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Relevance of the Lin's and Host hydropedological models to predict grape yield and wine quality

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Abstract. The adoption of precision agriculture in viticulture could be greatly enhanced by the diffusion of straightforward and easy to be applied hydropedological models, able to predict the spatial variability of available soil water. The Lin's and Host hydropedological models were applied to standard soil series descriptions and hillslope position, to predict the distribution of hydrological functional units in two vineyard and their relevance for grape yield and wine quality. A three-years trial was carried out in Chianti (Central Italy) on Sangiovese. The soils of the vineyards differentiated in structure, porosity and related hydropedological characteristics, as well as in salinity. Soil spatial variability was deeply affected by earth movement carried out before vine plantation. Six plots were selected in the different hydrological functional units of the two vineyards, that is, at summit, backslope and footslope morphological positions, to monitor soil hydrology, grape production and wine quality. Plot selection was based upon a cluster analysis of local slope, topographic wetness index (TWI), and cumulative moisture up to the root limiting layer, appreciated by means of a detailed combined geophysical survey. Water content, redox processes and temperature were monitored, as well as yield, phenological phases, and chemical analysis of grapes. The isotopic ratio δ^{13}C was measured in the wine ethanol upon harvesting to evaluate the degree of 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 combined application of the two hydropedological models can be used for the prevision of the moisture status of soils cultivated with grape during summertime in Mediterranean climate. As correctly foreseen by the models, the amount of mean daily transpirable soil water (TSW) during the growing season differed considerably between the vineyards and increased significantly along the three positions on slope in both vineyards. The water accumulation along slope occurred in every year, even during the very dry 2006. The installation of indicators of reduction in soils (IRIS) tubes allowed confirmation of the occurrence of reductive processes in the most shallow soil.

Both Sangiovese grape yield and quality of wine were influenced by the interaction between TSW content and salinity, sometimes contrary to expectations. Therefore, the studied hydropedological models were not relevant to predict grape yield and wine quality in all the hydrological functional units. The diffusion of hydropedological models in precision viticulture could be boosted considering salinity along with topography and soil hydrological characteristics.

1 Introduction

In the Mediterranean environment, characterized by a summer water deficit, crop phenology, production, and quality of yield are significantly determined by water supply. 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 which regulate water nutrition, 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

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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); however, the geographic pattern of hydrological functional units inside a vineyard 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 levelling, 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 hydrological functioning of the vineyard soils is above all important during the vine vegetative season, particularly in summer, when water availability greatly influences wine quality, but limited rainfall and heavy storms make water circulation particularly difficult to predict. To this respect, some Authors claim that during dry periods soil moisture patterns depend primarily on soil properties, with little effect from topography (Grayson et al., 2002).

We used a hydropedological perspective, which considers soils and topography simultaneously, to study the hydrological functioning of vineyard and its consequences on vine behavior, through the application of the Lin's (Lin et al., 2006) and Host (Boorman et al., 1995) hydropedological models. The models have been created to be applied to a standard soil series profile description to predict flow pathways through the soil and along a hillside. The Lin's model is qualitative, and stresses the importance of the interaction between soil characteristics and morphological position on the slope in determining subsurface flow, as well as runoff. The rationale stands upon the assumption that relatively static properties, such as topography and soil type, can be mapped to develop a model of soil-water dynamics. In particular, Lin et al. (2006) classed soil series locations that exhibited different spatio-temporal patterns of subsurface soil moisture in a catchment by means of a cluster analysis, based on the depth to bedrock, topographic wetness index (TWI), and local slope.

The Host model distinguishes 11 conceptual models of soil hydrology, regulating water flow to streams, on the basis of soil profile and parent material characteristics. The soil properties used to derive the Host classification are depth to a gleyed layer, depth to a slowly permeable layer, integrated air capacity and presence of a peaty surface layer. Combining soil type, parent material type, presence of shallow groundwater and dominant flow pathway, the model classifies 29 types of soil hydrological units that could be encountered within watersheds in the UK. The 29 types have been statistically correlated with the base flow index, that is, the long-term average proportion of flow that occurs as base flow.

Both hydropedological models were validated in temperate humid climates (Eastern USA and North Europe), where summer water deficit is limited, and with different herbaceous crops and forest stands, where soil is not, or it is only shallow ploughed. The results of their implementation in environments characterized by strong seasonality and contrasted rainfall and temperature regimes is unknown, as it is unknown their applicability to soils that are deeply disturbed by agricultural practices.

The general aim of this research work was to test the prediction capacity of the Lin's and Host hydropedological models in Mediterranean vineyards. More particularly, the objective was to use the models to delineate hydrological functional units, characterized by differences of available water during vine growing, large enough to significantly affect grape yield and wine quality.

This knowledge can be very important to foster the application of hydropedological models worldwide and, in particular, it may be relevant for farmers who want to put in practice precision viticulture.

2 Materials and methods

2.1 Study vineyards 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, plant density 3500 per ha, the rootstock 420A, which is a hybrid between *Vitis Berlandieri* and *Riparia*, considered to be resistant to drought and active lime, but not to salinity. Both vineyards were planted in 1991, after slope reshaping by bulldozing and deep ploughing up to about 0.8–1.0 m. Viticultural husbandry was similar and the soil surface was periodically cultivated to limit weed growth, interrupt capillarity and reduce evaporation. The two vineyards were planted on slopes with similar steepness (from 2 to 13 or 18%) and aspect (E and NE) (Figs. 1a and 2a). The soils formed from fine silty marine sediments of Pliocene, having almost horizontal layers. 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, superactive, or Haplic Cambisol (Calcaric). The two soils differentiated mainly as a result of land levelling before vine planting. Vineyard 1 was scalped more intensively than

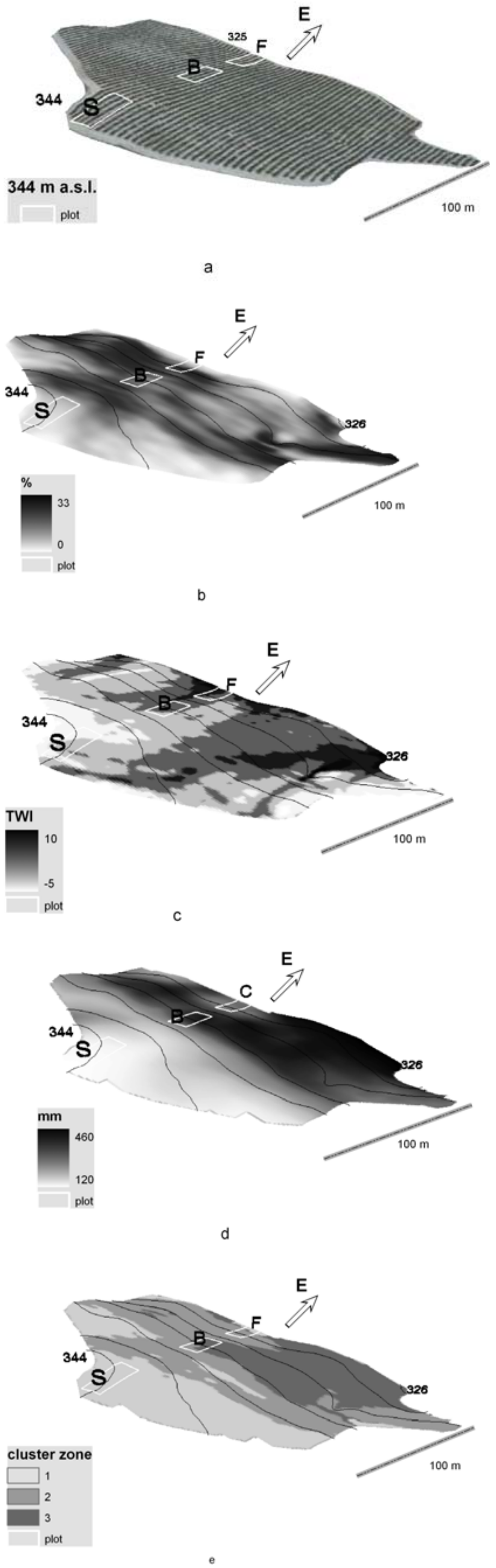

Fig. 1. Vineyard 1; **a**: 3-D orthophoto with indication of aspect, elevation, and plots (summit S, backslope B, and footslope F); **b**: slope; **c**: topographic wetness index (TWI); **d**: cumulative soil moisture up to the root limiting layer at bud bursting of vines (RL-moist); **e**: cluster zones.

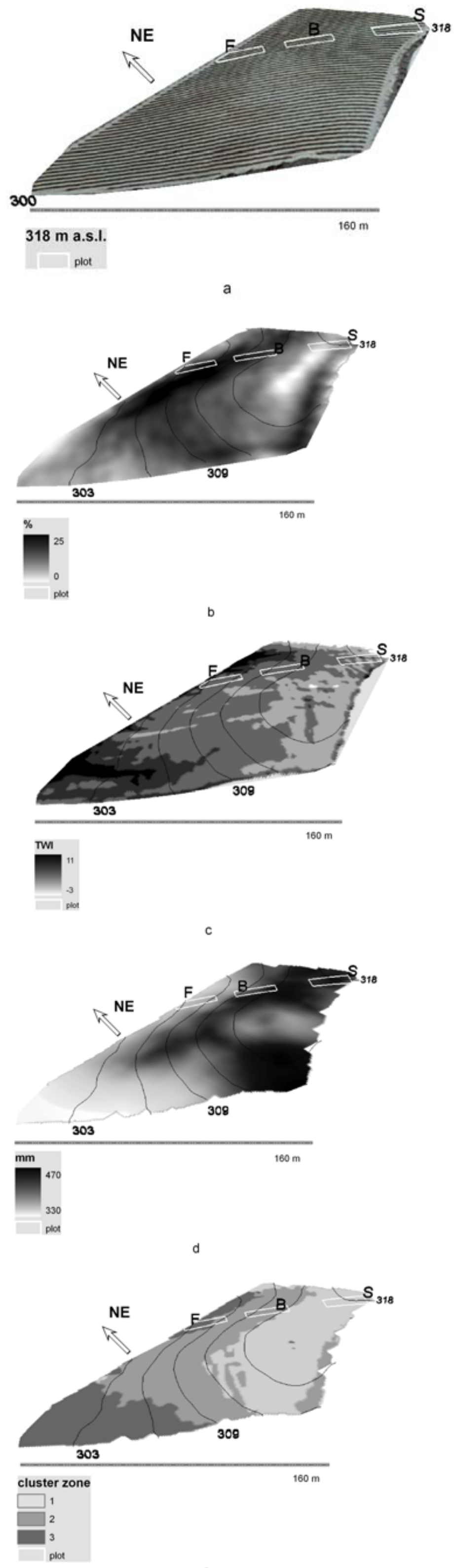

Fig. 2. Vineyard 2; **a**: 3-D orthophoto with indication of aspect, elevation, and plots (summit S, backslope B, and footslope F); **b**: slope; **c**: topographic wetness index (TWI); **d**: cumulative soil moisture up to the root limiting layer at bud bursting of vines (RL-moist); **e**: cluster zones.

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. The 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. 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 properties (consistence, structure, cone resistance, and bulk density). 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).

2.2 Application of hydropedological models

The hydropedological models used to differentiate functional hydrological units in the vineyards were the conceptual model of Lin et al. (2006) and the Host classification (Boorman et al., 1995). We could apply this models since horizontal geological layers excluded water transfer from different watersheds. The Lin's model was used to separate the morphological positions of each vineyard, whereas the Host classification to differentiate the soil series of the two vineyards.

According to the first model, the main functional hydrological units of both vineyards should correspond to the morphological positions of summit (position S), backslope (position B), and footslope and swales (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. To single out the tree zones in the two vineyards we operated a cluster analysis of slope, TWI, and cumulative soil moisture in the rooting zone at the time of bud bursting.

A detailed DEM (1 m) was developed together with a detailed geophysical survey in collaboration with the Soil Information System (SIS) of John Deere Agri Services at bud bursting of vines, 4 April 2005. Local slope was calculate from the DEM, according to the polynomial of Zevenbergen and Thorne (1987) (Figs. 1b and 2b). TWI of every cell was the ratio between catchment area and slope, and was calculated by means of the software SAGA (Institute of Geography at the University of Hamburg, Germany), using default algorithms (Figs. 1c and 2c). The cumulative soil moisture until the root limiting layer (RL-moist) was estimated by SIS using a Frequency Domain Reflectometer (FDR) to estimate moisture, and a cone penetrometer to evaluate soil consistence. The root limiting layer was assumed to be the first layer 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. Spatialization was obtained with the Inverse Distance Weighting method (Figs. 1d and 2d). The software ArcGIS (ESRI Inc., Redlands, CA, USA) was used to elaborate spatial information. The module ArcScene was utilized to drape the orthophotos on the Triangular Irregular Network and create the 3-D map of the vineyards. The resulting map allowed to estimate RL-moist of the experimental plots as well as of the whole vineyard. The calculation used the zonal statistic tool of the spatial analyst module of the software ArcGIS.

The cluster analysis of the three attributes of each pixel (slope, TWI, and RL-moist) was performed after data normalization (mean=0 and standard deviation=1), using the software Statistica (StatSoft Inc., Tulsa, OK, USA) and the k-means clustering. This method of cluster analysis aims to partition n observations into k clusters in which each observation belongs to the cluster with the nearest mean. In the cluster analysis module of Statistica, the k-means algorithm uses the unscaled squared Euclidean distances for the distance measure; for example, the distance $D\ (i,k)$ of an observation i from cluster k, for M continuous variables Xj is computed as:

$$D(i,k) = \sqrt{\frac{1}{M}\sum_{j=1}^{M}\left(X_{ij} - \overline{X}_j^{(k)}\right)^2}$$

where $\overline{X}_j^{(k)}$ is the mean for variable j and cluster k.

Using pixels as observations and clustering of cases within three groups, the software attributed each pixel of the two vineyards to one group (Figs. 1e and 2e).

The Host classification was utilized to distinguish the flow pathways through the two soil series and vineyards. The benchmark profile of the San Quirico series (vineyard 1) showed no significant groundwater or aquifer, but a shallow impermeable substrate (horizon Cr, Table 1) impeded vertical

Table 1. Soil series characteristics in the two vineyards.

Horizon and limits (m)	Clay (dag kg^{-1})	Sand (dag kg^{-1})	Consistence[a]	Structure[b]	Redox features[c] (%)	CEC (cmol(+) kg^{-1})	ESP (%)	El. cond. dS m^{-1} (1:2.5)	Total $CaCO_3$ (% w w^{-1})	OM (% w w^{-1})
San Quirico (vineyard 1)										
Ap 0.00–0.20	28.6	8.8	RE	SB	5			0.19	17.3	1.13
Bg 0.20–0.75	25.7	5.3	RE	AB	8	13.7	7.4	0.25	17.9	0.64
Cr 0.75–1.20	29.1	2.5	RE	MA	18			1.34	19.2	0.33
Pietrafitta (vineyard 2)										
Ap 0.00–0.20	26.2	7.8	FR	SB	–			0.27	15.7	1.65
Bw1 0.20–0.70	24.6	7.3	FR	SB	–	15.1	1.1	0.24	14.5	1.69
Bw2 0.70–1.20	22.1	9.3	FR	SB	4			0.16	18.9	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 colours 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 (dag kg^{-1})	Sand (dag kg^{-1})	Consistence[a]	Structure[b]	Redox features[c] (%)	Roots[d] (n dm^{-2})	Cone index (kPa)	Bulk density[e] (g cm^{-3})	Saturation[e] (% v v^{-1})	FC[f] (% v v^{-1})	WP[g] (% v v^{-1})
1S 0.00–0.15	35.0	11.0	FR	SB	2	4	453	1.60	39.6	36.0	14.2
1S 0.15–0.60	35.7	5.9	RE	AB	20	5	1435	1.58	40.5	38.0	14.9
1B 0.00–0.15	39.3	3.5	FR	SB	2	1	616	1.53	42.3	32.8	13.7
1B 0.15–0.50	33.4	0.8	RE	AB	15	2	1476	1.60	39.8	33.7	14.7
1F 0.00–0.10	38.0	0.3	FR	SB	3	0	236	1.55	41.6	38.1	14.5
1F 0.10–0.45	22.9	5.2	FR	AB	50	3	1032	1.59	39.9	38.8	14.0
2S 0.00–0.15	22.3	10.8	FR	SB	2	2	315	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
2S 0.35–0.65	24.2	10.3	FR	SB	20	2	1072	1.52	42.5	33.9	13.1
2B 0.00–0.15	22.5	17.0	FR	SB	0	3	371	1.48	44.1	36.0	14.4
2B 0.15–0.65	21.7	4.6	FR	SB	10	3	773	1.50	43.3	34.5	17.1
2F 0.00–0.15	29.0	19.6	FR	SB	8	2	443	1.52	42.5	37.4	14.9
2F 0.15–0.65	32.4	0.1	FR	SB	8	3	952	1.50	43.4	37.8	15.8

[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 colours are, respectively 10 YR 6/1 or 7/2, and 10 YR 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.

movement of water. Moreover, it had a slowly permeable layer within 1 m of the surface (horizon Bg) therefore it belonged to model I, class 13, which means some inhibition to water movement down through the soil profile. The slowly permeable material within 1 m of the surface 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

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

	Soil series									
	S. Quirico (vineyard 1)					Pietrafitta (vineyard 2)				
	Plot position					Plot position				
	S	B	F			S	B	F		
Depth (m)				mean					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	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***

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.

The benchmark profile of the Pietrafitta soil series (vineyard 2) belonged to model H, class 6, because it did not have inhibition to drainage within the first meter and, in addition, it permitted vertical unsaturated and by-pass flow through macropores to the depth of the underlying substrate. According to Host classification, the base flow indices (BSI) of classes 6 and 13 are 0.586 and 1.005, respectively, which means much larger base flow in San Quirico than in Pietrafitta soils.

Therefore, the application of the Host classification let us hypothesize larger subsurface lateral flow and moister conditions in position F of vineyard 1 than in vineyard 2.

2.3 Plot selection

The validation of the two hydropedological models was carried out in six 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) (Figs. 1 and 2). The plots were selected within the two vineyards, as reference of the hypothesized different hydrological and viticultural functional units, which were created with the cluster analysis performed following the suggestions of the Lin's model. Plot dimension was a compromise between the needs of representing the morphological zone and controlling the viticultural performance. 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.

2.4 Temporal monitoring of state variables

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 during the growing season, and monthly in the rest of the year. A daily value of the water content (total mm in the 0–0.7 m depth) at each position in the two vineyards was calculated using rainfall amount, 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. Other authors indeed found that vine can assume soil water at very high absolute tensions, even lower than conventional wilting point (White, 2003). 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 pt 100) at the same time of soil moisture monitoring.

2.5 Soil characterization

Soil description and routine analysis of the air-dried <2 mm fraction followed the Italian official methods (MiPAF, 2000; Costantini, 2007). In particular, root density was measured in the field by means of a 10×10 cm mesh, soil texture was carried out in the laboratory 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 $^{-1}$) 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). 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. 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.

Bulk density and water saturation were calculated from the field measured value of moisture when soil was saturated, assuming a particle density of 2.65 g cm^{-3}. We used this methods because of the difficulties encountered in using the core and the filled hole methods in the studied soils, caused by their high plasticity. Although the calculation of bulk density might lead to an underestimation of porosity, values were corrected to take into account the entrapped air, as follows:

$$\rho_b = \frac{100 * \rho_w * C}{\frac{100*\rho_w*C}{\rho_s} + \theta_m}$$

Where: ρ_b=soil bulk density (g cm^{-3}), ρ_w=water density (g cm^{-3}), C=ϕ_s/ϕ ratio between porosity at saturation and total porosity (assumed to be 0.95 according to Faybishenko, 1995), ρ_s=particle density (g cm^{-3}), θ_m=gravimetric water content (% w w^{-1}).

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.

An alternative method for assessing water saturation and reducing condition is the use of IRIS (Indicator of Reduction In Soil) PVC tubes, coated with ferrihydrite ($Fe(OH)_3$) on the surface (Jenkinson and Franzmeier, 2006). During periods of reducing conditions, 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.

Soil characterization included macroporosity quantification by image analysis. Three thin sections (60×70 mm) for each soil horizon were obtained by undisturbed samples collected at 0.1–0.3 and 0.4–0.7 m depth, and were analyzed to quantify pores >50 μm (Vignozzi et al., 2007). Two vertically oriented 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 Grape and wine characterization

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 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 colour 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).

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 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 days 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 Hydrological monitoring and testing of the models

According to the Lin's model, F positions in both vineyards should correspond to the wettest conditions, while the Host model pointed to moister soil and larger subsurface lateral flow in vineyard 1. At the beginning of the trial, both the geophysical survey performed by SIS, and the measured gravimetric water content, indicated that the soils of the two vineyards were close to or above field capacity. The maps RL-moist (Figs. 1d and 2d) also highlighted a different moisture in the soils of the two vineyards. In particular, at the time of survey, vineyard 1 had a smaller overall average of RL-moist (288 mm) and a larger variability (standard deviation 66.6) than vineyard 2, where the average RL-moist was 384 mm and standard deviation 34.1. Therefore, mean soil water holding capacity was very large in both vineyards, but with relevant local variations in vineyard 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. While in vineyard 2 differences between plots were limited, it is interesting to note that in vineyard 1 the shallower rooting depth at summit, caused by the scalping of the soil before the vine plantation, was the main differentiating factor.

The three groups created with the cluster analysis (Figs. 1e and 2e) did not have the same meaning in the two vineyards. In vineyard 1, cluster 1 fitted well the concept of summit morphological position, having the lowest mean value of normalized slope, TWI and RL-moist (Table 4). Cluster 2 showed the steepest slopes and intermediate TWI and RL-moist, which had instead maximum values in cluster 3. The clusters correspondence with backslope and footslope morphological positions was not evident, as they were unevenly distributed in the vineyard. In addition, the high standard deviations of mean values which occurred in clusters 2 and 3 indicated a large variability of conditions within the cluster. In fact, the correlation between the parameters was significant only for slope and RL-moist, along with a low determination coefficient (R^2=0.258). The direct relationship between slope and RL-moist, as well as the lack of correspondence with TWI, could be related to the earth movements before plantation, which irregularly distributed the earth along the vineyard and increased local soil variability.

Vineyard 2 instead showed a better correspondence between clusters and morphological positions. Passing from cluster 1 to cluster 2 and 3, TWI and RL-moist increased, while slope was the highest in cluster 2. In fact, TWI and RL-moist resulted rather well correlated (R^2=0.639). Also in vineyard 2, however, standard deviations of normalized mean values were often large (Table 4).

Both Lin's and Host models underlined the role played by subsurface later flow, which should increase transpirable soil water (TSW) at F positions and especially in vineyard 1, where there was more contrasted porosity between surface and deep horizons. TSW during the driest time of the growing season (10 June to 10 September) was rather high in all plots and years (Table 5 and Fig. 4). 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.

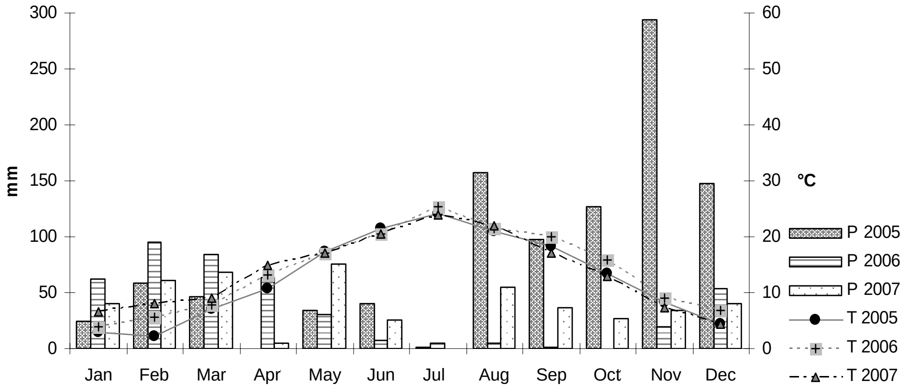

Fig. 3. Precipitation and air temperature during the study period.

Table 4. Mean and standard deviation of normalized values of slope, topographic wetness index (TWI), and cumulative moisture until the root limiting layer (RL-moist), in the three clusters of the two vineyards.

		Slope	TWI	RL-moist
		Vineyard 1		
cluster 1	mean	−1.020	−0.073	−1.158
	stand. dev.	0.680	1.983	0.570
cluster 2	mean	0.737	0.005	−0.022
	stand. dev.	0.676	0.047	0.580
cluster 3	mean	−0.379	0.060	1.162
	stand. dev.	0.608	0.043	0.483
		Vineyard 2		
cluster 1	mean	−0.653	−0.683	−0.667
	stand. dev.	0.650	0.708	0.391
cluster 2	mean	0.898	−0.056	−0.202
	stand. dev.	0.574	0.505	0.502
cluster 3	mean	−0.796	1.355	1.645
	stand. dev.	0.581	0.923	0.757

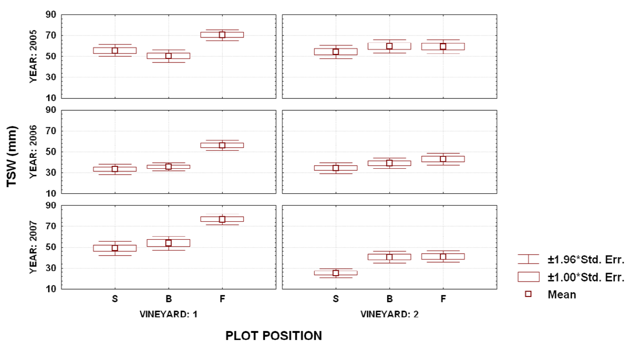

Fig. 4. Mean daily transpirable soil water (TSW) from the 10 June to the 10 September in the different soils, years and plot positions.

The interaction between the effects of soil series, year and morphological 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. Then the role played by subsurface later water flow was higher in the soil where land levelling and slope reshaping enhanced the permeability contrast of the soil horizons along the profile.

The Host classification also pointed to the possibility to have waterlogging at some time during the vine growing season in San Quirico plots. The possibility of hosting a perched water table was also suggested by the low soil macroporosity (<10%) that characterized all plots, although with variations between vineyards (Fig. 5), vineyard 2 being relatively more porous and better structured than vineyard 1. In vineyard 2, in particular, there was a higher percentage of elongated and irregular pores, very important for water movement (Costantini et al., 2006b), with respect to vineyard 1. In all the Pietrafitta plots, soil macroporosity was homogeneously distributed along the profile. On the contrary, in San Quirico plot S, porosity at 0.4–0.7 m depth was nearly 50% of the surface horizon. This sudden interruption in the continuity of pores might imply a poor drainage in this plot.

To confirm the presence of reducing conditions during the vine growing season, 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 effect of year (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. The interaction of position with soil series was also significant (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. 6). This result implies a high probability of the soil having undergone

Table 5. Mean daily transpirable soil water (mm) from the 10 June to the 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	1	53.4	A	362	a	21.6	a	1711	a	119.6	a	−25.5	b
(vineyard)	2	43.9	B	333	a	20.3	b	1411	b	83.9	b	−28.1	a
	2005	58.2	A	352	a	20.1	a	1488	a	98.3	a	−28.1	a
Year	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
	S	41.8	B c	304	b	21.4	a	1642	a	103.8	a	−26.6	a
Plot position	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

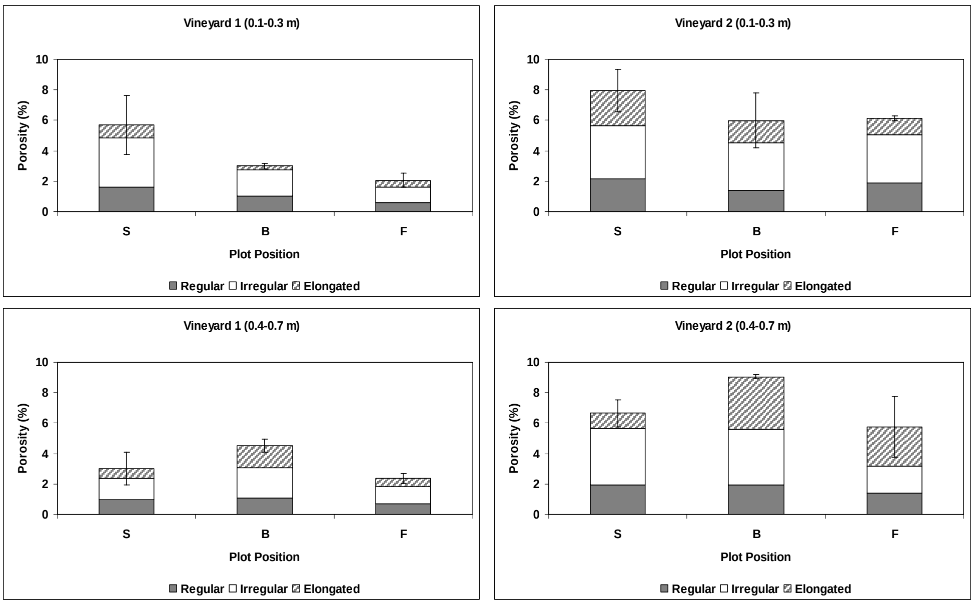

Fig. 5. Soil macroporosity in the three morphological positions of the two studied vineyards. Bars represent standard deviation of total macroporosity.

significant reducing conditions (Castenson and Rabenhorst, 2006). The more prominent reducing conditions of this plot then could be related to the worst internal drainage, caused by the relatively flat position and the presence of a dense and low permeable layer in depth (Table 2). 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.

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. Actually, in the pedoclimatic conditions under study, where short-term and locally restricted saturation occurs, the analysis of reduction pattern played a fundamental role to understand the removal mechanism of ferrihydrite (Jenkinson and Franzmeier, 2006). The spots of Fe removal present on most IRIS tubes were not only due to soil saturation, but also to proximity to an organic matter source like roots. It is probably for this reason that the percentage of discoloration was not related to the mean daily soil moisture during the time in which the tubes were in place.

Daily mean soil temperature seemed to influence the percentage of discolored area on IRIS (R^2=0.496, $P<0.01$, n=12) more than moisture. The influence of temperature on

Fig. 6. Discolored area on IRIS tubes in the different plot positions, soils, and years (2005 and 2006).

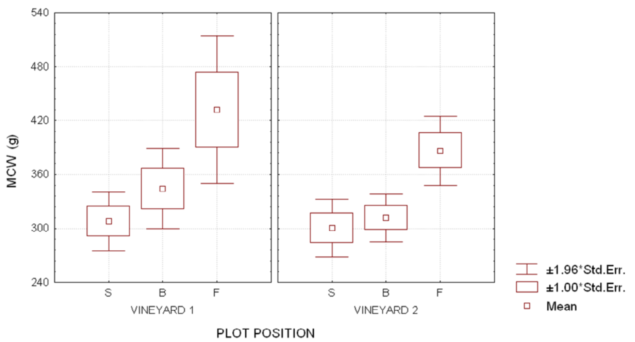

Fig. 7. Mean cluster weight (MCW) in the different soils and plot positions.

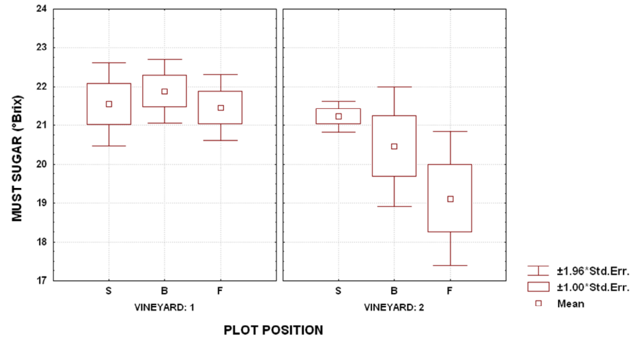

Fig. 8. Must sugar content in the different soils and plot positions.

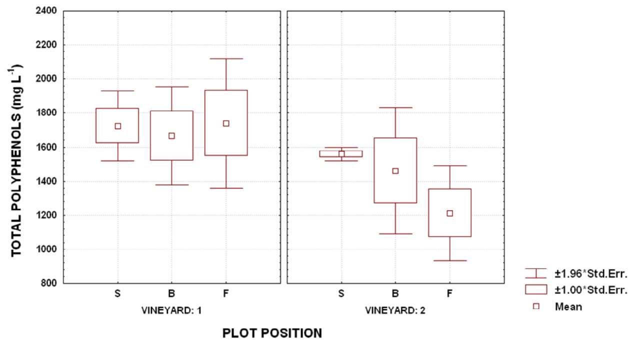

Fig. 9. Total polyphenols content in the different soils and plot positions.

the process of iron reduction was also observed by other authors (Rabenhorst and Castenson, 2005) in soils with stagnant water.

3.3 Relevance to predict grape yield and wine quality

The mean cluster weight (MCW) of grape was significantly influenced by plot position in both vineyards and three years of trial (Table 5 and Fig. 7). On the other hand, the sugar content and polyphenols were influenced by soil type (Table 5). Moreover, must sugar and polyphenols showed a significant difference between the F and S plots, but only in vineyard 2 (Figs. 8 and 9). On average, San Quirico soil (vineyard 1) produced a better oenological result than Pietrafitta soil (higher score at the panel test, Table 5).

Among the viticultural parameters, only cluster weight showed a direct relationship with TSW (R^2=0.37, $P<0.01$; Fig. 10). Also the panel test evaluation of the wines obtained in San Quirico soil evidenced a direct relationship with TSW (R^2=0.42, $P<0.05$; Fig. 11). This result 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 this particular oenological result (Fig. 12). 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 oenological result obtained from the vines cultivated on San Quirico soil should be attributed to a moderate physiological stress, that was most probably caused by the slight salinity of the lower horizons. In fact, all plots in both vineyards had a large, and even excessive, water supply, which excluded the occurrence of significant water stress (Table 3). Therefore soil salinity, being moderate and only affecting lower horizons, was a factor of Sangiovese wine quality. This outcome contrasted the general assumption that only consider salinity a limitation for vine (White, 2003; Layon et al., 2004).

Moreover, in the specific case of the F position of vineyard 1, a relatively higher TSW, coupled with a moderate salinity, improved the quality of wine as well as grape yield. This was also a really unexpected result, as it is assumed that Sangiovese wine quality has an inverse relationship with grape yield (Paoletti, 1995; Storchi et al., 2005). On the other hand, the stagnic conditions evidenced in the

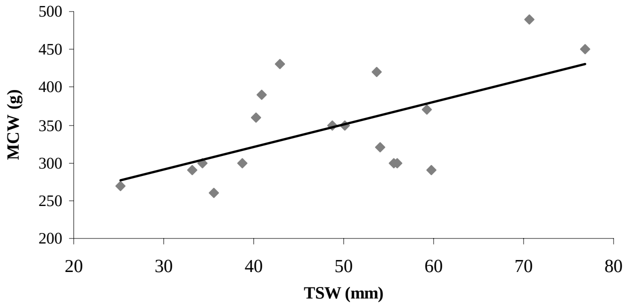

Fig. 10. Relationship between mean daily transpirable soil water (TSW) and mean cluster weight (MCW).

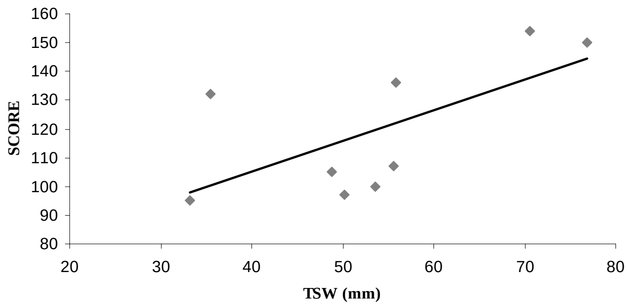

Fig. 11. Relationship between mean daily transpirable soil water (TSW) in San Quirico soil and wine organoleptic evaluation (score).

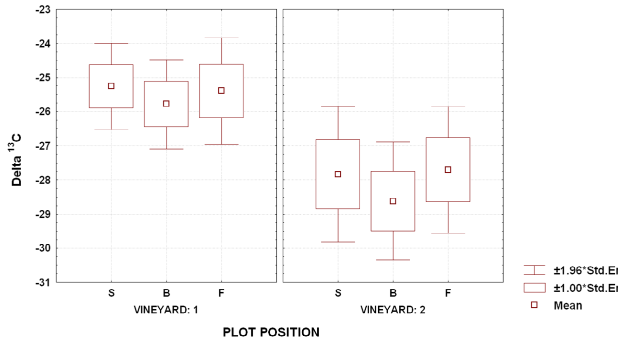

Fig. 12. Carbon isotopes ratio in the different soils and plot positions.

S position of the same vineyard did not affect the viticultural and oenological result of Sangiovese, most likely because they only occurred at the early stage of vine vegetation. These outcomes underlined the high site specificity of the oenological result of Sangiovese.

4 Conclusions

The trial proved that the combined application of the hydropedological model of Lin et al. (2006) and the Host classification (Boorman et al., 1995) can help to predict a qualitative estimation 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 one of the two study vineyards however, the mighty earth movements and bulldozing performed before vine plantation caused an increase in the soil hydrological spatial variability, and a weaker correspondence with the hydrological functional units delineated following the Lin's model suggestions, that is, by means of a cluster analysis of parameters derived from DEM and proximal soil sensors (local slope, TWI, and RL-moist). Furthermore, the soil scalping exacerbated the differences in permeability and salinity between the upper and lower soil horizons. Horizon differentiation along the profile deeply influenced water flows and plant available water, as well as soil salinity. This enhanced site specificity of the grape production and wine quality.

Our study demonstrated that delineating hydrological functional units remains fundamental in viticulture, but it is not always enough to predict grape yield and wine quality. Actually, other neglected soil properties, like moderate soil salinity in depth, can play a role more important than water availability. Also the interaction between water availability and moderate soil salinity can have an unexpected weight on both grape yield and wine quality. Therefore, the relevance of hydropedological models for precision viticulture may be enhanced if soil salinity, along with topography and soil hydrological characteristics, is taken into account. Such integrated models can guide the viticultural management of soils formed on marine or other potentially saline sediments, as well address the choice of pre-planting operations of the vineyard, in particular, plowing depth, slope reshaping, and earth movements.

It is recommended that hydropedological model application should be always coupled with monitoring (Lin, 2009). As for the monitoring of water saturation, which was foreseen by the Host classification in one of the two soils, our results confirmed that the occurrence of reductive processes in soil could be assessed through the installation of IRIS tubes, although the pattern of the mottling on the tubes must be carefully examined.

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