adequate rainfall, to provide additional water to maintain grape quality and production in dry years is necessary (Calame, 1984). Some indices for measuring risk of developing mildew are based on precipitation (Branas et al., 1946).

The grapevines require a minimum between 1500 and 1600 sunshine hours per year, of which 1200 hours must occur during the growing season, depending on latitude (Hidalgo, 1999). The solar radiation or photophase has an important physiological effect on grapevine growing and has a great influence on wine quality (Ribéreau-Gayon and Peynaud, 1960). Some indices based on solar radiation and temperature have been developed in order to assess the possibilities of grapevine cultivation (Branas et al., 1946; Huglin, 1978).

The relative humidity affects the photosynthetic rate when soil water supply is limited (Champagnol, 1984). Low values of relative humidity and high temperatures lead to increasing pH in berries and decrease grape production per unit of transpired water (Gladstones, 1992). Moreover, high values of relative humidity can increase the incidence of diseases.

Strong winds during spring and early summer may affect flowering, reducing the number of grape clusters. Winds over 3-4 $m \cdot s^{-1}$ can cause closure of stomata, resulting in an inhibition of photosynthesis (Hamilton, 1989). However, adequate air circulation can prevent the effects on grapevine development of excessive relative humidities and temperatures.

As mentioned above, the climatic variables most affecting wine production are precipitation, temperature and sunshine. These three variables are often used for viticultural zoning at the regional scale, by means of indices that allow the delimitation of viticultural regions (Constantinescu, 1967; Hidalgo, 1999; Tonietto and Carbonneau, 2000). These indices can be used to estimate grape properties, such as the theoretical grape sugar potential at maturity (Riou, 1998; Carbonneau, 2002), and wine properties, such as acidity and aromatic development (Tonietto and Carbonneau, 1999).

This regional climate can be influenced by particular geographic conditions, resulting in local climates or mesoclimates. The factor that most influences the mesoclimate is topography, namely altitude, slope and aspect (Dumas et al., 1997). The effects of topography on climate can be indirect, due to water drainage and wind exposure, or direct, due to changes in the sunlight incidence on the earth surface (Crowe, 1971). The effect of topography on temperature variability is a major factor affecting grape quality (Gladstones, 1992). Convex slopes tend to have less variation in temperature between day and night, compared with concave slopes (Branas et al., 1946). Vineyard cultivation on slopes has usually been considered better for grape quality than cultivation on flat areas, since slopes are generally less fertile and less susceptible to over-production and the consequent reduction of grape quality (Hidalgo, 1999).

For a specific mesoclimate and cultivar, soil is the most important factor in viticultural zoning, due to its direct effect on vine development and wine quality (Sotés and Gómez-

Miguel, 2003). This fact explains why soil maps are usually used as the basic cartography for viticultural zoning studies at detailed scales.

The viticultural suitability of a soil is marked initially by its geological origin. A priori, any geological formation may be better than others in terms of quality of production, although some authors prefer Oligocene and Miocene materials (Hidalgo, 1999). There is little literature on the relationship between geology and wine (Carey, 2001). However, geology is a factor considered in some viticultural zoning studies (Morlat, 1996), and some authors consider geology as the most important static component of 'terroir' affecting the character and quality of the final product (Dubos, 1984). The effect of rock mineralogy on the chemical composition of wine was studied by Van Schoor (2001). Nevertheless, the most significant effect of geology on wine quality appears through its contribution to the physical properties of soils (Seguin, 1986).

The soil properties with the greatest influence on grapevine growing are soil depth and the physical properties which control soil water content (Seguin, 1986) and have a direct effect on the equilibrium between vegetative vigour and grape production (Van Leeuwen and Seguin, 1994). This effect of soil moisture on vegetative and reproductive growth is mainly determined through the hormonal equilibrium. An unrestricted soil moisture regime may favour hormones responsible for vegetative growth (auxin, gibberellin, cytokinin) and disfavour hormones responsible for fruit ripening (abscisic acid) (Champagnol, 1984). As a result, total production and berry weight increase, but sugar, anthocyanin and phenolic content decrease (Esteban et al., 2001; Trégoat et al., 2002), diminishing wine quality (Gurovich and Páez, 2004). Generally, a moderately limited water regime has positive effects on berry composition and wine quality (Kounduras et al., 1999). In this case, stomatal regulation limits photosynthesis, favouring a growth shutdown of buds and berries (Van Leeuwen and Seguin, 1994) and causing an hormonal equilibrium more favourable for grape quality (Champagnol, 1984). The limitations on berry size, abscisic acid production and carbon competition between berries and shoots, associated with a moderate water stress situation, increase grape sugar, anthocyanin and tannin contents and also increase the grape ripening speed (Van Leeuwen and Seguin, 1994).

The judgement of the availability of soil water for the vineyard crop can be made by means of soil moisture sensors, such as neutron probes (Lebon et al., 2003) or TDR probes (Sivilotti et al., 2004); physiological parameters, such as leaf or stem water potential (Trégoat et al., 2002; Van Leeuwen et al., 2001) or carbon-13 discrimination (Gaudillère et al., 2002); or soil water balance models (Riou and Lebon, 2000; Oliveira, 2001). These data can be correlated with data of grape and wine composition, often to advise on cultivar selection, irrigation or fertilization purposes (Choné et al., 2001; Peyrot Des Gachons et al., 2005).

In general, direct relationships between soil minerals and wine quality cannot be established (Seguin 1986), unless severe deficiencies affecting vineyard growing occur (Van Leeuwen et al., 2004). Nitrogen deficiency results in severe vine growing limitation and decrease in grape harvest. Excessive nitrogen contents can increase grape production, but grape quality can be severely diminished (Choné et al., 2001; Hilbert et al., 2003). A deficiency of phosphorus and potassium leads to a decrease of shoot length, weak flowering, a delayed veraison and small berries. An excess of active calcium carbonate can cause problems of iron chlorosis, with a large decrease in production (Hidalgo, 1999). Some studies have shown an effect of soil cations on grape composition, which can influence wine quality (Peña et al., 1999; Mackenzie and Christy, 2005).

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). 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 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. Many viticultural zoning studies note the importance of water availability, since this property integrates edaphoclimatic, biological and human factors (Duteau, 1981; Sotés and Gómez-Miguel, 1992; Van Leeuwen et al., 2002).

Trends in viticultural zoning refer mainly to an increase in spatial resolution of geographic information, thanks to the development of new technologies in precision viticulture. These technologies aim to georeference different variables important for vineyard management, in order to determine their spatial variability and to manage it properly according to production objectives. The variability of the harvest is monitored by means of sensors for grape harvesters, which allow the georeferencing of production (kg) and grape composition (sugar, pH, acidity, temperature) (Bramley and Hamilton, 2004; Arnó et al., 2005; Baguena et al., 2009). The variability of vegetative vigour can be determined from high resolution multispectral aerial images recorded by satellites or airplanes (Hall et al., 2002; Martínez-Casasnovas et al., 2005) or from terrestrial proximal sensors, such as GreenSeeker (Goutouly et al., 2006; Martínez-Casasnovas et al., 2008). The variability of vine water status can be measured with thermal infrared cameras that can capture canopy temperature (Roby et al., 2004). Finally, the variability of soil can be characterized with sensors of electromagnetic induction or ground penetrating radar (Lunt et al., 2005). By means of these non-intrusive sensors, different soil properties can be mapped, for instance soil moisture, clay content, clay mineralogy, cation exchange capacity, bulk density or soil temperature (Corwin and Lesch, 2005; Dabas et al., 2001). These soil maps are relatively faster to obtain than conventional soil surveys, and allow the representation of soil properties as a continuum. However, conventional soil surveys remain essential, because they are necessary for the proper calibration of these sensors and for the correct interpretation of these data (Van Leeuwen et al., 2002).

This study was carried out in vineyards located in Catalonia (North-East Spain), which are oriented towards high quality wine production. These vineyards belong to Miguel Torres Winery, a fifth-generation family company whose main commitment is to offer high quality products. Approximately ten years ago, this company opted for soil survey techniques as the basic tool to optimize grape and wine quality through the implementation of viticultural practices that consider soil variability within the vineyard plots. The soil survey method selected is based on Soil Taxonomy classification, which is the system used by the official institutions of the study area. Soil Taxonomy is a worldwide hierarchical classification system, which is not intended for any particular crop. Thus, some questions arose: Is Soil Taxonomy adequate to sort out soils with important implications for wine growing? Can this soil classification system reflect the soil forming processes which occur in the study area? Are the soil moisture regimes of Soil Taxonomy suitable to characterize soil moisture dynamics in vineyards? To what extent does soil affect the quality of grapes and wine? May the climate or other environmental factors have more influence than soil in grape and wine composition?

The overall objective of this thesis is to determine the suitability of very detailed soil surveys, based on Soil Taxonomy, for viticultural zoning purposes and to quantify the effects of soil and climate on grape and wine quality in some representative soil map units.

This objective can be divided into specific objectives: (1) to analyse the variability of physico-chemical properties of soil map units, which are determining in grape production, (2) to determine the suitability of the soil classification system for reflecting this variability, (3) to elucidate the implications of soil forming processes, which affect soil properties determining in grape production, on soil classification, (4) to determine the suitability of the soil classification system to characterize the soil moisture regime for viticultural zoning purposes, (5) to quantify the influence of edaphoclimatic parameters on grape harvest and (6) to quantify the effects of soil and climate on grape ripening and wine quality.

Chapter 2

APPLICATION OF A VERY DETAILED SOIL SURVEY METHOD IN VITICULTURAL ZONING AT PLOT LEVEL

Abstract

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

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

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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 characterization 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 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 (Sotés and Gómez-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; Trégoat et al., 2002; Gurovich and Páez, 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 Chéry, 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 edaphoclimatic, biological and human factors (Duteau, 1981; Sotés and Gómez-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

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 41º 8’ N and 42º13’N and between 0º 38’ E and 1º 43’ E. The altitude ranges between 200 m and 1000 m.

The climate type is Mediterranean, characterized 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 1441 ºC (zone II) to 2382 ºC (zone V), and the heliothermal index of Huglin (Huglin, 1978) ranges from 1877 ºC to 2500 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 characterized by a xeric soil moisture regime and a mesic or thermic soil temperature regime (SSS, 1999).

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 (Fig. 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 equivalent (Bernard calcimeter), active calcium carbonate equivalent (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).

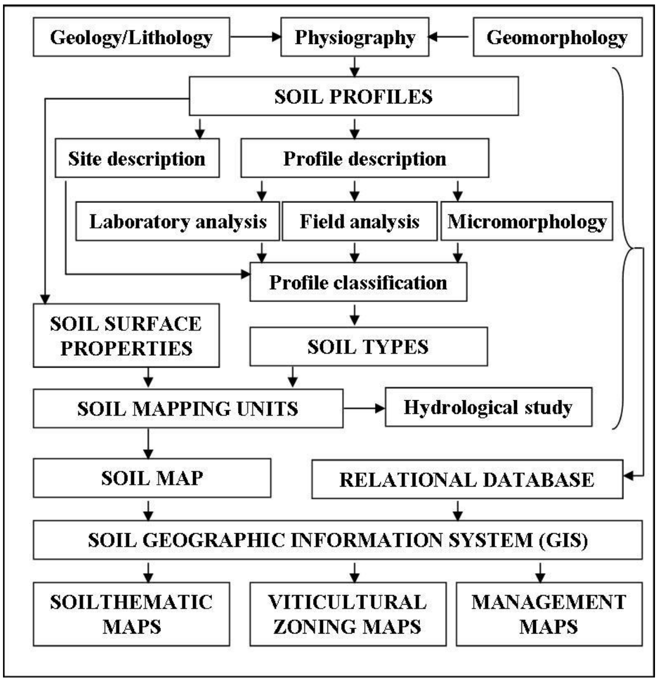

Figure 1. Flow chart of the vineyard soil mapping methodology (Ubalde et al., 2008).

When soil profiles were fully characterized, 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®).

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 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 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 $p\text{-level} < 0.05$. 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

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).

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

The most frequent soil order was Entisols, which are characterized 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 characterized 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 characterized 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 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).

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 sand and gravel) from soils with high contents of clay and high capacity of water retention. The only different subgroup is Xeropsamments, which are characterized 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 calcium carbonate and high iron chlorosis occurrence index from soils with high contents of iron. The only different subgroup is Calcixerepts, which are characterized 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 (Choné et al., 2001). The only different subgroup is Xerolls (Haploxerolls and Palexerolls), which are characterized 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.

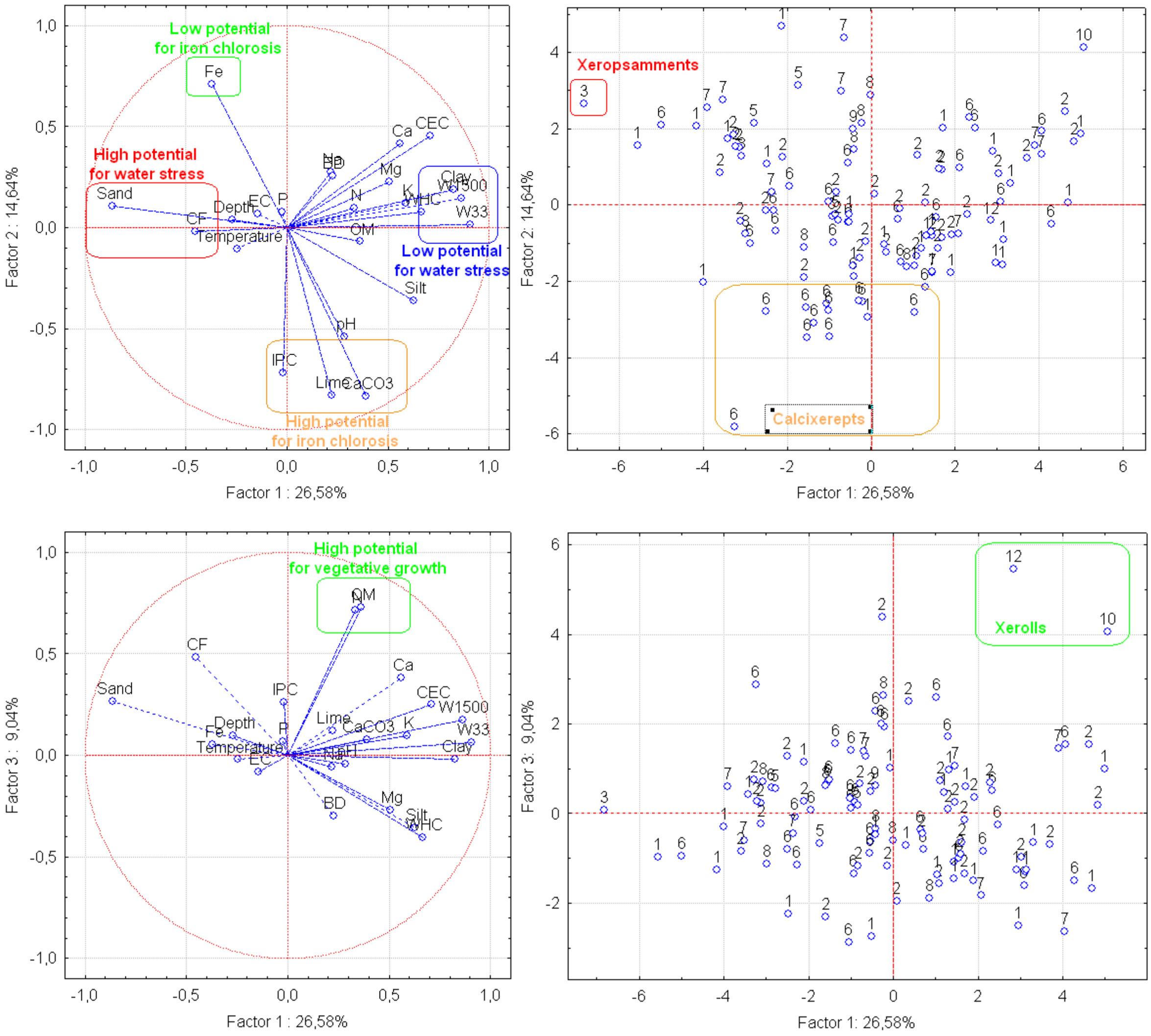

Figure 2. PCA of physical and chemical surface properties for soil series of the study area. In the first column there is the projection of variables and in the second column there is the projection of cases. In the first row there is represented factor 1 x factor 2, and the second row represents factor 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 iron chlorosis occurrence index; Lime, active calcium carbonate equivalent; Depth, thickness of rooting zone; Temperature, soil 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.

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.

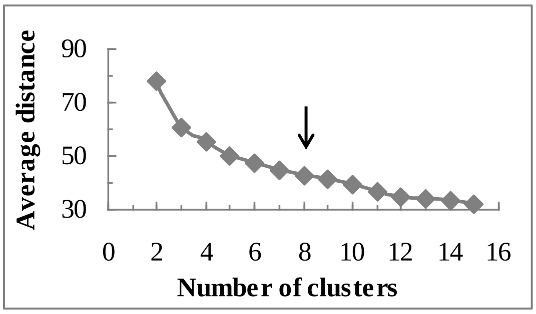

Figure 3. Estimation of final cluster number according to average distance between clusters.

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.

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 calcium carbonate equivalent (%); CEC, cation exchange capacity (cmol_c/kg); EC, electrical conductivity (dS/m); W1500 and W33, water content at -1500 and -33 kPa, respectively (%); WHC, water holding capacity (mm/10cm); IPC, iron-chlorosis occurrence index; Percent: Frequency of SMU into each cluster in percentage.

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 PCA.

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 properties are the ones that were used for cluster determination.

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

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.

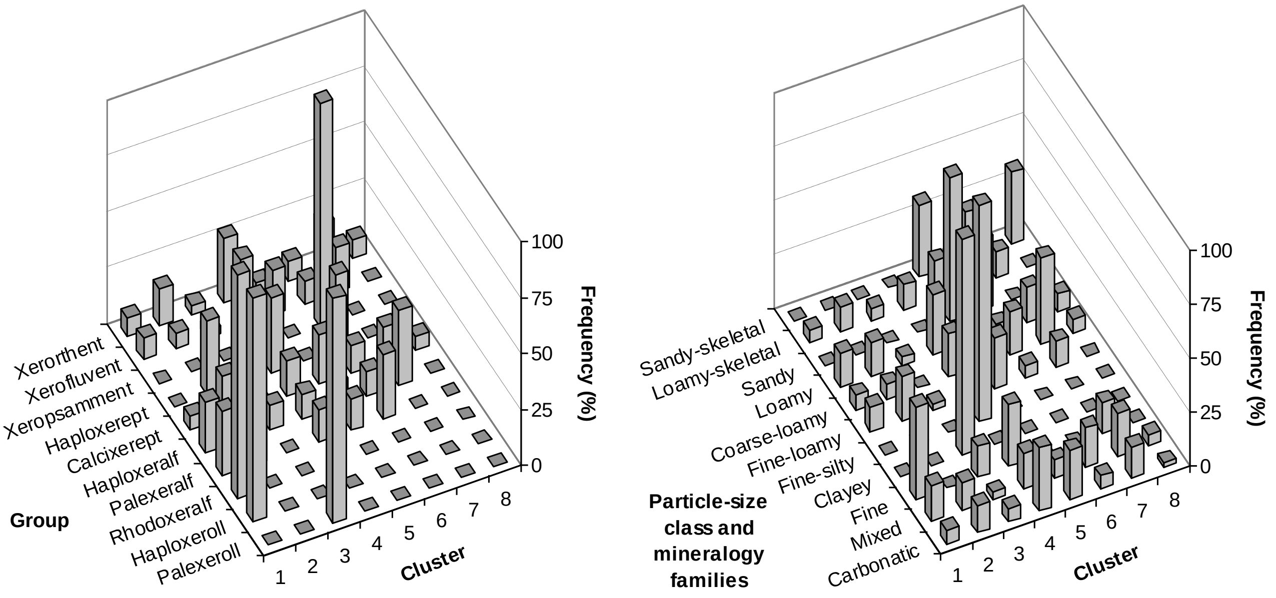

Figure 4. Frequency of each taxa into each cluster in percentage.

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 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.

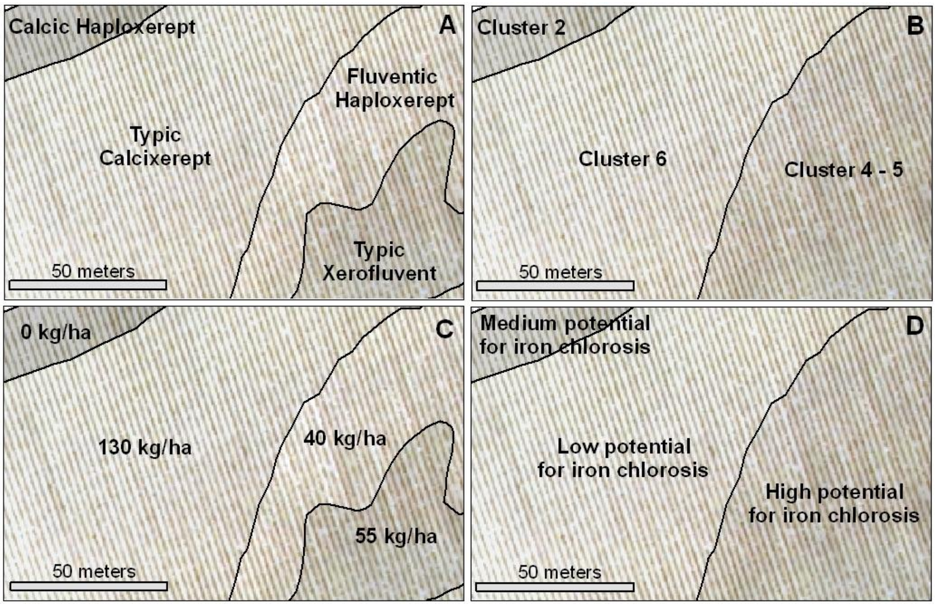

Figure 5. Detail of (A) the soil map according to Soil Taxonomy, (B) the cluster classes map, (C) the map for block management, concretely for mineral fertilization, and (D) the map of potential for vineyard growing, concretely for iron chlorosis.

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.

Chapter 3

HOW SOIL FORMING PROCESSES DETERMINE A VITICULTURAL ZONING BASED ON VERY DETAILED SOIL SURVEYS

Abstract

The aim of this study was to elucidate the soil forming processes of representative vineyard soils, and discuss about the implications on a soil-based viticultural zoning at very detailed scale. The study area is located in Priorat, Penedès and Conca de Barberà viticultural areas (Catalonia, North-eastern Spain). The studied soils belong to representative soil map units determined at 1:5,000 scale. The soil forming processes, identified through morphological and micromorphological analyses, have significant effects on some soil properties (clay content, cation exchange capacity, available water capacity and calcium carbonate content). These properties, especially those related to soil moisture regime, have a direct influence on vineyard management and grape quality. However, soil forming processes are not always reflected on soil classification, especially in soils modified by man. We show that climate or geology alone cannot be used in viticultural zoning, unless soil forming processes are taken into account.

Keywords: Soil formation, soil micromorphology, Soil Taxonomy, vineyard soil, terroir

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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 characterization of zones that produce grapes or wines of similar composition, while enabling operational decisions to be implemented (Vaudour, 2003). Among the various environmental factors and for a specific climate, soil is the most important factor on viticultural zoning, due to its direct effect on vine development and wine quality (Sotés and Gómez-Miguel, 2003). 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; Trégoat et al., 2002; Gurovich and Páez, 2004). In general, relationships between soil minerals and wine quality cannot be established (Seguin, 1986), except for nitrogen (Choné et al., 2001; Hilbert et al., 2003), unless severe deficiencies affecting vineyard growing occur (Van Leeuwen et al., 2004). For example, a calcium excess may be responsible of iron deficiencies (iron chlorosis), which can greatly affect grape production. However, some studies have shown an effect of soil cations on grapes and wine quality (Peña et al., 1999; Mackenzie and Christy, 2005). The physicochemical properties of soils are determined by the soil forming processes under which they form (Ritter, 2006). Some soil forming processes, such as clay accumulation or mineral weathering, may have a great influence on soil physical properties, which are the most important for grapevine cultivation.

There are several approaches through soil studies which are oriented to viticultural zoning (Van Leeuwen et al., 2002), but the methods that provide more information 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 Chéry, 2001). Therefore, soil maps are usually used as the basic maps for zoning studies. In Dutt et al. (1981) distinct viticultural regions were determined by considering the soil temperature regime. Astruc et al. (1980) considered the water availability as the most important factor, followed by carbonates and other chemical components. Morlat et al. (1998) considered the effective soil depth as the main property, 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 edaphoclimatic, biological and human factors (Duteau, 1981; Sotés and Gómez-Miguel, 1992; Van Leeuwen et al., 2002). Soil survey methods based on Soil Taxonomy classification (SSS, 1999) were useful for viticultural zoning studies at different detail levels (Gómez-Miguel and Sotés, 2001; Gómez-Miguel and Sotés, 2003, Ubalde et al., 2009). Soil forming processes are determining most of the diagnostic horizons and characteristics for the higher categories of Soil Taxonomy, thus the soil genesis is fundamental to soil taxonomy and soil survey.

In this way, soil forming processes, through their effects on edaphic properties and their implications on Soil Taxonomy, may have a great importance on a viticultural zoning based on soil surveys. However, as mentioned above, many viticultural zoning studies are based on the relationships between grape and wine quality and certain soil properties or different soil forming factors, namely climate (Coombe, 1987; Hamilton, 1989), geology (Van Schoor, 2001) and topography (Dumas et al., 1997), but there are no studies that consider possible relationships with soil forming processes. This fact may be due to difficulties in determining some of these processes, because soil genesis cannot be observed or measured directly and pedologists could differ about it (SSS, 1999). Evidences of some soil forming processes can be detected only by microscopic studies, which require a specific training. Furthermore, some soil forming processes are not adequately addressed by the taxonomic system, especially those related to human activity (SSS, 1999). The International Committee on Anthropogenic Soils (ICOMANTH) was created to improve anthropogenic soil classification in Soil Taxonomy. These last years, soils deeply affected by men have greatly increased in many viticultural areas, related to the expansion of global wine market (Cots-Folch et al., 2005; Ramos et al., 2007; Dazzi et al., 2009).

In this study, representative soils of a very detailed soil survey, which was carried out for viticultural zoning purposes, were selected. The study area is composed of high quality producing vineyards of Catalonia, namely the viticultural regions of Priorat, Conca de Barberà and Penedès. The relationship between soils and grape and wine quality in the study area is discussed elsewhere (Andrés-de-Prado et al., 2007, Ubalde et al., 2007, 2009). In this paper we want to analyse whether the soil forming processes, through their effects on soil properties and classification, deserve to be considered in a viticultural zoning based on soil surveys. At our knowledge, this approach has never been addressed before. In short, the aim of this study was to elucidate the soil forming processes of representative vineyard soils, and discuss about the implications on soil classification and viticultural zoning.

Materials and methods

The study area is high quality producing vineyards, located in different protected viticultural areas of Catalonia: Conca de Barberà, Priorat and Penedès. The area is enclosed approximately between 41º 3’ N and 41º 48’ N and between 0º 40’ E and 1º 53’ E. The altitude ranges approximately between 220 m and 550 m. The study area has an old viticultural history, which started in some cases during the 4th century BC. Since the 1980s - 1990s, the systems of grapevine cultivation have evolved to highly mechanized farms, which seek to obtain maximum profitability but maintaining high quality products. Thus, a widespread practice was the removal of old stone walls, in order to obtain larger plots. In these cases, land levelling usually involved a change in the arrangement of soil horizons, sometimes leading to a decline of soil fertility.

The vineyards are situated on the Catalan Coastal Range and the Ebro Basin. The Catalan Coastal Range is an alpine folding chain formed by both massifs and tectonic trenches (Anadón et al., 1979). The Conca de Barberà soils are located in the footslope of the massif, named ‘Serra de Prades’ in this region. The soils are developed from gravel deposits of different ages, which are composed of siliceous Paleozoic materials (Silurian and Carboniferous slates and granites) (IGME, 1975a). The Priorat soils are located in the hillslope of the Priorat Massif, which is composed of Carboniferous slates and granodiorites (IGME, 1978). The slates are named ‘llicorella’ in this region, and they are considered the main responsible for grape quality. The selected Penedès soils are located in 2 subdivisions, which can be called Upper Penedès and Middle Penedès. The Middle Penedès soils are located in a tectonic trench named Penedès Basin, where calcareous Miocene materials (marls, conglomerates, limes) outcrop (IGME, 1982). The Upper Penedès soils are located in the Ebro basin margin, next to the Alt Gaià Massif. Calcareous materials from Oligocene and Eocene predominate in this region (IGME, 1975b).

The climate type is Mediterranean, characterized 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 ranges from 520 mm in Penedès to 589 mm in Priorat, showing seasonal variations (Fig. 1). In all regions, the precipitation has a bimodal distribution (peaks in spring and autumn) and a minimum of precipitation in summer, particularly in July. The highest temperatures occur in summer, particularly in July or August, while the lowest temperatures occur in winter (January). Comparing different regions, the warmest one is Penedès, with an average annual temperature of 14.9 ºC, and the coolest one is Priorat, with an average annual temperature of 12.7 ºC. The soil moisture regime is xeric and the soil temperature regime is mesic (Priorat and Conca de Barberà) or thermic (Penedès) (SSS, 1999).

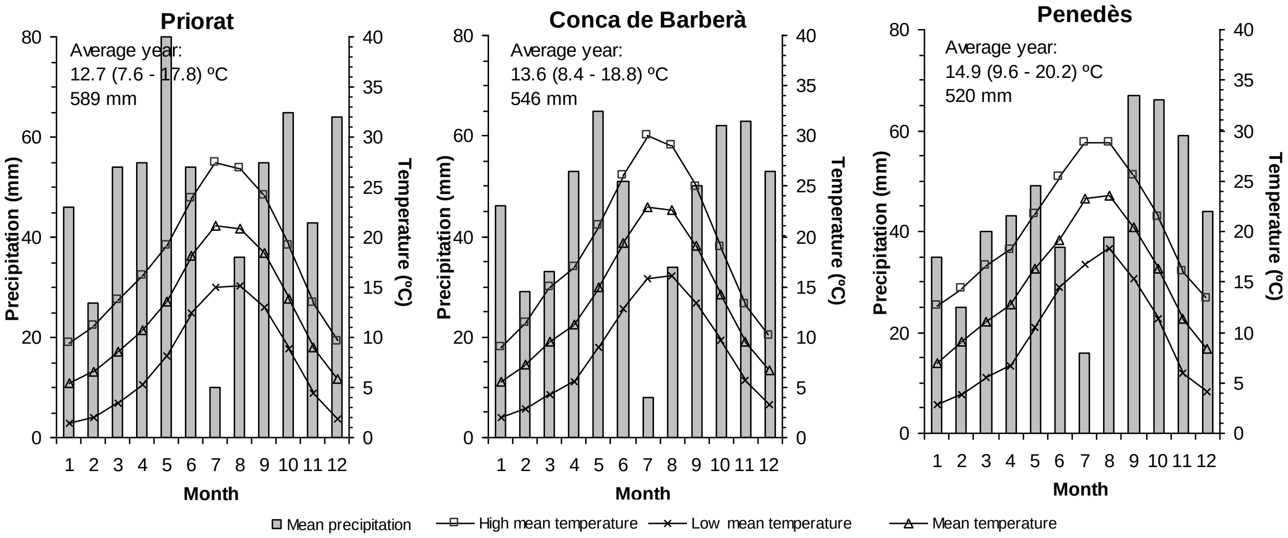

Fig. 1. Average climatic data of the viticultural areas of Priorat, Conca de Barberà and Penedès.

The studied soils belong to soil map units determined according to the Soil Survey Manual of the Department of Agriculture of United States (SSS, 1993), at very detailed scale (1:5,000). Soil map units were delineated as polygons from soil observations, which were selected according to different landforms and lithologies. 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. When applying a ratio of soil pit:soil auger hole 1:5, 0.7 soil pits by hectare were dug. 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), total calcium carbonate equivalent (Bernard calcimeter), active calcium carbonate equivalent (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. For the micromorphological study, thin sections were elaborated from undisturbed soil material according to Benyarku and Stoops (2005). Samples were taken of deep horizons, since surface horizons were disturbed by ploughing. One to two samples were collected for each selected profile. We described a total of 23 thin sections from 19 different profiles and 8 soil map units. The criteria of Stoops (2003) were used in thin section description.

When soil profiles were fully characterized, they were classified according to Soil Taxonomy (SSS, 2006) at series level. Each series consists of soil layers that are similar in colour, texture, structure, pH, consistence, mineral and chemical composition, and arrangement in the profile. In the study area every 3 to 4 soil profiles belonged to one soil series, by average.

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 and stoniness. When all SMU were delineated, they were listed and codified and the soil map legend could be designed. The final number of SMU was approximately twice the number of soil series. The mean surface of the delineated SMU was 1.4 hectares.

Significant differences among soil series were analysed by ANOVA, considering the analytical properties of soil series as dependent variables and soil series as categorical factors. This analysis was done for each horizon separately. Means were separated by Newman-Keuls post-hoc analysis ($p < 0.05$). The software used was STATISTICA (StatSoft, Inc.).

Results and discussion

In this study, a wide range of soil forming processes was identified in vineyard soils of Catalonia, which is reflected in their classification. The studied soils belong to Entisol, Inceptisol and Alfisol orders (SSS, 2006), according to a wide variety of soil forming processes and their resulting diagnostic horizons and characteristics (Table 1). Entisols are characterized by little or no evidence of soil formation, so that any diagnostic horizons are not developed, except to an ochric horizon. Within that order, the suborders found are Orthents, Fluvents, Psamments and Arents. Orthents are formed on recent erosional surfaces, and most of them are shallow soils with a root-limiting layer (lithic or paralithic contact). Fluvents are formed in alluvial and colluvial parent materials, and are characterized by being deep soils, which are rich in organic matter in depth. Psamments are characterized by being sandy. Arents are anthropogenic soils, deeply mixed by methods of moving by humans. Arents should present diagnostic horizons not arranged in any discernible order. With regard to Inceptisols, these soils are characterized by being in early stages of soil formation. These soils could undergo distinct accumulation processes of carbonates and gypsum or simply evidences of physicochemical transformations or removals. Soils with well-developed carbonate accumulations (calcic horizon) or cementations (petrocalcic horizon) are classified as Calcixerepts and soils with gypsum accumulations (gypsic horizon) are classified as Gypsic Haploxerepts. The Haploxerept group is also used when accumulations processes are too incipient to form calcic or gypsic horizons, or when a change of colour occurred. In this case, the diagnostic horizon described is cambic. Finally, Alfisols are characterized by silicate clay illuviation (argillic horizon) and a base saturation greater than 50 %. In the study area, these soils could present carbonate accumulations (calcic horizon), covering clay accumulations.

The presence of carbonates in parent material determines the carbonate accumulation processes identified in Penedès area, much more intense than those of Priorat and Conca de Barberà. Calcium carbonate accumulations in soils are possible thanks to a Mediterranean climate, which are responsible of seasonal soil water deficits. However, some processes, such as clay illuviation in calcareous soils, can only be explained by a wetter relict climate, which would allow a substantial base leaching and a slight acidification. The time effect can be observed in Conca de Barberà soils, which are developed from colluvial deposits of different ages but same origin. In modern colluvial deposits, the most developed soil forming process is in situ clay neoformation. However, a process of clay illuviation and then a process of secondary carbonate accumulation could take place in the old colluvial deposits. Obviously, the variations in climate over time had strongly influenced these processes. Regarding the relief factor, Priorat soils on hillslopes or Penedès soils on valley bottoms were more exposed to processes of soil rejuvenation than Conca de Barberà soils on more stable positions. The main effects of biological activity are related to bioturbation. However, biogenic carbonate accumulations are described in Penedès region. Finally, human activity has a strong influence on the formation of some soils of the study area. The most aggressive activities are related to land levelling and terracing. Soil tillage and the application of fertilizers and manures also affect surface horizons.

Table 1. Classification and main characteristics of vineyard soils in the Catalan Coastal Range.

Order	**Suborder**	**Group**	**Subgroups**	**Diagnostic horizons**	**Main characteristics**
Entisols	Orthents	Xerorthents	Typic	Ochric	Paralithic contact
			Lithic	Ochric	Lithic contact
	Fluvents	Xerofluvents	Typic	Ochric	High content of organic carbon in deep horizons
	Psamments	Xeropsamments	Typic	Ochric	Texture coarser than sandy loam
	Arents	Xerarents	Alfic	Ochric, argillic	Diagnostic horizons not arranged in any discernible order
Inceptisols	Xerepts	Haploxerepts	Typic	Ochric, cambic	Evidences of the removal of carbonates or rubefaction
			Fluventic	Ochric, cambic	Rubefaction and high content of organic carbon in deep horizons
			Gypsic	Ochric, gypsic	Significant secondary gypsum accumulations
		Calcixerepts	Typic	Ochric, calcic	Significant secondary carbonate accumulations
			Petrocalcic	Ochric, petrocalcic	Horizons indurated by secondary carbonates
Alfisols	Xeralfs	Palexeralfs	Calcic	Ochric, argillic, calcic	Evidence of clay illuviation and significant secondary carbonate accumulations

Soil forming processes in Priorat

The selected Priorat soils are developed in the Priorat Massif, which is composed mainly of Paleozoic slates, which are intruded by granodiorite veins in some areas. Generally, these soils are poorly developed, that is, they show little evidence of soil formation. This is because these soils are formed on recent erosional surfaces (hillslopes), with shallow parent materials, which are greatly affecting soil properties. Moreover, the properties of the parent materials are not particularly favourable for the development of soil structure. Slates are highly exfoliated, favouring high rock fragment contents, and the weathering product of granodiorites is granitic sands, named ‘sauló’ in the study area, which greatly hinder the aggregation of particles (soil structure formation).

As mentioned above, soils developed from granodiorites are characterized by being shallow and with very high sand content, in relation to the parent material composition. The parent material is a granitic regolith up to 2-5 m, which is a product of in situ alteration of the granodiorite, and it correspond to a sandstone formation with a small proportion of clay and silt. This sand could be broken up with a shovel, but it is too compact to permit root development. The parent material is composed of eye-visible crystals of quartz, feldspar (plagioclase and orthose) and mica (biotite) (Fig. 1). These minerals are generally unaltered, but locally some biotite crystals are transformed to chlorite and vermiculite. Generally, this regolith is light-coloured, but in some cases is strongly rubefacted. This red colour is related to clay accumulations, whose origin is mainly biotite alteration, which resulted in pseudomorphic units of oriented clay (Fig. 2). However, some clay could have an illuvial origin, as suggested by McKeague (1983) in similar soils. The clay pedofeatures are pure microlaminated coatings on sand grains (0.05 - 0.1 mm width).

On the other hand, soils developed from slates are shallow and with high rock fragment contents, representing a strong limitation to root development. However, the parent material, composed of iron and magnesium silicates, present a planar exfoliation that roots can use for their development. In addition, clay accumulation processes are found in some cracks, creating intercalations of clayey material in the rock (Fig. 3). These intercalations could suppose until 15% in total slate volume. The described pedofeatures are coatings and infillings of clay in pores and cracks of coarse components. In all these types of accumulations, clay is pure, that is, it do not present other particles sizes (silt). Accumulations show a microlaminated internal contexture, sometimes hard to see. The origin of clay is probably illuvial, as it meets the characteristics of an ideal argillic horizon (McKeague, 1983): continuous coatings on both sides of the pores, strongly oriented, with microlamination, without sand grains and clearly different from the matrix which does not contain any fragment of oriented clay.

In all soils, redoximorphic mottles of iron and manganese are described related to clay accumulations. The pedofeatures are impregnative nodules, associated to pores and coarse components. These nodules are dark, with a gradual boundary, an irregular shape and a diameter between 0.1 and 0.4 mm. These nodules indicate an incipient hydromorphy, caused by perched water tables, of limited influence area, which would be possible thanks to high clay content.

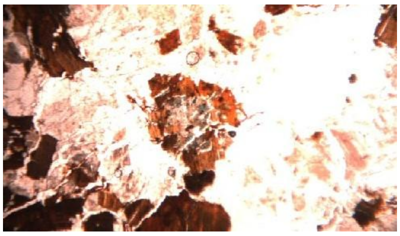

Figure 1. Mineral composition of granitic regolith (quartz in pure white, feldspars in impure white, mica in dark), with mica alteration in the centre of the picture (6.4 mm width, PPL).

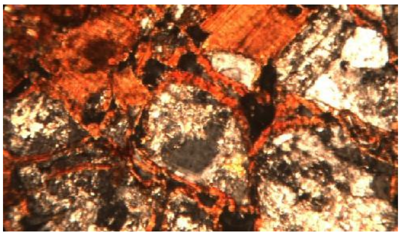

Figure 2. In situ clay neoformation in rubefacted granitic regolith: microlaminated coatings on sand grains (1.5 mm width, XPL).

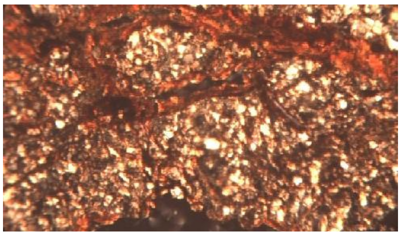

Figure 3. Clay illuviation in slates: clay infillings in cracks and clay coatings in pores (1.5 mm width, XPL).

The Priorat soils are classified as Entisols, since the soil forming processes are not enough developed to determine any diagnostic horizon, except an ochric horizon. In general, soils developed from granodiorites are classified as Xeropsamments, which are characterized by a texture coarser than loamy fine sand and less than 35 % of rock fragments (Table 3). However, soils developed from rubefacted granitic regolith, are classified as Typic Xerorthents. These soils cannot be classified as Alfisols, since evidences of illuvial clay is required for an argillic horizon, and in this case, the clay origin is biotite alteration. Moreover, these soils cannot be classified as inceptisols because the deep horizons maintain the rock structure, and consequently the criteria for cambic horizon are not accomplished. With respect to soils developed from slates, they are classified as Lithic Xerorthents, in spite of presenting an exfoliated rock with intercalations of material enriched in illuvial clay. There is a subgroup in the Alfisols, named Lithic ruptic-inceptic Haploxeralfs, which is defined by presenting a lithic contact and an argillic horizon discontinuous horizontally. However, in the studied soils, the thickness of material with illuvial clay is generally lower than 7.5 cm, so the criteria for argillic horizon are not accomplished.

In Priorat soils, the clay formation supposes an improvement of the soil water reservoir for the vineyard, a fact which is specially important in a very stressful environment, related to a Mediterranean climate with a dry season with high temperatures, soil shallowness and high content of gravels or sands, which confer a very quick internal drainage of soil. In soils developed from slates, the available water capacity (AWC) of plough horizons is moderate (42.4 mm between 0 and 45 cm depth), so the water retained by the clay-rich materials among the rock cracks is worth considering (23.3 mm between 45 and 138 cm depth) (Table 3). Moreover, the presence of redoximorphic features related to clay features would indicate that clay accumulation is causing an alteration in the soil moisture regime. In soils formed from granodiorites, processes with major implications for grapevine cultivation are also identified. These soils, in addition to shallowness, are composed practically by sand (Table 3), so that there are not particles of silt or clay to retain water. As a result, these soils produce a higher water stress than soils formed from slates, because they have a very low AWC (12.4 mm between 0 and 42 cm depth). In order to obtain a high quality production, irrigation with low doses applied frequently is needed. The existence of rubefacted granodiorites with neoformed clay (Typic Xerorthents) result in soils with finer textures, with a significant increase of the AWC (45.8 mm between 0 and 37 cm depth) in comparison with the non-rubified Xeropsamment. Although irrigation is still necessary, water losses may be smaller. Another soil property improved with clay accumulations is the cation exchange capacity (CEC) of surface and deep horizons. In surface horizons, CEC significantly increases from 4.4 to 9.9 cmol_c/kg. This increase represents a substantial improvement of nutrient availability for the vine and the possibilities of development of soil structure and stability of soil aggregates, which is especially important in these soils that are poor in organic matter (contents lower than 0.5%). In short, clay accumulations improve the AWC and CEC, although not always involve major changes in soil classification.

Table 3. Analytical properties of representative vineyard soils in Priorat region *.

Properties	Horizon	Sandy, mixed, mesic, shallow, Typic Xeropsamments	Loamy, mixed, active, mesic, shallow, Typic Xerorthents	Loamy-skeletal, mixed, semiactive, mesic, Lythic Xerorthents
Soil Forming Processes		Mineral weathering, incipient mica alteration	Clay neoformation and rubefaction, generalized clay coatings on sand grains	Clay illuviation, clay coatings limited on rock cracks
Genetic horizon (SSS, 2006)	**1**	Ap_1	Ap_1	Ap_1
	2	Ap_2	Ap_2	Ap_2
	3	C	C	R/Bt (15% volume)
Lower depth (cm)	**1**	22.8 (1.18) a	14.5 (0.50) b	20.4 (2.06) ns
	2	42.1 (3.06) ns	37.0 (3.00) ns	45.0 (1.83) ns
	3	123.7 (8.85) ns	140.0 (10.00) ns	138.3 (18.90) ns
Munsell Colour	**1**	10YR5/4	5YR4/5	10YR4/4
	2	10YR5/5	5YR4/6	10YR4/4
	3	10YR5/6	5YR5/7	2.5Y5/4
pH (H_2O 1:2.5)	**1**	8.4 (0.07) a	8.4 (0.05) a	7.4 (0.19) b
	2	8.3 (0.11) a	8.4 (0.05) a	7.3 (0.17) b
	3	8.4 (0.08) a	8.4 (0.25) a	7.1 (0.31) b
Electrical Conductivity (1:5, dS/m)	**1**	0.20 (0.03) ns	0.16 (0.02) ns	0.41 (0.16) ns
	2	0.23 (0.03) ns	0.15 (0.01) ns	0.26 (0.04) ns
	3	0.21 (0.03) ns	0.23 (0.05) ns	0.38 (0.14) ns
Organic matter (%)	**1**	0.1 (0.03) ns	0.4 (0.10) ns	1.6 (0.99) ns
	2	0.3 (0.07) b	0.2 (0.10) b	1.4 (0.27) a
	3	trace	trace	trace
$CaCO_3$ equivalent (%)	**1**	trace	trace	trace
	2	trace	trace	trace
	3	trace	trace	trace
Cation Exchange Capacity (cmol$_c$/kg)	**1**	4.4 (1.02) b	9.9 (0.80) a	12.7 (0.46) a
	2	5.3 (0.13) c	9.0 (0.20) b	12.0 (0.80) a
	3	5.3 (0.65) b	8.9 (0.28) b	15.0 (0.00) a
Sand (%)	**1**	92.1 (0.64) a	62.9 (8.85) b	70.4 (2.98) b
	2	91.0 (0.52) a	72.1 (6.50) b	73.0 (4.54) b
	3	94.8 (0.51) a	89.4 (3.50) a	53.6 (0.00) b
Silt (%)	**1**	5.6 (0.46) b	22.3 (6.35) a	19.5 (3.24) a
	2	6.8 (0.45) b	16.4 (3.75) a	18.4 (3.87) a
	3	4.2 (0.32) b	7.4 (1.25) b	27.8 (0.00) a
Clay (%)	**1**	2.4 (0.56) b	14.9 (2.50) a	10.1 (0.42) a
	2	2.2 (0.50) b	11.6 (2.75) a	8.6 (1.15) a
	3	1.0 (0.41) b	3.3 (2.25) b	18.6 (0.00) a
Textural class (SSS, 2006)	**1**	Sand	Sandy loam	Sandy loam
	2	Sand	Loamy sand	Sandy loam
	3	Sand	Loamy sand	Sandy loam
Bulk density (kg/m^3)	**1**	1507.9 (10.25) b	1373.5 (10.42) b	1764.3 (97.75) a
	2	1545.1 (32.46) b	1665.9 (27.93) b	1931.0 (89.51) a
	3	1963.6 (16.42) a	1888.0 (0.74) b	1918.2 (20.86) ns
Coarse fragments (%)	**1**	trace	trace	53.3 (2.90)
	2	trace	trace	59.3 (2.73)
	3	-	-	22.0 (4.00)
Water retention at -33 kPa (%)	**1**	4.7 (0.33) b	16.0 (1.00) a	21.4 (1.75) a
	2	5.7 (0.67) b	14.2 (2.00) a	18.3 (2.25) a
	3	-	-	22.0 (1.50)
Water retention at -1500 kPa (%)	**1**	3.2 (0.00) b	7.5 (0.50) a	8.0 (0.73) a
	2	3.3 (0.33) b	6.5 (0.50) a	8.0 (0.89) a
	3	-	-	11.0 (2.50)
Available Water Capacity (mm/10 cm)	**1**	2.3 (0.02) b	11.7 (0.09) a	11.0 (0.31) a
	2	3.7 (0.08) c	12.8 (0.22) a	8.1 (0.49) b
	3	-	-	2.5 (0.35)

*Numbers between brackets correspond to standard errors and different letters indicate significant differences ($p<0.05$) among the same horizons of different soil series, according to Newman-Keuls test (n=3).

Soil forming processes in Penedès

The Penedès soils differ from the soils in the other areas by their parent materials which are richer in calcium carbonate, so that carbonate-related soil forming processes are better represented. Much of the carbonate accumulations are due to the precipitation of calcite from saturated solutions, which is leached from upper horizons or from lateral water flow caused by an impervious horizon. However, some carbonate accumulations come from biological activity, which cause a carbonate microdistribution around biopores (Boixadera et al., 2000). The features of biological accumulations are infillings of citomorphic calcite (quesparite) in pores (Fig. 4). The features of carbonate illuviation are representative of different degrees of calcification. First, a process of crystallization produced acicular crystals and few hypocoatings of micrite and microsparite (Fig. 5). Then, a process of recrystallization produced abundant coatings and well-developed hypocoatings, pendants, nodules and infillings of sparite and microsparite (Fig. 6). Later, carbonates (micrite) began to occupy the micromass. In this stage, processes of displacement and replacement of grains or clay coatings by carbonates could occur. The most evolved stage correspond to carbonate cementation (petrocalcic horizons).

Besides carbonate accumulation, processes of gypsum accumulation are found in the Upper Penedès soils. The gypsum-related features are coatings of lenticular crystals. In addition, mixed silt and clay hypocoatings around pores and coarse components, poorly oriented, are very common in clayey soils. These features corresponded to whole-soil hypocoatings (Fitzpatrick, 1990, 1993), originated by the downward flow of a suspension of fine material, which may disperse after a single rain. It is a characteristic feature of clayey, continuously cultivated soils, which loose their structure, crack and form wide planar vertical pores.

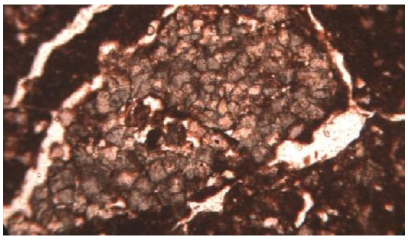

Figure 4. Biological carbonate accumulation in Typic Xerofluvents: pore infillings of citomorphic calcite. (1.5 mm width, PPL).

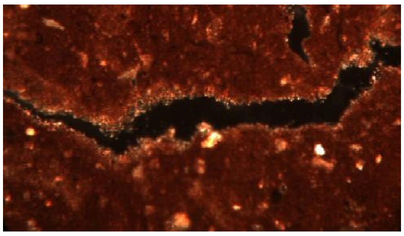

Figure 5. Carbonate redistribution in Typic Xerofluvents: acicular crystals infillings and microsparite hypocoating. (1.5 mm width, XPL).

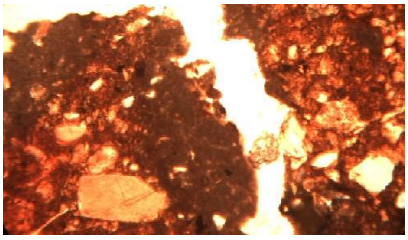

Figure 6. Carbonate redistribution in Typic Calcixerepts: well-developed microsparite hypocoating. (1.5 mm width, PPL).

Most of the Penedès soils are classified as Inceptisols, because carbonate or gypsum accumulations are expressed enough to identify calcic, petrocalcic or gypsic horizons. Generally, they are classified as Typic Calcixerepts, Petrocalcic Calcixerepts and Gypsic Haploxerepts, respectively. However, not all soils with carbonate accumulations can be classified as Calcixerepts, since they do not meet the criteria for a calcic horizon. A calcic horizon requires a minimum thickness of 15 cm, a minimum $CaCO_3$ content of 15 % and identifiable secondary calcium carbonate, with some exceptions. Some described soils show incipient accumulations or present too low $CaCO_3$ content. Generally, these accumulations lead to cambic horizons, and soils are classified as Typic Haploxerepts. Even in some cases, where carbonate accumulations are not visible at the naked eye, a cambic horizon cannot be determined, and soils are classified as Entisols. Moreover, accumulations of mixed silt and clay (whole-soil hypocoatings) do not have any connotation in soil classification. Table 4 shows the analytical properties and the description of accumulations in a soil with a well-developed calcic horizon (Typic Calcixerept), a soil with incipient accumulations of carbonates and accumulations of mixed silt and clay (Typic Xerofluvent), as well as a soil with a gypsic horizon (Gypsic Haploxerept).

The soil forming processes in Penedès are marked by the accumulation of secondary carbonates, which can be highly evolved, as it is indicate by the types of accumulations and their morphology This evolution is reflected with the calcium carbonate content, with mean values near 60 % (Table 4), and with carbonate cementations. The evolution of carbonates in these soils may be a limiting factor for grapevine cultivation. High contents in calcium carbonate can cause a weakening in non-resistant vines, due to iron chlorosis. The carbonates increase the concentration of the HCO_3^- anion in the soil solution, and this blocks the absorption of iron by plants. The main consequences are the rickets, the foliage destruction, a reduced production and even the death of the plant. These problems may be mitigated by the choice of resistant rootstocks, such as 41B and 140R. Furthermore, very intense processes of carbonate accumulation, which leads to a micromass cementation, may constitute a limitation for the development of the root system. Moreover, carbonate accumulations in the form of nodules increase the coarse fragment content, and thus reduce the available water capacity (AWC). In deep horizons of a Typic Calcixerept, a loss of 11 mm of AWC can be quantified (between 50 and 100 cm depth), considering a volume of 20% of carbonate accumulations. However, the main implications of carbonate accumulations on vineyard management are related to rootstock selection and ploughing, which should not be too deep to prevent mixing of calcic horizons with surface horizons.

Table 4. Analytical properties of representative vineyard soils in Penedès region *.

Properties	Horizon	Fine, mixed, semiactive, thermic, Typic Xerofluvents	Coarse-loamy, carbonatic, thermic, Typic Calcixerepts	Coarse-loamy, mixed, active, thermic, Gypsic Haploxerepts
Soil Forming Processes		Incipient carbonate accumulations: microscopic nodules, infillings and hypocoatings. Silt and clay accumulations.	Well-developed carbonate accumulations: macroscopic coatings on pores, geopetal cement and nodules; slight cementation.	Gypsum accumulations, crystals and coatings on pores.
Genetic horizon (SSS, 2006)	**1**	Ap_1	Ap_1	Ap_1
	2	Ap_2	Ap_2	Ap_2
	3	Bw	Bkn	By
Lower depth (cm)	**1**	13.0 (1.00) ns	17.0 (1.91) ns	13.3 (3.33) ns
	2	41.7 (1.67) ns	49.7 (4.63) ns	40.3 (1.45) ns
	3	98.3 (1.67) ns	99.2 (13.31) ns	78.3 (9.28) ns
pH (H_2O 1:2.5)	**1**	8.2 (0.09) a	8.5 (0.09) a	7.9 (0.00) b
	2	8.3 (0.10) a	8.5 (0.06) a	7.9 (0.00) b
	3	8.2 (0.15) ns	8.4 (0.05) a	8.0 (0.06) b
Electrical Conductivity (1:5, dS/m)	**1**	0.19 (0.01) b	0.19 (0.01) b	2.29 (0.01) a
	2	0.20 (0.03) b	0.21 (0.02) b	2.42 (0.08) a
	3	0.37 (0.15) b	0.32 (0.06) b	2.39 (0.04) a
Organic matter (%)	**1**	1.6 (0.17) ns	1.4 (0.12) ns	1.5 (0.13) ns
	2	1.2 (0.12) ns	1.1 (0.20) ns	1.2 (0.15) ns
	3	1.0 (0.23) ns	0.8 (0.16) ns	0.4 (0.10) ns
$CaCO_3$ equivalent (%)	**1**	33.0 (3.01) b	55.5 (8.41) a	26.3 (2.40) b
	2	35.7 (3.18) b	57.7 (9.96) a	25.0 (2.52) b
	3	28.3 (7.62) b	56.8 (6.54) a	22.0 (6.81) b
Gypsum (%)	**1**	trace	trace	32.7 (3.53)
	2	trace	trace	34.3 (3.53)
	3	trace	trace	44.0 (5.51)
Cation Exchange Capacity ($cmol_c$/kg)	**1**	14.0 (1.76) a	6.5 (1.06) b	10.9 (0.65) ns
	2	13.3 (1.82) a	6.4 (1.03) b	10.0 (0.75)ns
	3	16.5 (0.94) a	5.1 (0.58) b	7.8 (0.25) b
Sand (%)	**1**	31.9 (6.87) b	51.8 (3.82) a	42.2 (3.03) ns
	2	30.9 (7.75) b	50.1 (3.46) a	42.0 (1.91) ns
	3	19.3 (4.99) b	54.0 (4.83) a	59.5 (11.45) a
Silt (%)	**1**	35.4 (2.84) b	33.7 (2.67) b	50.5 (3.77) a
	2	38.6 (3.69) b	33.9 (2.19) b	53.2 (3.23) a
	3	36.2 (7.61) ns	31.5 (3.42) ns	34.3 (11.70) ns
Clay (%)	**1**	32.7 (4.43) a	14.5 (1.42) b	7.2 (0.91) b
	2	30.5 (5.50) a	16.1 (1.60) b	4.8 (1.32) c
	3	44.5 (4.42) a	14.5 (1.94) b	6.3 (0.25) b
Textural class (SSS, 2006)	**1**	Silty clay	Sandy loam	Silty loam
	2	Silty clay	Sandy loam	Silty loam
	3	Silty clay	Sandy loam	Sandy loam
Bulk density (kg/m^3)	**1**	1488.0 (120.00) ns	1383.8 (73.26) ns	1481.0 (42.00) ns
	2	1802.0 (29.00) ns	1517.3 (114.19)ns	1869.0 (46.00) ns
	3	1766.0 (12.00) ns	1502.5 (62.98) ns	1735.0 (40.00) ns
Coarse fragments (%)	**1**	trace	14.3 (10.65)	trace
	2	trace	12.0 (8.55)	trace
	3	trace	28.0 (7.40)	trace
Water retention at -33 kPa (%)	**1**	23.3 (1.86) a	14.8 (0.75) b	26.7 (0.88) a
	2	23.0 (2.08) a	15.8 (0.95) b	26.7 (0.33) a
	3	26.7 (0.88) a	13.3 (1.65) c	22.0 (1.00) b
Water retention at -1500 kPa (%)	**1**	12.0 (1.53) a	6.0 (0.41) b	13.3 (0.67) a
	2	12.3 (1.45) b	7.0 (0.58) c	15.3 (0.33) a
	3	15.0 (0.58) a	5.8 (0.63) b	13.3 (0.67) a
Available Water Capacity (mm/10 cm)	**1**	15.0 (1.40) ns	10.5 (1.84) ns	19.3 (0.55) ns
	2	18.7 (2.58) ns	11.8 (1.89) ns	21.5 (1.46) ns
	3	20.7 (1.16) a	8.1 (1.82) b	14.8 (1.21) ns

*Numbers between brackets correspond to standard errors and different letters indicate significant differences ($p<0.05$) among the same horizons of different soil series, according to Newman-Keuls test (n=3).

Soil forming processes in Conca de Barberà

The selected Conca de Barberà soils are developed on deposits of gravels coming from the massif of 'Serra de Prades', mainly Carboniferous slates and sandstones, with granodiorite intrusions. During the Quaternary, these deposits covered the Ebro basin margin in the form of alluvial fans, which left two types of gravel deposits. There are ancient deposits, hanged at a considerable height over the current river bed, and other modern deposits, at a little height about the current river bed and connected with the fluvial terraces.

The modern deposits correspond to extensive, flattened alluvial cones, merged with each other, which are formed by Paleozoic materials (mainly slates) and with little matrix. In soils developed from these deposits, a process of clay accumulation is identified, in the form of coatings (<0.05 mm) and infillings (<0.25 mm) of clay, covering the pores and sides of coarse components (Fig. 7). These coatings are quite impure, showing silt and clay embedded. The clay origin is probably the neoformation from mica alteration, since many coatings with embedded altered mica crystals could be observed. Many of these coatings are fragmented and incorporated into the micromass. Other authors found that in these conditions the clay origin is probably clay neoformation from mica (Mermut and Jongerius, 1980; McKeague, 1983).

The old deposits were much more extensive before, so that now some vestiges are only preserved. These deposits have a thickness of 3-4 m and are formed by very weathered polygenic gravels (granodiorites, sandstones and slates) and a reddish cement composed of clay and sand. In these soils, which are more developed that modern deposits, processes of clay and carbonate illuviation are identified. The textural features are coatings and infillings of microlaminated pure clay, up to 0.8 mm width, covering the cracks and sides of coarse components and pores (Fig. 8). Many of these coatings are fragmented and incorporated to micromass, so few of them are related to present pores. The carbonate-related features described in the field are carbonate pendants (up to 15 mm width), and microscopically the described features are microsparite coatings and infillings in pores, and sometimes on clay coatings, sparite pendants (Fig. 9), micritic nodules and fragments of laminar petrocalcic horizons.

Both soils presented redoximorphic features, in the form of suborthic manganese nodules, between 0.1 and 1 mm of diameter, with rounded shapes and clear limits (not impregnative). The nodules in old deposits are more frequent and more altered than nodules in modern deposits. In general, the presence of these nodules indicates an incipient hydromorphy. However, in old deposits a paleohidromorphy seems more probable.

The soils of modern deposits are classified as Inceptisols, since the rubefaction process associated with the clay accumulation is enough developed to identify a cambic horizon. The soils of old deposits are classified as Alfisols, which are characterized by illuvial clay accumulation and a base saturation greater than 50 %. The classification at subgroup level is Calcic Palexeralfs, since carbonate accumulations were enough to define a calcic horizon. Thus, it is evident how a longer time of soil formation allowed in these deposits a higher number of soil forming processes. Comparing the two soils, the soils of old deposits are redder, with significant higher content of clay, a significant higher available water capacity (in deep horizons) and cation exchange capacity (Table 5). However, their deep horizons are significantly more compacted, which meant a major limitation to root development.

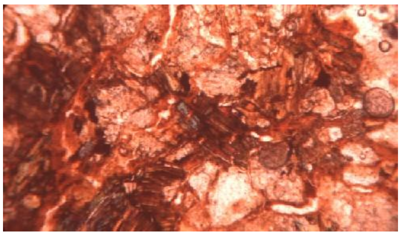

Figure 7. Clay neoformation from mica alteration in Fluventic Haploxerepts: clay coatings on pores and infillings (1.5 mm width, PPL).

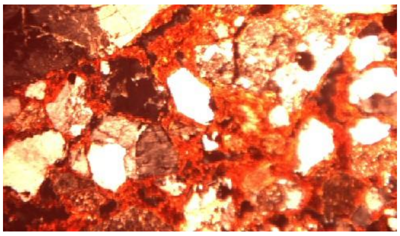

Figure 8 . Clay illuviation in Calcic Palexeralfs: rubefacted clay coatings on pores (6.4 mm width, XPL).

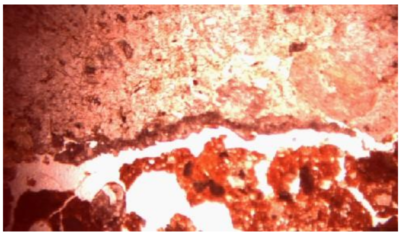

Figure 9. Carbonate accumulation by illuviation in Calcic Palexeralfs: sparitic calcite pendent (6.4 mm width, PPL).

The soil forming processes of these soils have a direct influence on their physical properties. In the modern gravel deposits, which a priori could have a very quick drainage because of gravels, the clay neoformation made possible the existence of more balanced textures, allowing a moderate to high available water capacity (AWC). These soils have very favourable properties for grapevine cultivation, as the balanced textures assure a minimal water retention and the gravels facilitate the drainage of water surplus. In addition, these soils favour the development of a deep root system, so that in years of drought the roots could take water from deep water tables. In the old gravel deposits, the properties are more unfavourable than other soils, because the roots have more difficulties to explore deep horizons. This is due to a greater compactness, related to higher clay content. Moreover, the presence of fragments of laminar petrocalcic and other forms of accumulations, which are representative of a long genetic process, are indicative of possible problems related to micromass cementation. However, these soils have a moderate to high AWC, inferred by the clayey matrix and the relatively porous rock fragments, which are capable to retain water.

Table 5. Analytical properties of representative vineyard soils in Conca de Barberà region *.

Properties	Horizon	Fine loamy, mixed, active, mesic, Fluventic Haploxerepts	Loamy-skeletal, mixed, active, mesic, Calcic Palexeralfs
Soil Forming Processes		Clay neoformation from mica weathering, clay coatings on pores. Incipient hydromorphy.	Clay illuviation and recarbonation, clay coatings and sparite pendants on coarse components. Palaeohydromorphy.
Genetic horizon (SSS, 2006)	1	Ap$_1$	Ap$_1$
	2	Ap$_2$	Ap$_2$
	3	Bw	Btk
Lower depth (cm)	1	20.5 (0.96) a	13.4 (0.99) b
	2	45.8 (1.54) a	40.8 (0.93) b
	3	107.1 (2.23) ns	92.8 (7.94) ns
Munsell Colour	1	7.5YR3/3	5YR4/6
	2	7.5YR4/3	5YR4/7
	3	7.5YR3/4	5YR4/8
pH (H$_2$O 1:2.5)	1	8.4 (0.05) ns	8.5 (0.04) ns
	2	8.4 (0.08) ns	8.5 (0.04) ns
	3	8.4 (0.03) ns	8.5 (0.07) ns
Electrical Conductivity (1:5, dS/m)	1	0.17 (0.01) ns	0.18 (0.01) ns
	2	0.18 (0.01) ns	0.19 (0.01) ns
	3	0.19 (0.01) ns	0.19 (0.01) ns
Organic matter (%)	1	2.1 (0.55) a	1.1 (0.10) b
	2	1.8 (0.44) a	0.7 (0.14) b
	3	1.4 (0.45) ns	0.6 (0.11) ns
CaCO$_3$ equivalent (%)	1	10.2 (2.15) ns	13.7 (4.24) ns
	2	9.2 (1.49) ns	11.8 (3.13) ns
	3	7.4 (2.20) b	17.6 (3.39) a
Cation Exchange Capacity (cmol$_c$/kg)	1	11.1 (0.55) b	13.8 (0.23) a
	2	12.2 (0.65) ns	14.2 (0.35) ns
	3	10.5 (1.08) b	13.3 (0.26) a
Sand (%)	1	50.4 (2.12) ns	49.8 (1.89) ns
	2	46.9 (0.84) ns	51.1 (2.19) ns
	3	46.5 (2.20) b	52.6 (0.38) a
Silt (%)	1	31.8 (1.70) a	23.9 (0.31) b
	2	33.7 (0.64) a	21.2 (0.95) b
	3	35.1 (1.00) a	17.8 (1.09) b
Clay (%)	1	17.7 (0.83) b	26.3 (1.60) a
	2	19.4 (0.23) b	27.7 (1.40) a
	3	18.4 (1.20) b	29.6 (0.99) a
Textural class (SSS, 2006)	1	Loam	Sandy clay loam
	2	Loam	Sandy clay loam
	3	Loam	Sandy clay loam
Bulk density (kg/m^3)	1	1299.6 (44.59) ns	1312.0 (18.15) ns
	2	1514.3 (33.76) ns	1525.3 (15.17) ns
	3	1453.1 (11.45) b	1787.0 (45.35) a
Coarse fragments (%)	1	11.9 (3.51) ns	9.0 (1.73) ns
	2	12.7 (1.48) ns	6.7 (1.76) ns
	3	26.2 (3.58) a	12.4 (0.49) b
Water retention at -33 kPa (%)	1	20.3 (0.33) a	18.0 (0.58) b
	2	21.7 (0.88) ns	20.7 (0.67) ns
	3	20.0 (0.37) ns	20.3 (0.33) ns
Water retention at -1500 kPa (%)	1	8.3 (0.33) ns	7.3 (0.33) ns
	2	9.7 (0.88) ns	9.0 (0.58) ns
	3	9.5 (0.34) b	11.7 (0.33) a
Available Water Capacity (mm/10 cm)	1	13.8 (1.01) ns	12.7 (0.78) ns
	2	15.9 (0.55) ns	16.6 (1.82) ns
	3	11.3 (0.64) b	13.5 (0.21) a

*Numbers between brackets correspond to standard errors and different letters indicate significant differences ($p<0.05$) among the same horizons of different soil series, according to Newman-Keuls test (n=3).

Soils affected by human activities

In the study area, some soils where human activity caused major changes in soil composition are found. The main changes are related to topography and horizon arrangement. The main effects described as a result of these changes are the buried of fertile surface horizons, and horizons not arranged in any discernible order. One of the features used to determine human activity is the presence of very abrupt limits between horizons.

Properties of two soils deeply affected by men are shown in Table 6. Both profiles are classified as Entisols. One soil present an argillic horizon inserted among other horizons that have no relation with its formation. This soil is classified into the suborder Arents, because there are fragments of diagnostic horizons. When this diagnostic horizon is an argillic, in a xeric regime, soils can be classified as Alfic Xerarents. The other profile, which corresponds to a soil with a buried horizon, does not contain any diagnostic horizon. So, this soil cannot be classified as Arents. In this particular case, the soil is classified as Fluvents, since an irregular decrease in content of organic carbon occurs. Thus, despite the drastic change in profile composition, the anthropic soil origin is not reflected in its classification.

Table 6. Analytical properties of 2 soil profiles affected by anthropogenic activities *.

Horizon	Lower depth (cm)	Munsell colour (moist)	pH (H_2O 1:2.5)	EC (1:5 dS/m)	Organic matter (%)	$CaCO_3$ eq. (%)	CEC (cmol/kg)	Sand (%)	Silt (%)	Clay (%)	Textural class (SSS, 2006)	Bulk density (kg/m^3)	Coarse fragment (%)	Water retention -33 kPa (%)	Water retention -1500 kPa (%)	AWC (mm)
Fine loamy, mixed, active, mesic, Alfic Xerarents. Accumulations (55/60-80 cm depth): Illuvial clay coatings.																
Ap	40/45	7.5YR4/6	8.4	0.16	0.7	12	14.7	45.2	28.4	26.4	L	1228	20	22	11	45
Ab	55/60	7.5YR4/4	8.3	0.23	1.1	6	10.3	57.3	25.9	16.8	SaL	1360	20	18	8	17
2Bt	80	5YR4/4	8.3	0.22	1.3	trace	16.2	39.5	27.7	32.8	CL	1350	20	24	13	25
3Bw	120	7.5YR4/6	8.3	0.23	1.3	15	12.8	47.3	29.8	22.9	L	1319	20	20	10	42
Loamy-skeletal mixed, superactive, mesic, Typic Xerofluvents																
Ap	15	7.5YR4/6	8.1	0.19	0.76	24	9.8	37.6	47.5	14.9	L	1435	5	22	8	29
Bw	60	7.5YR4/6	8.5	0.19	0.29	16	7.7	38.8	48.7	12.5	L	1580	10	14	7	45
2Ab	100	10YR3/2	8.4	0.16	1.81	trace	10.0	56.6	33.1	10.3	SaL	1250	40	17	8	27

* EC: electrical conductivity; CEC: cation exchange capacity; Textural classes: SaL: sandy loam, L: loam, CL: clay loam; AWC: available water capacity.

The soils formed by land levelling may have serious problems of soil erosion and often produce a negative effect on productivity and vigour of vines, and also on grape quality, especially in white varieties, due to a decrease in acidity and aromatic potential (Bazzofi et al., 2009). However, soils deeply affected by men cannot always be considered worse than unaltered soils, because sometimes grape quality is better in less fertile soils, especially in red varieties. Bazzofi et al. (2009) found a significant increase in the content of anthocyanins and total polyphenols of grape berries on soils affected by land levelling, improving grape quality for red wines. Moreover, in table grape production areas of Sicily (Italy) strong earthworks are conducted to bury fertile surface horizons with calcareous materials, in order to improve grape quality (Dazzi, 2008).

Conclusions

In the region of the Catalan Coastal Range (Catalonia, Spain), a high variety of soil forming processes has been identified, in relation to the existing differences in soil forming factors. In this study, we found that the soil forming processes, identified through morphological and micromorphological analyses, have significant effects on soil properties. The different processes of clay accumulation in soils developed from granodiorites in Priorat or gravel deposits in Conca de Barberà, are primarily responsible for significant differences in clay content, available water capacity and cation exchange capacity. Similarly, carbonate accumulation in Penedès soils have significant effects on calcium carbonate content and also on available water capacity. These soil properties, especially those related to soil moisture regime, available water capacity and calcium carbonate content, have a direct influence on the type of management and quality of grapevine production according to different authors. Specially important are the effects that have drastic earthworks on profile characteristics. However, soil classification does not always reflect these important pedogenic processes which have remarkable implications on vineyard soil management. For instance, clay accumulations in soils developed from slates in Priorat, incipient carbonate accumulations in Penedès, or drastic changes in the arrangement of horizons, with a decrease in soil fertility, in the case of soils modified by man. The main conclusion of this study is that parent material or climate alone cannot be used in viticultural zoning, unless soil forming processes are taken into account.

Chapter 4

CHARACTERIZATION OF THE SOIL MOISTURE REGIME FOR VITICULTURAL ZONING PURPOSES

Abstract

This paper aims to analyse the suitability of Soil Taxonomy to characterize the soil moisture regime for viticultural zoning studies, comparing the soil moisture parameters used in the Soil Taxonomy classification with soil moisture parameters relevant to the grapevine phenological stages. The results show that Soil Taxonomy does not adequately reflect the variability of soil moisture dynamics during vineyard growing. Then, a proposal for soil moisture regime classification is realised by means of a cluster analysis. This classification is based on determining dry days, as indicated by Soil Taxonomy, in different vine phenological periods, and grouping the cases according to their variability. The soil moisture regime classes, resulting from cluster analysis, show significant differences in soil moisture status in all phenological periods, and therefore present different implications for viticulture, related to potential for vegetative growth, grape production and the grape ripening process.

Keywords: Soil Taxonomy, soil survey, soil classification, cluster analysis, viticultural potential

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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 characterization of zones that produce grapes or wines of similar composition, while enabling operational decisions to be implemented (Vaudour, 2003). 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 climate, soil is the most important factor in viticultural zoning (Sotés and Gómez-Miguel, 2003), due to its direct effect on vine development and wine quality. There are several approaches through soil studies which are oriented to viticultural zoning (Van Leeuwen et al., 2002), but the methods that provide the most information 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 Chéry, 2001). Soil survey methods based on Soil Taxonomy classification (SSS, 1999) are useful for viticultural zoning studies at different levels of detail (Gómez-Miguel and Sotés, 2001; Gómez-Miguel and Sotés, 2003; Ubalde et al., 2009).

The soil properties which have the most influence on viticultural zoning are the ones related to soil moisture regime (Seguin, 1986), which is determining in the equilibrium between vegetative vigour and grape production (Van Leeuwen and Seguin, 1994), and consequently on grape and wine quality (Trégoat et al., 2002; Esteban et al., 2001; Gurovich and Páez, 2004). Generally, a moderately limited soil moisture regime induces positive effects on berry composition and wine quality (Kounduras et al., 1999), with an increase of berry sugar (Jones and Davis, 2000), anthocyanin and tannin contents and also an increase of grape ripening speed (Van Leeuwen and Seguin, 1994). After flowering, water limitation reduces potential berry size by reducing the number of cells per berry (Ojeda et al., 2002). After veraison, a reduced water regime involves an earlier growth shutdown, reduces berry weight and yield (Van Leeuwen et al., 2003), and increases sugar content, since berry weight has a strong negative linear correlation with sugar content (Hunter and Deloire, 2005). Moreover, an earlier growth shutdown limits the development of secondary leaf area, improving grape microclimate conditions, with higher exposure to solar radiation (Trégoat et al., 2002). With regard to phenolic compounds, soil water availability controls skin/pulp ratio, affecting polyphenol biosynthesis (Matthews and Anderson, 1988; Ginestar et al., 1998; Sipiora and Gutiérrez-Granda, 1998; Esteban et al., 2001; Gurovich and Páez, 2004; Sivilotti et al., 2005). Other studies attribute the positive effect on polyphenol synthesis to an improvement of the microclimate, related to the decrease of leaf area and a better berry exposure (Dry et al., 2001; Trégoat et al., 2002), but not all studies can demonstrate this effect (Hilbert et al., 2003). Thus, the knowledge of the soil moisture regime, considered as the evolution over time of the soil moisture status, is indispensable to appraise the vineyard potential for grape and wine production.

There are different methods to characterize the seasonal soil moisture dynamics. Soil Taxonomy (SSS, 2006) is the only worldwide classification system which considers the soil moisture regime (SMR). The Soil Taxonomy SMR, which can be defined as the distribution of periods of dryness and wetness during a normal year, is determined by cumulative and consecutive days of dryness (soil water potential < -1500 kPa) and moistness (soil water potential > -1500 kPa) in the soil moisture control section (SMCS), which corresponds to the depth to which a dry soil will be moistened by 25 mm (upper limit) and 75 mm (lower limit). The periods considered by Soil Taxonomy are the four months following the winter and summer solstice, and the period when soil temperatures are higher than 5 and 8 ºC. At European level, the Georeferenced Soil Database of Europe (Finke et al., 2001) defines the annual SMR from cumulative periods of moistness (water potential > -1 kPa) within 40 and 80 cm soil depth. Kamara and Jackson (1997) proposed a rain-soil moisture index classification for tropical regions, which considers the frequency of rainy days (daily rain > 0.25 mm) and the daily percentage of the soil moisture storage capacity. All these studies show that, despite the existence of few methods to characterize SMR, the soil moisture parameters and the periods considered are very variable. Furthermore, the variables considered do not take into account the vine phenological stages, so probably these methods are not the most suitable to separate SMRs according their potential effects on viticulture. Some studies of soil moisture orientated to vineyard crops are Payan and Salançon (2002), who characterized the evolution of soil moisture in vineyards for irrigation purposes, using hydric itineraries, which represent the soil water deficit (fraction of transpirable soil water) in the different vine phenological stages, or Tonietto and Carbonneau (2004), who proposed a worldwide multicriteria climatic classification, which defined climatic classes according to a dryness index, calculated from the potential soil water reserve at grape maturity.

As said before, soil moisture regime is determining in grape and wine quality, and is also necessary to implement Soil Taxonomy classification. In this study, soil water content is monitored in 10 representative soil map units, belonging to a Soil Taxonomy-based viticultural zoning (Ubalde et al., 2009), in order to characterize the soil moisture regime. This paper aims to analyse the suitability of Soil Taxonomy to characterize the soil moisture regime for viticultural zoning purposes and also to compare Soil Taxonomy classification with a classification based on the variability of soil moisture during the grapevine phenological stages.

Materials and Methods

Setting

The study area was located in high quality producing vineyards, in different counties of Catalonia (North-Eastern Spain): Priorat, Anoia, Pallars Jussà, Alt Penedès and Conca de Barberà (Table 1). The altitude ranges between 196 m and 902 m. The studied plots were vines of different cultivars (Cabernet sauvignon, Pinot noir, Grenache noir and Tempranillo) and rootstocks (R110, SO4, 1103, 41B and 140R), ages (8 - 35 years old) and vine densities (3,300 - 4,500 vines per hectare). All vineyards followed similar management: vines were trained to an espalier-type canopy system and were double cordon Royat pruned (12 buds per vine), vineyards were dry-land farmed and weeds were controlled by ploughing.

Table 1. Location and viticultural characteristics of the studied plots.

County	Plot name	Location	Altitude (m)	Cultivar	Rootstock	Age (years)	Vines/hectare
Priorat	Arenal	0º 49' E, 41º 7' N	313	Tempranillo	R110	10	4,500
	Solana 1	0º 52' E, 41º 12' N	493	Grenache noir	R110	12	3,300
	Solana 2	0º 52' E, 41º 12' N	493	Grenache noir	R110	12	3,300
Anoia	Ca l'Atzet	1º 30' E, 41º 30' N	542	Pinot noir	SO4	23	4,500
Pallars Jussà	St. Miquel	0º 50' E, 42º 12' N	902	Pinot noir	1103	8	4,500
Alt Penedès	Plana	1º 40' E, 41º 21' N	196	Cabernet sauvignon	41B	35	3,700
	Sivill	1º 39' E, 41º 21' N	237	Cabernet sauvignon	140R	30	4,500
Conca de Barberà	Llarga	1º 4' E, 41º 23' N	450	Cabernet sauvignon	140R	20	3,700
	Solar	1º 4' E, 41º 23' N	459	Cabernet sauvignon	SO4	20	3,700
	Peu del bosc	1º 5' E, 41º 22' N	532	Grenache noir	R110	15	4,500

These vineyards are located on three distinct main geological units of Catalonia, more specifically on the Catalan Coastal Range, the Ebro Basin and the Prepyrenees (Figure 1). The Catalan Coastal Range is an alpine folded chain formed by both massifs and tectonic trenches (Anadón et al., 1979). The Priorat vineyards are located in the hillslope of the massif, on Carboniferous slates ('Solana 1 and 2') and granodiorites ('Arenal'). 'Peu del bosc' vineyard is located in the footslope of the massif, on siliceous gravel deposits (slates and granites). The Alt Penedès plots are located in a tectonic trench, where calcareous materials from Miocene predominate. In particular, 'Plana' is located in a bottom valley and 'Sivill' is located in a residual platform. The vineyards of the Ebro basin margin are 'Ca l'Atzet' (Anoia) and 'Llarga' (Conca de Barberà), where calcareous materials from Eocene and Oligocene predominate, respectively. Finally, 'Sant Miquel' is located in the Prepyrenees, on glacis formed by calcareous gravel deposits.

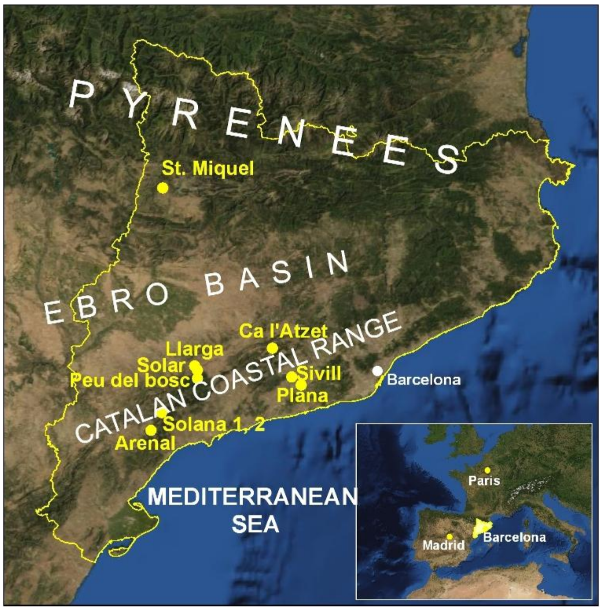

Figure 1. Location map of the studied plots.

A high variability of physicochemical soil properties can be identified (Table 2), in relation to the existing differences in lithologies and landforms. The selected soils are classified as Entisol, Inceptisol and Mollisol orders (SSS, 2006) (Table 3). Entisols are characterized by little or no evidence of soil formation. The groups described were Xerorthents ('Solana 1, 2'), characterized by being shallow soils with a root-limiting layer, Xerofluvents ('Ca l'Atzet', 'Plana' and 'Llarga'), which are deep soils, rich in organic matter in depth, and Xeropsamments ('Arenal'), which are sandy soils. Inceptisols are characterized by being in the early stages of soil formation. The groups described were Haploxerepts, which showed evidences of carbonate removals (‘Solar’) or clay neoformation (‘Peu del bosc’), and Calcixerepts (‘Sivill’), characterized by calcium carbonate accumulations. Mollisols are base-rich soils with a dark coloured surface horizon, due to organic matter accumulation. The group identified was Palexerolls (‘St. Miquel’), which was characterized by high organic matter content and calcium carbonate cementations.

Table 2. Physicochemical properties of the selected soils.

Soil	Depth (cm)	pH	EC (1:5, dS/m)	Organic matter (%)	$CaCO_3$ eq. (%)	Sand (%)	Silt (%)	Clay (%)	Textural class* (SSS, 2003)	Rock fragments (%)	Moisture at -33kPa (%)	Moisture at -1500 kPa (%)	Water holding capacity (mm/10cm)
Arenal	20	8.6	0.12	0.1	trace	91.5	4.9	3.6	Sa	trace	5	3	3.0
	40	8.6	0.11	0.1	trace	91.8	6.9	1.3	Sa	trace	5	3	3.1
Solana 1	15	7.6	0.31	3.9	trace	66.4	20.8	12.8	SaL	58	20	8	8.5
Solana 2	15	7.6	0.26	3.5	trace	69.5	19.8	10.7	SaL	48	21	8	10.6
	45	7.7	0.22	1.9	trace	71.1	18.3	10.6	SaL	37	18	8	13.2
Ca l’Atzet	9	8.3	0.22	1.8	43	23.7	44.0	32.3	CL	trace	24	12	19.1
	52	8.5	0.28	1.1	43	28.2	38.4	33.4	CL	trace	22	12	17.8
	86	8.5	0.25	0.5	49	36.4	36.6	27.0	CL	trace	21	10	19.8
	120	8.4	0.33	0.5	51	42.2	33.0	24.8	L	trace	20	10	18.0
St. Miquel	12	8.6	0.20	4.3	29	35.8	50.7	13.5	SiL	28	24	13	11.9
	32	8.5	0.19	3.9	34	37.8	47.6	14.6	L	29	25	14	12.6
	120	8.9	0.14	0.4	78	73.7	20.7	5.6	SaL	50	17	4	12.3
Plana	14	8.4	0.17	1.7	28	28.1	50.1	21.8	SiL	trace	23	10	18.2
	50	8.4	0.20	1.2	28	27.8	49.5	22.7	SiL	trace	22	11	17.4
	93	8.4	0.22	0.8	27	30.1	45.5	24.4	L	trace	22	12	16.3
	135	8.4	0.19	1.0	34	32.9	40.5	26.6	L	trace	23	12	19.7
Sivill	10	8.5	0.18	2.2	37	37.7	36.7	25.6	L	37	25	13	9.3
	50	8.6	0.20	1.6	72	63.3	25.3	11.4	SaL	36	20	9	10.1
Llarga	19	8.4	0.23	1.1	45	23.0	55.5	21.5	SiL	trace	21	8	17.7
	40	8.4	0.22	0.9	46	21.8	56.4	21.8	SiL	trace	21	8	21.6
	80	8.4	0.30	1.3	47	20.8	56.1	23.1	SiL	trace	23	9	20.3
	110	8.0	1.42	1.2	45	15.5	58.0	26.5	SiL	trace	19	7	17.1
Solar	15	8.3	0.40	2.0	17	43.8	39.9	16.3	L	22	21	8	11.3
	38	8.5	0.19	1.0	9	71.1	18.8	10.1	SaL	54	12	5	4.7
	70	8.5	0.22	0.5	trace	89.6	4.7	5.7	Sa	65	5	2	1.2
	130	8.5	0.19	0.4	trace	89.1	3.3	7.6	Sa	50	4	2	0.6
Peu del bosc	20	8.4	0.17	1.4	4	54.6	28.5	16.9	SaL	28	20	8	14.1
	50	8.4	0.19	1.1	5	46.2	34.4	19.4	L	30	22	10	13.6
	85	8.4	0.19	0.7	4	45.1	37.4	17.5	L	31	21	9	13.2
	120	8.3	0.17	1.1	4	52.3	30.8	16.9	L	48	19	9	10.6

* CL: clay loam, SiL: silt loam, L: loam; SaL: sandy loam, Sa: sand.

The climate type is Mediterranean, characterized 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 (Penedès) to 650 mm (Pallars Jussà), showing seasonal variations. In all regions, the precipitation has a bimodal distribution (peaks in spring and autumn) and a minimum of precipitation in summer, particularly in July. Moreover, the annual precipitation has a high interannual variability (from 305 mm to 1110 mm in Priorat). The mean annual temperature ranges between 12.7 (Priorat) and 16.4ºC (Anoia). The highest temperatures occur in summer, particularly in July or August, while the lowest temperatures occur in winter (January). 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.

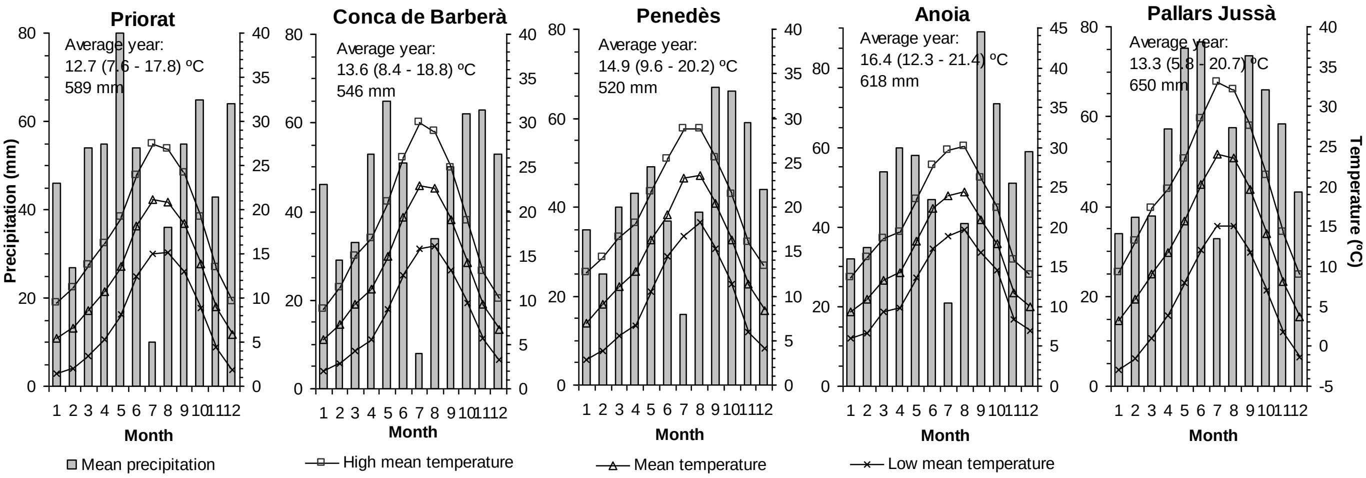

Figure 2. Average climate data in the study area.

Soil moisture and climate monitoring

The soil water content was monitored by capacitance sensors (ECHO EC20, Decagon Devices Inc.), continuously (every 30 min) and at different depths, in 10 soil series (SSS, 2006) located in 5 viticultural climates (Tonietto and Carbonneau, 2004) (Table 3). In order to minimize the effect of internal soil variability, 3 capacitance sensors at 20 m of distance (forming a triangle) were installed for each depth. A calibration was performed in order to convert capacitance data (mV) to volumetric moisture data (%). This calibration was made by means of linear regressions between capacitance data and soil moisture data, registered at different seasons of the year. Field capacity (FC) was determined by capacitance sensors after 48 hours of soil saturation during periods of continuous, heavy rains. Similar methods were used in previous studies (Lebon et al., 2003). Permanent wilting point (PWP) was estimated as soil moisture to -1500 kPa, determined by pressure-plate extraction from disturbed samples (sieved to 2 mm).

Daily climatic data were recorded in automatic weather stations of the Meteorological Service of Catalonia or Miguel Torres Winery, which were close the monitored plots. Data of rainfall, air temperature, solar radiation, wind, relative humidity, atmospheric pressure and reference evapotranspiration were available. Moreover, one rain gauge was installed for each soil type. Soil temperature data were estimated from air temperature, according to Jarauta (1989).

Table 3. Capacitance sensors distribution.

Climatic zone	Soil series	Plot name	Depths (cm)	Years
Subhumid, temperate, cool nights	Sandy, mixed, mesic, shallow, Typic Xeropsamments	Arenal	15 – 30	2004 a 2006
	Loamy-skeletal, mixed, semiactive, mesic, Lythic Xerorthents (very shallow)	Solana 1	15	2005 a 2007
	Loamy-skeletal, mixed, semiactive, mesic, Lythic Xerorthents (shallow)	Solana 2	15 – 30	2005 a 2006
Subhumid, warm, temperate nights	Fine, mixed, semiactive, thermic, Typic Xerofluvents	Ca l'Atzet	15 – 30 – 60 – 90	2005 a 2007
Subhumid, warm, very cool nights	Loamy, carbonatic, mesic, shallow, Petrocalcic Palexerolls	St. Miquel	15 – 30	2005 a 2007
Moderately dry, temperate warm, temperate nights	Fine-loamy, mixed, active, thermic, Typic Xerofluvents	Plana	15 – 30 – 60 – 90	2005 a 2007
	Loamy, carbonatic, thermic, Petrocalcic Calcixerepts	Sivill	15 – 30	2005 a 2007
Moderately dry, temperate warm, cool nights	Fine-loamy, carbonatic, mesic, Typic Xerofluvents	Llarga	15 – 30 – 60 – 90	2004 a 2006
	Sandy-skeletal, mixed, mesic, Typic Haploxerepts	Solar	15 – 30	2004 a 2006
	Fine-loamy, mixed, active, mesic, Fluventic Haploxerepts	Peu del bosc	15 – 30 – 60 – 90	2004 a 2006

Soil moisture regime characterization

As said before, Soil Taxonomy is the only worldwide classification of soil moisture regimes (SMRs). The Soil Taxonomy SMRs are defined in terms of presence or absence of water held at a tension of less than 1500 kPa during certain periods (SSS, 2006). The periods considered by Soil Taxonomy do not correspond to grapevine phenological stages, so the suitability of Soil Taxonomy SMR to characterize soil moisture dynamics in vineyards is not clear. In order to analyse this suitability, soil moisture status in the soil moisture control section (SMCS) was determined for the periods which dictate Soil Taxonomy and the phenological stages of vines. In this study, 3 soil moisture statuses were considered: (1) dry in all parts when all capacitance sensors within the SMCS were below the PWP, (2) moist in some parts when some capacitance sensors within the SMCS were above the PWP and (3) moist in all parts when all capacitance sensors within the SMCS were above the PWP.

The periods considered by Soil Taxonomy are the four months following the winter and summer solstice, and the period when soil temperatures are higher than 5 and 8ºC. The variables which determine the Soil Taxonomy SMR are defined by the number of cumulative and consecutive days or the percentage of days during these periods in which the SMCS presents a particular soil moisture status (Table 4). The values that achieve these variables define the soil moisture regimes in Soil Taxonomy (Table 5): aridic, xeric, ustic and udic.

Table 4. Variables determining the soil moisture regime in Soil Taxonomy (SSS, 2006; Loaiza, 2007).

Variable	Description
ST1	Percentage of days per year when the soil temperature is > 5ºC where the soil moisture control section is dry in all parts.
ST2	Consecutive days when the soil temperature is > 8ºC where the soil moisture control section is moist in some or all parts.
ST3	Cumulative days per year where the soil moisture control section is moist in all parts.
ST4	Consecutive days in the 4 months following the summer solstice where the soil moisture control section is dry in all parts.
ST5	Consecutive days in the 4 months following the winter solstice where the soil moisture control section is moist in all parts.

Table 5. Criteria for determining the soil moisture regime in Soil Taxonomy (Gascó-Ibañez, 1978; Jarauta, 1989).

ST1 < 50	ST2 >= 90	ST3 < 275	ST4 >= 45	ST5 >= 45	SMR
False	False	-	-	-	Aridic
-	-	False	False	-	Udic
True	-	True	False	True	Ustic (1)
True	-	True	-	False	Ustic (2)
True	False	-	True	True	Xeric (1)
False	True	-	True	True	Xeric (2)
True	True	-	True	True	Xeric (3)

The soil moisture variables related to grapevine phenological stages are consecutive days and percentage of days per year where the SMCS presents a particular soil moisture status, for the following periods: dormant season (October-March), growing season (April -September), period between budbreak and flowering (April-May), period between flowering and veraison

(June-July) and period between veraison and maturity (August-September). These months are representative of grapevine phenological stages in Mediterranean climates of the Northern Hemisphere (Martínez de Toda, 1991; Hidalgo, 1999), and are also representative for the climates and cultivars considered in this study. Moreover, the period with air temperatures above 10°C, which is the thermal threshold for grapevine vegetative activity (Hidalgo, 1999), was considered.

Soil Taxonomy SMR classification is meant for "normal years", defined as years that have plus or minus one standard deviation of the long-term mean annual precipitation. However, in this study, in order to have more data availability, the Soil Taxonomy SMR was determined for every year, assuming that certain annual weather conditions may correspond to "normal years" of different climates. This approach was possible because we were not analyzing the effect of climate or soil on soil moisture conditions, but we wanted to compare Soil Taxonomy variables with variables related to grapevine phenological stages.

Statistics

At first, a Pearson correlation analysis was performed for the variables related to soil moisture regime characterization, in order to simplify the number of dependent variables. Then, the variability of parameters related to grapevine phenological stages was compared with the Soil Taxonomy SMRs, by means of variance analysis (ANOVA). Means were separated by Newman-Keuls post-hoc analysis ($p < 0.05$). Moreover, a proposal of SMR classification in vineyard soils was realised by means of a cluster analysis (*k*-means method). 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. Finally, classes formed by cluster analysis were compared with SMR of Soil Taxonomy, by the Pearson's chi-square test. In this analysis, the null hypothesis was the independence (no association) between variables. All statistical analyses were performed in STATISTICA®.

Results and Discussion

During this study, the climatic conditions did not show remarkable trends for years or counties (Table 6). For example, the rainiest or warmest year in a county was not necessarily the same for other counties, and no particular county was always the rainiest or the warmest. The rainiest year was 2004 in Priorat (554 mm) and the driest year was 2005 in Anoia (318 mm). Different trends were observed for the growing season and the ripening period. The rainiest growing season was 2007 in Pallars Jussà (325 mm) and the driest one was 2006 in Alt Penedès (173 mm). The rainiest ripening season was 2006 in Conca de Barberà (166 mm) and the driest one was 2004 in Priorat (12 mm). Regarding the temperatures, 2006 in Priorat was the warmest year during the year (16.1ºC), the growing season (21.6 ºC) and the ripening period (23.2ºC). The coolest year was 2007 in Pallars Jussà (12.8 ºC), but during the growing season was 2004 in Conca de Barberà (17.8ºC) and during the ripening season 2006 in Conca de Barberà (19.3ºC).

Table 6. Meteorological data for the growing season (Apr-Oct), the ripening period (Aug-Sep) and year in the study area (2004-2007).

County	**Year**	**Total rainfall (mm)**			**Mean Temperature (ºC)**			**Average maximum Temperature (ºC)**			**Average minimum Temperature (ºC)**		
		Aug-Sep	**Apr-Oct**	**Year**	**Aug-Sep**	**Apr-Oct**	**Year**	**Aug-Sep**	**Apr-Oct**	**Annual**	**Aug-Sep**	**Apr-Oct**	**Year**
Priorat	2004	12	252	554	22.7	19.1	14.2	30.0	26.1	20.5	17.3	13.6	9.3
	2005	145	272	465	22.6	20.7	14.8	29.9	27.6	21.4	16.1	14.5	9.3
	2006	145	225	350	23.2	21.6	16.1	30.4	28.9	22.9	16.6	14.8	10.1
	2007	28	287	407	21.5	19.2	14.8	28.7	26.0	21.1	15.8	13.8	9.8
Anoia	2005	105	204	318	19.8	18.3	13.3	26.6	25.5	19.8	13.0	11.2	6.8
	2006	119	257	453	20.2	18.8	13.9	29.2	28.0	22.3	12.9	10.6	6.8
	2007	84	303	421	19.7	17.8	13.0	28.5	26.4	21.5	12.0	9.9	5.7
Pallars Jussà	2005	153	325	353	21	19.9	13.1	29.5	28.4	21.3	13.7	12.3	6.2
	2006	71	246	361	20.4	20.0	13.9	29.6	29.1	21.9	13.6	12.5	7.4
	2007	30	364	429	20.8	18.5	12.8	29.3	26.9	21.0	13.0	11.0	6.0
Alt Penedès	2005	144	286	480	21.3	19.8	14.6	28.7	27.1	22.0	15.2	13.5	8.6
	2006	122	173	357	22.0	20.5	15.9	29.1	27.8	22.9	16.1	14.1	10.0
	2007	85	308	399	20.8	19.0	14.9	26.8	25.2	21.6	15.5	13.3	9.3
Conca de Barberà	2004	35	283	495	21.8	17.8	13.2	28.1	24.0	18.8	16.2	12.1	8.2
	2005	73	192	366	20.4	19.0	13.5	26.8	25.4	19.4	14.6	12.9	8.2
	2006	166	256	380	19.3	18.7	14.1	27.7	26.2	20.5	15.3	13.3	9.2

The predominant SMR was xeric (50% of cases), which agrees with the Mediterranean climate of the study area (Table 7). The second most important SMR was ustic (28% of cases). Those cases could not be classified as xeric because they do not accomplish the criteria of either at least 45 consecutive dry days in the 4 months following the summer solstice or at least 45 consecutive humid days in the 4 months following the winter solstice. The SMR was aridic in 3 cases (Plana and Sivill in 2005 and Llarga in 2004), since they presented more than 50% of dry days when the soil temperature was > 5ºC and less than 90 consecutive humid days when the soil temperature was > 8ºC. Finally, the SMR was udic in 3 cases (Arenal in 2004 and 2005 and Peu del Bosc in 2006), since they presented less than 90 consecutive dry days per year and less than 45 consecutive dry days in the 4 months following the summer solstice.

Table 7. Characterization of soil moisture dynamics using variables from Soil Taxonomy SMR for each plot and year (Description of variables in table 3).

Plot name	Year	ST1	ST2	ST3	ST4	ST5	Regime
Arenal	2004	23	115	291	33	51	Udic
	2005	0	255	365	0	122	Udic
	2006	36	100	260	58	123	Xeric (3)
Solana 1	2005	48	59	179	51	26	Ustic (2)
	2006	43	81	238	83	105	Xeric (1)
	2007	45	99	246	94	122	Xeric (2)
Solana 2	2005	43	134	198	68	25	Ustic (2)
	2006	26	99	234	74	122	Xeric (3)
Ca l'Atzet	2005	25	117	218	56	121	Xeric (3)
	2006	21	118	278	59	121	Xeric (3)
	2007	38	104	211	76	121	Xeric (3)
St. Miquel	2005	32	63	184	24	0	Ustic (1)
	2006	31	96	275	83	105	Xeric (3)
	2007	53	116	183	82	123	Xeric (2)
Plana	2005	65	89	116	78	0	Aridic
	2006	14	140	167	39	100	Ustic (1)
	2007	46	81	0	48	0	Ustic (2)
Sivill	2005	65	89	116	78	0	Aridic
	2006	16	130	316	49	123	Xeric (3)
	2007	5	89	248	15	123	Ustic (1)
Llarga	2004	57	67	188	113	61	Aridic
	2005	33	95	243	75	113	Xeric (3)
	2006	26	87	220	26	104	Ustic (1)
Solar	2004	39	75	252	67	123	Xeric (1)
	2005	32	84	284	79	122	Xeric (1)
	2006	28	92	252	30	112	Ustic (1)
Peu del bosc	2004	47	98	197	87	61	Xeric (3)
	2005	19	119	282	50	122	Xeric (3)
	2006	12	111	277	35	122	Udic

Regarding the variables related to phenological stages, a significant high correlation between consecutive dry days and percentage of dry days was determined by means of a Pearson analysis ($r = 0.87 - 1.00$, $p < 0.05$, $n = 29$). So, from now, the statistical analyses only consider the variables calculated as percentage of dry days, which are easier to determine. Moreover, a significant correlation was determined between the percentage of dry days between April and

September and the months with temperature exceeding 10 °C (r = 0.74, $p < 0.05$, n = 29), so this last variable is also removed. Thus, the variables related to vineyard phenology considered in the statistical analysis are the percentage of dry days during the dormant season, growing season, budbreak-flowering, flowering-veraison and veraison-harvest.

Table 8 shows the results of the analysis of variance (ANOVA), considering as independent variables the percentage of dry days in different phenological periods and as dependent (categorical) variable the Soil Taxonomy SMR. Mean values for each SMR and significant differences ($p < 0.05$) between means are shown. In general, significant differences were found between the Soil Taxonomy SMRs in all phenological periods, except for flowering-veraison period. However, the separation of means was poor, since no more than 2 groups of SMR with significant differences could be distinguished. The aridic and ustic (2) SMR were separated from the remainder SMR during the dormant season, aridic was separated from ustic (1) and udic during the growing season, aridic was separated from xeric (2, 3) and udic during the budbreak-flowering period and xeric (2) was separated from ustic and udic during the veraison-harvest period. As mentioned above, no significant differences between the SMRs were found during the flowering-veraison period. Soil moisture during this period is very important to grape production, since it determines the number of cells per berry and consequently the potential berry size (Ojeda et al., 2002). Thus, the Soil Taxonomy SMR does not adequately reflect differences in the soil moisture status during the grapevine phenological periods.

Table 8. Comparison of the percentage of dry days during every grapevine phenological stage between the different Soil Taxonomy SMR (N: number of observations).

	Percentage of dry days					
SMR	**Dormant season**	**Growing season**	**Budbreak-Flowering**	**Flowering-Veraison**	**Veraison-Harvest**	**N**
Aridic	66.7 a	75.3 a	66.7 a	85.3 ns	73.7 ab	3
Xeric (1)	12.3 b	49.3 ab	25.7 ab	53.3 ns	68.0 ab	3
Xeric (2)	0.0 b	42.0 ab	0.0 b	64.0 ns	94.0 a	2
Xeric (3)	9.2 b	38.7 ab	1.5 b	43.7 ns	62.2 ab	10
Ustic (1)	11.0 b	31.6 b	17.4 ab	52.6 ns	39.8 b	5
Ustic (2)	60.0 a	49.7 ab	28.0 ab	77.0 ns	29.3 b	3
Udic	6.3 b	15.7 b	0.0 b	4.0 ns	27.7 b	3

Different letters indicate significant differences at $p \leq 0.05$ within one column using Newman-Keuls test.

When the ANOVA is performed without xeric and ustic subdivisions (Table 9), significant differences are also found in the flowering-veraison season. However, the separation of means was still poor. During the growing season, the aridic regime was significantly drier than the rest and the udic regime was significantly wetter than the rest. Xeric and ustic regimes represented intermediate regimes between aridic and udic, but they showed significant differences during the phenological stages. The xeric regime was grouped with udic regime during budbreak-flowering and with aridic regime during flowering-harvest. Moreover, the ustic regime was grouped with udic in all stages, except during flowering-veraison, which would be as dry as aridic.

Table 9. Comparison of the percentage of dry days during every grapevine phenological stage between the different Soil Taxonomy SMR without subdivisions (N: number of observations).

	Percentage of dry days					
SMR	**Dormant season**	**Growing season**	**Budbreak-Flowering**	**Flowering-Veraison**	**Veraison-Harvest**	**N**
Aridic	66.7 a	75.3 a	66.7 a	85.3 a	73.7 a	3
Xeric	8.6 b	41.3 ab	6.1 b	48.3 a	67.6 a	15
Ustic	29.4 b	38.4 ab	21.4 b	61.8 a	35.9 b	8
Udic	6.3 b	15.7 b	0.0 b	4.0 b	27.7 b	3

Different letters indicate significant differences at $p \leq 0.05$ within one column using Newman-Keuls test.

A cluster analysis was performed in order to find a classification of SMR that could better reflect the variability of soil moisture with implications for vineyard growing. The *k*-means algorithm was applied to data of percentage of dry days during the grapevine phenological periods. This method was selected because it allows grouping data, minimizing within-group variability while maximizing among-group variability (Young and Hammer, 2000). Six clusters were obtained in this way. Averages of percentage of dry days in different phenological stages for each cluster are shown in Table 10. In this classification, the cluster classes showed significant differences in all phenological periods, even for flowering-veraison period, and therefore present different implications for viticulture, related to potential for vegetative growth, the grape ripening process and grape production (Table 11). Cluster 5 represents a very dry soil moisture regime, with 100% of dry days until veraison and 60% during ripening in average, which may imply low grape production, with excessive sugar content and insufficient phenolic compounds (Van Leeuwen and Seguin, 1994; Van Leeuwen et al., 2003; Hunter and Deloire, 2005). At the other extreme, cluster 4 represents a humid soil moisture regime, with approximately 10% of dry days during the dormant season and growing season until veraison and 25% of dry days during grape ripening. In this case, soil moisture can favour an imbalance between vegetative vigour and grape production, at the expense of grape quality (Van Leeuwen and Seguin, 1994). Cluster 2 is similar to cluster 4, except for presenting a dry ripening period (75% of dry days in average), which may relatively favour the grape ripening process. The remaining clusters represent intermediate situations, which are characterized by a moderately dry growing season, with approximately 50% of dry days. A moderately limited water regime induces generally positive effects on berry composition and wine quality (Kounduras et al., 1999), with an increase of berry sugar, anthocyanin and tannin content and also an increase of the grape ripening speed (Van Leeuwen and Seguin, 1994).

Table 10. Comparison of the percentage of dry days during every grapevine phenological stage between cluster classes, determined by means of the *k*-means clustering algorithm (N: number of observations).

	Percentage of dry days					
Cluster classes	**Dormant season**	**Growing season**	**Budbreak-Flowering**	**Flowering-Veraison**	**Veraison-Harvest**	**N**
1	13.7 c	48.3 b	19 c	86.7 b	17 b	3
2	1.4 c	29.6 c	0 d	18.5 d	75.8 a	8
3	49.3 b	54.5 b	51.5 b	86.3 b	52.5 a	4
4	10.6 c	16.6 c	0 d	11 d	24.6 b	5
5	100 a	87 a	100 a	100 a	60.5 a	2
6	11.6 c	48.9 b	0 d	68.4 c	70.6 a	7

Different letters indicate significant differences at p≤ 0.05 within one column using Newman-Keuls test.

Table 11. Interpretation of cluster classes for viticulture.

Cluster	SMR description	Implications for viticulture
5	Dry dormant and growing season.	Low potential for vegetative growth, limited production, early grape ripening, possible excess of grape sugar content.
3	Moderately dry dormant and growing season.	Moderate potential for vegetative growth, possible early grape ripening, possible balanced grape ripening.
6	Humid dormant season and moderately dry growing season, but dry veraison-harvest period.	High potential for vegetative growth, balanced grape ripening respect to the phenolics and sugar content.
1	Humid dormant season and moderately dry growing season, but humid veraison-harvest period.	High potential for vegetative growth, possible balanced grape ripening respect to the phenolics and sugar content.
2	Humid dormant and growing season, but dry veraison-harvest period.	Very high potential for vegetative growth, possible delay of the grape ripening process.
4	Humid dormant and growing season.	Very high potential for vegetative growth, delay and/or difficulties to reach grape ripeness.

The chi-squared test of independence showed a significant association between cluster classes and Soil Taxonomy classification (χ^2 = 51.3, df = 30, p = 0.009). In order to analyse this association, the frequency in which SMR distribute in cluster classes is shown in Figure 3. All cases belonging to cluster 5, which represents the most limited soil moisture regime during grapevine growing, are classified as aridic. Nevertheless, aridic SMR was also found in other clusters (16 % of cluster 6). Moreover, all udic cases belong to cluster 4, which represents the most humid soil moisture regime. However, udic cases only represent the 60% of cases in cluster 4. Thus, there is a significant association but it is not strong enough to predict accurately the Soil Taxonomy SMR from cluster memberships, or vice versa.

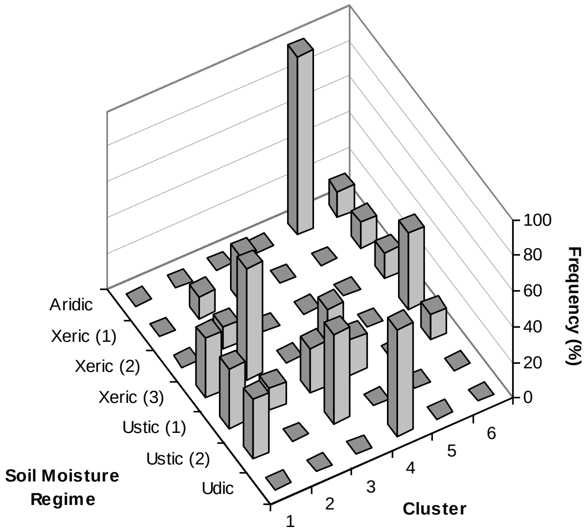

Figure 3. Frequency (%) of each soil moisture regime according to Soil Taxonomy into each cluster.

These results demonstrate that Soil Taxonomy SMRs are able to characterize differences in soil moisture dynamics that have implications in vineyard cultivation only in the most extreme cases (aridic and udic), but have limitations when xeric and ustic regimes are considered. In addition, Soil Taxonomy SMRs present other limitations in relation to the difficulty of determination of some variables, which require the calculation of consecutive days and periods with a given soil temperature. Furthermore, the control section for calculating the SMR is apparently a good approximation to estimate where the root system develops, but often some roots can explore very deep soil horizons in vineyards. This aspect should be taken into account when interpreting the results. In some cases, the SMCS is dry during the whole vegetative cycle, and vines would not survive if roots could not explore very deep horizons. The proposal of this study is based on applying the *k*-means cluster method to the percentage of dry days in the control section during different grapevine phenological stages. This method has the same limitations about the control section, but the variables are easier to determine, since consecutive days and soil temperatures are not considered. In addition, the statistical analysis groups the soil moisture regimes so that they reflect the maximum variability of water availabilities for the vineyard at different stages of development.

Conclusions

The SMR determination is an important requirement in viticultural zoning studies based on soil surveys, because of the effects of SMR in both wine production and soil classification. Soil Taxonomy classification is the most widely used, but this system shows some limitations when applied in viticultural zoning. The most important limitation refers to ustic and xeric SMR, which do not adequately reflect differences in the soil moisture dynamics during the grapevine phenological stages. This study proposes a classification based on determining dry days, as indicated by Soil Taxonomy, in different grapevine phenological periods and grouping the cases according to their variability, by means of a cluster analysis. Annual SMR resulting from cluster analysis show significant differences in percentage of dry days in all phenological periods, and therefore present different implications for viticulture, related to potential for vegetative growth, grape production and the grape ripening process that may determine wine quality for a given year.

Chapter 5

INFLUENCE OF SOIL AND CLIMATE ON GRAPE HARVEST QUALITY AT PLOT LEVEL

Abstract

Soil and climate of 3 vineyards located in Catalonia (Spain) have been characterized in order to determine their influence on grape quality (yield and berry composition). All 3 plots are very close, so only interannual climatic data of the nearest meteorological station have been considered. Besides determining chemical and physical properties of soils, the soil water availability has been characterized using capacitance sensors for the period from 2003 to 2005. Both yield and berry composition data were available from Miguel Torres Winery. Climatic data and water availability explained 70% of vintage variability and soil data explained 28% of vintage variability. The edaphoclimatic factors had generally a high power of estimation of yield and quality of grapes ($R^2 > 0.75$). Climate appeared to be the most influencing factor, followed by water availability, in particular for models referring to must data. Generally, soil data had influence on yield and some must data. The edaphoclimatic data explain most of the vintage variability and have a high power of estimation on grape quality. This study remarks the importance of a global approach which takes into account at least climate and soil water availability to understand the functioning of vines and evolution of berry composition.

Key words: vineyard soil, Mediterranean climate, terroir, soil moisture, grape quality.

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Introduction

The main objective of modern oenology is to elaborate wines of recognised quality and typicality. This quality is often associated to very especial conditions of soil, climate, cultural practices, training system, in interaction with a variety, which form the concept of terroir (Falcetti, 1994; Vaudour, 2003; Deloire et al., 2005). This terroir generally is defined as a spatial and temporal entity, which is characterized by an interaction between the environmental potentialities and viticultural and oenological technologies, significant for grapes and/or wine (Vaudour, 2003; Deloire et al., 2005). There are few studies that consider all the factors of the ecosystem as a whole (Van Leeuwen et al., 2004), however some investigators have identified units of terroir considering different factors (Carey, 2001; Morlat, 2001). Probably, climate is the factor that determines with more intensity the suitability of the environment for vineyard growing (Hidalgo, 1999). Soil has an important weight, but often it is studied together with climate, because its effects on wine quality are only consistent under the same climatic conditions (Saayman, 1977; Conradie, 1998). The soil properties which have the most influence on grape quality are the physical ones, namely the properties that control the soil water content (Seguin, 1986), due to its direct effect on equilibrium between vegetative vigour and grape production (Van Leeuwen and Seguin, 1994).

The aim of this study was to establish the influence of edaphoclimatic parameters on grape quality, in particular on both grape yield and berry composition.

Materials and methods

Setting

This study was developed from 2003 to 2005 in three vineyards (Milmanda, Riu Sec and Muralles) situated in Conca de Barberà region (NE Spain), near the Catalan Coastal Range. The sites are located between latitudes 41º 22’ 7’’N and 41º 24’ 8’’N and between longitudes 1º 3’ 53’’E and 1º 5’’ 24’’E. The altitudes are 450 m (Milmanda), 459 m (Riu Sec) and 515 m (Muralles).

Climate data

All three plots have a homogeneous climate, since they are located less than 1.2 km apart. The climate type is Mediterranean with a continental influence, with a mean annual precipitation of 550 mm and a mean annual temperature of 13.6ºC. The viticultural climate (Tonietto and Carbonneau, 2004) is moderately dry, temperate warm and cool nights.

No differences are expected in mesoclimate between Milmanda and Riu Sec, because both plots have similar topographic characteristics (similar altitude, flat landform). However, Muralles plot differs in topography (higher altitude, north-faced landform), having slightly lower temperatures and solar radiation. In this study, only interannual climatic data of the nearest meteorological station have been used, without considering the slight differences of Muralles mesoclimate.

Climatic data were recorded in an automatic weather station (Espluga de Francolí) of the Meteorological Service of Catalonia, located at 41º 23’ 39’’N, 1º 6’ 1’’E and 441 m of altitude. This station is located less than 2 km from all plots, having the same topographic position than Milmanda and Riu Sec. Hourly, daily and monthly data of rainfall, temperature, solar radiation, wind, relative humidity, atmospheric pressure and ETo were available.

Different climatic indices have been calculated for each year of the study: Thermal Index of Winkler (Winkler, 1962), Heliothermal Index of Huglin (Huglin, 1978), Heliothermal Index of Branas (Branas et al., 1946), Bioclimatic Index of Hidalgo (Hidalgo, 1980), Bioclimatic Index of Constantinescu (Constantinescu, 1967), August-September daily temperature range (Tonietto and Carbonneau, 2002), dryness index (Tonietto and Carbonneau, 2004) and cool night index (Tonietto and Carbonneau, 2004).

Soil data

The chosen plots belong to three representative soil mapping units of the region determined in a very detailed (1:5000) soil map made by Miguel Torres Winery. The soil mapping followed the criteria of the Soil Inventory of Catalonia (Boixadera et al., 1989, Herrero et al., 1993) and the Soil Survey Manual (SSS, 1993).

The Milmanda soil (Table 1), classified as Typic Xerofluvent, fine-loamy, carbonatic, mesic (SSS, 2003), is a very deep soil, rich in silt (56.5 %) and carbonates (45.8 %), without stones, moderately well drained and with a high water holding capacity (1,541 $m^3 \cdot ha^{-1}$). The Riu Sec soil, classified as Typic Haploxerept, sandy-skeletal, mixed, mesic (SSS, 2003), is a moderately deep soil, rich in sand (89.4 %) and gravels (60 %) in deep horizons, somewhat excessively drained and with a low water holding capacity (384 $m^3 \cdot ha^{-1}$). The Muralles soil, classified as Fluventic Haploxerept, loamy-skeletal, mixed, active, mesic (SSS, 2003), is a deep loam soil, stony, well drained and with a high water holding capacity (1,522 $m^3 \cdot ha^{-1}$).

The soil water content was determined by capacitance sensors (ECHO EC20, Decagon Devices Inc.), continuously (every 30 min) and at different depths (15, 30, 60 and 90 cm). In order to minimise the effect of the internal variability of the soil mapping unit, 3 sensors at 20 m of distance were installed for each depth. To make sensors comparable in different soils, without calibration, a water availability index (WA) was calculated. This WA takes the 100 value when the soil moisture content is at field capacity and the 0 value at the minimum soil moisture observed during the study. Field capacity was determined with the capacitance sensors following heavy rainfall periods. Similar methods were used in different previous studies (Lebon et al., 2003).

Table 1. Main analytical data of studied soils at different depths.

Soil	Depth (cm)	pH	CE (1:5, dS/m)	Organic matter (%)	$CaCO_3$ eq. (%)	Sand (%)	Silt (%)	Clay (%)	Textural class* (SSS, 2003)	Bulk density (kg/m^3)	Rock fragments (%)	Moisture at -33 kPa (%)	Moisture at -1500 kPa (%)	Water holding capacity (mm/10cm)
Milmanda	20	8.4	0.23	1.1	45	23.0	55.5	21.5	SiL	1360	0	21	8	17.7
	40	8.4	0.22	0.9	46	21.8	56.4	21.8	SiL	1659	0	21	8	21.6
	80	8.4	0.30	1.3	47	20.8	56.1	23.1	SiL	1450	0	23	9	20.3
	120	8.0	1.42	1.2	45	15.5	58.0	26.5	SiL	1429	0	19	7	17.1
Riu Sec	20	8.3	0.40	2.0	17	43.8	39.9	16.3	L	1110	22	21	8	11.3
	40	8.5	0.19	1.0	9	71.1	18.8	10.1	SaL	1449	54	12	5	4.7
	80	8.5	0.22	0.5	< 2	89.6	4.7	5.7	Sa	1143	65	5	2	1.2
	120	8.5	0.19	0.4	< 2	89.1	3.3	7.6	Sa	572	50	4	2	0.6
Muralles	20	8.4	0.17	1.4	4	54.6	28.5	16.9	SaL	1128	28	20	8	14.1
	40	8.4	0.19	1.1	5	46.2	34.4	19.4	L	1463	30	22	10	13.6
	80	8.4	0.19	0.7	4	45.1	37.4	17.5	L	1070	31	21	9	13.2
	120	8.3	0.17	1.1	4	52.3	30.8	16.9	L	1038	48	19	9	10.6

* SiL: silt loam, L: loam; SaL: sandy loam; Sa: sand

Grape quality data

The Milmanda and Riu sec plots are formed of 20-year-old vines of Cabernet Sauvignon cultivar, grafted onto 140R (Milmanda) and SO4 (Riu Sec) rootstock. The Muralles plot is formed of 13-year-old vines of Grenache noir cultivar, grafted onto R110 rootstock. Vine density is 2,800 (Milmanda) and 3,700 (Riu Sec and Muralles) vines per hectare with vines at 1.2 x 2.8 m (Milmanda) and 1 x 2.2 m (Riu Sec and Muralles) (vine x row spacing). All plots followed similar management: vines were trained to an espalier-type canopy system and were double cordon de Royat pruned, vineyards were dry-land farmed, weeds were controlled by ploughing and there was no subtraction of grape to limit yield.

Data of grape quality were measured directly from containers at the winery entrance, between 25th September and 5th October. Yield ($kg \cdot vine^{-1}$) was determined at the weight bridge and alcoholic degree, pH and total acidity (g tartaric acid/L) were analysed by the Maselli SM-03 Winery Grape Must Analyser. Both anthocyanins (extracted at pH 3.2, in mg/L) and grape seed ripening (difference between absorbance at 280nm and anthocyanins at pH 3.2) were measured in laboratory, for Cabernet Sauvignon plots, following the method of Saint-Cricq de Gaulejac et al. (1998).

Statistical analysis

Data analysis was done by multiple regression, considering data of quality of grapes as dependent variables (DV) and considering edaphoclimatic data as independent variables (IV). Correlation matrices and Principal Components Analysis were performed to explore data and make a first selection of variables. The procedure « All possible regressions » was used to select the most representative models (higher R^2) with selected variables. Then, assumptions of multiple regression were checked. Independent variables were changed until most of the assumptions were accomplished and, if possible, model was significant (confidence level of 0.05 %). The software used was NCSS (Hintze, 2004).

Results and discussion

During the study period, a great interannual variability of rain (from 366 mm to 756 mm) and mean temperature (from 13.2 ºC to 14.9 ºC) is remarkable (Table 2). The wettest year was 2003 (756 mm·year^{-1}), with rains concentrated in the beginning and at the end of the vegetative cycle. This year was the warmest (annual mean of 14.9 ºC), so thermal indexes were the highest too (Huglin Index = 2672) (Table 3). In 2004, rainfall was lower (495 mm) than in 2003, but during the growing season was higher, so rainfall April-august was the highest of the period (211 mm). Temperatures were the lowest of the period (annual mean of 13.2 ºC), except for maturation period, as reflected in a high cool-night index (14.6 ºC). In 2005, rain was low during the whole year and very low during the growing season (rainfall April-August = 76.8 mm). Temperatures were intermediate, except for maturation period, where temperatures were the lowest (cool-night index = 13 ºC). In 2003, solar radiation was fairly higher than other years, and in 2004 was slightly higher than in 2005.

Figure 1 shows water availability (WA) evolution from June 2003 to October 2005. Generally, summer WA seems inversely proportional to annual rainfall, and spring WA too. The lowest summer WA (< 20 %) occurred in 2003 (Riu Sec) and 2004 (Milmanda and Muralles), when rain and spring WA were the highest (generally, higher than 80 %). The high rain and WA could have favoured vegetative development, and vines would be most water demanding in summer. On the contrary, WA values during 2005 were low (< 60 %) in the first months of the growing season, and summer WA were high (> 20 % in Milmanda and > 40 % in Muralles). Some differences between soil types can be observed. In Riu Sec soil, WA usually is lower than in other soils, probably due to quick drainage and low water holding capacity. In Muralles, WA is slightly higher than in Milmanda. Between these soils, important differences occur at different depths. During 2005, the horizon at 90 cm depth recovered the WA in Muralles, but not in Milmanda: the rain in Milmanda was not enough to reach field capacity in superficial horizon, so deep horizons did not increase their WA. In Muralles, where water holding capacity is lower, the WA increases at all depths.

Table 2. Monthly and annual meteorological data from 2003 to 2005 of Espluga de Francolí automatic weather station.

Variable	Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Rain (mm)	2003	9.2	130	38.4	21.4	92.2	11.2	4.0	53	48.8	190	114	43.4	756
	2004	2.0	68.8	68.2	88.6	60.4	10.4	50.8	1.2	34.2	37.6	1.4	71.8	495
	2005	0.0	27.2	12.4	2.6	46.6	7.2	1.4	19	54.2	61.2	130	3.6	366
Mean high temperatures (ºC)	2003	10.7	10.2	17.2	19.3	23.6	31.7	31.8	33.5	25.7	18.3	13.7	9.9	20.5
	2004	11.4	10.1	12.8	15.4	19.6	27.5	26.9	29.7	26.4	22.2	13.2	10.5	18.8
	2005	9.0	9.2	14.8	19	24.3	29.6	30.9	28.5	25.1	20.3	13.4	8.9	19.4
Mean temperatures (ºC)	2003	6.8	6.3	11.0	13.2	17.3	24.3	25.1	26.2	19.7	13.9	9.5	5.9	14.9
	2004	7.4	4.8	7.3	10.3	13.8	20.2	20.6	23.5	20.1	16.0	7.9	6.6	13.2
	2005	3.5	4.0	8.3	12.7	17.4	22.4	24.1	22.0	18.8	15.3	9.1	4.0	13.5
Mean low temperatures (ºC)	2003	3.2	2.7	5.2	7.8	11.6	17.4	18.3	19.1	14.2	9.9	5.7	2.2	9.8
	2004	3.8	0.6	2.4	5.3	8.4	13.4	14.9	17.7	14.6	10.7	3.5	3.0	8.2
	2005	-0.5	-0.6	2.8	6.7	10.9	15.3	17.6	16.1	13	11	5.4	0.6	8.2
Solar radiation (MJ·m^{-2}·day^{-1})	2003	7.0	7.7	15.1	17.7	22.3	24.4	24.3	21.5	15.5	9.7	6.6	5.6	14.8
	2004	7.1	9.5	13.2	16.9	20.6	23.7	17.6	19.2	15.4	11.1	7.6	4.8	13.9
	2005	7.6	9.6	14.1	17.1	20.3	21.0	21.8	19.0	13.1	8.7	6.0	5.8	13.7

Table 3. Viticulture climatic indices from 2003 to 2005

Index	2003	2004	2005
Period of vegetative activity (PVA) (Mean T > 10ºC)	March - October	April - October	April - October
Mean temperature during PVA (ºC)	18.8	17.8	19
Sum of degree-day during PVA	4612	3809	4060
Thermal index of Winkler	2162	1669	1920
Heliothermal index of Branas	7.08	4.86	5.59
Bioclimatic index of Hidalgo	9.4	9.8	15.3
Bioclimatic index of Constantinescu	12.0	18.3	28.8
August-September daily temperature range	12.9	11.9	12.3
Rainfall April-August	182	211	76.8
Dryness index - DI (Geoviticulture CCM System)	-21	71.8	56.5
Huglin index - HI (Geoviticulture CCM System)	2672	2088	2413
Cool night index - CI (Geoviticulture CCM System)	14.2	14.6	13

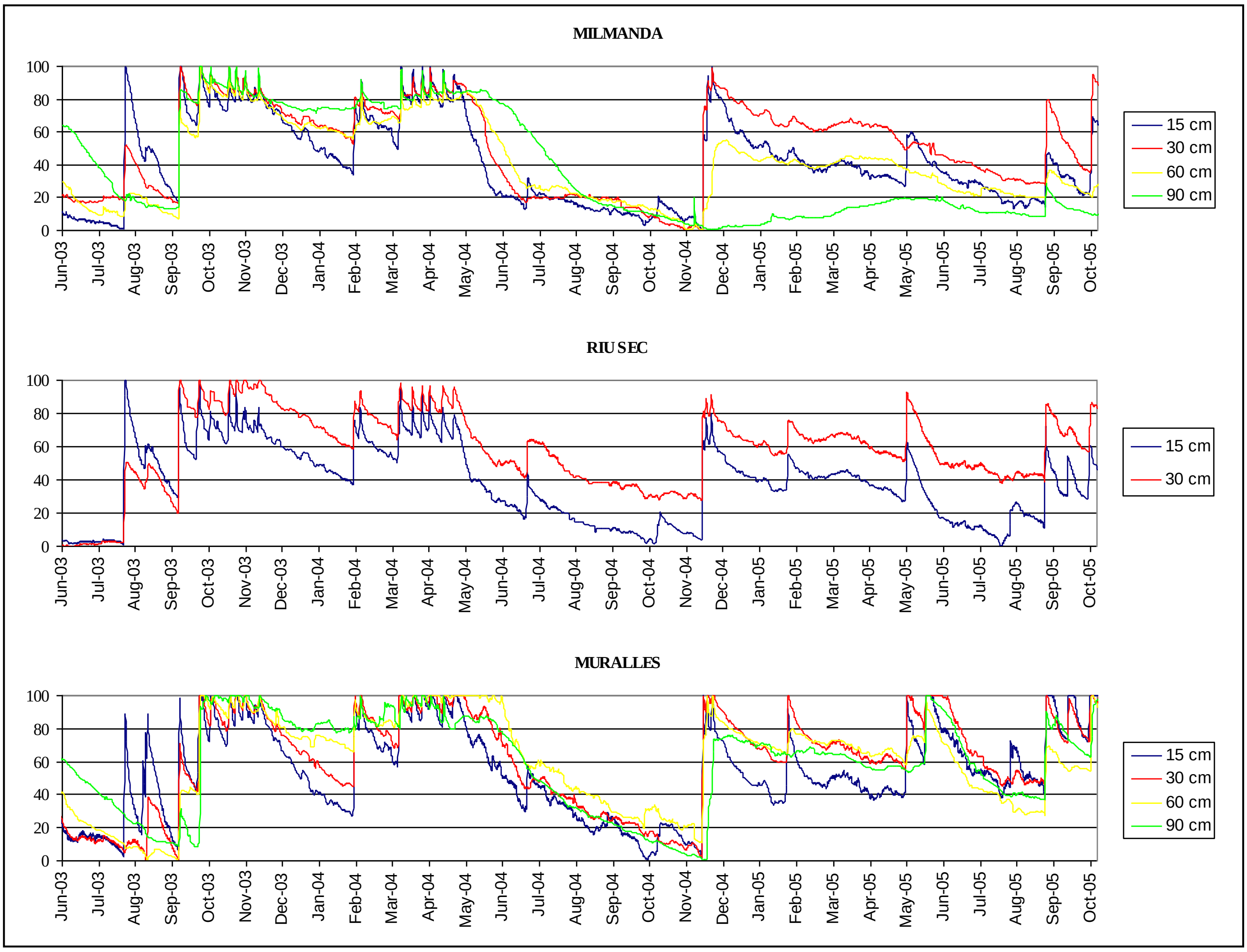

Figure 1. Water availability index, in continuum and at different depths, for Milmanda, Riu Sec and Muralles plots.

The most productive vintage was 2003 in Milmanda and Riu Sec, except for Muralles which suffered an abnormal yield in 2004 (Table 4). The vintage least productive was 2005 except for Milmanda (2004): the great development of vegetation could have broken the equilibrium between vegetative activity and fruit production. The highest grape alcoholic degree was in 2004, except for Muralles (2003). The highest pH of must took place in 2003. The highest total acidity took place in 2004. Grape seed ripening had the highest value in 2003, but the minimum value was in 2005 for Milmanda and 2004 for Riu Sec. Anthocyanins had the highest value in 2004, but the minimum value was in 2005 for Milmanda and 2003 for Riu Sec.

Matrix correlations and PCA were done in order to explore data and select the best explicative factors. Figure 2 shows a PCA considering only the selected variables, which is more understandable. Factor 1, which explains 35.98 % of variability, separates 2004 vintage from

2003 and 2005 vintages. 2004 vintage has higher rainfall during October-September (R oct-sep), meanwhile 2003 and 2005 vintages are both characterized by a higher mean daily temperature range for vineyard growing season (TR act). Factor 2, which explains 33.72 % of variability, distinguishes between 2003 and 2005 vintages. The 2003 vintage is situated in an area with high thermal indexes (sum of degree-day for vineyard growing season (DD act), Winkler index, Huglin index). On the other side, 2005 is characterized by a high water availability index (WA); year 2004 shows the same trend than 2005. Factor 3, which explains 17.85 % of variability, clearly separates Muralles soil from Milmanda soil, mainly by $CaCO_3$ content and ratio absorption sodium (RAS). Factor 4, explaining 9.74 % of variability, separates each vineyard by its Cation Exchange Capacity (CEC), having Muralles the highest CEC and Riu Sec the lowest one. In conclusion, climatic data and water availability explain 70 % of variability (factors 1 and 2). For this reason, climate and water availability are the main factors allowing to distinguish vintages, with climate having probably more influence than water availability. Finally, soil data explain 28 % of variability (factors 3 and 4).

Table 4. Data of grape quality for Cabernet Sauvignon (Milmanda and Riu Sec) and Grenache Noir (Muralles)

Plot	Milmanda			Riu Sec			Muralles		
Year	2003	2004	2005	2003	2004	2005	2003	2004	2005
Yield (kg·vine^{-1})	1.78	1.34	1.65	1.42	1.07	1.01	2.15	3.91	1.60
Alcoholic degree	15.3	16.1	13.3	14.5	15.5	14.4	15.8	13.7	15.6
pH	3.64	3.26	3.57	3.58	3.30	3.47	3.45	3.4	3.27
Total acidity (g/L)	8.81	10.67	7.13	6.21	11.1	7.26	6.02	6.55	6.38
Grape seed ripening	10.13	8.56	7.20	17.03	3.57	7.71	-	-	-
Anthocyanins (mg/L)	387	424	318	442	666	540	-	-	-

Models for grape quality were performed by Multiple Regression Analysis (Table 5). These models have a high estimation capacity, with R^2 higher than 0.75 (except for pH and grape seed ripening). The models are significant ($p < 0.05$) for yield, total acidity and anthocyanins; and slightly non significant ($0.05 < p < 0.07$) for alcoholic degree, pH and grape seed ripening. Yield is highly correlated with edaphoclimatic data ($R^2 = 0.88$). The chosen independent variables are CEC and Winkler Index, with a similar importance (similar standardized regression coefficient). The properties of must can be highly estimated, except for pH and grape seed ripening ($R^2 = 0.63$). Anthocyanins is the most correlated variable ($R^2 = 0.9$). In models for must properties, a climatic index (SR september, R oct-sep, Huglin index and DD act) and a water availability index (WA summer) is always present, except for grape seed ripening, where there is only a climatic index (DD act). Climatic indices have higher influence than WA indices, except for anthocyanins, where WA summer has the greatest weight. Soil data appear in alcoholic degree model, having few importance (CEC); and total acidity model, having high importance (RAS).

Climatic data have the highest influence on regression models, as it is shown by the PCA, particularly the climatic indices which estimate must data. These results agree with the conclusions obtained in previous studies (Van Leeuwen et al., 2004), where climate appears as the most influencing factor on must quality. It is known the effect of climate, mainly temperatures and solar radiation, on grape maturation and accumulation of phenolic compounds (Coombe, 1987; Jackson and Lombard, 1993; Tonietto and Carbonneau, 2002).

Water availability is the second important predictor, specially in must data. Water supply to vines strongly influences the quantity and quality of their grape production (Oliveira, 1995; Van Leeuwen et al., 2003; Hunter and Deloire, 2005). This can be explained by the effect of water supply on the balance between vegetative and reproductive growth (Matthews et al., 1987; Van Leeuwen and Seguin, 1994). Grape maturation can improve in case of moderate water limitation, increasing the content of sugars and phenolic compounds, and decreasing malic acid content (Trégoat et al., 2002; Ojeda et al., 2002).

On the other hand, soil characteristics are important to predict yield and total acidity. Generally, it is difficult to establish a direct correlation between soil characteristics and wine quality (Seguin, 1986). However, soil properties, mainly nitrogen status and soil depth, can affect grape and wine quality, even more than water supply (Choné et al., 2001).

All the studied parameters have an influence on grapevine functioning in relation with the grape berry development, composition and the evolution of the fruit maturation (Brenon et al., 2005). A global approach which takes into account at least edaphoclimatic data is necessary to understand the functioning of vines and evolution of berry composition (Deloire et al., 2005).

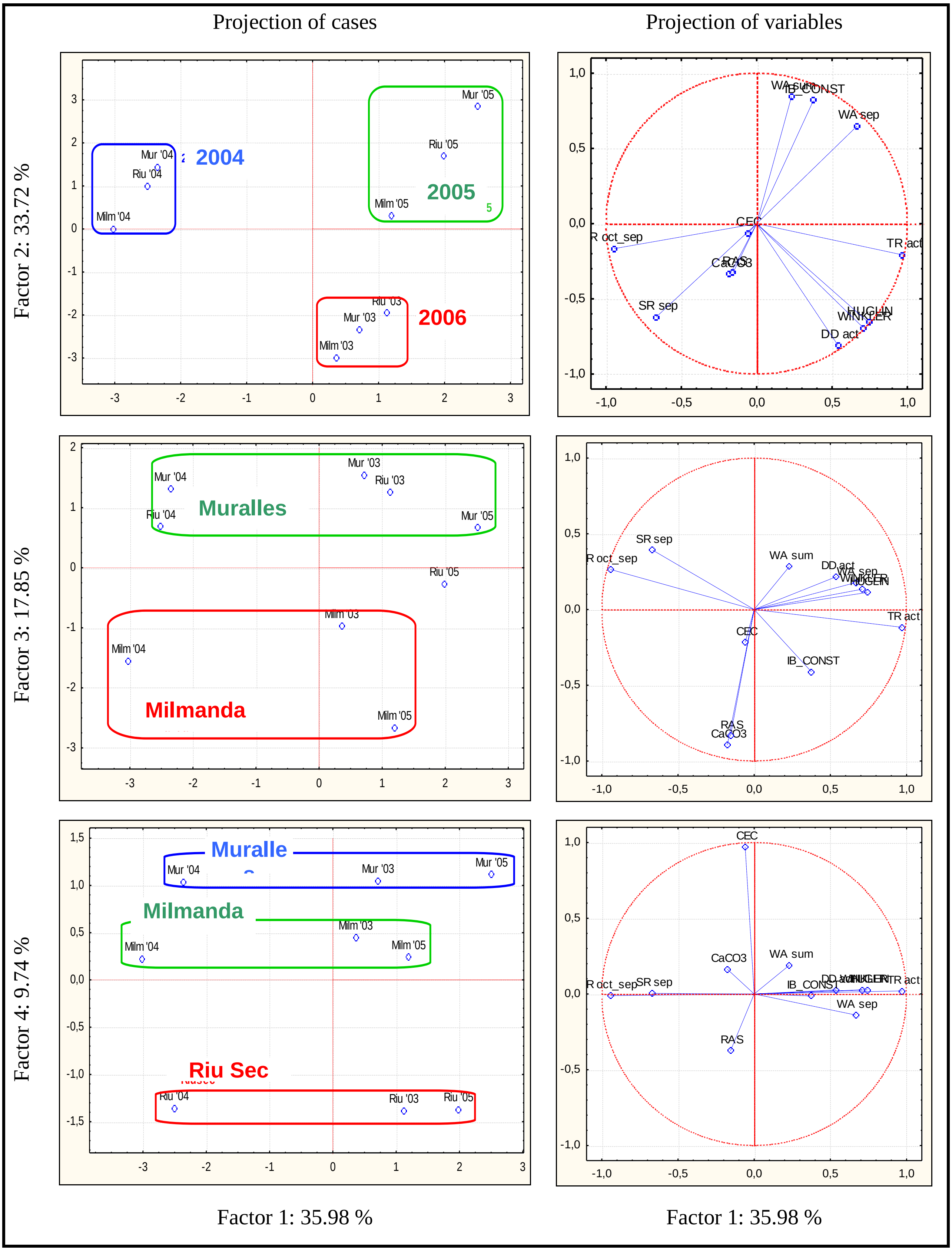

Figure 2. Projection of cases and variables on the factor-planes of the PCA performed with selected variables. (WA sum: mean WA in summer, WA sep: mean WA in September, CEC: Cation Exchange Capacity, RAS: ratio absorption sodium, SR set: mean daily solar radiation in September, TR act: mean daily temperature range for vineyard growing season, DD act: sum of degree-day for vineyard growing season, R oct-sep: Rain during October-September, Winkler: Winkler index, Huglin: Huglin index, Const: Constantinescu index)

Table 5. Results of Multiple Regression Analysis for grape quality variables.

Dependent variable	Independent variables[1]	Regression coefficient (b)	Model quality	
Yield	CEC	0.6795 **	R^2	0.8795
	Winkler index	0.5566 *	n	8
			Significance (p level)	0.005
Alcoholic degree	CEC	0.3619 ns	R^2	0.8128
	SR september	1.1050 *	n	8
	WA summer	0.8318 *	Significance (p level)	0.062
Total acidity	R oct-sep	0.6736 *	R^2	0.7663
	RAS	0.8190 *	n	9
	WA summer	0.4280 ns	Significance (p level)	0.049
pH	Huglin index	0.6092 ns	R^2	0.6256
	WA summer	-0.3406 ns	n	9
			Significance (p level)	0.052
Anthocyanins	R oct-sep	0.5594 *	R^2	0.9040
	WA summer	0.8623 *	n	6
			Significance (p level)	0.030
Grape seed ripening	DD act	0.791 ns	R^2	0.6257
			n	6
			Significance (p level)	0.061

*, **, ns indicate significance at $p < 0.05$, $p < 0.01$ and no significant, respectively.

[1] CEC: Cation Exchange Capacity, SR september: mean daily solar radiation in September, WA summer: mean water availability index in summer, R oct-sep: Rain during October-September, RAS: ratio absorption sodium, DD act: sum of degree-day for vineyard growing season.

Conclusion

The effect of both soil and interannual climate parameters on grape quality were studied, without considering cultivar effect and considering the same climate for all plots. As cultivar has an influence on wine typicality, this study is focused on yield and some parameters of berry composition, without analysing implications on wine quality. A water availability index was calculated from soil moisture data measured by capacitance sensors. The water availability index resulted a useful tool to predict grape must quality. However, the style of the wine can not be predicted from this study, since it does not consider cultivar differences. According to the performed PCA, climatic data and water availability explained 70 % of vintage variability and soil data explained 28 % of vintage variability. Climatic data seemed slightly more explicative than water availability. The Multiple Regression Analysis showed that edaphoclimatic factors had generally a high power of estimation of yield and quality of grapes, with R^2 higher than 0.75. All models were significant at 90 % probability ($p < 0.07$). Climate appeared to be the most influencing factor, followed by water availability, in particular for models referring to must data. Climatic data used in models were climatic indices, as Huglin index or Winkler index. The selected water availability index was the mean water availability in summer. Generally, soil data had influence on yield and some must data.

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Chapter 6

EFFECTS OF SOIL AND CLIMATE ON GRAPE RIPENING AND WINE QUALITY OF CABERNET SAUVIGNON

Abstract

The effects of climatic conditions and soil type on grape ripening and wine quality were studied for the period 2003-2005, in two Cabernet Sauvignon vineyards under the same climate but on very distinct soils. Climate effect was estimated by studying annual variations. Climatic conditions and soil had overall a significant effect on grape ripening. The effects of soil and climate could be explained mainly by their influence on plant water availability status. Soil type appeared to be determining wine phenolic composition, and related wine tasting characteristics.

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Introduction

Grape and wine quality are often associated with specific conditions of soil, climate, cultural practices, training system, all of which interact with the grape variety and form the concept of 'terroir' (Falcetti, 1994; Vaudour, 2003; Deloire et al., 2005). This 'terroir' generally is defined as a spatial and temporal entity, which is characterized by an interaction between the environmental potentialities and viticultural and oenological technologies, significant for grapes and/or wine (Vaudour, 2003; Deloire et al., 2005). A wide range of methods is used for the determination of 'terroir' (Vaudour and Shaw, 2005). The simplest methods only consider soil, climate or the interaction between soil and climate (Morlat, 2001). But other factors can be added, such as cultivar and viticultural and oenological technology (Carbonneau, 2001), as well as historical and sociological wine-growing factors (Vaudour, 2003).

Climate is the factor that has the greatest influence on the suitability of the environment for grapevine growing and wine production (Hidalgo, 1999). The cold limit for viticulture without winter protection can be considered as -1ºC of mean temperature for the coldest month (Gladstones 2000). Spring average minimum temperatures can be used in order to assess frost risk after budbreak (Gladstones, 1992). A minimum of cumulated temperatures during the growing season is necessary to ensure complete ripening for a certain cultivar (Winkler, 1962; Huglin, 1978). Also, cumulated temperatures determine pulp ripening speed and harvesting date (Duteau, 1990). Night temperatures during the ripening period affect the accumulation of grape phenolic compounds and wine aroma and colour (Kliewer and Torres, 1972; Tonietto and Carbonneau, 2002; Deloire et al., 2005). Anthocyanin accumulation can be severely undermined by high diurnal temperatures during the ripening period (Van Leeuwen et al., 2004). Water balance, calculated from precipitation and evapotranspiration (Riou, 1998; Carbonneau, 2002), has implications on the potential for grape sugar and secondary metabolites (polyphenols and aromas) at maturity, and also on wine characteristics (acidity, aroma).

Within a specific climate, soil is the most important environmental factor affecting vine development and wine quality (Sotés and Gómez-Miguel, 2003). The soil properties which have the greater influence on grapevine growing are soil depth and physical properties, the properties which control soil water content (Seguin, 1986), and have a direct effect on the equilibrium between vegetative vigour and grape production (Van Leeuwen and Seguin, 1994), and consequently on grape and wine quality (Esteban et al., 2001; Trégoat et al., 2002; Gurovich and Páez, 2004). A moderately reduced water regime induces generally positive effects on berry composition and wine quality (Kounduras et al., 1999), with an increase of berry sugar, anthocyanin and tannin content and also an increase of the grape ripening speed (Van Leeuwen and Seguin, 1994). In general, relationships between soil minerals and wine quality cannot be established (Seguin, 1986), unless severe deficiencies affecting vineyard growing occur (Van Leeuwen et al., 2004). However, some studies have shown an effect of soil cations on grape composition, which can influence wine quality (Peña et al., 1999; Mackenzie and Christy, 2005). One mineral component that can be correlated with grape and wine quality is nitrogen, which in excess can affect the sugar and phenolic compounds content of grapes (Choné et al., 2001; Hilbert et al., 2003).

There are many studies to determine the effects on grape production and composition of a single ‘terroir’ factor, whether the climate (Jones and Davis, 2000; Tonietto and Carbonneau, 2004), soil (Trégoat et al., 2002; Sivilotti et al., 2005) or other factors (Murisier and Zufferey, 1997). However, there are few studies that examine the joint effects of more than one factor, whether climate and soil or soil and cultivar (Van Leeuwen, 1995). Van Leeuwen et al. (2004) analysed simultaneously the effects of three factors (climate, soil and cultivar) on grape quality. Moreover, studies that consider ‘terroir’ effects on wine quality are even more limited (Choné et al., 2001; Andrés-de-Prado et al., 2007). In this study, we focused on the effects of the main environmental factors of ‘terroir’, climate and soil, on grape ripening and wine quality. Two vineyards on distinct soil types were used to study soil effect, and climate effect was studied through interannual climatic conditions.

The objective of this study was to establish the effect of soil and climatic conditions on grape ripening and wine quality of Cabernet sauvignon, using the following steps: (i) characterization of edaphoclimatic factors, (ii) determination of grape composition during ripening (grape yield, pulp and phenolic composition) and speed of ripening, (iii) determination of wine quality (wine composition and organoleptic properties) and (iv) analysis of the effects of soil and climate on grape composition at harvest and wine quality.

Materials and Methods

Setting

This study was carried out from 2003 to 2005 in two vineyards (‘Solar’ and ‘Llarga’) situated in the Conca de Barberà viticultural area (Catalonia, Spain). ‘Llarga’ is located at 41º 23’ 43’’ North, 1º 4’ 23’’ East and 450 m of altitude; and ‘Solar’ is located at 41º 23’ 21’’ North, 1º 4’ 44’’ East and 459 m of altitude. The studied plots were 20-year-old vines of the Cabernet Sauvignon cultivar (3,700 vines per hectare), which followed similar management: vines were trained to an espalier-type canopy system and were double cordon Royat pruned (12 buds per vine), vineyards were dry-land farmed and weeds were controlled by ploughing.

Climate

Both studied plots had a similar mesoclimate, since they are located next to each other (600 m apart) and they had similar topographic characteristics (altitude, slope and orientation). The climate type is Mediterranean but with some continental features due to the barrier effect of the Catalan Coastal Range. The mean annual precipitation is 550 mm and mean annual temperature 13.6ºC. The viticultural climate (Tonietto and Carbonneau, 2004) is moderately dry, temperate warm and with cool nights.

Daily meteorological data were recorded in an automatic weather station (Espluga de Francolí) of the Meteorological Service of Catalonia (Government of Catalonia), located at 41º 23’ 39’’ North, 1º 6’ 1’’ East and 441 m of altitude. This station is located less than 2 km from both plots, and has the same topographic position.

Soils

The chosen soils belonged to two representative soil map units of the region, identified in a very detailed (1:5000 scale) soil map prepared by the Miguel Torres Winery. The soil survey method followed the criteria of the Soil Inventory of Catalonia (Porta et al., 2009) and the Soil Survey Manual (SSS, 1993).

The selected soils presented very different chemical (Table 1) and physical properties (Table 2). The ‘Llarga’ soil, classified as Typic Xerofluvent, fine-loamy, carbonatic, mesic (SSS, 2006), was a soil rich in silt and carbonates, without stones, moderately well drained and with a high water holding capacity. The ‘Solar’ soil, classified as Typic Haploxerept, sandy-skeletal, mixed, mesic (SSS, 2006), is a soil rich in sand and stones in the deep horizons, somewhat excessively drained and with a low water holding capacity.

Table 1. Chemical properties of the selected soils at different depths.

Plot	Depth (cm)	pH (H_2O 1:2.5)	EC[a] (1:5, dS/m)	Organic matter (%)	N (%)	C/N	$CaCO_3$ equivalent (%)	Active $CaCO_3$ eq. (%)	Fe (mg/ kg)	CEC[b] (cmol(+)/ kg)
Llarga	0 – 20	8.4	0.23	1.1	0.09	7.1	45	9	70	10.1
	20 – 40	8.4	0.22	0.9	0.08	6.5	46	10	63	9.9
	40 – 80	8.4	0.30	1.3	0.06	12.6	47	8	68	9.7
	80 – 120	8.0	1.42	1.2	0.05	14.0	45	9	65	10.9
Solar	0 – 20	8.3	0.40	2.0	0.10	11.6	17	2	151	9.8
	20 – 40	8.5	0.19	1.0	0.05	11.6	9	trace	104	6.5
	40 – 80	8.5	0.22	0.5	0.02	14.5	trace	trace	76	3.6
	80 – 120	8.5	0.19	0.4	0.02	11.6	trace	trace	93	3.7

[a] Electrical conductivity, [b] Cation Exchange Capacity

Table 2. Physical properties of the selected soils at different depths.

Plot	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Textural class (SSS, 2003)	Bulk density (kg/m3)	Coarse fragments (%)	Moisture at -33kPa (%)	Moisture at -1500 kPa (%)	Water Holding Capacity (mm/10 cm)
Llarga	0 – 20	23.0	55.5	21.5	SiL[a]	1360	trace	21	8	17.7
	20 – 40	21.8	56.4	21.8	SiL[a]	1659	trace	21	8	21.6
	40 – 80	20.8	56.1	23.1	SiL[a]	1450	trace	23	9	20.3
	80 – 120	15.5	58.0	26.5	SiL[a]	1429	trace	19	7	17.1
Solar	0 – 20	43.8	39.9	16.3	L[b]	1110	22	21	8	11.3
	20 – 40	71.1	18.8	10.1	SaL[c]	1449	54	12	5	4.7
	40 – 80	89.6	4.7	5.7	Sa[d]	1143	65	5	2	1.2
	80 – 120	89.1	3.3	7.6	Sa[d]	572	50	4	2	0.6

[a] silt loam, [b] loam, [c] sandy loam, [d] sand

In each soil type, soil water content was monitored by capacitance sensors (ECHO EC20, Decagon Devices Inc.), obtaining values continuously (every 30 minutes) and at different depths (15, 30, 60 and 90 cm for ‘Llarga’ and 15 and 30 cm for “Solar”). Deep soil horizons of ‘Solar’ were not monitored, because of very low water holding capacity and high gravel content, which strongly limited root development. The fraction of transpirable soil water (FTSW) was estimated for each depth as the amount of water between the soil moisture content at field capacity and the minimum soil moisture observed during the study (Ritchie, 1981). Field capacity was determined with the capacitance sensors following heavy rainfall periods. Lebon et al. (2003) estimated that soil water shortage, with stomatal closure, occurred when FTSW was lower than 0.4.

Grape Ripening

During grape ripening, different parameters of berry composition were measured approximately twice a week according to a completely randomized design with three replications. In every plot and each replication, 200 berries from 25 vines located at five different rows, were randomly sampled, as much at vine level as at berry bunch level. From this sample, 100 berries were used for must analysis and the other 100 berries were used for the analysis of phenolic maturation. The data of pulp maturation selected for the statistical analysis was weight of 100 berries (g), sugar content (g/L), acidity (g/L of tartaric acid) and pH. Sugar content was calculated with a conversion table (Blouin and Guimberteau, 2004) from Brix degrees determined with the hand refractometer Zuzi 0-32 Brix and total acidity was determined with an acid-base reaction. For the phenolic maturation measurements included anthocyanins (mg/L, extracted at pH 3.2) and grape seed tannins, calculated as (absorbance at 280 nm) – (anthocyanins extracted at pH 3.2 / 1000 x 40), according to Saint-Cricq De Gaulejac et al. (1998).

Moreover, pulp ripening speed was calculated for each soil and climatic condition, according to Duteau (1990). In this method, ripening speed is represented by the slope of the linear regression between a climatic index and a ripening index. The climatic index (Ci) is calculated by the cumulative sum of mean and average maximum temperatures, from 1st August. The ripening index (Ij) is calculated by dividing sugar concentration (g/L) by total acidity (g/L of sulphuric acid).

Microvinification

For every year and soil, a microvinification was carried out in triplicate, following similar methods. The grapes were picked when values of around 23 - 24 ºBrix were recorded (3rd October, 2003 and 30th September, 2004 and 2005, at both plots) and after being crushed and their stems removed, 30 kg of the resulting whole grapes were put into a stainless steel tank. Alcoholic fermentation was enhanced with L-2056 yeast (Lalvin® yeast by Lallemand®, Canada), at a rate of 0.2 g/L. During alcoholic fermentation, there was a pumping over twice a day and maceration lasted 8-10 days. The fermentation and maceration temperature was at 26ºC. After alcoholic fermentation, there followed malolactic fermentation.

Different variables of the resulting wines were analysed (for each replication): degree of alcohol, sugar concentration (g/L), volatile acidity (g/L of acetic acid), total acidity (g/L of tartaric acid), pH, absorbance at 420 nm, 520 nm and 620 nm, colour intensity (sum of absorbance at 420 and 520 nm), total polyphenols (absorbance at 280 nm), tannins (g/L) and anthocyanins (mg/L). Degree of alcohol was measured with Alcolyzer Wine (Anton Paar). Volatile acidity and sugar were determined with a continuous-flow autoanalyser (TDI). Tannins and anthocyanins were determined with spectrophotometry (Spectrophotometer EλIOS β UV-Vis), according to Ribéreau-Gayon and Stonestreet (1965, 1966).

An experienced wine tasting panel judged the wines resulting from mixing the 3 replications of every year and soil. A blind tasting was performed in order to ensure an impartial judgment at ambient temperature. The panel was composed of 4 people, 2 men and 2 women aged between 30 and 60 years, who scored the wines for colour (red, blue, brown), aroma (aromatic intensity) and taste (total intensity, unctuosness) between 0 and 5, as well as for some descriptive terms concerning aroma and taste. Finally, they were asked for an overall judgement, with a score between 0 and 10. All these appraisals were carried out individually.

Statistics

The statistical analysis used in order to find significant differences was done by ANOVA, considering grape and wine properties as dependent variables and both soil and climate as categorical factors. Means were separated by Newman-Keuls post-hoc analysis ($p \leq 0.05$). Moreover, the percentages of variance attributable to each factor were calculated, from the division between the sum of squares of each factor and the total, multiplied by 100. Linear regression analysis was used for ripening speed modelling. The software used was STATISTICA (StatSoft, Inc.).

Results

Edaphoclimatic conditions

Precipitation and temperature showed a high interannual variability (Table 3). The annual precipitation ranged between 756 mm in 2003 and 366 mm in 2005. 2003 was also the rainiest year during the growing season (421 mm), doubling the lowest precipitation, which was 192 mm in 2005. 2003 was also the rainiest year during the ripening period (102 mm), tripling the lowest, which was 35 mm in 2004. With respect to temperatures, 2003 was significantly warmer than other years, with an annual average of 14.9ºC, with more than 1.5ºC of difference from the coldest year, 13.2ºC in 2004. 2005 presented intermediate values, but was closer to 2004 than to 2003. The annual maximum and minimum mean temperatures had a similar trend, showing the highest values in 2003 (maximum of 20.5ºC and minimum of 9.8ºC), and the lowest ones in 2004 (maximum 13.2ºC and minimum 8.2ºC). 2005 presented maximum temperatures slightly above and minimum temperatures equal to 2004. Regarding temperatures during the growing season, 2003 was the warmest year, with 2ºC more than 2004 and 1°C more than 2005, for average maximum and minimum temperatures. This fact is reflected in cumulated growing degree days for 2003 (2135ºC), considerably higher than 2004 (1622ºC). 2005 presented intermediate temperatures during the growing season. Regarding ripening temperatures, 2003 was the warmest year, with an average of 22.9ºC, and 2005 the coldest with a mean of 20.4ºC. 2004 presented intermediate values. Maximum and minimum temperatures showed a similar trend to the average, although the minimum in 2005 (14.6ºC) were lower than the other two years (16.7ºC in 2003 and 16.2ºC in 2004).

Table 3. Temperature and precipitation parameters for the growing season (Apr-Oct) and the ripening period (Aug-Sep) in the study area (2003-2005).

Period	Rain (mm)			Mean Temperature (ºC)			Average maximum Temperature (ºC)			Average minimum Temperature (ºC)			Growing Degree Days (ºC)		
	Aug-Sep	Apr-Oct	Year	Aug-Sep	Apr-Oct	Year	Aug-Sep	Apr-Oct	Year	Aug-Sep	Apr-Oct	Year	Aug-Sep	Apr-Oct	Year
2003	102	421	756	22.9	20.0	14.9	29.6	26.3	20.5	16.7	14.1	9.8	791	2135	2208
2004	35	283	495	21.8	17.8	13.2	28.1	24.0	18.8	16.2	12.1	8.2	711	1622	1654
2005	73	192	366	20.4	19.0	13.5	26.8	25.4	19.4	14.6	12.9	8.2	609	1897	1960

Regarding the seasonal evolution of temperature and precipitation (Fig. 1), 2003 presented most of the rain from veraison. Moreover, temperatures until veraison were very warm, reaching over 35 ºC, and also during ripening, with days around 30 °C. 2004 and 2005 did not differ much in terms of total precipitation and average temperature between flowering and harvest, although the period between veraison and harvest was driest in 2004 and coolest in 2005.

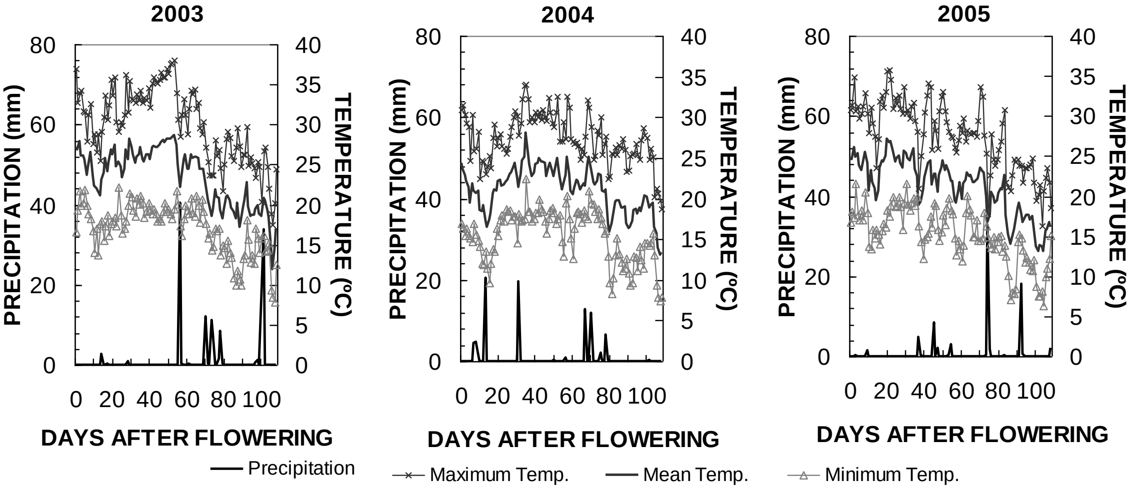

Figure 1. Evolution of mean, maximum and minimum daily temperature and precipitation from flowering through harvest in the study area (2003-2005).

The fraction of transpirable soil water (FTSW) was used in order to assess soil moisture dynamics after flowering (Fig. 2). In 2003, soil water limitation occurred until 14 days before veraison, being less important on ‘Llarga’ than on ’Solar’, since on ‘Llarga’ FTSW remained above 0.4 from 60 cm soil depth. During ripening, soil water content decreased until FTSW was slightly below 0.4. However, just 3 days before harvest, soil water content recovered due to a rain event. 2004 had the highest FTSW over the soil profile between flowering and veraison. From veraison until harvest, soil water limitation appeared in ‘Solar’, but not in ‘Llarga’, where FTSW remained above 0.4 approximately from 40 to 60 cm soil depth. 2005 was the driest year, having the lowest values of FTSW over the soil profile between flowering and veraison and the first half of the days between veraison and harvest. During this period, ‘Llarga’ soil had FTSW higher than 0.4 at approximately 40-60 cm soil depth. However, during the second half of the days between veraison and harvest soil water limitations did not appear, because of the rain.

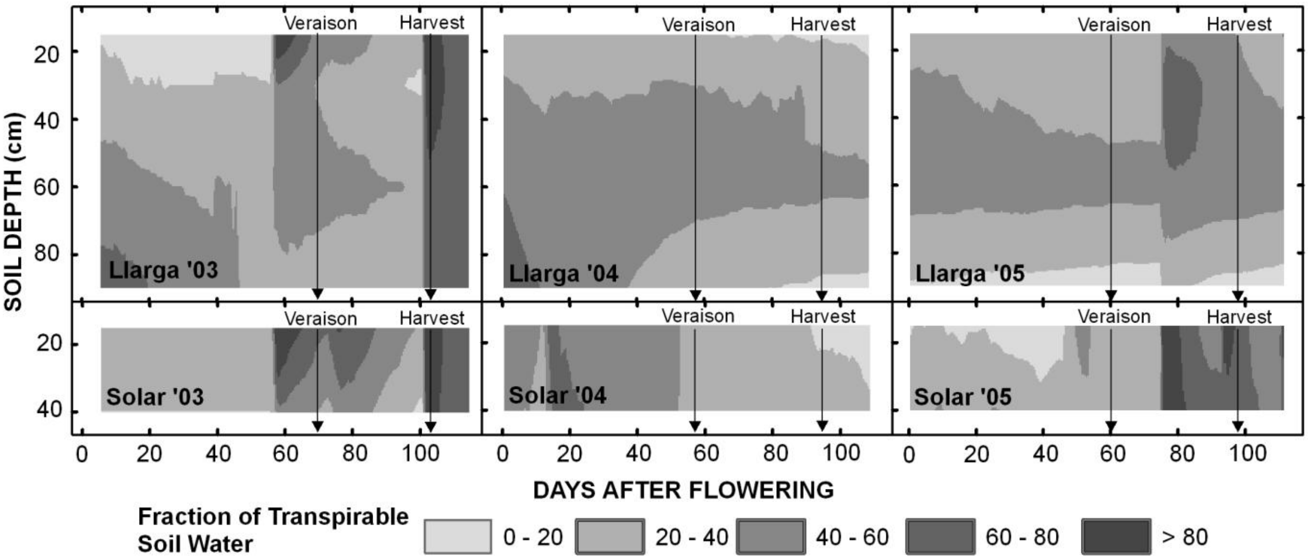

Figure 2. Evolution of Fraction of Transpirable Soil Water after flowering (%) at different depths, for each plot (‘Solar’ and ‘Llarga’) and year (2003-2005).

Grape Ripening

100-berry weight presented higher values on ‘Llarga’ than on ‘Solar’ for all the years of the trial, although it seems that differences are minor at the beginning and at the end of the maturation process (Fig. 3). However, sugar content was higher on ‘Solar’ than on ‘Llarga’ in all years. Acidity values were lower on ‘Solar’ than on ‘Llarga’ at the beginning of grape ripening period in 2003 and 2005, but there were no differences between soils at the end of grape ripening period and during 2004. pH values were higher on ‘Solar’ in 2003, but lower in 2004 and 2005. However, these differences were not significant, either between soils or between years.

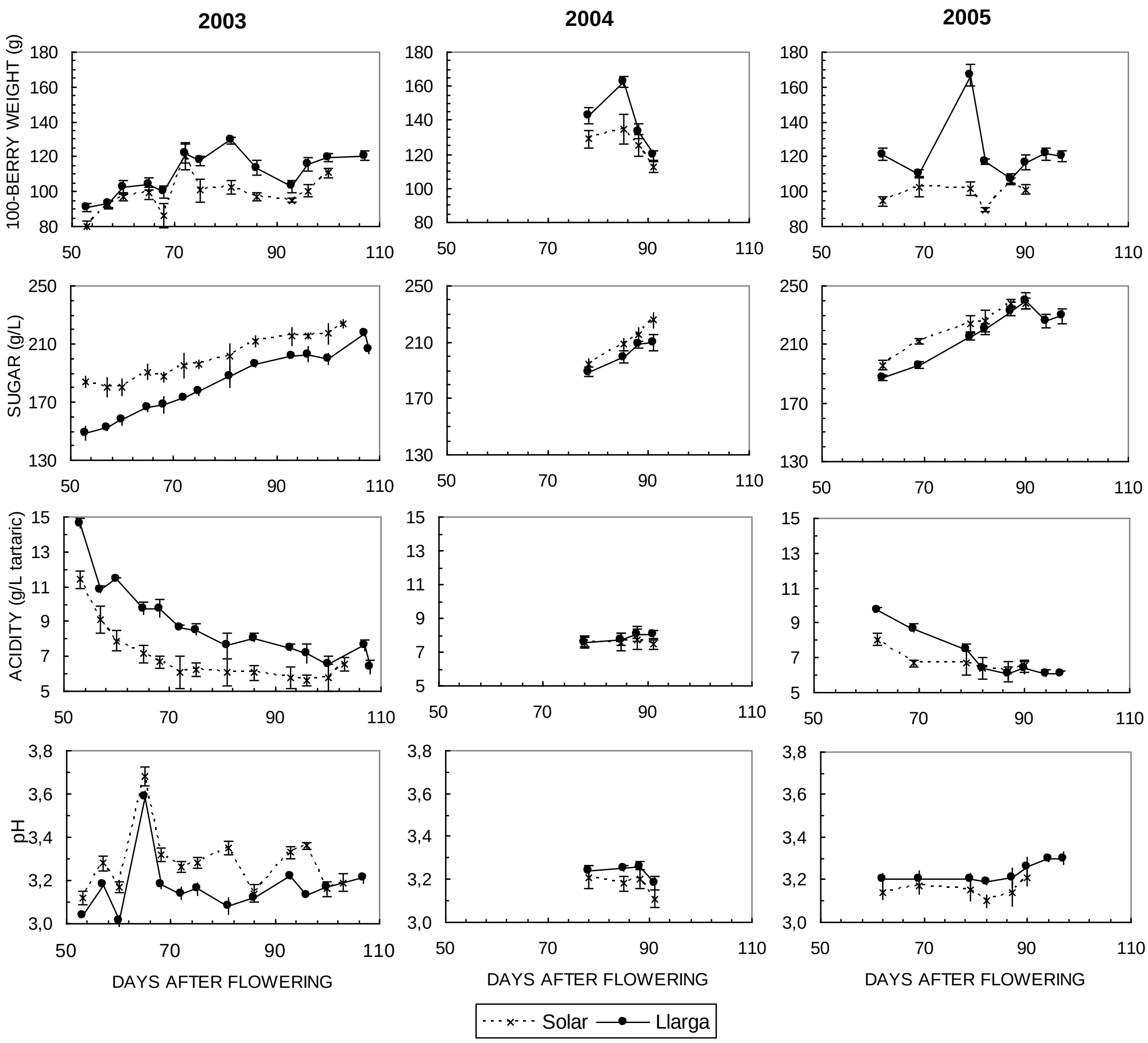

Figure 3. Evolution of pulp maturation of Cabernet Sauvignon grapes (2003-2005).

Bars represent the standard error of the mean.

Anthocyanin content showed no differences between 'Solar' and 'Llarga' in 2003 and 2005, and in 2004 it only differed in the final value, which was lower on 'Solar' than in 'Llarga' (Fig. 4). Regarding grape seed tannins, there were no differences between soils in 2005, and in 2003 they differed only at the end of the maturity period, with a lower value on 'Solar' than on 'Llarga'. 'Solar' had no available data in 2004. With regard to interannual differences, as a general trend, 2003 was characterized by the lowest anthocyanins and the highest tannins, 2005 presented the highest anthocyanins and lowest grape seed tannins and 2004 presented intermediate values.

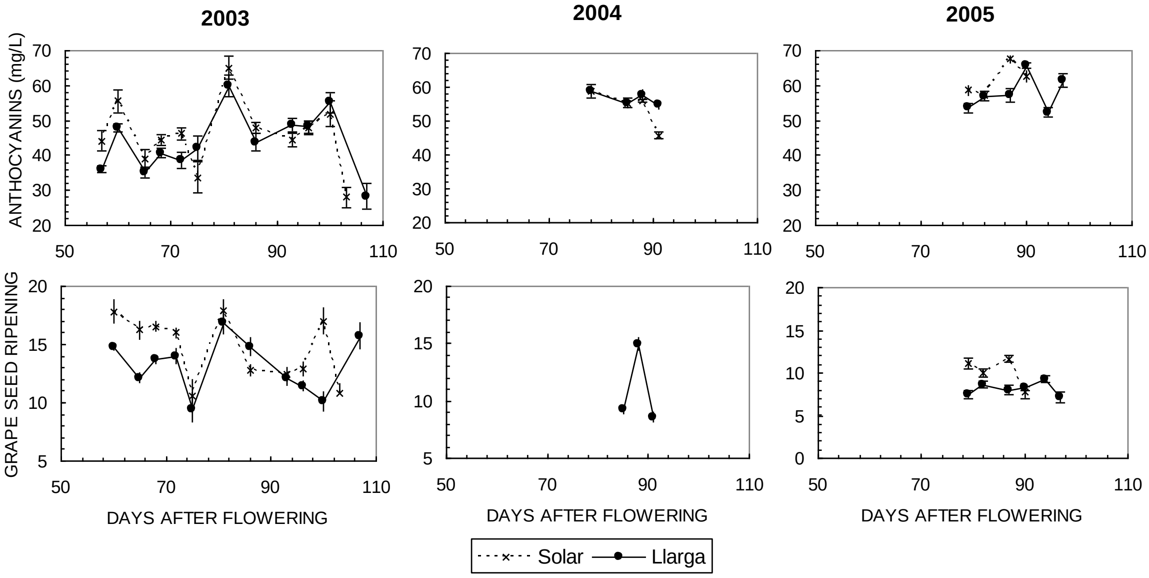

Figure 4. Evolution of phenolic maturation of Cabernet Sauvignon grapes (2003-2005).

Bars represent the standard error of the mean.

Regarding the ripening speed index (Duteau, 1990), there were no differences between sites in 2003, whereas 'Solar' had higher ripening speed in 2004, but lower in 2005.

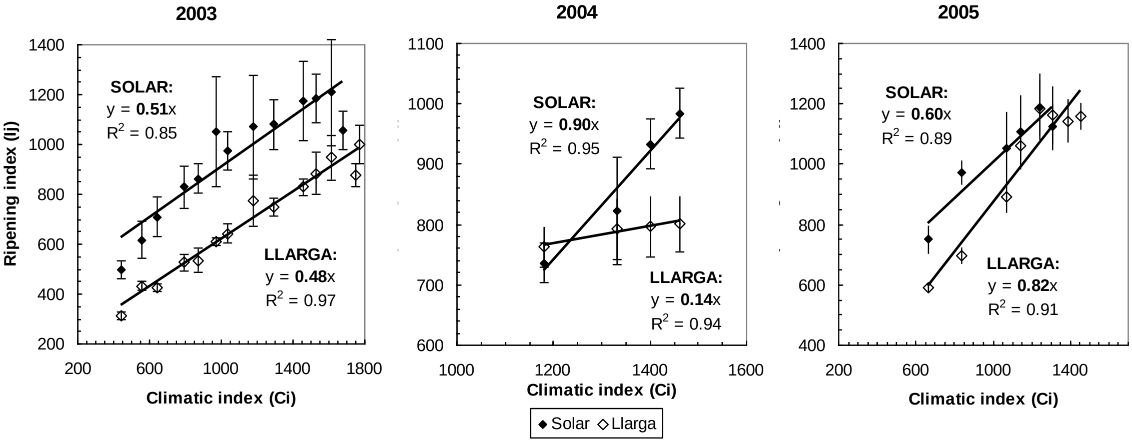

Figure 5. Calculation of speed ripening (slope of the regression) according to Duteau (1990), using data from all plots per site.

Table 4 presents the 2x3 factorial (soil x year) analysis of variance for pulp and phenolic maturity at harvest (sampling of the maturation period) and for ripening speed. Table 5 contains the percentages of variance attributable to each factor (soil, climate and soil x climate interaction). 100-berry weight was only significantly affected by soil, which explained 55% of the total variance. 'Llarga' presented higher values than 'Solar'. Soil and climatic conditions explained 30% and 40%, respectively, of the total variance of sugar content. 'Solar' presented higher values than ‘Llarga’. With respect to climatic conditions, the highest sugar content was reached in 2005 and the lowest in 2003 and 2004. Sugar was negatively correlated with berry weight (r = -0.47, n = 18, p< 0.05). Acidity and pH were determined only by climatic conditions, which explained 65% of variability for acidity and 33% for pH. The highest value for acidity was in 2004, and the lowest in 2003 and 2005. The highest value for pH was in 2005 and the lowest in 2004. Acidity was negatively correlated with sugar content (r = -0.48, n = 18, p < 0.05), but not with berry weight (r = -0.01, n = 18, ns). pH was not correlated either with sugar (r = 0. 05, n = 18, p < 0.05) or with berry weight (r = 0.02, n = 18, p < 0.05). Anthocyanin content was mostly dependent on climatic conditions (92% of the total variance), having the highest value in 2005, and the lowest in 2003. Grape seed tannins were mainly affected by climate (65% of the total variance), but they were also significantly affected by soil (9% of the total variance). The values were higher on ‘Llarga’ than on ‘Solar’, and were higher in 2003 than in 2005. Grape seed tannins were negatively correlated to anthocyanin content (r = -0.75, n = 15, p < 0.05). This negative correlation might be explained by the different dynamics followed by grape seed tannins and anthocyanins during ripening. During maturation, anthocyanins increase regularly, unlike grape seed tannins, which reach a maximum before veraison and decrease until maturity (Blouin and Guimberteau, 2004). Finally, soil x climate interaction, climate and soil explained 56%, 14% and 12%, respectively, of the total variance in speed of ripening. The speed of ripening was higher in ‘Llarga’ than in ‘Solar’, and was higher in 2005 than in 2003 and 2004. Grape ripening speed was positively correlated with sugar (r = 0.61, n = 15, p < 0.05) and negatively correlated with acidity (r = -0.58, n = 15, p < 0.05).

Table 4. Effects of soil and climate on grape composition at harvest and speed of ripening.

	Soil		**Climate**		
	Llarga	**Solar**	**2003**	**2004**	**2005**
100-berry weight (g)	120.1 a	108.2 b	115.5 ns	116.1 ns	110.9 ns
Sugar (g/L)	215.2 b	229.2 a	215.2 b	217.9 b	233.6 a
Acidity (g/L tartaric)	6.8 ns	6.8 ns	6.46 b	7.75 a	6.31 b
pH	3.23 ns	3.17 ns	3.2 ab	3.15 b	3.26 a
Anthocyanins (mg/L)	48.20 ns	45.46 ns	28.11 b	50.31 a	62.06 a
Grape seed tannins	11.47 a	9.28 b	13.30 a	-	7.45 b
Ripening speed index	0.48 b	0.66 a	0.49 b	0.52 b	0.71 a

Different letters indicate significant differences at p≤ 0.05 using Newman-Keuls test (n = 9 for soil, n=6 for year).

Table 5. Percentage of variance attributable to soil, climate and soil x climate interaction.

	Soil (%)	Climate (%)	Soil x climate (%)	Error (%)
100-berry weight	55.3 ***	8.5 ns	11.1 ns	25.1
Sugar	29.5 **	39.7 **	2.2 ns	28.6
Acidity	0.0 ns	64.6 ***	7.8 ns	27.6
pH	14.5 ns	32.6 *	3.5 ns	49.4
Anthocyanins	0.9 ns	91.9 ***	2.4 ns	4.8
Grape seed tannins	9.1 *	64.5 ***	13.8 *	12.6
Ripening speed index	12.4 *	13.7 *	56.4 ***	16.8

* $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$, ns $p > 0.05$.

Wine Quality

Table 6 shows the 2x2 factorial (soil x year) analysis of variance for wine properties. Table 7 contains the percentages of variance attributable to each factor (soil, climate and soil x climate interaction). 2003 data were not considered due to oxidation of 'Llarga' wine. All parameters were significantly affected by soil and climate, except for pH, which was only significantly affected by climate. Degree of alcohol and total acidity were more influenced by climate than soil type. However, soil had a greater effect than climate in wine properties related to colour and polyphenols (absorption at 420, 520 and 620 nm, colour intensity, total polyphenols, tannins and anthocyanins). Degree of alcohol was high in 2005 and low in 2004, whereas total acidity and pH were high in 2004 and low in 2005. The remaining wine properties were also high in 2004 and low in 2005. Regarding soil effect, all wine parameters were higher on 'Solar' than on 'Llarga', except for pH.

Table 6. Effects of soil and climate on wine quality.

	Soil		Climate	
	Llarga	**Solar**	**2004**	**2005**
Degree of alcohol	13.1 b	13.7 a	12.7 b	14.0 a
Total acidity (g/L)	5.1 b	5.4 a	5.4 a	5.1 b
pH	3.3 ns	3.4 ns	3.4 a	3.3 b
A420a	3.3 b	5.2 a	4.7 a	3.8 b
A520a	6.1 b	10.1 a	9.8 a	6.4 b
A620a	1.0 b	2.0 a	1.7 a	1.3 b
Colour intensity	9.4 b	15.4 a	14.7 a	10.2 b
Total polyphenols (A280)	47.8 b	65.2 a	61.7 a	51.2 b
Tannins (g/L)	2.7 b	4.2 a	3.9 a	3.0 b
Anthocyanins (mg/L)	601.2 b	831.5 a	770.0 a	662.7 b

Different letters indicate significant differences at $p \leq 0.05$ using Newman-Keuls test ($n = 6$).

Table 7. Percentage of wine parameter variance attributable to soil, climate and soil x climate interaction.

	Soil (%)	Climate (%)	Soil x climate (%)	Error (%)
Degree of alcohol	11.3 *	56.1 ***	17.0 *	15.5
Total acidity (g/L)	19.5 *	56.0 **	0.0 ns	24.4
pH	12.4 ns	52.7 **	15.5 *	19.4
A420a	73.7 ***	18.3 **	1.1 ns	6.8
A520a	54.6 ***	39.1 ***	0.2 ns	6.1
A620a	77.7 ***	13.9 **	2.9 ns	5.5
Colour intensity	59.9 ***	33.0 ***	0.7 ns	6.4
Total polyphenols (A280)	63.8 ***	23.5 ***	6.2 *	6.5
Tannins (g/L)	64.6 ***	22.4 **	2.6 ns	10.4
Anthocyanins (mg/L)	75.5 ***	16.4 **	0.3 ns	7.8

* $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$, ns $p > 0.05$.

Regarding wine tasting, comparisons between wines in 2003 were not possible because of oxidation signs of ‘Llarga’ wine (Table 8). In 2004, no significant differences were found between the global notes of the two wines, although the wine from ‘Solar’ had a slightly higher rating, which could be due to a more intense colouration in the red and blue tones, more ripe fruit on the nose and a mouth-feel with more complexity and tannin sensation. In 2005, ‘Solar’ wine scored significantly higher than ‘Llarga’ wine. The wine ‘Solar’ was appreciated more, possibly because it was more intense, with more mature fruit on the nose, a more intense colour and more concentrated and tannin feeling (round) in the mouth. In general, there was a trend in which ‘Solar’ wine was preferable to ‘Llarga’ wine, since ‘Solar’ wine presented a more intense colour, more ripe fruit and intensity on the nose and more tannin sensation and concentration in the mouth.

Table 8. Sensory analysis of Cabernet Sauvignon wines (2003-2005).

YEAR	Plot	TASTING COMMENTS			GLOBAL NOTE
		Colour	Aroma	Taste	
2003	Llarga	r-2 m-1	I-2, varietal, skins, cherry jam, oxidation, evolution.	Ethanol, skins, dry stem, vegetal, light, thin.	-
2003	Solar	r-3 b-2	I-3, ft-2, pyrazine:2-3, leather, vegetal, spicy, compote.	U-2, Ft-2, ti:2-3, green-1, astringent, vegetal touch, concentration.	7.4
2004	Llarga	r:2-3 b-2	I-3, fruit, pyrazine.	U-2, ti:2-3, dry, simple, short, light, acid.	7.6 ns
2004	Solar	r:3-4 b:2-3	I-3, ripe fruit, raisin, pyrazine, tobacco.	U:2-3, ti-3, dry , green, vegetal, pyrazine, concentration, acid.	7.7 ns
2005	Llarga	r-2 b:1-2	I:2-3, jam, leather, bitumen, green, thin.	U:1-2, ti-3, dry, green, monothematic, simple, light, tobacco leaf, bitter:0-1.	6.4 b
2005	Solar	r-3 b:2-3	I-3, ripe fruit, jam, pyrazine, vegetal, leather.	U:2-3, ti:2-3, round, soft, VL:2-3, sweet, fine grain, concentration.	7.6 a

r: red colour, b: blue colour, m: brown colour, I: aromatic intensity, ft: fruity aromas, U: unctuosness; ti: total aromatic intensity; VL: varietal aroma, In global note: Different letters indicate significant differences at $p \leq 0.05$ ($n = 4$).

Discussion

Berry weight was only influenced by soil type. Van Leeuwen et al. (2004) also found that berry weight was significantly influenced by soil type but not by climatic differences. Berry weight was high in the soil with the higher water holding capacity, consistent with the view that low water supply causes a reduction in berry weight and yield (Peyrot des Gachons et al., 2005; Van Leeuwen et al., 2003). Sugar content showed differences with regard to climatic conditions and soil type, the soil factor having a minor influence. The soil effect on sugar content might be explained partially by the existing negative correlation between sugar and berry weight, also reported by other authors (Hunter and Deloire, 2005). Highest sugar content was found in the driest year during the growing season, while the lowest was in the rainiest one. These results could be explained by the effect of water limitation on plant hormonal equilibrium and berry weight, which are responsible for directing sugar accumulation in grapes (Champagnol, 1984; Blouin and Guimberteau, 2004).

Regarding phenolic maturation, anthocyanin content was only affected by climate, contrary to the findings of Van Leeuwen et al. (2004), who also found a soil effect. The highest anthocyanin content was recorded in the driest year, possibly as a result of water limitation on skin/pulp ratio and consequently on anthocyanin content (Esteban et al., 2001; Trégoat et al., 2002; Gurovich and Páez, 2004). However, air temperatures might also have had an influence on anthocyanin accumulation. The lowest anthocyanin content occurred during the hotter year (2003) and the highest in 2005. Previous studies demonstrated the negative effect of high temperatures (Buttrose et al., 1971; Kliewer and Torres, 1972), and the positive effect of low minimum temperatures during ripening (Tonietto and Carbonneau, 2002) on anthocyanin accumulation. In terms of grape seed tannins, the highest content was in the wettest year and the lowest in the driest. Moreover, grape seed tannins showed significant differences between soils, being the highest on the soil with the highest water holding capacity. Thus, water limitation was associated with better phenolic ripening (higher anthocyanin content and lower grape seed tannins).

Grape ripening speed was significantly higher on the soil with lower water holding capacity. It was also higher in the driest year and lower in the wettest year. This result agrees with previous observations that grape ripening speed is determined largely by the soil water regime and soil temperature (Van Leeuwen and Seguin, 1994). According to Van Leeuwen et al. (2003), the wettest soils are also the coolest, causing delay and deceleration in the maturation process. Soil and climate affected grape ripening speed, but soil x climate interaction had the highest effect. This means that for a certain year, the speed was higher in one soil and in another year the opposite. In 2004, speed ripening on ‘Solar’ was noticeably higher than on ‘Llarga’, probably related to higher soil water limitation on ‘Solar’. However, ripening speed on ‘Llarga’ was higher than on ‘Solar’ in 2005, when soil moisture during grape ripening was higher on ‘Solar’ than on ‘Llarga’. During 2003, both soils showed similar grape ripening speed, perhaps due to both soils followed similar soil water dynamics.

As shown before, more alcoholic wines were obtained on the soil with a more limited water regime and that was drier and warmer during the growing season. All variables related to the phenolic compounds were significantly higher on the soil with the more limited water regime. Andres-de-Prado et al. (2007) compared wines of the Grenache cultivar on two soils, and they also found that wines produced on the soil with higher water holding capacity presented significantly lower colour intensity and phenolic composition. As for interannual differences, the highest values occurred in the year with the lowest temperatures during the growing season, and the lowest rainfall between veraison and harvest. Wines produced on the soil with the more limited water regime achieved better scores for colour intensity, aroma intensity and unctuosness, with more ripe fruit aromatic notes, and were more concentrated and structured in the mouth. These differences in tasting notes could be due to a higher content in phenolic compounds, as found by Choné et al. (2001) in Cabernet Sauvignon wine.

Conclusions

This study determined the effects of soil and climate on grape ripening and wine quality. The climate factor affected almost all variables of grape composition, except for berry weight, as well as on grape ripening speed and wine composition. In addition, the soil factor affected berry weight, grape ripening speed and wine composition. The effects of soil on wine composition were not negligible: these effects were even greater than those of climate in wine properties related to colour and polyphenols. The effects of soil and climate could be explained mainly by their influence on plant water availability, although temperatures could be important, for example in the synthesis of phenolic compounds. Top-rated wines in the tasting were from the soil with a more limited water regime, probably due to its effect on the accumulation of phenolic compounds, which are responsible for wine colour and taste. Thus, despite the variability of grape and wine composition associated with climatic conditions, soil type could be decisive when it comes to differentiating wines of different qualities, depending on the intensity of colours and flavours and structure and concentration in the mouth.

Acknowledgements: We would like to thank the Department of Oenology of Miguel Torres Winery for their collaboration in must analysis, microvinifications and wine analysis.

Chapter 7

GLOBAL DISCUSSION

This study determines the suitability of very detailed soil surveys, based on Soil Taxonomy, for viticultural zoning studies, which are directed at the delimitation of homogeneous areas with distinct potential for viticulture. Soil Taxonomy is a worldwide hierarchical classification system, which is not intended for any particular crop. Previous studies show that this classification system may not be entirely satisfactory, since the resulting classification of soil map units can separate soils with differences that may not be important for some interpretations or uses. For instance, Young and Hammer (2000) found that some Soil Taxonomy classes had no relationship to distributional patterns of some soil properties. Chapter 2 shows that the classification of soil map units does not reflect the variability of important soil properties for vineyard cropping, such as texture, available water capacity and contents of coarse fragments, carbonate, iron, organic matter and nitrogen. In addition, Chapter 4 shows that the classification of soil moisture regimes of Soil Taxonomy reflects differences in the soil moisture dynamics during the stages of grapevine development only in the cases of very humid (udic) or very dry (aridic) moisture regimes.

Multivariate statistical analysis can be used to address these limitations. Previous studies used these analyses in order to find other classifications more adjusted to the natural distribution of soils (Areola, 1979; Young and Hammer, 2000). In this thesis, cluster analysis was selected, among different statistical analyses used in soil science (Courtney and Nortcliff, 1977), because this method allows the grouping of data, minimizing within-group variability while maximizing among-group variability. The application of cluster analysis on properties of soil map units allowed us to differentiate soils according their viticultural potential, in relation to water stress, iron chlorosis and vegetative growth. In addition, the application of cluster analysis on soil moisture data during grapevine development allowed us to differentiate soil moisture regimes according their viticultural implications, referring to vegetative growth and grape ripening.

Moreover, chapter 3 determines the effect of soil forming processes on soil properties and soil classification. The results show significant effects on soil properties important for vineyard production. For instance, clay accumulation processes increased significantly the available water capacity and cation exchange capacity. These soil properties, especially those related to vine water availability status, have direct influences on grape and wine quality (Esteban et al., 2001; Trégoat et al., 2002; Gurovich and Páez, 2004). Some identified soil forming processes were not reflected in soil classification, especially in soils modified by man. Land levelling and terracing by earthmoving equipment can dramatically change soil horizon arrangement and decrease soil fertility, with effects on productivity and vigour of vines (Bazzofi et al., 2009). However, the anthropic soil origin was not always reflected in soil classification. This fact highlights the limitations of Soil Taxonomy to classify anthropogenic soils. In fact, an international committee, named ICOMANTH, was created to improve anthropogenic soil classification in Soil Taxonomy. It should be noted that Dazzi et al. (2009) propose a new diagnostic horizon for anthrosols of the WRB classification (FAO/ISSS/ISRIC, 2006), named geomiscic, which can be applied in cases of land levelling by heavy machinery.

Chapter 5 establishes the influence of edaphoclimatic parameters on grape harvest quality at plot level, in particular on both yield and berry composition variability. Climate and water availability explained 70% of variability and soil explained 28% of variability. These results agree with other studies, where climate appears as the most influencing factor on must quality (Van Leeuwen et al., 2004). Water availability also strongly influences the quantity and quality of grape production (Oliveira, 1995; Van Leeuwen et al., 2003; Hunter and Deloire, 2005), due to the effect of water supply on the balance between vegetative and reproductive growth (Matthews et al., 1987; Van Leeuwen and Seguin, 1994). Generally, it is difficult to establish a direct correlation between soil characteristics and wine quality (Seguin, 1986). Some soil properties, such as nitrogen status and soil depth, can affect grape and wine quality, even more than water supply (Choné et al., 2001). In our study, we found that soil had influence on yield and some must data.

There are many studies to determine the effect of a single factor on grape quality, whether the climate (Jones and Davis, 2000; Tonietto and Carbonneau, 2004), soil (Trégoat et al., 2002, Sivilotti et al., 2005) or other factors, but few studies consider the joint effects of more than one factor (Van Leeuwen et al., 2004). Moreover, studies that consider the effects on wine quality are even more limited (Choné et al., 2001; Andrés-de-Prado et al., 2007). The joint effect of soil and climate on grape ripening and wine quality is determined in chapter 6. The results referring to grape ripening show that soil was the only factor determining berry weight, sugar content was affected by soil and climate, the soil factor having a minor influence, and anthocyanin content was only affected by climate. These results can be explained by the effect of vine water availability status on berry weight (Peyrot des Gachons et al., 2005; Van Leeuwen et al., 2003) and the plant hormonal equilibrium, which are responsible for directing sugar accumulation in grapes (Champagnol, 1984; Blouin and Guimberterau, 2004), and also on skin/pulp ratio, which determines anthocyanin content (Esteban et al., 2001; Trégoat et al., 2002; Gurovich and Páez, 2004). Regarding wine quality, climate and soil had significant effects on wine composition, the soil having more influence than climate on wine phenolic composition. The soil also affected wine sensory analysis, probably due to the relationship between the phenolic compounds and colour and taste of wine (Choné et al., 2001). Wines produced on the soil with more limited water regime achieved better scores for colour intensity, aroma intensity and unctuosity, and more ripe fruit aromatic notes and were more concentrated and structured in the mouth. Similar results were found in Andrés-de-Prado et al. (2007).

Chapter 8

FINAL CONCLUSIONS

A very detailed soil survey method, based on Soil Taxonomy, allows us to differentiate a great number of soil map units, but in return it shows certain deficiencies when reflecting the variability of important soil properties for vineyard cropping. Thus, very detailed soil surveys are suitable for a viticultural zoning oriented to a differentiated viticultural management, but not when viticultural zoning is directed at the differentiation of zones of distinct potential for vineyard growing. In this case, we propose a methodology based on cluster analysis, which allow us to group soil map units according their distinct potential for vine growing, in relation to water stress, iron chlorosis and vegetative growth.

This methodology was developed from soil surveys at plot level in Catalan vineyards, but according to the zoning objective it can also be applied at different scales, performing the cluster analysis at level of vineyard estate, county or country. The groups resulting from cluster analysis are also conditioned by the variability of soil properties, which is characteristic or predominant in the study area. Thus, the soil properties involved in the viticultural zoning can vary from one area to another. In the study area, and for a zoning aimed to determine the viticultural potential, soil properties that at least should be considered in cluster analysis are texture, available water capacity and contents of coarse fragments, total calcium carbonate, active calcium carbonate, iron, organic matter and nitrogen.

In the study area, a high variety of soil forming processes can be determined by means of morphological and micromorphological analysis. These soil forming processes have significant effects on soil properties, which are important for vineyard growing, namely clay content, available water capacity, calcium carbonate content and cation exchange capacity. However, soil classification does not always reflect these pedogenic processes. This fact highlights the importance of considering soil forming processes when performing a viticultural zoning based on very detailed soil surveys.

According to soil moisture data monitored by capacitance sensors, continuously and at different depths, in different representative soil map units, the soil moisture regimes of Soil

Taxonomy do not adequately reflect differences in the soil moisture dynamics of xeric and ustic soil moisture regimes during the grapevine phenological stages. We propose a methodology based on determining dry days, as indicated by Soil Taxonomy, in different grapevine phenological periods and grouping the cases by means of a cluster analysis. The soil moisture regimes resulting from this method show significant differences in percentage of dry days in all phenological periods, and therefore present different implications for viticulture, related to vegetative growth, grape production and the grape ripening process.

The determination of annual soil moisture regime in a vineyard soil, considering the phenological stages, can be useful as a decision tool for vineyard management, as well as for grape harvest prediction. To this purpose, studies to correlate annual soil moisture regimes with parameters related to vineyard cropping (such as yield, alcoholic degree, pruning weight) should be performed. The cluster analysis can be also applied over the long term, when the zoning objective is to differentiate soils according to their potential for vineyard growing. In this case, soil moisture data for many years should be considered, in order to determine the most frequent soil moisture regime. For this purpose, modelling studies to predict soil moisture data from crop and climate data can be also useful.

Based on the characterization of soil properties and interannual climatic indices in three representative soil map units located in the same viticultural area, climate and soil water availability explain 70 % of vintage variability and soil properties explain 28 % of vintage variability. The models performed to predict grape harvest parameters from soil and climate parameters show that edaphoclimatic factors have generally a high power of estimation of yield and must composition of the grape harvest. Climate appears to be the most influential factor on must composition, followed by water availability. Generally, soil properties are the most influential factor on yield. These results show that viticultural zoning studies should have a global approach, which considers soil and at least climate, if it is intended to understand the functioning of vines and vintage composition. Further studies could be carried out to improve the proposed soil-based viticultural zoning, by considering climate variability. According to this study, climate parameters that could be considered are cumulative degree days and precipitation during the growing season and solar radiation during ripening. Moreover, average soil moisture regimes during the grapevine growing season could complete the characterization of viticultural zoning units.

The determination of the effects of soil and climate on grape ripening and wine composition shows that climate affects grape composition, except for berry weight, as well as grape ripening speed and wine composition. In addition, soil factors affect berry weight, grape ripening speed and phenolic composition of wines. The effect of soil on wine composition is not negligible, since these effects are even greater than those of climate in wine properties related to colour and polyphenols. Significant differences between soil types are found in the wine tasting, related to the intensity of colours and flavours and structure and concentration in the mouth. Thus, despite the variability of grape and wine composition associated with climate, soil type is decisive when it comes to differentiating wine quality. This study only considers the vintages of two soil types for three years, so it would be advisable to extend this study to more soils and climates, to somehow validate that the viticultural zoning units reflect the maximum variability of grape and wine composition.

As a main conclusion of this thesis, very detailed soil surveys based on Soil Taxonomy are a valuable source of information for viticultural zoning studies, although its implementation can be improved with statistical analysis that considers the variability of soil properties related to grapevine growing. Moreover, although climate explains most of the vintage variability, soil type is decisive in determining the vineyard potential for wine quality.

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