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Influence of hydropedology on viticulture and oenology of Sangiovese vine in the Chianti area (Central Italy)

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Abstract

The adoption of precision agriculture in viticulture requires the knowledge of the spatial and temporal variability of available soil water. A three-years trial was carried out in Chianti (Central Italy) on Sangiovese vine to test the prediction capacity of selected hydropedological models for two soil series cultivated with grape and for delineating hydrological functional units within two vineyards. The soils of the vineyards differentiated in structure, porosity and related hydropedological characteristics, as well as in salinity. Soils were mapped with a geophysical survey and six plots were selected in different morphological positions: summit, backslope and footslope. Water content, redox processes and temperature were monitored, and yield, phenological phases, and chemical analysis of grapes were determined. The isotopic ratio δ^{13}C was measured in the wine ethanol upon harvesting to evaluate the degree of water stress suffered by vines. The grapes in each plot were collected for wine making in small barrels. The wines obtained were analysed and submitted to a blind organoleptic testing.

The results demonstrated that the tested hydropedological models can be used for the prevision of the moisture status of soils cultivated with grape during summertime in Mediterranean climate. As foreseen by the models, the amount of mean daily transpirable soil water differed considerably between the vineyards and increased significantly along the three positions on slope in both vineyards and in every year, even during the very dry 2006. However, both the response of Sangiovese to water stress and the quality of wine were influenced by the interaction between transpirable water and salinity. The installation of IRIS tubes allowed confirmation of the occurrence of redox processes, although discoloration was influenced more by soil temperature, rather than by moisture. The map produced by once only geophysical survey mirrored only partially the seasonal hydropedology of these heavily tilled soils on slope.

1 Introduction

In the Mediterranean environment, characterized by a summer water deficit, crop phenology, production, and quality of yield are significantly determined by water nutrition. Also the vegetative and reproductive activity of the grapevine, which renews a good part of its absorption system each year, is deeply influenced by soil water availability (Champagnol, 1984). The adoption of precision agriculture techniques in viticulture requires the knowledge of the spatial and temporal variability of available soil water in the vineyard, which is often high, even at the detailed scales, because of the interaction of numerous factors. Besides amount of rain and irrigation, soil water holding capacity and salinity are the main variables, along with rooting depth, runoff, and subsurface flows. Runoff and subsurface flows, in particular, can convey a remarkable portion of rainwater to different places of the hillslope (Lin, 2003). Hydrological functioning of soil landscape and consequent vine behavior are then determined by the interaction between soil profile characteristics (including underlying bedrock) and slope morphology.

Common information about soil profile characteristics is provided by soil series description (Soil Survey Division Staff, 1993). The distinction of the soil cover into soil series has proved to be relevant for viticulture in different parts of the world (Costantini et al., 1996; Deloire et al., 2005; Morlat and Bodin, 2006; Costantini et al., 2006a; Lambert et al., 2008), and some hydropedological models (Boorman et al., 1995; Lin et al., 2006) can be applied to a soil series to predict flow pathways through the soil and moisture profile distribution on hillslope. However, the geographic pattern of hydrological functional units inside a soil series cultivated with grape is particularly difficult to predict, not only because of local topography and underlying bedrock, but also of pre-planting operations. In fact, agricultural practices carried out before vineyard planting, namely land leveling, slope reshaping, deep ploughing or ripping, have important consequences on profile characteristics, modifying soil depth, porosity, organic matter content, redox conditions, calcium carbonate accumulation, and relationships between horizons (Costantini, 1992; Costantini et al., 2006b). In addition, the hydropedology of a vineyard is above all important during the vine vegetative season, particularly in summer, when water availability greatly influences wine quality, but when limited rainfall and heavy storms make water circulation particularly difficult to predict.

The general aim of this work was to test the prediction capacity of selected hydropedological models for two soil series cultivated with grape. More particularly, the objective was to delineate hydrological functional units inside vineyards i.e., soil series distinctions that effectively determine differences of available water during vine growing, which are large enough to significantly affect grape yield and wine quality. This kind of information is particularly relevant for the farmers who want to put in practice precision agriculture, because every change in management inside a single vineyard has a cost, which must be economically justified.

2 Materials and methods

2.1 Study area and soil series

Two specialized rainfed vineyards (2 ha each) were investigated at Cetona (Chianti area, Central Italy, 42°57′ N, 11°54′ E), in similar climatic, lithological, and geomorphological settings, but with different soil series. Long term mean air temperature at Cetona was 12.7°C and annual rainfall 644 mm. The vine variety was Sangiovese, the rootstock 420A, plant density 3500 per ha. Both vineyards were deep ploughed up to about 0.8–1 m before planting, viticultural husbandry was similar and the soil surface was periodically cultivated to limit weed growth. The two vineyards were planted on slopes with similar steepness (from 2 to 13 or 18%) and aspect (E and NE) (Figs. 1 and 2). The soils formed from fine silty marine sediments of Pliocene, but the soil of vineyard 1 belonged to San Quirico silty clay loam Aquic Haplustept, fine silty, mixed, mesic, active, following Soil Taxonomy (Soil Survey Staff, 1998), or Stagnic Cambisol (Calcaric, Hyposodic, Hyposalic) according to WRB (FAO et al., 2006), whereas vineyard 2 soil was a Pietrafitta silt loam Typic Haplustept, fine silty, mixed, mesic, super-

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active, or Haplic Cambisol (Calcaric). The two soils differentiated mainly as a result of land leveling before vine planting. Vineyard 1 was scalped more intensively than vineyard 2, so that the unweathered marine substratum was brought up to a shallow depth, and the soil showed moderate salinity and sodicity in the lower horizons. Two soil profiles were dug and described within each vineyard, at the summit position, to check soil series classification.

2.2 Hydropedological models

The hydropedological models used to differentiate functional hydrological units in the vineyards were the conceptual model of Lin and coll. (Lin et al., 2006) and the Host classification (Boorman et al., 1995). According to the first model, the main functional hydrological units of both vineyards may correspond to the morphological positions of summit (position S), backslope (position B), and footslope (position F), where soil moisture conditions should pass from relatively dry at S, to moderately wet or moderately dry at B, and to wet at F. The Host classification instead allowed us to distinguish the flow pathways through the two soil series. San Quirico belongs to model I, class 13, which means some inhibition to water movement down through the soil profile. The slowly permeable material is within 1 m of the surface which can lead to the development of perched water tables for a few weeks in the year. By-pass flow may be possible when the soil is not saturated. When a perched water table forms, the dominant flow regime will be largely saturated lateral flow; however at other times, or where no water table forms, the flow will be predominantly vertical, albeit within a restricted depth. Pietrafitta belongs to model H, class 6, i.e., no inhibition to drainage within the first meter and vertical unsaturated and by-pass flow through macropores to the depth of the underlying substrates. Therefore, according to Host classification, we expected moister conditions and larger subsurface later flow in vineyard 1 than in vineyard 2.

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2.3 Plot selection

Three plots, about 300 m^2 each, placed in the morphological positions S, (slope 2%), B (slope 13 and 18% vineyards 1 and 2, respectively) and F (slope 2 and 5% vineyards 1 and 2, respectively) were selected within the two vineyards, as reference of the hypothesized different hydrological and viticultural functional units. A soil mini-pit was dug, described, sampled and analyzed in each plot, up to 0.45–0.60 m depth, according to soil horizons. The results of a detailed geophysical survey, carried out in collaboration with the Soil Information System of John Deere Agri Services, were used to spatialize the soils of the three morphological positions. The system provided for a map of soil moisture in the rooting layer at the date of the survey (bud bursting of vines, 4 April), which resulted from the measurement of soil water content, by means of a Frequency Domain Reflectometer (FDR), and soil consistence, through a cone penetrometer, assuming that the root limiting layer was the first horizon offering a resistance higher than 350 psi (2413 kPa). A combined probe with both sensors was inserted into the soil to about 1.5 m depth in 21 random locations in each vineyard.

2.4 Monitoring of hydropedological properties

A meteorological station was placed only inside vineyard 1, as vineyard 2 was only few dozen meters away from it. Hydropedological properties were characterized by means of a 3 year monitoring of soil water content, redox conditions and temperature. Soil water content was measured by the gravimetric method (three samplings per position with a hand auger) at 0.1–0.3 m and 0.4–0.7 m depth. Experimental plots were unrestricted and the use of permanent equipment, like neutron probes or transducer tensiometers, was not possible. Measurements were replicated every one/two weeks. A daily value of the water content (total mm in the 0–0.7 m depth) at every position in the two vineyards was calculated using rainfall, estimating vineyard evapotranspiration and runoff, and calibrating the results with the measured soil moisture. In particular, daily precipitation was reduced with estimated runoff, which was attained following the

Soil Conservation Service Curve Number methodology (SCS-CN USDA, 1969; USDA, 1985). Mean daily potential evapotranspiration (ETp) was calculated with the Priestley-Taylor equation (Priestley and Taylor, 1972). Cultural coefficients (Kc) were applied to ETp to evaluate real evapotranspiration (ETr) according to the methodology proposed by Allen et al. (1998). The Kc increased from the beginning of vegetation in March, up to flowering in early June, and then remained stable until complete veraison, that is, at the end of August, and afterwards gradually decreased until harvest. The Kc values were the same for all the plots, but varied in function of the year rainfall and relative humidity i.e., they were higher in the moister 2005, increasing from 0.42 to 0.76, and then decreasing to 0.5, while in 2006 and 2007 they passed from 0.40 to 0.74, and then to 0.45. The estimated ETr of the vineyard reduced the soil water content according to the logarithmic function reported in Thornthwaite and Mather (1957). The water uptake was uniformly distributed along the soil moisture control section (from the surface to 0.7 m). The difference between the soil water content measured on the day of sampling, and the value coming from the daily calculation, was the sum of errors made in the estimations and the possible further undifferentiated losses or gains of water (i.e. subsurface flows, deep percolation, capillary rise). The resulting positive or negative values were added to the soil moisture of the days after the rainfall events which occurred between two samplings. A daily mean of transpirable soil water (TSW) was computed. The daily TSW of each plot was the difference between the calculated soil water content and the absolute minimum value measured during the three years of trial. We chose this value, instead of the standard wilting point measured with the pressure chamber apparatus, because it was much lower, thus underlining the ability of Sangiovese vine, grafted onto the rootstock 420A, to uptake water at matric potential lower than −1500 kPa in this environment. The period 10 June–10 September was chosen as reference time because it corresponded to the most sensitive vine phenological phases (from flowering to complete ripening).

Soil temperature was measured at 0.2 and 0.5 m depth (portable pt100), and redox potential at 0.15 m (hand-held Barnant pH/mV/ORP meter, two measurements) at the same time as water content. Electrode calibration followed the instruction of Barnant Company (Barrington, IL, USA) using solutions buffered to pH 7 and 4 with Quinhydrone. Redox potentials, measured only during rainy seasons, were normalized at pH 7 according to Patrick et al. (1996). An alternative method for assessing reducing soil condition is the use of IRIS (Indicator of Reduction In Soil) (Jenkinson and Franzmeier, 2006), PVC tubes coated with ferrihydrite ($Fe(OH)_3$) on the surface. During periods of reducing conditions in soil, ferrihydrite painted on IRIS tubes is removed, through reduction and dissolution caused by heterotrophic microbes using Fe(III) as an electron acceptor while oxidizing soil organic matter. The amount of reduction that occurred was estimated from the area of Fe removed that was discolored. In 2005 and 2006, at the beginning of the vegetative growth period in both vineyards, three IRIS tubes for each of the different morphological positions S, B and F were inserted up to 0.5 m depth into pilot holes made in the soil. The tubes were carefully removed at the grape harvest, paying attention not to remove the paint with rubbing.

After extraction, each tube was photographed on all sides (three photos, with the tube rotated 120° between photos). The digital images obtained were analyzed using the Image Pro-Plus software (Media Cybernetics, Silver Spring, MD, USA). The discolored areas of each image were identified and measured as a percentage of the total painted area.

2.5 Soil physical, chemical and hydrological characteristics

Bulk density and water saturation were calculated from the field measured value of humidity when soil was saturated, assuming a particle density of $2.65\,\mathrm{g\,cm^{-3}}$. Saturation was empirically assumed after a heavy spring rain, leaving ponds on the soil surface. Similarly, moisture content at field capacity was obtained by averaging sampling values recorded over about three days after soil saturation. Wilting point was the minimum soil water content recorded during the field core sampling during the whole trial. Saturated hydraulic conductivity was estimated according to Rosetta (Schaap, 2001). In-field cone resistance was measured by a hand-held electronic cone penetrometer

(Eijkelkamp Penetrologger 06.15.SA) following ASAE standard procedures (1994), using a cone with 2-cm^2 base area, 60° included angle and 80-cm driving shaft; readings were recorded at 10 mm intervals. Nine replicated measurements were carried out in each position along the slope. Routine analysis of the air-dried <2 mm fraction followed the Italian official methods (MiPAF, 2000). In particular, soil texture was carried out by the sieve and pipette method; $CaCO_3$ content was measured gas-volumetrically, by addition of HCl in a Dietrich-Frühling calcimeter; organic carbon content was determined using the Walkley-Black procedure; pH and electrical conductivity were measured in a 1:2.5 (w/w) water suspension; cation exchange capacity (CEC) was measured by use of 1 M Na-acetate solution at pH 7.0; exchangeable bases were extracted with 1 M NH_4^+ acetate solution at pH 7.0 and measured by flame photometry (Na, K and Ca) and atomic absorption spectrometry (Mg). Active $CaCO_3$ was analyzed with a solution of ammonium acetate. This is the more active fraction of $CaCO_3$, which easily dissolves and precipitates. Soil electrical conductivity of the plots was carried out every 0.2 m, excluding the first layer, to avoid possible surface contaminations of fertilizers and agrochemicals.

Soil characterization included macroporosity quantification by image analysis. Three thin sections of undisturbed samples for soil horizon (60×70 mm) were analyzed to quantify pores >50 μm (Vignozzi et al., 2007). Two images were captured with a video camera from each section. Total porosity and pore distribution were measured according to pore shape and size. Pore shape was expressed as perimeter^2/(4π area), and pores were divided into regular (shape factor 1–2), irregular (2–5) and elongated pores (>5). Pores of each shape group were further subdivided into size classes according to either the equivalent pore diameter for regular and irregular pores, or to the width for elongated pores (Pagliai, 1988).

2.6 Viticultural and oenological evaluation

Every year, three replicated sampling per plot were conducted on ten plants. The vegetative behavior of the plants was recorded, in particular the date of phenological

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phases, the yield components, the sugar content of grapes (OIV, 2005). One hundred kg of grapes were collected from each plot for wine making in small barrels, using the same oenological technique for all samples. The wines obtained were analyzed for color density and phenolic content (Di Stefano et al., 1997). Ten months later the wines were submitted to blind organoleptic testing with the aim of defining a rank of preferences in terms of general harmony (Weiss, 1981). The isotopic ratio $^{13}C/^{12}C$ ($\delta^{13}C$) was measured in the wine ethanol by Isotope Mass Spectrometry to assess possible water stress occurring during grape formation and ripening. The $\delta^{13}C$ was expressed in reference to the international standard V-PDB (Farquhar et al., 1989; Van Leeuwen et al., 2001). It is generally assumed that the range of values varies for vine between −21‰, in the case of strong water deficit, and −26‰ or more in total absence of stress (Van Leeuwen et al., 2003).

2.7 GIS and statistical analysis

The software Arcscene was used to drape the orthophotos on the Triangular Irregular Network and create the 3-D map of the vineyards. The average value of water content to the rooting layer was obtained by means of the zonal statistic tool of spatial analyst of Arc GIS. Map spatialization was obtained with the Inverse Distance Weighting method. The data were submitted to analysis of variance (ANOVA) and regression by means of the software Statistica (StatSoft Inc., Tulsa, OK, USA).

3 Results and discussion

3.1 Meteorological conditions during the trial

Meteorological conditions during the trial were characterized by a rather humid and mild 2005, with mean annual air temperature (MAAT) 12.6°C and annual rainfall (AR) 1028 mm (Fig. 3), whilst both years 2006 and 2007 were rather hot and dry (MAAT 13.9

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and 13.6°C; AR 427 and 470 mm, respectively). Spring and summer rainfall and temperatures are particularly relevant for vine growing. Taking as a reference the period 10 June–10 September, rainfall varied much more than temperature during the studied years. In particular, 225.8 mm of rain fell in 2005, 9.8 mm in 2006, and 60.0 in 2007, whereas daily mean air temperature was 22.4, 23.2, and 22.0°C, respectively. Air temperature as a whole can be considered rather high in all three years, with a relevant number of days with maximum temperature higher than 30°C (37 in 2005, 45 in 2006, and 38 in 2007), which is believed to be the upper threshold for efficient photosynthesis of Sangiovese (Intrieri et al., 2001). Estimated daily evapotranspiration deficit during the same reference period was only 2.5 mm in 2005, but reached 4.7 mm in 2006 and 4.0 mm in the year 2007.

3.2 Soil series and plot characteristics

The morphological and analytical characteristics of the two check profiles confirmed soil series classification and highlighted the differences in depth, consistence and structure between the two soil types (Table 1). The San Quirico soil was shallower, more dense and hydromorphic, less structured, and poorer in organic matter than Pietrafitta, but it had a higher lime content, electrical conductivity, and sodium percentage on the cation exchange complex.

According to the geophysical survey and gravimetric water content, the soils of the two vineyards were approximately close to field capacity when the map of moisture to the root limiting layer was created. The survey highlighted a different moisture status of the two vineyards, which was mainly related to the shallower rooting depth of vineyard 1 at summit. In particular, at the time of survey (bud bursting of vines), vineyard 1 had a smaller overall average (288 mm) and a larger variability (standard deviation 66.6) than vineyard 2, where the average moisture of the rooting layer was 384 mm and standard deviation 34.1. The plots S, B, and F of vineyard 1 had on average 154, 334, and 288 mm of water, while vineyard 2 plots had 357, 365, and 402 mm, respectively (Figs. 4 and 5).

The main soil characteristics of the three plots in the two vineyards are reported in Table 2. There was a limited textural variability between the plots of the same vineyard. The plots reflected rather well the soil series characteristics, although the texture of vineyard 1 plots was on average more clayey. In fact, similar to the San Quirico soil series, all the vineyard 1 plots showed a marked contrast between the surface and lower horizon in terms of physical (consistence, structure, penetrometry, and bulk density) and hydrological properties (saturated hydraulic conductivity). On the other hand, the plots in both vineyards showed some evidence of seasonal waterlogging (redox features) and had a limited root density in the studied horizons. The available water capacity (AWC, difference between water content at field capacity and wilting point) was rather high in all plots, ranging from a minimum of 19.1% at B in vineyard 1 to a maximum of 24.2% at F in the same vineyard.

Electrical conductivity of the studied plots confirmed the differences between the two soil series (Table 3). San Quirico plots were more saline than Pietrafitta, because of the sharp increase in salts in the lower horizons, while Pietrafitta soils had lower and uniform with depth values. Even the largest conductivity values of the lower horizon of San Quirico soils, however, did not reflect strong salinity conditions, but only moderate ones. Moderate salinity nevertheless may limit vine vigor when the rootstock is 420A (Lambert et al., 2008).

The possibility of hosting a perched water table was confirmed by the low soil macroporosity (<10%) that characterized all plots, although with variations between vineyards (Fig. 6), vineyard 2 being relatively more porous and better structured than vineyard 1. In vineyard 2 there was a higher percentage of elongated and irregular pores, very important for vertical water movement, with respect to vineyard 1. In all the Pietrafitta plots, soil macroporosity was homogenously distributed along the profile. On the contrary, in San Quirico plot S the decrease of porosity at 0.4–0.7 m depth reached 50% with respect to the surface horizon. This sudden interruption in the continuity of pores could be responsible for the poor drainage in this plot.

Data from image analysis on IRIS tubes were submitted to statistical analysis. Although the effect of soil type did not result significant, the San Quirico plots showed discolored area values which were on average 25% higher than Pietrafitta. Statistical analysis instead highlighted the significant interaction of position with soil series ($F=5.75$, $P<0.01$, $n=36$). The highest discolored area was detected in the S position of San Quirico, where more than 35% of the ferrihydrite was removed (Fig. 7). This result implies a high probability of the soil having undergone significant reducing conditions (Castenson and Rabenhorst, 2006). The more prominent reducing conditions of this plot were related to the worst internal drainage, caused by the rather flat position and the presence of a dense and low permeable layer in depth (Table 2 and Fig. 6). As reported by Fiedler et al. (2007), IRIS is also capable of showing the location and pattern of reduction. In San Quirico S plot, evidence of poor drainage was confirmed by the pattern of ferrihydrite removal. In fact, at 0.35–0.50 m depth, the whole tube surface was uniformly discolored; on the contrary, in the other plots IRIS tubes only exhibited white spots of Fe removal, due to reduction processes occurring in microsites.

The year effect was also significant ($F=15.91$, $P<0.001$, $n=36$). The year 2005 was moister and colder than 2006, when the plots exhibited the highest mean percentage of iron removal. Actually, in the pedoclimatic conditions under study, soil temperature influenced the percentage of discolored area on IRIS more than moisture. In fact, there was no relationship between the values of the monitored soil moisture and the percentage of tube discoloration, while the relationship with daily mean soil temperature registered during the time in which the tubes were in place was highly significant ($R^2=0.496$, $P<0.01$, $n=12$). The influence of temperature on the process of iron reduction was also observed by other authors (Rabenhorst and Castenson, 2005). It is interesting to note that the effect of the year was not significant just in the San Quirico plot position S, where the discoloration was the same in both years. Evidently, in this place the microbial activity was influenced more by moisture than by temperature.

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3.3 Transpirable soil water from 10 June to 10 September

Daily TSW during the driest time of the growing season was on average rather high in all plots and years (Table 4 and Fig. 8). The effects of the year, soil type (vineyard) and morphological position were all significant. The prominent effect of the year on TSW was expected, as the vineyards were not provided of irrigation water, but the effect of soil series was also significant. The plots on San Quirico soil series (vineyard 1) had on average more than 20% TSW than Pietrafitta plots (vineyard 2). TSW increased significantly along the three positions on slope in both vineyards and in all years, even during the very dry 2006. On average, the B and F positions had about 11% and 38% more TSW than S, respectively. The interaction between the effects of soil series, year and slope position, emphasized that the maximum relative increase in TSW happened in the driest year 2006, when the plot at footslope of the San Quirico vineyard had almost 70% more transpirable water than the uppermost position. Actually, there was a large variability in the TSW increase with slope position, due to the interaction with the year. The weaker increase of TSW at the F plot position of both vineyards in the most rainy year, in particular, was to be expected, given that we were operating in a Mediterranean type of climate, where the summer rain showers favor surface runoff in soils with reduced macroporosity, also when they have a large AWC and are not saturated.

3.4 Influence of hydropedology of vineyard on grape production and wine quality

The mean weight of grape cluster was significantly influenced by plot position in both vineyards and three years of trial (Fig. 9), most probably as a consequence of the amount of TSW. In fact, there was a linear relationship between TSW and cluster weight (R^2=0.37, P<0.01, n=18). On the other hand, the sugar content, polyphenols and panel test were only influenced by the soil type (Table 4). In spite of the fact that a better viticultural and oenological result was achieved in San Quirico soil, where TSW was higher, no significant relationships between these parameters and TSW resulted. Must sugar and polyphenols, however, showed a significant difference between the F and S plots, but only in vineyard 2 (Figs. 10 and 11). This would suggest that the increase of water along the slope only affected the grape and wine produced in Pietrafitta soil. The same holds true for the panel test evaluation (Fig. 12). Moreover, the evaluation of the wine produced in San Quirico soil showed a significant direct relationship with TSW (R^2=0.42, $P<0.05$, n=9), which was really unexpected, as it is generally believed that the quality of Sangiovese, like most red wines, decreases with increasing water availability (Van Leeuwen et al., 2003; Deloire et al., 2005). Carbon isotope values could help in explaining the particular viticultural and oenological results (Fig. 13). In fact, a moderate stress, highlighted by values higher than −26‰, was only registered in vineyard 1. It is well known that a moderate water stress after veraison enhances Sangiovese quality, also in terms of sugar and polyphenols content, as well as fullness and harmony of the wine (Costantini et al., 2006a). Thus, the superior viticultural and oenological result obtained from the vines cultivated on San Quirico soil series should be attributed to a moderate physiological stress, most probably caused by the slight salinity of the lower horizons (Table 3). Furthermore, in the specific case of the F position of vineyard 1, a relatively higher TSW coupled with a moderate salinity would have improved the quality of wine as well as grape yield. On the other hand, the stagnic conditions evidenced in the S position of the same vineyard would not have influenced the viticultural and oenological result of Sangiovese.

4 Conclusions

The trial showed that the conceptual hydropedological model of Lin and coll. (Lin et al., 2006) and the Host classification (Boorman et al., 1995) can be used for the prevision of the moisture status of vineyard soils during summertime in a Mediterranean type of climate. Therefore, they can be adopted to delineate hydrological functional units inside soil series cultivated with vine. In the study case, the effect of the soil series was particularly important, as the soil's physical and hydrological characteristics determined water flows and plant available water, while its chemical properties influenced the salinity of the solution and in turn water uptake. The combined modeling of water and salt movements would be thus particularly relevant for viticultural management of these soils. Such models could also address the choice of the pre-planting operations of the vineyard, in particular, plowing depth, slope reshaping, and earth movements. The occurrence of redox processes in soil could be confirmed through the installation of IRIS tubes, although the mottling was mostly influenced by soil temperature, rather than water content. The map of soil moisture in the rooting layer at vine bud bursting, produced by a geophysical survey carried out "una tantum", only partially reflected the actual seasonal hydropedology of these heavily tilled soils on slope. More surveys, carried out at the other main phenological phases of vine, would be needed to better delineate vineyard functional units for precision agriculture.

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Table 1. Soil series characteristics in the two vineyards.

Horizon and limits (m)	Clay	Sand	Consistence[a]	Structure[b]	Redox features[c] (%)	CEC (cmol(+) kg^{-1})	ESP (%)	El. cond. dS m^{-1} (1:2.5)	Total $CaCO_3$	Active $CaCO_3$	OM
	(dag kg^{-1})								(% w w^{-1})		
San Quirico (vineyard 1)											
Ap 0–0.20	28.6	8.8	RE	SB	5	13.7	7.4	0.19	17.3	4.1	1.13
Bg 0.20–0.75	25.7	5.3	RE	AB	8			0.25	17.9	8.1	0.64
Cr 0.75–1.20	29.1	2.5	RE	MA	18			1.34	19.2	5.9	0.33
Pietrafitta (vineyard 2)											
Ap 0–0.20	26.2	7.8	FR	SB	–	15.1	1.1	0.27	15.7	3.0	1.65
Bw1 0.20–0.70	24.6	7.3	FR	SB	–			0.24	14.5	2.9	1.69
Bw2 0.70–1.20	22.1	9.3	FR	SB	4			0.16	18.9	4.7	0.69

[a] Consistence moist: FR=friable, RE=resistant

[b] Structure: SB =subangular blocky. AB=angular blocky. MA=massive

[c] Redox features are mainly iron depletion on faces of aggregates and pores, and masses of iron and manganese concentrations inside aggregates. Modal Munsell colors are, respectively, 10 YR 6/1 or 7/2, and 10 YR or 7.5 YR 6/8.

Table 2. Plot main pedological characteristics.

Vineyard, plot and horizon's limits (m)	Clay	Sand	Consistence[a]	Structure[b]	Redox features[c] (%)	Roots[d] ($\mathrm{n\,dm^{-2}}$)	Cone index (kPa)	Bulk density[e] ($\mathrm{g\,cm^{-3}}$)	Saturation[e]	FC[f]	WP[g]	Ksat[h] ($\mathrm{cm\,h^{-1}}$)
	($\mathrm{dag\,kg^{-1}}$)								(% v/v)			
1S 0–0.15	35.0	11.0	FR	SB	2	4	453	1.60	39.6	36.0	14.2	0.101
1S 0.15–0.60	35.7	5.9	RE	AB	20	5	1,435	1.58	40.5	38.0	14.9	0.102
1B 0–0.15	39.3	3.5	FR	SB	2	1	616	1.53	42.3	32.8	13.7	0.203
1B 0.15–0.50	33.4	0.8	RE	AB	15	2	1.476	1.60	39.8	33.7	14.7	0.142
1F 0–0.10	38.0	0.3	FR	SB	3	0	236	1.55	41.6	38.1	14.5	0.114
1F 0.10–0.45	22.9	5.2	FR	AB	50	3	1.032	1.59	39.9	38.8	14.0	0.134
2S 0–0.15	22.3	10.8	FR	SB	2	2	315	n.d.	n.d.	n.d.	n.d.	n.d.
2S 0.15–0.35	24.2	7.9	FR	SB	15	2	668	1.57	40.7	35.5	14.2	0.232
2S 0.35–0.65	24.2	10.3	FR	SB	20	2	1072	1.52	42.5	33.9	13.1	0.351
2B 0–0.15	22.5	17.0	FR	SB	0	3	371	1.48	44.1	36.0	14.4	0.385
2B 0.15–0.65	21.7	4.6	FR	SB	10	3	773	1.50	43.3	34.5	17.1	0.463
2F 0–0.15	29.0	19.6	FR	SB	8	2	443	1.52	42.5	37.4	14.9	0.160
2F 0.15–0.65	32.4	0.1	FR	SB	8	3	952	1.50	43.4	37.8	15.8	0.196

[a] Consistence moist: FR=friable, RE=resistant

[b] Structure: SB =subangular blocky. AB=angular blocky

[c] Redox features are mainly iron depletion on faces of aggregates and pores, and masses of iron and manganese concentrations inside aggregates. Modal Munsell colors are respectively 10YR 6/1 or 7/2, and 10YR or 7.5 YR 6/8.

[d] Fine roots (1–2 mm)

[e] Calculated from the field measured value of humidity when soil was saturated

[f] Field capacity: soil water content obtained from field core sampling three days after soil was saturated

[g] Wilting point: minimum soil water content obtained from field core sampling

[h] Saturated hydraulic conductivity according to Rosetta (Schapp, 2001)

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Table 3. Soil electrical conductivity of the plots (1:2.5 $\mathrm{w\,w^{-1}}$, $\mathrm{dS\,m^{-1}}$). Variables with different letters differ significantly for $P<0.05$ (test of Tukey).

	Soil series									
	S. Quirico (vineyard 1) Plot position					Pietrafitta (vineyard 2) Plot position				
Depth (m)	S	B	F	mean			S	B	F	mean
0.2–0.4	0.244	0.215	0.255	*0.238*	b	0.217	0.300	0.222	*0.246*	a
0.4–0.6	0.331	0.368	0.366	*0.355*	b	0.260	0.260	0.223	*0.248*	a
0.6–0.8	0.734	0.215	0.520	*0.490*	ab	0.226	0.215	0.224	*0.222*	a
0.8–1	0.991	0.380	0.924	*0.765*	a	0.267	0.178	0.318	*0.254*	a
mean	*0.575 a*	*0.295 a*	*0.516 a*	*0.462*	*a*	*0.243 a*	*0.238 a*	*0.247 a*	*0.243*	*b*

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Table 4. Mean daily transpirable soil water (mm) from 10 June to 10 September. Cluster weight, must sugar, total polyphenols, δ^{13}C, and panel test score attained by the wines. Variables with capital letters differ significantly for P<0.01, with lowercase letters for P<0.05 (HSD Tukey test).

		Transpirable soil water (mm)		Cluster weight (g)		Must sugar (°Brix)		Total polyphen. (mg L^{-1})		Panel test score		δ^{13}C (‰)	
Soil type (vineyard)	1	53.4	A	362	a	21.6	a	1711	a	119.6	a	−25.5	b
	2	43.9	B	333	a	20.3	b	1411	b	83.9	b	−28.1	a a
Year	2005	58.2	A	352	a	20.1	a	1488	a	98.3	a	−28.1	
	2006	40.1	C	312	a	21.3	a	1646	a	98.5	a	−26.7	ab
	2007	47.6	B	373	a	21.5	a	1549	a	108.3	a	−25.6	b a
Plot position	S	41.8	B c	304	b	21.4	a	1642	a	103.8	a	−26.6	
	B	46.3	B b	328	b	21.2	a	1564	a	97.7	a	−27.2	a
	F	57.7	A a	409	a	20.3	a	1477	a	103.7	a	−26.6	a

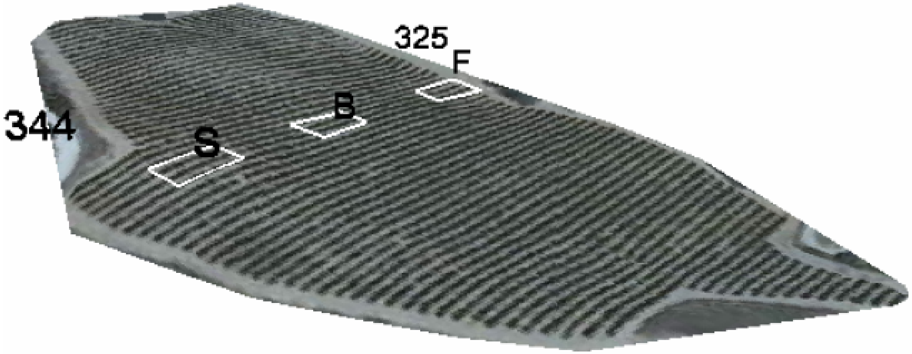

Fig. 1. 3-D orthophoto of vineyard 1, with indication of the study areas (summit-position S, backslope-position B, and footslope-position F), and elevation.

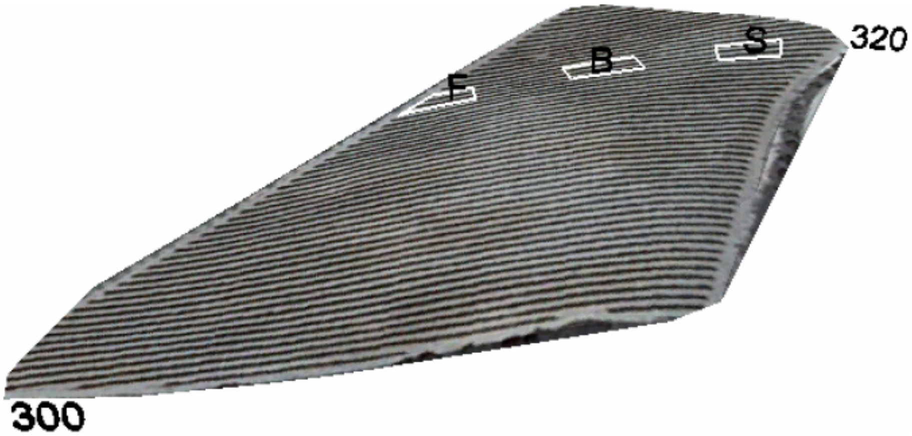

Fig. 2. 3-D orthophoto of vineyard 2, with indication of the study areas (summit-position S, backslope-position B, and footslope-position F) and elevation.

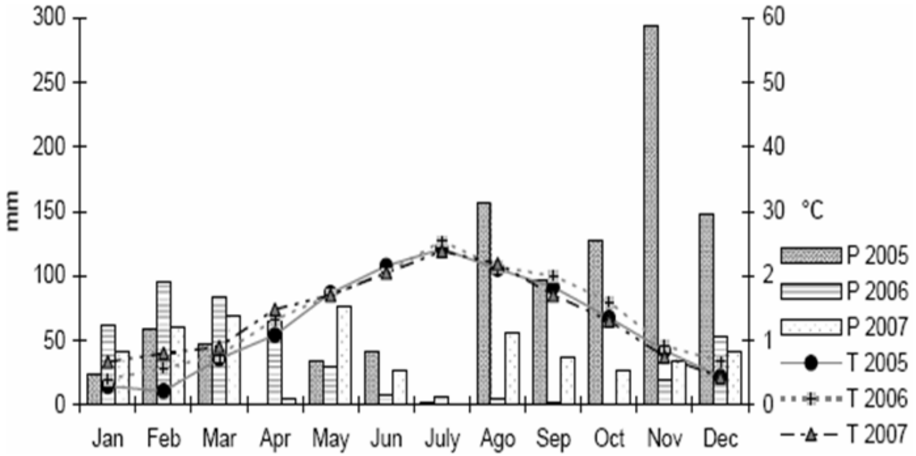

Fig. 3. Precipitation and air temperature during the study period.

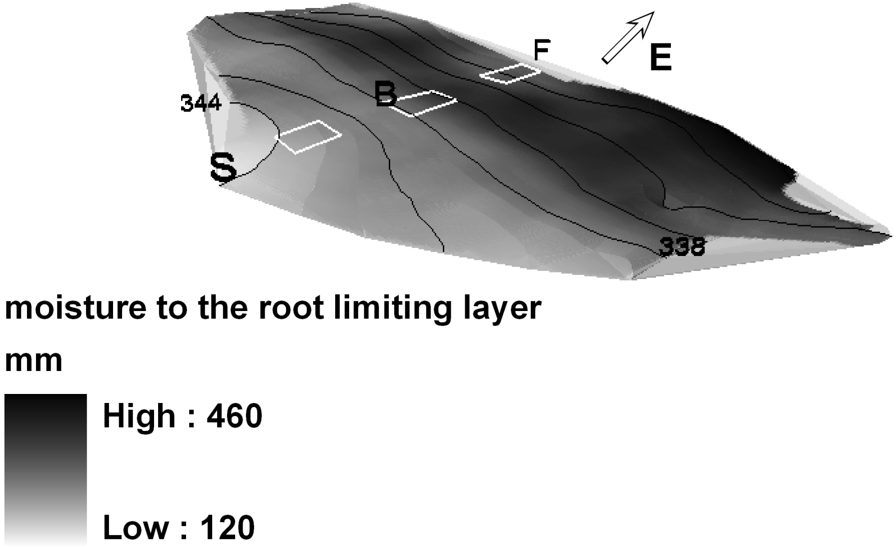

Fig. 4. Map of cumulative soil moisture up to the root limiting layer in vineyard 1 at bud bursting of vines.

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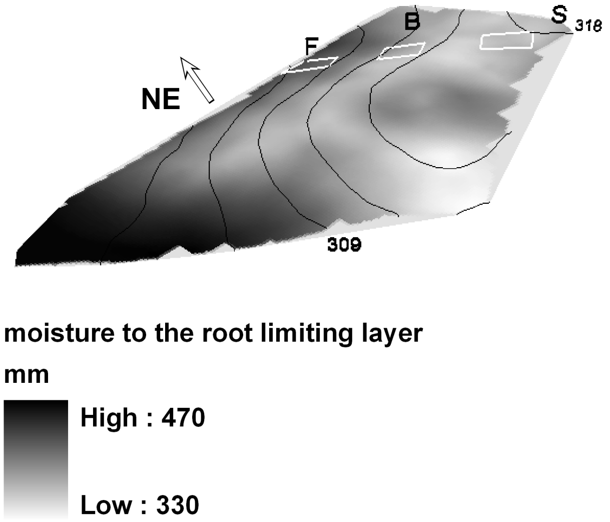

Fig. 5. Map of cumulative soil moisture up to the root limiting layer in vineyard 2 at bud bursting of vines.

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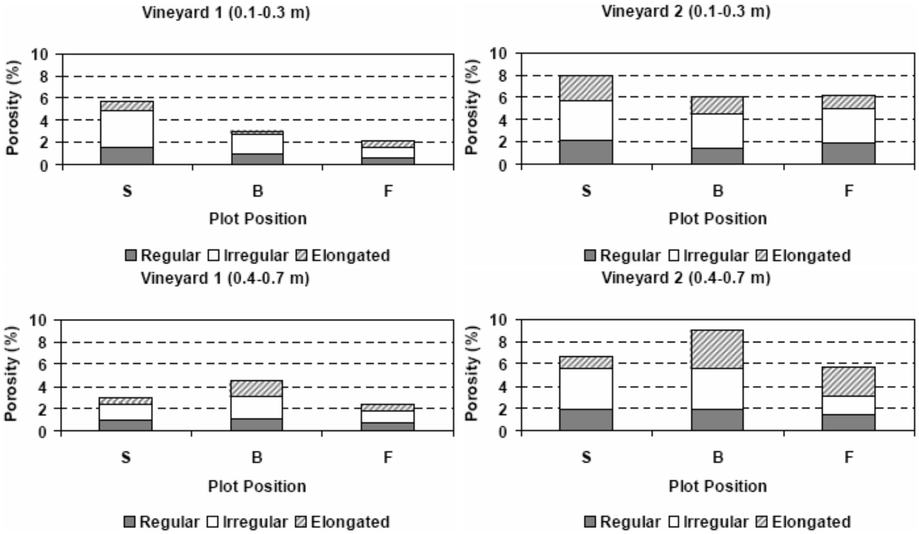

Fig. 6. Soil macroporosity in the three morphological positions of the two studied vineyards.

Fig. 7. Discolored area (%) on IRIS tubes in the different plot positions, soils, and years (2005 and 2006).

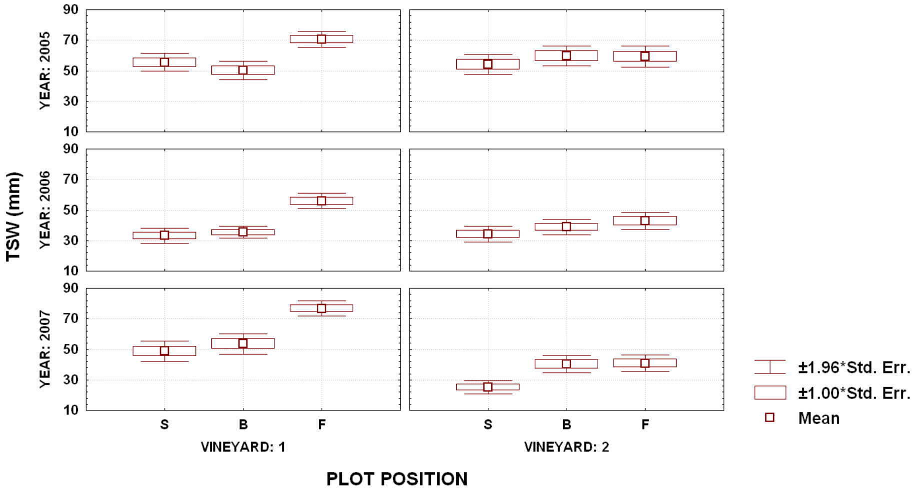

Fig. 8. Mean daily transpirable soil water (mm) from 10 June to 10 September in the different soils, years and plot positions.

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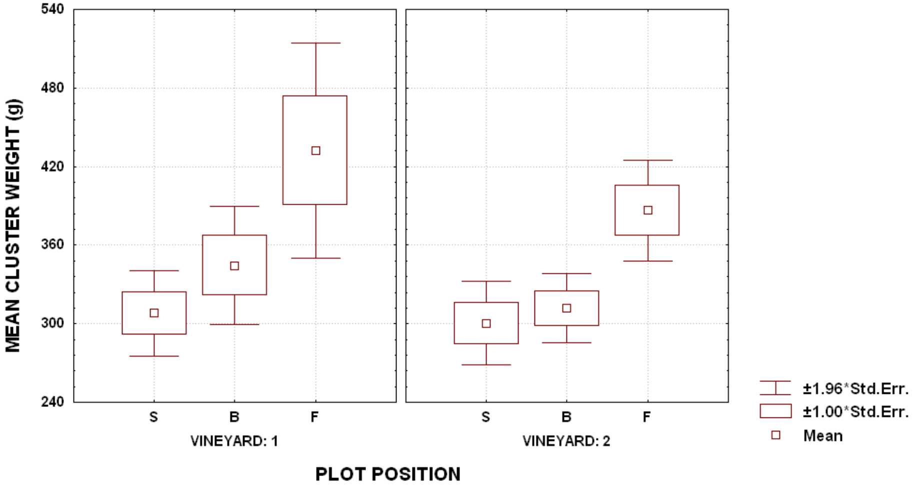

Fig. 9. Mean weight of grape clusters in the different soils and plot positions.

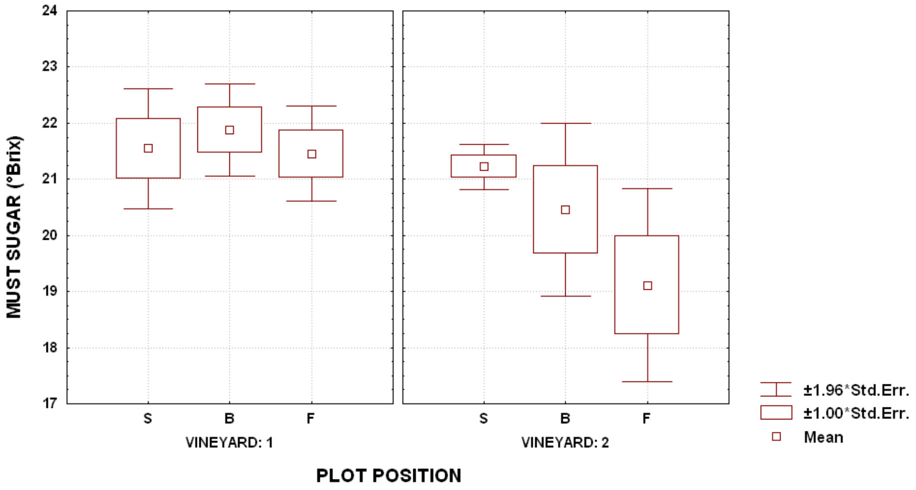

Fig. 10. Must sugar content in the different soils and plot positions.

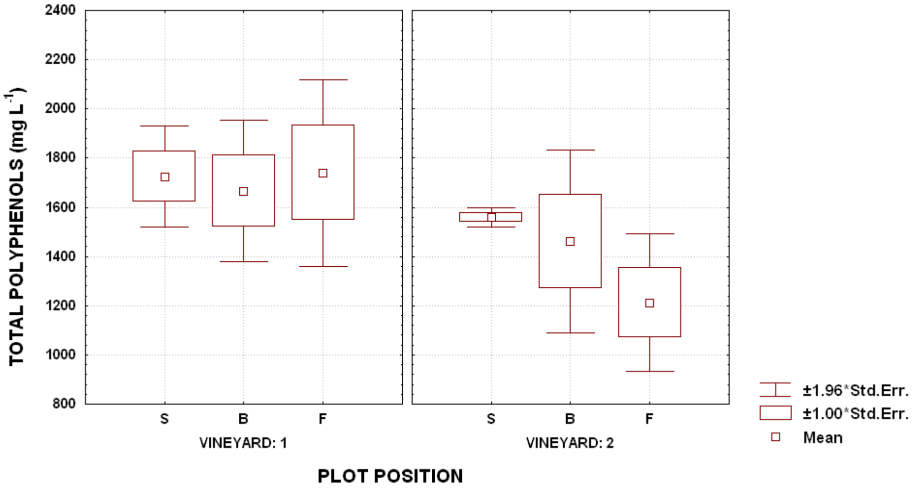

Fig. 11. Total polyphenols content in the different soils and plot positions.

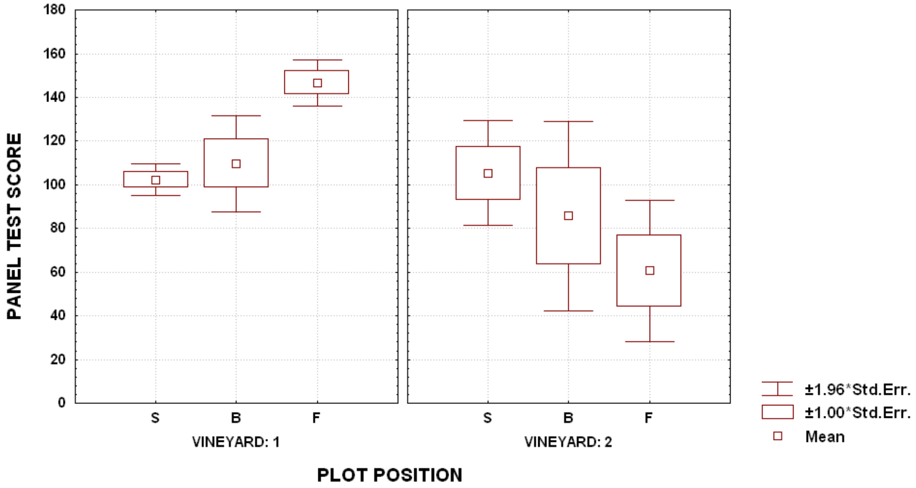

Fig. 12. Panel test score in the different soils and plot positions.

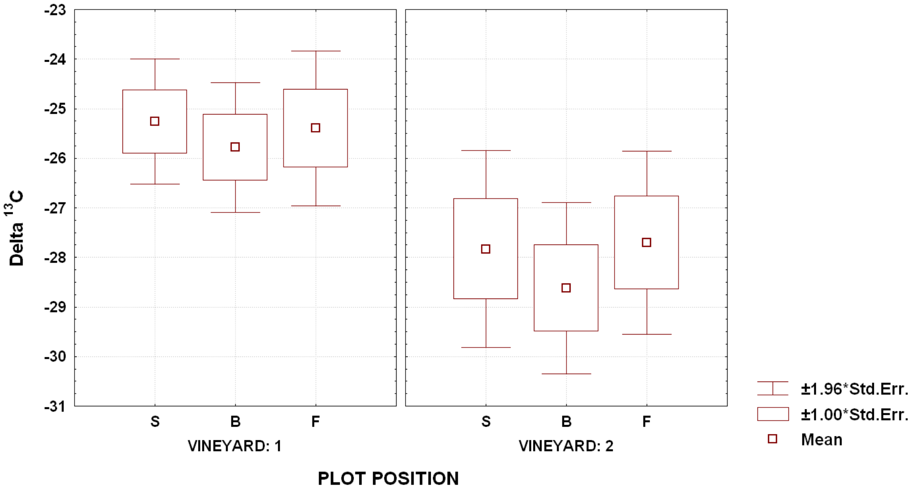

Fig. 13. Carbon isotopes ratio in the different soils and plot positions.