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Viticulture microzoning: a functional approach aiming to grape and wine qualities

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Abstract

This paper aims to test a new physically oriented approach to viticulture zoning at the farm scale, strongly rooted on hydropedology and aiming to achieve a better use of environmental features with respect to plant requirement and wine production. The physics of our approach is defined by the use of soil-plant-atmosphere simulation models which applies physically-based equations to describe the soil hydrological processes and solves soil-plant water status.

This study (ZOVISA project) was conducted in a farm devoted to high quality wines production (Aglianico DOC), located in South Italy (Campania region, Mirabella Eclano-AV). The soil spatial distribution was obtained after standard soil survey informed by geophysical survey. Two Homogenous Zones (HZs) were identified; in each one of those a physically based model was applied to solve the soil water balance and estimate the soil functional behaviour (crop water stress index, CWSI) defining the functional Homogeneous Zones (fHzs). In these last, experimental plots were established and monitored for investigating soil-plant water status, crop development (biometric and physiological parameters) and daily climate variables (temperature, solar radiation, rainfall, wind).

The effects of crop water status on crop response over must and wine quality were then evaluated in the fHZs. This was performed by comparing crop water stress with (i) crop physiological measurement (leaf gas exchange, chlorophyll *a* fluorescence, leaf water potential, chlorophyll content, LAI measurement), (ii) grape bunches measurements (berry weight, sugar content, titratable acidity, etc.) and (iii) wine quality (aromatic response). Eventually this experiment has proved the usefulness of the physical based approach also in the case of mapping viticulture microzoning.

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1 Introduction

Concepts such as terroir and viticulture zoning are becoming increasingly more important for planning and managing vineyards aiming towards high quality wine (Gladstones and Smart, 1997; Carey, 2001; Vaudour, 2003) Basically their practical implementation (Deloire et al., 2005; Fregoni, 1988) aims to classify the landscape (mainly climate and soil) studying its interaction with vineyard and wine quality. Mapping of terroir and viticulture zoning have been developed at all scales, especially since the 1990s following the widespread use of geomatics (Girard and Girard, 2003).

The methodology (even if not unique) indeed enabled many positive results, but also showed some important limitations to be mainly related to its strongly empirical base. In other words the terroir is a sort of “black box” in which the quantitative linkage between climate–soil–plant and wine is empirically or statistically described (e.g. Brousset et al., 2010) and not analyzed in its mechanics (Bonfante et al., 2011).

Recently some changing are occurring and the spatial analysis of terroirs has improved incorporating some key features known to strongly affect wine quality. Between them solar radiation and bioclimatic indexes (Failla et al., 2004; Vaudour, 2001) and also morphometric data and multitemporal remotely sensed images (Vaudour et al., 2010).

Moreover Bonfante et al. (2011) demonstrated that terroir analysis – applied at a district scale (mesoscale sensu Vaudour and Shaw, 2005) – can be further profitable integrated combining high quality GIS (as bioclimatic indexes) with water balance simulation modelling for addressing the key and very complex issue of soil-plant water stress. This is very important because even if it is well known that water stress strongly affects grape quality, its spatial description can be a very difficult issue.

Despite this result it is still very questionable whether a similar approach can be usefully applied at a more local – less aggregated – spatial scale where ecophysiological functioning and land management play a key role. Moreover this detailed scale is very

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useful because it enables to evaluate the functional relationships between viticulture zones, *plant-soil water stress*, vineyard status and grape wine quality.

To address this issue here we refer to "micro-zoning" in coherence to the term "micro-scale" employed by Vaudour and Shaw (2005) for terroir zoning.

In this perspective, the aim of this paper is to prove that physically based approached can be usefully employed also at very detailed scale such as for viticulture microzoning enabling to effectively separate different viticulture zones (Functional Homogeneous Zones, fHZ) on the base of their potential functionality (e.g. potential water stress) and by doing so better orienting viticulture management.

This was done on an experimental site (3 ha over an homogeneous hilly slope) characterized by large soil variation under the very same climatic conditions.

2 Materials and methods

2.1 Study area

The study area is located in hilly environment of southern Italy (Mirabella Eclano-AV, Campania region: Lat. 41.047808°, Lon. 14.991684°, elev. 368 m a.s.l.), in a farm oriented to the high quality wines production, namely Quintodecimo.

The study area is included in the landscape system of "marl-sandstone/carbonate hills" (D3); the main soil type being Haplic Calcisols and Calcaric Cambisols (soil-landscape map of of Campania Region at 250 000 scale, Di Gennaro et al., 2002).

The vineyard studied was Aglianico cultivar (controlled designation of origin-DOC/AOC), standard clone population planted in the year 2000 on 1103 Paulsen rootstocks (espalier system, cordon spur pruning, 5000 units per hectare) placed along a slope of 90 m length with 11 % of gradient. The "green manure" management is applied.

The long-term (2003–2013) mean daily temperature at the study area was 14.7 (±0.9) °C, while the mean annual rainfall was 802 (±129) mm (data from the Regional weather station of Mirabella Eclano-AV – at 1 km of study area).

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The climate monitoring within the farm during the vintage 2011 to 2013 showed that during the cropping season (April to early of October) the mean daily temperature was of 20.9 (±1.2) °C while the precipitation was variable during the three vintages ranging from 200 to 285 mm.

2.2 Method employed for mapping Homogeneous Zones

The employed viticulture microzoning procedure is rooted in procedures already applied at various scales. This includes standard soil mapping and geomatic spatial analysis of solar radiation, bioclimatic indexes, morphometric data and remotely sensed images (Failla et al., 2004; Vaudour, 2001; Vaudour et al., 2010). Moreover the procedure included geophysical mapping which has proved to be a very useful tool for soil spatial analysis also in precision viticulture (Andrenelli et al., 2010; Priori et al., 2010, 2012).

More specifically, the employed procedure is given in the flow diagram reported in Fig. 1:

- Step 1: identification of Homogeneous Zones (HZs) obtained by standard soil mapping (landscape units, soil profiles, minipits, etc.) at detailed scale informed by geophysical survey. These HZs were also statistically described in terms of their DTM and DSM derived parameters.

- Step 2: evaluation of hydrological indicator of crop water status (potential crop water stress index – CWSI) by applying physically based simulation modelling to the representative soils of the previously defined HZs, and definition of functional Homogeneous Zones (fHZs);

- Step 3: vine/must/wine monitoring over the fHZs.

The realization of step 1 allows to achieve an advanced but "static" description of landscape useful to make a standard Land Evaluation (qualitative and empirical approach) to evaluate the land suitability to grapevine. The innovation is enclosed in the step 2

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where a key component of the functional behavior of soils to grapevine responses is described dynamically by means of a physically based approach (Bonfante et al., 2011). This last step allows to discriminate the soils behavior through a hydrological indicator of plant water status (Crop Water Stress Index – CWSI) and to identify the functional Homogeneous Zones (fHZs) from the HZs. The term "functional" is employed in order to strengths the soil-plant-climate functionality. Finally, the step 3 allows evaluating the plant behavior within any fHZs and testing the occurring CWSI.

2.3 Pedological survey and soil measurements

A combined geophysical-pedological approach was used to derive the map of preliminary Homogeneous Zones (HZs) of the study area. These HZs were obtained after detailed soil survey adapted to the specific need of this research. A preliminary map of the most important soil forming factors in the area was obtained combining geomorphological analysis of LIDAR derived DEM with local geology information. This lead to the identification of the main soil-landscape units. The actual soil survey (soil profiles, minipit and augering) was supported by geophysical survey technique. This last based on non-invasive tools (generally applied for environmental studies, e.g. for geological prospecting), used as very quick survey systems allowing to have a first information on the general spatial variability of soils investigated. Allowing a better planning of the field investigation in the pedological survey and improving the soil map resolution emphasizing the spatial soil micro-variability (traditional soil surveys and soil analysis are usually time-consuming and expensive, especially for high resolution maps). Geoelectrical soil mapping has become widely accepted and considered a successful geophysical method that provides the spatial distribution of relevant agronomic information for precision farming (Lück et al., 2009).

Methods based on the electrical properties are particularly promising as support to pedological survey because important soil physical properties are strongly correlated to electrical conductivity, which, changing in the space, can represent a spatial soil distribution. The geophysical methods offer a valuable mean to obtain subsidiary data

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in an efficient way, and have been widely applied in soil sciences for a considerable period of time (Samouëlian et al., 2005).

In this study the soil apparent electric conductivity (ECa), was carried out by Electro-Magnetic Induction (EMI) sensors, which represents a very useful tool for identifying soil map units and soil properties in respect to clay content (Morari et al., 2009), soil depth (Saey et al., 2009), water content (Davies, 2004; Cousin et al., 2009; Lück et al., 2009; Tromp-van Meerveld and McDonnell, 2009) and water salinity (Doolittle et al., 2001).

However soils, like every other geological materials, are not uniform, consequently what is specifically measured is an apparent electrical conductivity (ECa), which can be defined as the actual conductivity of a rock homogeneous and isotropic equivalent to a real heterogeneous and anisotropic.

The instrument used for surface mapping of electric conductivity was the EM38-DD (Geonics Ltd., Ontario, Canada) used in both VDM (vertical dipole mode) and HDM (Horizontal dipole mode). The survey was performed in July 2011 during the grape ripening, in the same day, and at the beginning of survey the sensor was calibrated to minimize errors. The instrument was placed on a PVC sledge and pulled by a tractor along the inter-rows, at a distance of about 5 m to avoid interference phenomena. The use of the sledge makes it possible to maintain a constant distance of the instrument from the soil making the acquisition more easier and more accurate.

The data were recorded on a GPS-supplied data-logger with European Geostationary Navigation Overlay Service (EGNOS)–Wide-Area Augmentation System (WAAS) correction (accuracy 3 m), this has allowed to georeferencing and map the measured property. The instrument was set to acquire one measurement per second.

Post-processing of data was performed by ordinary kriging with 1 m resolution. The final result of the EM38-DD survey was therefore a regular grid of data points including ECa for two depths (1.6 m for VDM and 0.76 m for HDM). These horizontal (HDM)and vertical (VDM) ECa maps were used as baseline data for pedological survey based on soil augerings and soil profiles description. This was done similarly to the classic use

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(overlying procedures) in soil survey of other thematic layers (geology, geomorphology, etc.).

The soil profiles were described according to FAO (2006). Chemical analyses were performed according to the official methods of the Italian Ministry of Agriculture and Forestry REF. The grain size distribution (GSD) was determined by a laser granulometer (Malvern Mastersizer, 2000).

Undisturbed soil samples (volume $\cong 750\,cm^3$) were collected in each soil horizon and in laboratory, hydraulic properties were determined in order to simulate soils' hydrological conditions by means of an agro-hydrological model, which is illustrated in Sect. 2.5.

Soil samples were saturated from the bottom and the saturated hydraulic conductivity was measured by a permeameter (Reynolds and Elrick, 2002). Then, after sealing the bottom surface to set a zero flux, measurements were performed during drying: at appropriately pre-set time intervals, the weight of the whole sample and the pressure head at three different depths (by means of tensiometers) were determined. An iterative procedure was applied for estimating the water retention curve from these measurements. The instantaneous profile method was used to determine the unsaturated hydraulic conductivity. Moreover, some points at lower water content of the dry branch of the water retention curve were determined by a dew-point system (WP4 dew-point potentiameter, Decagon devices, Inc.). Details on the tests and overall calculation procedures were described by Basile et al. (2012) and Bonfante et al. (2010).

2.4 The hydrological indicator: Crop Water Stress Index (CWSI)

The effects of water stress on wines quality, wines appearance, flavour, taste and aroma have been clearly highlighted by Matthews et al. (1990) differentiating the effects between early- or late-water deficit treatments. Thus, the estimate of water stress at the different phenological stages can indeed represent an important tool in terroirs classification. Different variables (e.g. air temperature, wet-bulb temperature, etc.) could be applied to develop a proper water stress index (Kozak et al., 2006). In this approach,

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we use a daily crop water stress index (CWSI), following defined as:

$$\mathrm{CWSI} = \left[1 - \left(T_\mathrm{r}/T_\mathrm{p}\right)\right] \cdot 100 \tag{1}$$

where T_r is the daily actual water uptake ant T_p is the daily potential transpiration.

The sum of daily CWSI in the required period represents the cumulated stress $\mathrm{CWSI_{cum}}$:

$$\mathrm{CWSI_{cum}} = \frac{\left[\int_{t_1}^{t_2} 1 - \left(T_\mathrm{r}/T_\mathrm{p}\right) \cdot \mathrm{d}t\right]}{(t_2 - t_1)} \cdot 100 \tag{2}$$

The application of this index enables, changing the integration time (t_1 and t_2), to estimate plant water stress at different stages of the crop growth (shoot growth, flowering, berry formation, berry ripening) (Fig. 2).

Finally, this index was used to analyse the PHZs behaviours and successively define the HZs.

2.5 Simulation modelling

The Soil–Water–Atmosphere–Plant (SWAP) model (Kroes and van Dam, 2008) was applied to solve the soil water balance and to calculate the CWSI for each soil identified by the soil survey.

SWAP is an integrated physically based simulation model of water, solute and heat transport in the saturated–unsaturated zone in relation to crop growth. In this study only the water flow model was used; it assumes 1-D vertical flow processes and calculates the soil water flow through the Richards' equation:

$$C(h) \cdot \frac{\partial h}{\partial t} = \frac{\partial \left[K(h) \cdot \left(\frac{\partial h}{\partial z} + 1\right)\right]}{\partial z} - S(h) \tag{3}$$

where $C(h) = \partial\theta/\partial h$ is the differential soil water capacity, θ ($\mathrm{cm^3\,cm^{-3}}$) is the volumetric soil water content, h (cm) is the soil water pressure head, t (d) is the time, z (cm) is

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the vertical coordinate taken positively upward, K (cm d^{-1}) is the hydraulic conductivity and S (cm^3 cm^{-3} d^{-1}) is the water extraction rate by plant roots.

Soil water retention is described by the unimodal $\theta(h)$ relationship proposed by van Genuchten (1980), expressed in terms of the effective saturation, S_e, as follows:

$$S_e = \left[\frac{1}{1+\left(\alpha|h|\right)^n}\right]^m \tag{4}$$

where $S_e = (\theta - \theta_r)/(\theta_0 - \theta_r)$, θ_r and θ_0 are the residual water content and the water content at $h = 0$, respectively, and α (cm^{-1}), n and m are curve-fitting parameters.

Mualem's expression (Mualem, 1976) is applied to calculate relative hydraulic conductivity, K_r. Assuming $m = 1 - 1/n$, van Genuchten (1980) obtained a closed-form analytical solution to predict K_r at a specified volumetric water content:

$$K_r(S_e) = \frac{K(S_e)}{K_0} = S_e{}^{\tau} \cdot \left[1 - \left(1 - S_e{}^{1/m}\right)^m\right]^2 \tag{5}$$

where K_0 is the hydraulic conductivity measured at θ_0, and τ is a parameter which accounts for the dependence of the tortuosity and partial correlation between adjacent pores.

The condition at the bottom boundary can be set in several ways (e.g. pressure head, water table height, fluxes, impermeable layer, unit gradient, etc.).

The upper boundary conditions of SWAP in agricultural crops are generally described by the potential evapotranspiration ET_0, irrigation and daily precipitation. Then the potential evapotranspiration is partitioned into potential evaporation, E_p, and potential transpiration, T_p, according to the LAI evolution, following the approach of Ritchie et al. (1972).

SWAP simulates water uptake and actual transpiration according to the model proposed by Feddes et al. (1978), where root water uptake S is described as a function of

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the pressure head, h:

$$S(h) = \alpha(h) \cdot S_{\max} = \alpha(h) \cdot \frac{T_p}{|z_r|} \tag{6}$$

Being z_r (cm) the thickness of the root zone and $\alpha(h)$ a semi-empirical function of pressure head h, varying between 0 and 1. The shape of the function $\alpha(h)$ depends on four critical values of h, which are related to crop type and to potential transpiration rates. The actual transpiration rate T_a (cm d^{-1}) is computed by the integration of S over the root layer. The root depth is specified by the user as function of development stage.

Model parameters and data for simulations:

- upper boundary condition comes from the daily data of Regional weather station of Mirabella Eclano (1 km from the study area)integrated with the micrometeorological station located in the farm. Daily potential Evapotranspiration (ET_0) was determined applying the Penman-Monteith equation.

- bottom boundary condition was set as unit gradient.

- crop data. Leaf Area Index was estimated by a ceptometer (ACCUPAR LP 80, Decagon Devices, Pullman, WA, USA), rooting depth was measured during the profile description, water uptake function's parameters were derived from literature (Taylor and Ashcroft, 1972).

- hydraulic properties were parameterised through a fitting procedure of the van Genuchten-Mualem model to the experimental data (see Sect. 2.2).

2.6 GIS analysis: DTM and DSM information

High resolution Digital Surface Models (DSM) and Digital Terrain Model (DTM) of the study area were acquired (respectively in April 2011, 1 m spatial resolution – DTM and July 2013, 0.30 m spatial resolution- DSM) with LiDAR technologies, as part of ongoing

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project in the study area. These models represent the elevation values of the ground level plus that the aboveground (i.e. canopy). They were processed with specific software coupled with GIS environment (ArcGIS, QGIS and SAGA open source software). These high spatial resolution acquisitions enabled to get detailed auxiliary spatial information; such the estimate of solar radiation taking into consideration shadows from vineyards. These auxiliary information were useful to investigate the variation within the Homogeneous Zones of study area, and some climatic indices known to be involved in vineyards development. Specifically, were obtained continuous maps of slope and aspect from the DTM and the topographic wetness index (TWI) and potential insolation at very high spatial resolution from DSM. More specifically, these last two derived maps were realized considering the presence of vineyard rows, as a 3-D objects in the space, able to influence (i) the insolation through the formation of intra-rows shadows and (ii) to create a waterproof surface inside of vineyard that transfers the water from rainfall to the principal streams of slope. Subsequently this information was used to characterize the differences between the fHZs identified into the vineyard.

2.7 Crop measurements

The monitoring was conducted within the fHZs (identified in the step 2) on 27 plants, for three years (2011 to 2013) by the vegetative growth until the harvest. The measurements were realized randomly on a weekly or biweekly base, in relation to the measured variable and the physiological crop stage.

Leaf water potential (MPa) was assessed for each site on an individual set of 10 plants using a Scholander type pressure bomb (SAPS II, 3115, Soil moisture Equipment Corp., Santa Barbara CA, USA). Photosynthetic CO_2 assimilation (µmol m^{-2} s^{-1}), stomatal conductance to water vapour (mol m^{-2} s^{-1}) and effective quantum yield of PSII photochemistry (ΦPSII) in light-adapted leaves were measured by means of a portable photosynthesis system (Li-6400-40, LiCor, Lincoln, NE, USA). Instantaneous water use efficiency was calculated as the ratio of assimilation to stomatal conductance. The light source was set at a saturating Photosynthetic Photon flux density of

1800 μmol m^{-2} s^{-1}while the external CO_2 source was set at 370 μmol mol^{-1}. The instrument software calculated the various gas-exchange parameters on the base on the von Caemmerer and Farquhar (1981) model, and ΦPSII according to Genty et al. (1989). Chlorophyll content of leaves was optically estimated as a relative index (CCL) by a handheld meter (CCM200, Chlorophyll content meter Apogee Instruments, Inc., Logan, UT.) as the ratio of the fractional transmittances at 653 and 931 nm.

2.8 Must/wine characteristics

As well as for the crop measurements, the must and wine characteristics were monitored within the fHZs (identified in the step 2) on 27 plants, for three years (2011 to 2013). In particular, of the 27 plants monitored, 12 were used to collect the grapes at harvest and 15 for sampling scalar grapes.

The Standard chemical analyses and spectrophotometric measurements of must and wine were done as following:

Standard chemical analyses (soluble solids, total acidity, pH, total polyphenols (Folin–Ciocalteau Index) and Absorbances (Abs) were measured according to the OIV Compendium of International Methods of Analysis of Wine and Musts [OIV 2007]. Color intensity (CI) and hue were evaluated according to the Glories method (1984). Total anthocyanins were determined by the spectrophotometric method based on SO_2 bleaching (Ribéreau-Gayon and Stonestreet, 1965). Tannins were determined according to Ribèreau-Gayon and Stonestreet (1966). Analyses were performed in duplicate using basic analytical equipment and a Shimadzu UV-1800 (Kyoto, Japan) UV spectrophotometer.

The polyphenol extraction from grapes was done as following: separate extraction of berry components was carried out in duplicate simulating the maceration process necessary for the production of red wines (Mattivi et al., 2002b; Vacca et al., 2009). Briefly: berries (200 g) were cut in two with a razor blade, and seeds and skins were carefully removed from each berry-half. The pulp on the inner face of berry skin was

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removed using an end-flattened spatula trying to preserve the skin integrity. Skins and seeds were immediately immersed in a 200 mL solution consisting of ethanol: water (12 : 88 v/v), 100 mg L^{-1} of SO_2, 5 g L^{-1} tartaric acid and a pH value adjusted to 3.2 (with NaOH) and extracted for five days at 30 °C. The extracts were shaken by hand once a day. Skins and seeds were removed from the hydro-alcoholic solution after five days and the skin extract was centrifuged for 10 min at 3500 × g. Extracts were poured into dark glass bottles, flushed with nitrogen and stored at 4 °C until spectrophotometric analyses.

3 Results and discussion

3.1 Homogeneous Zones (HZ) identification after soil and geophysical mapping

In order to identify potential different environments leading to Homogeneous Zones we performed a standard soil mapping adapted to the specific need of this research. The combination of geomorphological analysis of LIDAR derived DEM and local geological data lead to the production of preliminary landscape mapping units. These mapping units (not reported) depict three different environment namely (i) a summit landscape unit having a slope gradient of about 5–10 % developed over clayey sediments with clear signs of local erosional processes, (ii) an upslope landscape unit having about 25–30 % slope gradient developed over clayey sediments with little signs of erosional processes, (iii) a downslope landscape unit having about 7–15 % slope gradient developed over a colluvium landform with no signs of erosion.

Then on these units an EMI survey was produced to orient the pedological survey (also in terms of soil variability) and to define the boundaries of HZs.

The maps of ECa obtained were used as baseline data in the pedological survey.

ECa maps (Fig. 3) showed that the vineyard was clearly characterized by the presence of two major patterns of ECa, generally homogenous, corresponding to two areas: (i) summit and upper slope (red area in Fig. 3c) and (ii) down-slope (bluish area

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in Fig. 3c). ECa mean difference between the two areas was statistically significant ($P < 0.05$). Then the difference between summit and upslope previously observed by the preliminary landscape analysis (on high resolution DTM) did not always correspond to ECa mapping and moreover the boundaries between the two main area identified by ECa pattern is oblique (with respect to slope) and not linear as it would be expected by DTM analysis.

Combining both landscape mapping unit analysis with ECa mapping and also observing ECa homogenous and heterogeneous areas, six soil profiles and 25 augers were localized to include major variability, described and sampled. Only samples from the soil profiles were submitted for chemical and physical analysis.

From the pedological characterization (76 soil samples in total, 51 from 6 soil profiles and 25 from augers; augers data are not shown), two main soil types were identified: Cambic Calcisol (Clayic, Aric) and Eutric Cambisol (Clayic, Aric, Colluvic) (WRB, 2014).

These soils are likely to have evolved from a different parent material; the Cambisol was evolved over colluvium (including traces of pumices), not present in the upper part of the vineyard, while the Calcisol was evolved from the clayey sedimentary bedrock. The different origin is also expressed by the soils color: brown (10YR) for the Cambisol and yellowish (5Y) for the Calcisol.

Calcisol is richer in total carbonates compared to the Cambisol (mean 232.7 and 41.2 $g\,kg^{-1}$ respectively), with a Bk horizon at about 45 cm depth with common accumulation of carbonates. This induces a differentiation of the pH between the two pedons (Calcisol mean 8.2; Cambisol mean 7.0). The organic Carbon Content (O.C) and Cation Exchange Capacity (CEC) are higher in the Cambisol (avg. values of O.C. in the topsoil was 1.0 and 2.1 % for the Calcisol and Cambisol respectively; avg. value of CEC along the soil profile is 24.3 $cmol\,kg^{-1}$ in the Cambisol and 16.8 $cmol\,kg^{-1}$ in the Calcisol) The electrical conductivity (EC) is generally low, in both soils, highlighting the absence of significant quantities of salts in solution (173 and 246 $mS\,cm^{-1}$ for the Cambisol and Calcisol respectively). The texture is clay loam in both soils.

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The physical characteristics of two soil profiles, representative of the two soil types are reported in the Table 1.

Despite the similar texture, hydraulic properties measured in lab showed some important differences (Table 1).

Among them: (i) Calcisol shows a pronounced vertical heterogeneity (i.e. k_0 and l of the Bk horizon are very different from the adjacent upper and lower horizons); (ii) Cambisol shows a relative vertical homogeneity, especially in the Bw horizons; (iii) despite the porosity of the Calcisol is higher than that one of the Cambisol (see saturated soil water contents, θ_0) the available water content (AWC) in the first 80 cm of soil depth is lower (i.e. Calcisol 80 mm and Cambisol 145 mm).

Then the integration of soil and geophysical survey along with physical, hydrological and chemical soil analysis enable to separate two main preliminary Homogeneous Zones:

- CAL: Haplic Calcisol (Clayic, Aric) developing in summit and upslope landscape position and

- CAM: Haplic Cambisol (Clayic, Aric, Colluvic) developing in downslope landscape position.

3.2 Modelling application (potential CWSI estimation)

The potential Crop water stress index (CWSI) data have been obtained analyzing the water balance in the soil–vegetation–atmosphere (SVA) system in the two HZs using the SWAP hydrological model applied over eleven years of daily climate data (2003–2013).This information is especially important because it enables to evaluate the dynamics of water stress of soils present in the study area, representing a very powerful tool for vineyard planning.

In particular, it is possible to compare the level of CWSI between the two HZs in each plant phenological phases (Figs. 2 and 4) defining the functional Homogeneous Zones

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(fHZs) on the base of their similarity functional behavior for grapevine and correlate it to different plant responses in terms of must quality and plant production.

On average, in CAL the potential CWSI was two times higher (13.9 %) than CAM (5.9 %), with a clearly difference increases during the cropping season (from flowering to harvesting) (Table 2, Figs. 2 and 4).

The maximum values of CWSI were obtained during the berry formation with average values of 32.7 % (±20.7) for CAL and 13.5 % (±9.6) for CAM.

From the results of potential CWSI analysis, is clear that the two representative soils of the study area, under the same climate and plant conditions, show a different susceptibility to vineyard water stress. These results allow to state that the two identified CAL and CAM HZs behave as Homogeneous Zone also in terms of their functional behavior. Then to describe this output of the microzoning procedure from here on we shall refer to CAL and CAM functional Homogeneous Zones (fHZs): CAL and CAM fHZs.

3.3 GIS analysis

Each functional Homogeneous Zone has then been analyzed with respect to the variability of environmental characteristics derived from the high resolution DMS and DTM (Table 2; Fig. 4). The elevation and slope of CAL was higher compared to CAM; their mean differences is always significant ($P < 0.05$) and it is about 15 m for the elevation and 4.7 % for the slope gradient. These differences are consistent with both geomorphic and soil settings.

The aspect shows a Nord-West and West orientation respectively for CAL and CAM fHZs. This aspect difference ($P < 0.05$) induces – at the vineyard rows – a differentiation in terms of total potential insolation ($P < 0.05$) during the cropping season (1 April to 15 October) of about 55 kwh m^{-2} higher in the case of the CAM fHZ. Such differences are mainly due to the direct vineyard rows insolation.

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3.4 Vineyard records (crop/must measurements)

Inside of the two fHZs, the experimental plots were identified and the phenological and physiological grapevine data collected on 27 plants over three years (2011–2013).

Despite the experimental plots had the same cultivar (Aglianico), the same rootstocks (1103P) and the same management, the crop responses in terms of biomass development and must quality were very different.

Plants of CAM have shown a major vigour compared to those of CAL (at fruit thinning, an average value of 11.1 bunches $plant^{-1}$ vs. 10.0 were measured, with a peak of 14.6 vs. 8.7 bunches $plant^{-1}$ in the year 2011). Despite a very similar number of bunches $plant^{-1}$ at harvesting (average value of 4.6 bunches $plant^{-1}$ for CAM and CAL respectively), at the harvest time the plant production of the CAM was generally higher (1.81 ± 0.29 kg $plant^{-1}$) compared to the CAL (0.97 ± 0.36 kg $plant^{-1}$). Last results are in agreement to the different weight and volume of berries recognized during the three years (Table 2).

The analyses carried out on grape bunches over the three years of measurements have shown a very robust qualitative differentiation between the two fHZs. Investigated parameters like sugar (avg. 23.2° Brix in the CAL and 21.3° Brix in CAM), anthocyanins (avg. 627 mg kg^{-1} for CAL and 471 mg kg^{-1} CAM), poliphenols in the skin (avg. 1874 mg kg^{-1} for CAL and 1745 mg kg^{-1} for CAM), color intensity (avg. 5.4 and 4.1 for CAL and CAM), tannins in the skin (avg. 2.4 g kg^{-1} for CAL and 2.5 g kg^{-1} for CAM) and pH (avg. 3.4 and 3.2 for CAL and CAM) were always higher in the CAL during the berry ripening if compared to the CAM. But the titratable acidity (avg. 6.6 g L^{-1} for CAL and 7.7 g L^{-1} for CAM), the volume (avg. 188 cm^3 for CAL and 205 cm^3 for CAM) and weight of 100 berries (avg. 205 g for CAL and 221 g for CAM) were lower in CAL. The first results of microvinification have shown higher values of ethanol (12.2 %v for CAM and 13.3 %v for CAL), colour intensity (7.8 for CAM and 12.8 for CAL) and tannins (2.9 g L^{-1} for CAM and 4.6 g L^{-1} for CAL) in CAL compared to CAM.

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In both fHZs the minimum absolute values of LWP (−0.37 and −0.40 MPa in CAM and in CAL, respectively) were registered at the beginning of crop season, while the maximum absolute values were reached at the end of August (−1.65 and −1.85 MPa in CAM and in CAL, respectively). Nevertheless, during the three years of measurements the plants belonging to Calcisol (CAL fHZ, up-slope) faced a more intense water stress than those belonging to Cambisol (CAM fHZ, down-slope), during the whole season. Consequently, stomatal conductance values during the three years, agreed with those of LWP, with the Calcisol plants experiencing lower values, and thus lower transpiration rates than those of Cambisol. Assimilation rates followed the same behavior of stomatal conductance, highlighting that in CAM the plants had a photosynthetic activity more pronounced than those of CAL; in agreement with that, also quantum yield of photosystem PSII in leaves adapted to light (PHIPSII), showed that CAM plants were more efficient than CAL plants to capture the energy of light absorbed by the photosystem PSII. Both photosynthetic activity and PHI PSII responded proportionally to the different content of chlorophyll *a* with the CAM plants showing the highest values. Leaf Area index (LAI) was lower in CAL plants (avg. 1.28), as compared to the CAM plants (avg. 1.48), as consequence of the more severe water stress suffered by plants grown in the former.

4 Discussion

The effects of combination of soil and climate on grapevine responses in terms of must characteristics and then on wine quality are well reported in literature and are at the base of concept of terroir. In this work, thanks to the small surface of study area (about 3 ha), the usefulness of the adopted microzoning procedure could be tested by quantifying the effect of soil properties on plant responses and must characteristics.

This was possible because the specific experimental setup was conducted in the same geomorphic land system, under the same climate conditions (only 90 m of slope, with about 15 m difference in elevation) on the same plant cultivar (Aglianico monoclonal population) and under the same vine management.

We believed that under these conditions, the realization of a large scale pedological survey supported by the EMI survey represented a very good cost/benefit approach to investigate the potentialities of the vineyard in view of soil-plant-climate relationships.

The identification and mapping of the main soil types included in the functional Homogeneous Zones (CAL fHZ, Cambic Calcisol (Clayic, Aric)and CAM fHZ, Eutric Cambisol (Clayic, Aric, Colluvic), has allowed to estimate and study, at vineyard scale, the different behaviour of these two soils, in terms of crop water stress, under the same climate and plant conditions, in the soil-plant-climate system. Discriminating their different abilities to produce quality in wine by means of three years of monitored plant responses (physiological, morphological and on must).

The potential CWSI estimated over the last eleven years was very different between the two HZs. The variability expressed by this index for each phenological phases of grapevine development was very high. This was due to the high variability of weather data used in the simulation modelling application.

These important differences between the two soils of the soil-crop-climate behaviour is mainly due to the different hydrological behaviour, due to the very different hydraulic properties (see Table 1). It is essential to notice the importance of the measurement respect the estimate of hydraulic properties. Indeed, estimate of hydraulic properties by applying pedotransfer functions PTF – mainly based on texture – will annul the differences between soils having very similar texture but very different hydraulic properties, like those reported in this study. This maintain also if the AWC is used as indicator of water availability for crop: the use of PFT for soils with similar texture, as in our case study, produce a clear mistake as reported in the Sect. 3.1.

Thus, the behaviour of each soil-plant and atmosphere system (CAL and CAM) was investigated in depth, making the conclusion about their different ability to produce crop water stress very robust. Thus from these different functional behaviors, for grapevineresponses, it was possible to identify two functional Homogeneous Zones, corresponding to the previous HZs.

The CAL fHZ represents a system where the Aglianico is subjected to a water stress twice stronger than those occurring in the Cambisol fHZ, with a progressive differentiation from flowering to harvesting.

This is clearly in agreement with the water stress felt by plants during the three years of monitoring (avg. 22 % of LWP increase in the CAL) in addition the *r* Pearson of CWSI estimated by model and LWP measured in field was −0.98. Moreover, the different behaviour described by the potential CWSI is also confirmed by other plant physiological measurements including: (i) the stomatal conductance (the plants in CAL experiencing lower values, and thus lower transpiration rates than those of CAM), (ii) assimilation CO_2 rates (in CAM the plants had a photosynthetic activity more pronounced than those of CAL) and (iii) quantum yield of photosystem PSII in leaves adapted to light (PHIPSII) (plants in CAM were more efficient than CAL plants to capture the energy of light absorbed by the photosystem PSII).

From the enological viewpoint, grapes analyzed in this study showed important differences. In CAL fHZ, grapes are richer in sugars, anthocyanins, total polyphenols and how lower content of total acids. Considering that Aglianico wines, as traditionally produced, are generally rather acid, astringent and easily downfall red color (Gambuti et al., 2007), then these data clearly suggest that grapes belonging from CAL fHZ can produce wine with a more balanced taste, more alcoholic and less acidic.

Grapes from CAL fHZ showed a content of extractable polyphenols higher than CAM fHZ indicating that a more long aged wine can be obtained from this part of vineyard. On the basis of sugar content of grapes wines obtained from this fHZ should be also characterized by higher content of ethanol (13.5 %v/V with respect to 12 %v/V for CAM fHZ wines) and should show a more intense colour because of the content of native pigments (anthocyanins) extracted from skins and their colour intensity. In contrast, CAM fHZ berries showed a lower content of total anthocyanins extracted from skins and a similar content of total polyphenols and tannins extracted from seeds. Taking

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into account the facts that: (i) anthocyanins are mainly extracted during first phases of red vinification (consisting in the maceration of whole berries during must fermentation), (ii) a complete extraction from seeds needs longer time of contact of berry skins and seeds with must-wine and, (iii) seed tannins are more astringent than skin tannins (Gambuti et al., 2006), these data suggest that a specific winemaking procedure, such as a short maceration, could help obtaining from CAM fHZ grapes a red wine with a good colour intensity, not astringent and more ready to drink.

Therefore, the enological potentials of grapes belonging to the two sites are very much different. Applying the proper winemaking procedure it is possible to obtain a more ready to drink wine from CAM fHZ site and a long age-able wine from CAL fHZ site.

Finally, the GIS analysis of high resolution DTM and DSM showed that differences in terms of slope and elevation between the two identified fHZs, at vineyard scale, were low and not much important. On the other hand, the aspect and the potential insolation calculated over the cropping season (1 April to 15 October) have shown that in the CAM fHZ the plants receive 7 % on more of total potential insolation during the cropping season compared to those cultivated in the CAL fHZ. This condition strengthens our results and confirm the hypothesis that – at the scale of our work, soil drives the Aglianico plant expression in terms of must quality and then wine quality.

5 Conclusions

The procedures adopted for viticulture microzoning – which included (i) standard large-scale soil mapping, (ii) geophysical mapping and (iii) soil-plant water stress evaluation on the identified fHZs, has shown its robustness in terms of its performance over plant, grape, must and wine quality.

The inclusion of the soil-plant water stress evaluation has shown to be fundamental because plant water status affects the characteristics of grape must, skin and seed of Aglianico. This was clearly explained by LWP measured during three years of plant

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monitoring and indirectly confirmed by the different vigour of plants in the fHZs. This last explained by the different biomass production (e.g. wood, leaves, berry weight, number of bunches, etc.), photosynthetic activity, stomatal conductance and chlorophyll content in the leaves.

In further detail, the relative difference in terms of mean CWSI potential between the two fHZs, previously identified from the pedological survey, gives an important information about what the winegrower could expect in terms of plant vigour and must quality. Moreover, the use of this index as discriminant information in the viticultural zoning was clearly supported by the results obtained in the three years of plant monitoring.

The accuracy of prediction of soil-plant and atmosphere system behaviour is strictly related to the quality of data collected on the soil physical system, crop development and climate.

For instance, it is very important to emphasise that in our case study the two soils have both the same textural class but very different hydrological behaviour. Then the use of hydrological properties measured in lab was fundamental to explain the different soil behaviour and to face environmental complexity in dynamic way.

This issue must be stressed especially considering the large use – in both applications and scientific literature – of not tested PTF, which in turn can induce smoothing of soil hydrological properties between otherwise very different soils. A positive point of our procedure is also the usefulness and cost-effective exhaustive EMI coverage given the fact that only few representative situations were actually analysed in detail. Considering our results, this low-cost sustainable approach was much appropriate.

On the other side here we must also stress one of the major drawback of our zoning procedure; namely soil hydrological measurements have a cost not always sustainable for farmers. Possibly – in future – more performing soil mapping incorporating soil hydrological measurements may partly overcome such limitation.

In order to produce a correct viticultural microzoning, the CWSI index must be a component of a more integrated approach taking into account soil spatial variability, landforms and a proper correct description (by measurements in lab or by means of pedotransfer functions tested and validated) of soil physical system.

This last point is critical in any land evaluation procedure involving the analysis of responses of the soil-plant and atmosphere system. In this work, the results obtained on Aglianico grapevine have shown clearly that the different hydrological soil properties, under the same climate conditions, strongly affect and determine must quality and then wine quality.

Then this information, in viticulture zoning, represents an opportunity for the farmer to plan their vineyard management and must vinification. For instance must vinification could be differentiated considering whether plants are subjected to different CWSI. This could bring opportunities in creating different wines and brands to improve farmer incomes.

This would require to know how specific cultivar responses to different CWSI level, then plant monitoring still represents a fundamental step to fulfil viticultural zoning.

Our results seem to suggest a future perspective where the preliminary spatial evaluation of different CWSI values in different pedo-climatic condition could suggest a preliminary spatial evaluation of plant responses and then possibly grape, must and wine quality. But all this would require much work into integrated framework with plant monitoring campaign (physiological responses, production, etc.) and enological campaign (must characteristics, etc.).

Moreover, after all the above evaluation, it is possible, through simulation realized with future climate conditions, to estimate future plants behaviour, emphasizing also if the future climate constrains will be an opportunity to improve product quality.

We can conclude that the use of physically based approach to identify the potential behaviour of soils in the viticultural zoning procedures has shown interesting results at the vineyard scale to identify the homogeneous zones where the grapevine produce different responses in terms of must quality and then wine; in addition since similar results have been show at district scale (Bonfante et al., 2011) it seems that physical

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based approach could help in producing a more robust crossing-scale methodology for viticulture zoning possibly overcoming current fragmentation in zoning methodology.

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Table 1. Physical properties of Calcisol (CAL HZ) and Cambisol (CAM HZ).

Soil/HZ	Soil horizon and thickness (cm)		Texture			Rocks fragments	Hydrological properties				
			Clay	Silty	Sand		Q_0	K_0	a	l	n
			(g 100 g^{-1})				(m^3 m^{-3})	(cm d^{-1})	(cm^{-1})		
Cambic Calcisol (Clayic, Aric)/CAL	Ap1	0–10/20	31.9	38.1	30.1	a	0.575	669.3	0.642	−1.78	1.30
	Ap2	10/20–45	32.0	37.7	30.3	*a*	0.474	171.5	0.223	−3.44	1.10
	Bk	45–80	32.6	39.7	27.7	*a*	0.435	9.7	0.126	−12.81	1.10
	BC	80–105	33.8	39.3	27.0	*a*	0.390	995.0	0.074	1.46	1.23
	CB	105–130 +	34.9	37.6	27.5	*a*	0.543	1000.0	0.078	0.50	1.23
Eutric Cambisol (Clayic, Aric, Colluvic)/CAM	Ap1	0–40	34.2	31.5	34.4	*a*	0.484	179.1	0.008	−1.00	1.45
	Bw1	40–90	37.6	30.0	32.5	*b*	0.462	2.3	0.003	−1.00	1.21
	Bw2	90–120	42.9	29.5	27.7	*b*	0.387	3.7	0.005	−1.00	1.15
	Bw3	120–160+	41.1	30.8	28.1	*b*	0.416	19.0	0.021	−2.70	1.17

a = absent; *b* = few fine sub-rounded pumiceous stones.

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Table 2. Summary of results obtained in CAL and CAM HZs and CAL and CAM fHZs: (i) GIS analysis on DSM and DTM; (ii) Simulation modelling application; (iii) Plant monitoring and the characteristics of bunches during the three years of monitoring (2011 to 2013) on Aglianico cv.

Environmental characteristics and plant responses			CAL HZ/CAL fHZ	CAM HZ/CAM fHZ
GIS Analysis	DTM (1 m)	Elevation (m.s.l.)	363.8 (±6.5)	348.5 (±6.5)
		Slope (%)	23.2 (±6.9)	18.5 (±5.9)
		Aspect (°N)	300.8 (±20.0)	276.6 (±26.2)
		TWI	−2.3 (±1.2)	−2.4 (±1.1)
	DSM (0.3 m)	Pot. direct insolation (kwh m^{-2})[a]	635.9 (±294.8)	708.1 (±326.3)
		Pot. diffuse insolation (kwh m^{-2})[a]	136.6 (±20.9)	137.3 (±21.0)
		Tot. Pot. insolation (kwh m^{-2})[a]	789.9 (±302.2)	845.4 (±335.7)
Modelling simulation SWAP	$CWSI^{b}_{cum}$	Shoot growth	1.0 % (±1.6)	0.23 % (±0.0)
		Flowering	6.9 % (±9.9)	1.4 % (±10.6)
		Berry Formation	10.8 % (±8.8)	5.7 % (±4.6)
		Berry ripening	32.7 % (±20.7)	13.5 % (±9.6)
		CWSI over cropping season	13.9 % (±8.6)	5.9 % (±3.9)
Plant monitoring[c]	Leaf Water Potential (LWP) (Mpa)	Mean	−1.12 (±0.33)	−0.92 (±0.27)
		Min (abs.)	−0,4	−0.37
		Max (abs.)	−1.85	−1.65
	Chlorophyll content of leaves (CCL)	Mean	13.9 (±4.3)	18.6 (±6.67)
	Phot. CO_2 Assimilation (mol m^{-2} s^{-1})		10.3 (±6.0)	15.7 (±5.9)
	Stomatal conductance (mo m^{-2} s^{-1})		0.15 (±0.1)	0.23 (±0.1)
	Instantaneous Water Use Efficiency iWUE (µmol mol^{-1})		81.6 (±34.0)	72.3 (±24.5)
	Leaf Area Index (m^2 m^{-2})		1.28 (±0.30)	1.48 (±0.46)
	Effective quantum yield of photosystem PSII (ΦPSII)		0.11 (±0.04)	0.15 (±0.04)
Characteristics of bunch[c]	100 Berries	Weight (g)	205.7 (±53.6)	221.7 (±31.6)
		Volume (cm^3)	188.3 (±50.5)	205.8 (±27.6)
		Density (g cm^{-3})	1.09 (±0.02)	1.05 (±0.05)
	Grape must	Sugar (Brix°)	23.2 (±0.7)	21.3 (±1.1)
		pH	3.4 (±0.09)	3.2 (±0.14)
		Titratable acidity (g L^{-1})	6.6 (±1.0)	7.7 (±1.5)
		Color intensity	5.4 (±1.0)	4.1 (±0.09)
		Color hue	0.53 (±0.02)	0.52 (±0.01)
		Total anthocyanins (mg kg^{-1})	627.6 (±67.6)	471.3 (±45.3)
	Grape skin	Tot. Polyphenols (mg kg^{-1})	1874.1 (±418.9)	1745 (±258.8)
		Tot. Tannins (mg kg^{-1})	2.4 (±0.4)	2.5 (±0.2)
	Grape seed	Tot. Polyphenols (mg kg^{-1})	1851.3 (±321.8)	1967.5 (±329.6)
		Tot. Tannins (mg kg^{-1})	1.8 (±0.37)	1.8 (±0.27)

[a] The potential insolation refer to period 1 April to 15 October. [b] Average values calculated over 11 years (2003–2013). [c] Average over three season of measurements (2011 to 2013).

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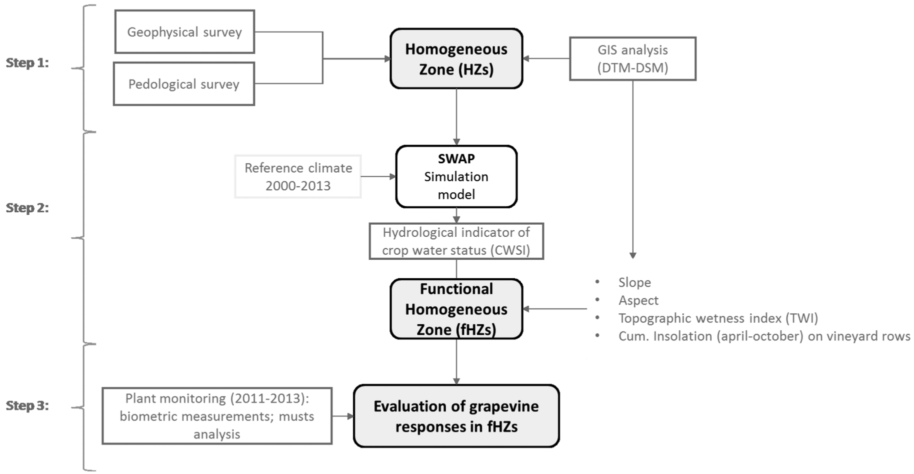

Figure 1. Flow diagram illustrating the proposed approach applied to the case study of Quintodecimo farm.

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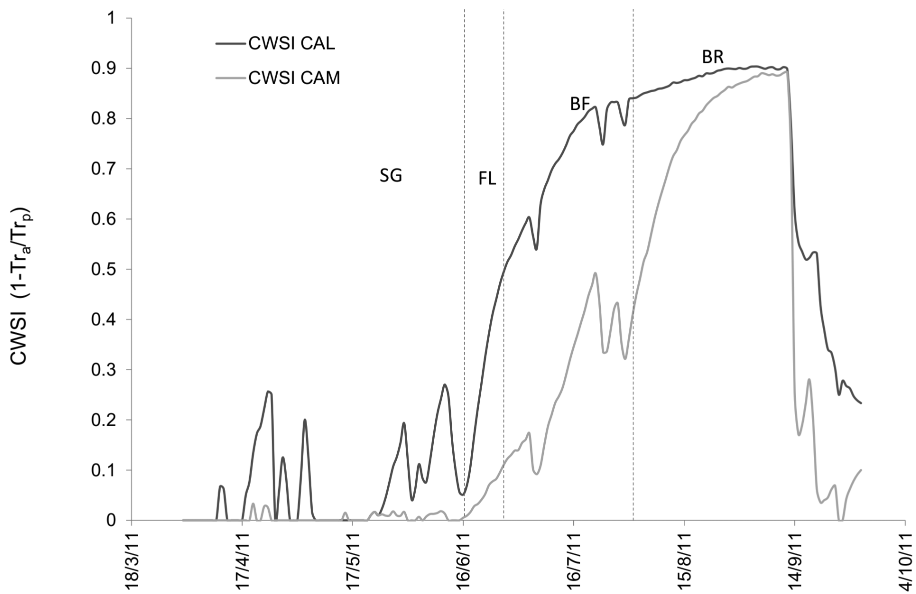

Figure 2. The crop water stress index (CWSI) simulated by SWAP in the HZs CAL and CAM in the year 2011 during the cropping season. (SG = Shoot growth; FL = Flowering; BF = Berry formation; BR = Berry Ripening.)

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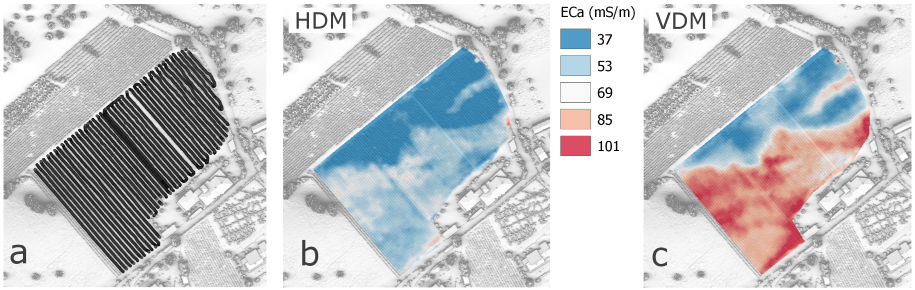

Figure 3. (a) Local acquisition recorded by GPS; **(b)** ECa map of Horizontal Dipole Mode (HDM); **(c)** ECa map of Vertical Dipole Mode (VDM)

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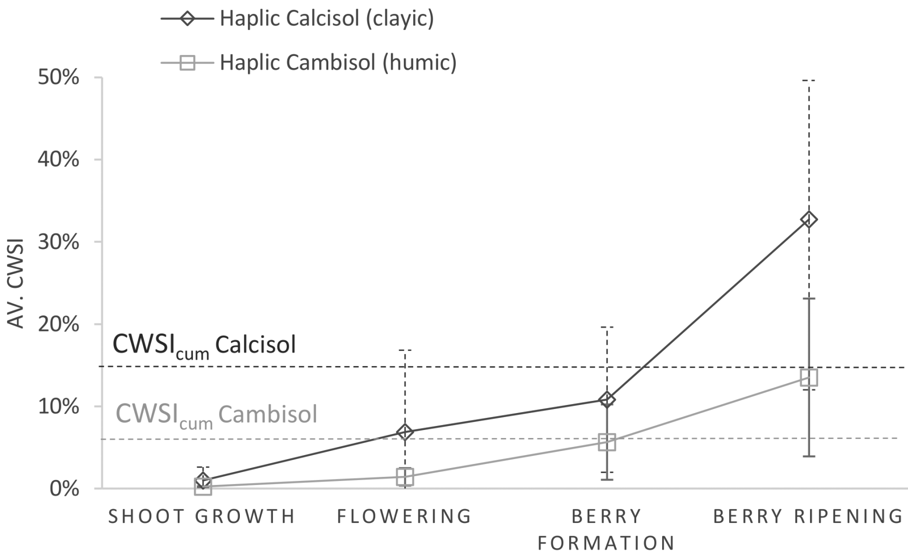

Figure 4. The average values and the standard deviation of the potential Crop Water Stress Index (CWSI) during the cropping season (reported in terms of phenological phases) of grapevine cultivated in the representative soils of homogeneous zones (CAL and CAM). The simulation were performed with SWAP model during the vintages 2003 to 2013.

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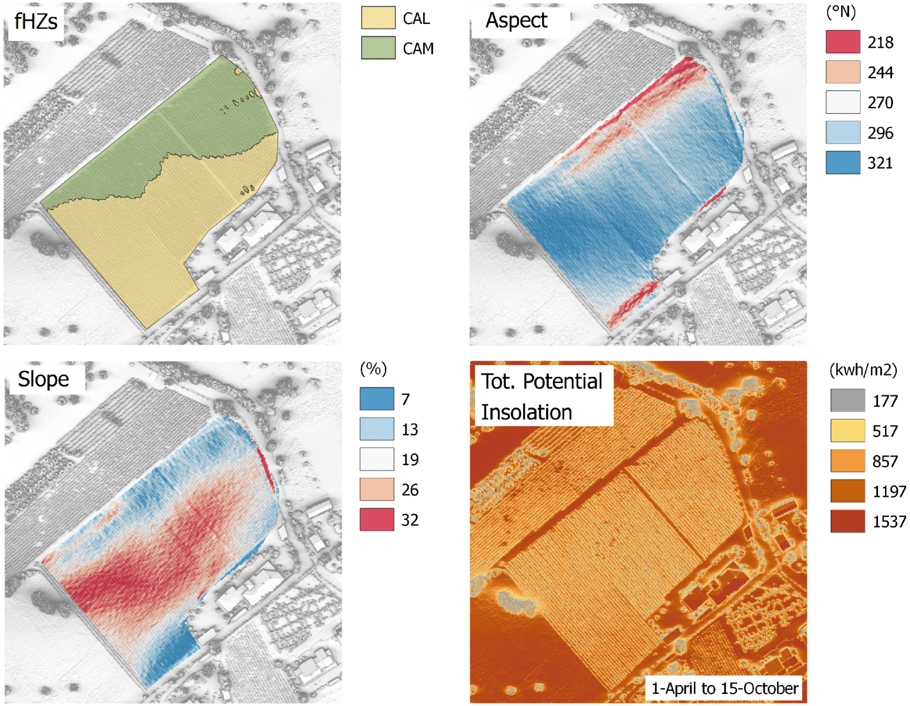

Figure 5. The functional homogenous zones (fHZs) identified in the study area and the three maps derived from DSM and DTM analysis in G.I.S environment: Aspect, Slope and Total Potential Insolation.