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Evaluation of the effects of future climate change on grape quality through a physically based model application: a case study for the Aglianico grapevine in Campania region, Italy

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ABSTRACT

Water deficit limiting yields is one of the negative aspects of climate change. However, this applies particularly when emphasis is on biomass production (e.g. for field crops), but not necessarily for plants where quality, not quantity is most relevant. For grapevine development, mild water stress occurring during specific phenological phases is an important factor when producing good quality wines. It induces the production of anthocyanins and aroma precursors and then could offer an opportunity to increase winegrower's income.

A multidisciplinary study was carried out in Campania region (Southern Italy), an area well known for high quality wine production. Growth of Aglianico grapevine cultivar, with a standard clone population on 1103 Paulsen rootstocks, was studied on two different types of soil: Calcisols and Cambisols occurring along a slope of 90 m length with 11% gradient.

The agro-hydrological model SWAP was calibrated and applied to estimate soil-plant water status during three consecutive seasons (2011–2013). Crop water stress index (CWSI), as estimated by the model, was related to leaf water potential, sugar content of grape bunches and wine quality (e.g. content of tannins). For both soils, the correlations between quality measurements and CWSI were high (e.g. -0.97^{**} with sugar; 0.895^{*} with anthocyanins in the grape skins).

The model was also applied to explore effects of future climate conditions (2021–2051) obtained from statistical downscaling of Global Circulation Models (AOGCM) and to estimate the effect of the climate on CWSI and hence on grape quality. Effects of climate change on grape quality indicate: (i) a resilient behavior of Calcisol to produce high quality wine, (ii) a good potentiality for improving the quality wine in Cambisol.

The present study represents an example of multidisciplinary approach in which soil scientists, hydro-pedologists, crop modellers, plant physiologists and oenologists have integrated their knowledge and skills in order to deal with the complex interactions among different components of an agricultural system.

1. Introduction

Crop productivity and profitability depend on several factors (e.g. soil fertility, climate, management practices, etc.) that drive soil-plant-atmosphere processes. Net profits for farmers depend on yields and quality of products (e.g. wine), considering all costs of production. For future planning, there is a need for a reliable assessment of the expected effects of climate change on both yield and quality of crops analyzing the components of different agricultural systems (e.g. soil, climate, plant) in an integrated way, as it can be properly done by dynamic simulation modelling approaches (quantitative approaches). In the past decades many process-based simulation models for food crops (SUCROS, CropSyst V.3, Wofost, SWAP, CERES, etc.), have been applied and tested to predict yields of various crops. In contrast, use of process-based simulation models to predict development and growth of grapevine is only recent (CropSyst V.4, Stöckle et al., 2003; SUCROS, as modified for grapevines in Nendel and Kersebaum, 2004; VineLogic, Godwin-Jones, 2002; Cola et al., 2014). However, it should pointed out that, in adaptation to climate change studies, the analysis is hampered by the requirement of the global solar radiation by several models (e.g. STICS, CropSyst, VIMO and VineLogic models); this last cannot directly be estimated for future weather forecasting through statistical downscaling procedure. It could be only estimated in a decoupled way

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by using an external procedure applied on estimated future weather dataset (e.g. software as RADEST, Donatelli et al., 2003). This implies that the results obtained by using these models can be unreliable on the evaluation of future climate change impacts on crop adaptation, because of the complexity of daily cloudiness prediction which determines the global solar radiation. Therefore, the choice of the modelling approach is crucial.

Obviously, the evaluation of future effects of climate change has to be focused on specific goals. For example, a food crop (e.g. maize) has to be evaluated on the base of its response to climate change in terms of adaptability and yield production (Sommer et al., 2013; Monaco et al., 2014), while for other crops such as grapevine, it is more important to evaluate impacts of future climate change in terms of quality. In future, climate change will strongly affect soil water availability. In the Mediterranean area of southern Europe, a decrease of rainfall associated with an increase of temperature is expected (IPCC, Field et al., 2014).

A reduction of water availability will produce different effects on yield and quality. For food crops (e.g. maize), water scarcity will produce a reduction in yield and thus in farmer's income. This relation is clearly expressed in the literature by the concept of Water Productivity (Steduto et al., 2009). On the contrary, for grapevine, water scarcity can represent an opportunity because grape quality is strongly related to the moderate degree of water stress suffered during the season (Van Leeuwen et al., 2009; Acevedo-Opazo et al., 2010; Intrigliolo and Castel, 2010). The well-established importance of the plant water status is not surprising, considering that water is the main regulator of the hormonal balance of the grapevine (Champagnol, 1997), while its interaction with nitrogen supply largely affects aroma potential (des Gachons et al., 2005). Therefore, the evaluation of climate impact on grapevine should primarily be focused on grape quality rather than on yield.

Generally, the use of crop simulation models requires: (i) a thorough understanding of the soil-plant-atmosphere system; (ii) an adequate and robust dataset, that is often lacking; (iii) a site specific calibration and a subsequent model validation, which is essential to allow accurate yield estimations in climate change studies (Wolf et al., 1996; Jagtap et al., 2002); (iv) an updated crop parameter dataset because available model parameters often refer to old varieties, (Rötter et al., 2011) and (v) a high computational capacity (Bonfante et al., 2015b).

In recent years, several papers were published on the effects of climate change on grapevine (Neethling et al., 2012; Xu et al., 2012; Moriondo et al., 2013; Dalu et al., 2013; Santos et al., 2013; Van Leeuwen et al., 2013; Quénol and Bonnardot, 2014; Valverde et al., 2015; Leibar et al., 2015), berry and wine quality (Lorenzo et al., 2013; Barnuud et al., 2014). Nevertheless, in many of these the evaluation of climate on crop adaptation was usually assessed by phenological considerations and expressed in terms of indexes (Amerine and Winkler, 1944; Huglin, 1986) and not in terms of an integrated analysis of the soil-plant-atmosphere (SPA) system, by means of process-based simulation models. The use of mechanistic models, it is crucial to link together all different processes occurring in the SPA system and to both identify and test a functional property of the simulated SPA system strongly correlated to grape quality.

Based on the scientific literature, it is evident that this property should be related to plant water stress. In fact, the effects of water stress on the wines' quality, appearance, flavour, taste and aroma have been clearly highlighted by different authors: Deluc et al. (2009) described the influence of water stress in metabolic processes of grapes Cabernet Sauvignon and Chardonnay. In particular, in Cabernet Sauvignon water deficits increased ABA (abscisic acid), proline, sugar and anthocyanin concentration. Acevedo-Opazo et al. (2010) showed how different irrigation schedules affected the stem water potential and consequently grape quality. In particular, they underlined the correlation between leaf water potential and berry quality. Intrigliolo and Castel (2010) highlighted how the irrigation amount rather than the system of application affected grape quality and yields. De la Hera et al. (2007) showed that water stress affects berry size and the overall quality. Moreover, these authors emphasized that application of water early or late in the growing season has different effects. So most of above studies mentioned focus only on the relationship between a single or a pair of environmental factors (water status, climate etc.) and grape quality.

In this paper, instead, we have realized an integrated and multidisciplinary analysis of the soil-plant-atmosphere (SPA) system addressed to the relation between SPA interactions and grape quality, in order to (i) identify the correlation between quality and water stress, for "Aglianico" grapevine grown under rain-fed conditions in two different soils, and (ii) evaluate the effects of future climate change on the expected grape quality.

2. Materials and methods

2.1. Methodology applied

Grape bunch characteristics at harvest, directly affecting wine quality, are the result of a dynamic equilibrium between the plant and its environment during the season. Currently, no numerical model is able to handle simultaneously the biochemical and biological aspects of plant. Thus, the only way to predict grape quality as a function of water stress, is an indirect method able to combine the crop water stress index (CWSI) obtained from model application with grape quality parameters. These values must be defined by using measured data and calibrated models results. Thus, in this work an effort was made to synthesize the information collected over three years of grape monitoring in terms of both grape quality, and crop water stress index cumulated at harvest ($CWSI_{cum-h}$), in order to identify the CWSI thresholds able to differentiate four grape quality classes for "Aglianico" cv. These last were determined from literature, considering that red wines obtained from grapes rich in phenolics such as Aglianico and the international grape cultivars Cabernet Sauvignon and Merlot, can be classified into two specific wine styles: ultra-quality wines that have a great aging potential, and standard-quality wines. Ritchey and Waterhouse (1999) showed that ultra-quality Cabernet Sauvignon wines have significantly higher phenolic levels (1999) and, apart from procedures used to obtain such wines, differences are mainly due to the composition of grapes used to produce them. Changes in wine quality can be effectively due to small changes in grape and berry skin composition (Hunter et al., 1991, 1995) and positive correlations between both berry total anthocyanins and berry total phenolics and wine quality were found (Kennedy et al., 2002).

Taking into account all these considerations and chemical composition of grapes analyzed in this study the quality potential of each site can be classify into four levels:

1) Ultra Quality Grapes (UQG) to obtain ultra-quality wines;
2) Standard Quality Grapes (SQG) that could be easily processed to obtain ultra-quality wines and standard-quality wines respectively;
3) Well Processed Quality Grapes (WPQG), grapes with base chemical parameters (sugar content, pH, malic acid) and phenolic composition (anthocyanins/tannins ratio and reactivity of grape tannins) that needs an "ad hoc" enological process to produce quality wines;
4) Low Quality Grapes (LQG), which cannot be used to produce good quality wines.

The methodology applied consists in a sequence of three main steps (Fig. 1).

1) Simulation model evaluation (calibration and validation of SWAP model on soil water balance); assessment of simulated CWSI as plant water status indicator through a relationship on measured leaf water potential $-\Psi_l$
2) Correlation between CWSI and grape quality (definition of CWSI thresholds for different grape quality)
3) Simulation of future climate change scenario over CWSI and evaluation of expected grape quality responses.

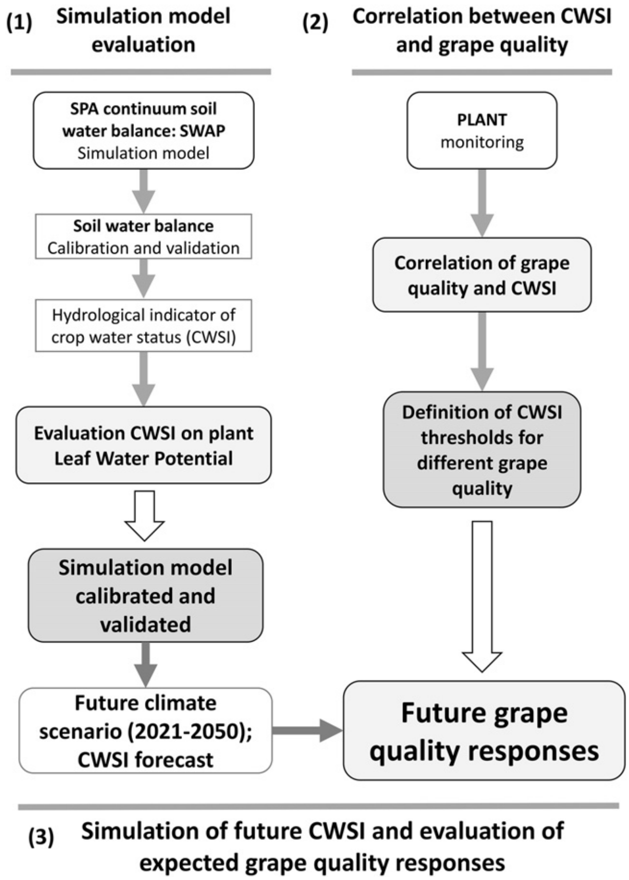

Fig. 1. The storyline of methodology applied.

2.2. 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 high quality wine production named Quintodecimo (2.3 ha). The study area is included in the landscape system of "marl-sandstone/carbonate hills" of Campania region; the main soil types being Haplic Calcisols and Calcaric Cambisols (soil-landscape map of Campania region at 250 000 scale, Di Gennaro, 2002).

The studied vine grape is the most important cultivar of Campania region for production of Taurasi and Aglianico wines ("Denominazione di Origine Controllata" - DOC[1]). The vineyard was planted in the year 2000 ("Aglianico" cultivar standard clone population) on 1103 Paulsen rootstocks (espalier system, cordon spur pruning, 5000 vines per hectare) placed along a slope of 90 m length with 11% gradient, grown under rain-fed condition.

The 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 about 1 km far from the farm, period 2003–2013).

2.3. Pedological and hydrological soil characterization

Pedological and hydrological soil characterization of study area, were reported and largely explained in Bonfante et al. (2015a). From this viticultural zoning study, two soils representative of two functional homogeneous zones (fHZs) of study area were identified and their data were fed into the SWAP model and used to forecast the soil plant and atmosphere system behavior following climate change:

CAL: Cambic Calcisol (Clayic, Aric) (FAO, Michéli et al., 2006) developing in summit and upslope landscape position;

CAM: Eutric Cambisol (Clayic, Aric, Colluvic) (FAO, Michéli et al., 2006) developing in downslope landscape position (Table 1).

Soil hydraulic properties were determined in the laboratory on undisturbed soil samples collected in each horizon of the two recognized soil profiles. Saturated hydraulic conductivity was determined applying the falling-head method (Reynolds et al., 2002). Water retention and unsaturated hydraulic conductivity functions were determined by means of the evaporation method (Wind, 1966). Moreover, some points at lower water content on the drying branch of the water retention curve were determined by a dew-point system. Details are reported in Basile et al. (2006, 2012).

Due to the incomplete saturation in the field, laboratory-based soil hydraulic characterization carried out on undisturbed cores does not reproduce properly the in situ soil hydraulic behavior. In such a way, a lower value of the maximum soil water content is observed, i.e. satiated soil water content. Basile et al. (2003, 2006) demonstrated that – due to the hysteresis in the soil water retention curve - also the saturated hydraulic conductivity and, only slightly, the air entry value are modified with respect to values observed under field conditions. Therefore, adopting the proposed procedure the lab-measured hydraulic properties were scaled to the field-ones just adjusting the parameters Θ_0 and K_0.

2.4. Simulation modelling

The Soil–Water–Atmosphere–Plant (SWAP) model (Kroes et al., 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 module was used; it assumes 1-D vertical flow processes and calculates the soil water flow through the Richards' equation. Soil water retention is described by the unimodal $\theta(h)$ relationship proposed by van Genuchten (1980), expressed in terms of the effective saturation, Se. 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. 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_p, irrigation and daily precipitation. Then the potential evapotranspiration is partitioned into potential soil evaporation, E_p, and potential transpiration, T_p, according to the leaf area index (LAI) evolution, following the approach of Ritchie (1972).

The SWAP model was previously used and tested in Italy and in the Campania region (Bonfante et al., 2010) and it is very often used in viticulture by different authors (Ben-Asher et al., 2006; Minacapilli et al., 2009; Rallo et al., 2012).

Few parameters were adjusted according to the trial-and-error procedure concerning the soil hydraulic properties (Table 1). The model parameters and data for simulation are reported in the Supplemental material S1.

2.5. The hydrological indicator: crop water stress index (CWSI)

The applied daily crop water stress index (CWSI) was defined as follows:

$$\mathrm{CWSI} = [1-(T_r/T_p)]\cdot 100 \quad (1)$$

[1] "Denominazione di Origine Controllata" (DOC) that means "Demarcation of controlled production areas".

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

Soil/fHZ	Soil horizon and thickness (cm)		Particle size fraction			Rock fragments	Hydrological properties				
			Clay (g 100 g^{-1})	Silty	Sand		Θ_0 (m^3 m^{-3})	K_0 (cm d^{-1})	a (1 cm^{-1})	l	n
Cambic Calcisol (Clayic, Aric)/CAL	Ap1	0–10/20	31.9	38.1	30.0	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	39.2	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	31.4	34.4	a	0.484	179.1	0.008	−1.00	1.45
	Bw1	40–90	37.5	30.0	32.5	b	0.462	2.3	0.003	−1.00	1.21
	Bw2	90–120	42.8	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.

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

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

$$CWSI_{cum} = \frac{\left[\int_{t_1}^{t_2} 1-(T_r/T_p)\cdot dt\right]}{(t_2-t_1)}\cdot 100 \quad (2)$$

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) (Bonfante et al., 2015a).

2.6. SWAP model performance evaluation

Soil water content was measured automatically in field in both soils CAL and CAM (representative of fHZs) by time domain reflectometry technique (TDR), applying the empirical Topp's formula to the measured soil bulk dielectric permittivity (Robinson et al., 2003). Ten probes were installed along the CAM soil profile at different soil depths: two vertically at depth of 0–15 cm and eight horizontally (−35, −75, −105 and −135 cm). Eight probes were installed along the CAL soil profile at different soil depths: two vertically at depth of 0–15 cm and six horizontally (−30, −60 and −100 cm). In 2011 we got 62 and 70 day of measurements of water content for CAL and CAM respectively and 111 and 184 in the 2012.

The agreement between observed and predicted soil water content values was expressed by using the following indexes: the root mean squared error (RMSE, minimum and optimum = 0) (Fox, 1981), the coefficient of residual mass (CRM, 0–1, optimum = 0, if positive indicates model underestimation) (Loague and Green, 1991) and the parameters of the linear regression equation between observed and predicted values (Addiscott and Whitmore, 1987).

2.7. Climate information

Daily weather information (temperature, rainfall, wind, solar radiation, etc.) were collected during three years (2011–2013) of crop and soil monitoring by means of a weather station in situ.

Daily weather data for future climate condition have been produced within the Italian project “Agroscenari” (www.agroscenari.it). Data is available over a 35 × 35 km resolution grid covering the entire Italian territory.

Daily values of maximum and minimum temperatures as well as precipitation in future climate period were produced in two phases. At first seasonal mean and standard deviation of the meteorological variables have been generated by a statistical downscaling model (SDM, Tomozeiu et al., 2007) starting from coupled atmosphere–ocean global climate models (AOGCMs) under emission scenario A1B (ENSAMBLE, Van der Linden and Mitchell, 2009). The results are then used by a weather generator to produce 50 realizations of the daily values of the same variables for a year taken as representative of the period between 2021 and 2050. Further details about the procedure were given by Villani et al. (2011) and Tomozeiu et al. (2014). Daily reference evapotranspiration (ET_0) was evaluated according to the equation of Hargreaves (Hargreaves and Samani, 1985) locally tested by Fagnano et al. (2001).

The choice of future climate time period limited to the 2021–2050 is due to the reduction of uncertainty between the scenario models until after 2040 (IPCC, Field et al., 2014) and to considering a time period according to the farmer planning time (10–15 years).

Finally it is important to stress that local site factors as slope, aspect, soil and crop, which have direct effects on spatial climate variability, are not taken into account by the climate models.

2.8. Crop measurements and grape characteristics

The crop monitoring was conducted within the two CAL and CAM fHZ on 27 plants each (54 plants over 2.3 ha), for two years during the season (2011 and 2012) and at harvest in 2013. In this last year only the crop information needed for the model application were collected during the season (e.g. LAI). Crop measurements were realized randomly on a weekly or biweekly base, in relation to the measured variable and physiological crop stages.

Leaf water potential (Ψ_l, MPa) was measured on one leaf of ten plants for each site using a Scholander type pressure bomb (SAPS II, 3115, Soilmoisture Equipment Corp., Santa Barbara CA, USA). After cutting, the leaf was inserted into the pressure bomb within a maximum of 30 s, and the pressure was increased at a rate of 2.0 MPa min^{-1}. Measurement were taken around midday and repeated about every two weeks. A linear Accupar LP-80 PAR-LAI ceptometer (Decagon Device Inc., Pullman, WA, USA) was used to measure light interception by the vineyard and to estimate LAI. The photosynthetic photon flux density (PPFD) transmitted through the canopy ($PPFD_T$) was measured at 0.25 cm above soil surface over a grid of 0.1 × 0.1 cm^2 across an area of 2 m along and 2 m between the rows. The measurements were carried out in 3–4 replicates in both sites, while the measurements taken in a clear area near the two sites were taken as the PPFD incident over the canopy ($PPFD_I$). Intercepted light ($PPFD_{Int}$) was calculated as the difference between incident and transmitted PPFD. Then, the instrument software calculates LAI (m^2 m^{-2}).

In addition to crop measurements, grape characteristics were monitored within the fHZs on 27 plants. In particular, of the 27 plants monitored, 12 were used to collect the grapes at harvest (2011–2013) and 15 for sampling scalar grapes during the growing seasons 2011 and 2012.

A representative sampling procedure was used to collect, for each fHZ, a minimum of 600 berries. Samples from both sides of the trellis and from top, middle, and bottom of selected clusters were collected. The sampling was carried out at the same time of day and berries were stored in a cooler and processed within 24 h. Each sample was weighted and divided in three 200 berries aliquot: one aliquot was pressed and obtained juice was used to determine soluble solids, total acidity and pH. The other two 200 berries samples were used for the extraction and analysis of grape skin and seed polyphenols.

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., 2002; 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 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 of SO_2, 5 g/L 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 $\times g$. Extracts were poured into dark glass bottles, flushed with nitrogen and stored at 4 °C until spectrophotometric analyses.

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

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, 2016). *Color intensity* (CI) and *hue* were evaluated according to the Glories method (Vivas, 1998). *Total anthocyanins* were determined by the spectrophotometric method based on SO_2 bleaching (Ribéreau-Gayon and Stonestreet, 1965). *Tannins* were determined according to Ribéreau-Gayon and Stonestreet (1965). Analyses were performed in duplicate using basic analytical equipment and a Shimadzu UV-1800 (Kyoto, Japan) UV spectrophotometer.

3. Results and discussion

3.1. SWAP model performances evaluation (calibration and validation)

The goodness of SWAP performance was evaluated in the representative soils of the fHZs (CAL and CAM), comparing soil water content (SWC) measured and estimated at different depths in the seasons 2011 and 2012. In both soils, the model was calibrated in 2011 and validated in 2012.

During these two cropping seasons (1 April to 15 October), the weather conditions were very different and they well represent a normal (2011) and dry year (2012) (Table 2). Therefore, the calibration and validation of SWAP model through these two different climatic years represents a lucky condition towards a more reliable simulation under climate change.

In Table 3, the results of the overall performance of SWAP, for both soils CAL and CAM, in the calibration (year 2011) and validation procedure (year 2012) are reported. The indexes are a weighted average over depths along the profile (until −100 cm, rooting zone).

For CAL, the agreement between the measured and estimated SWC was better in the year 2012 (validation). In particular, there was a reduction of RMSE and an increase of correlation index compared to the year 2011. The CRM index has shown an overestimation of SWC in the calibration year and an underestimation in the validation year.

Table 2
Principal weather information used in the simulation model evaluation (years 2011 and 2012).

Phenological stage	T min (°C)		T max (°C)		ET_0 (mm)		Rain (mm)	
	2011	2012	2011	2012	2011	2012	2011	2012
Shoot growth	2	0	31	29	220	205	129	80
Flowering	12	8	32	29	35	49	20	3
Berry formation	13	12	36	36	209	274	18	75
Berry ripening	11	8	39	39	274	300	97	42
Total	–	–	–	–	738	827	263	200

Table 3
Main performance indexes of SWAP application in the two soils (CAL and CAM). (Standard deviation - SD).

Indexes		Calcisol (CAL)		Cambisol (CAM)	
		2011	2012	2011	2012
CRM	Mean	−0.13	0.06	−0.05	−0.08
	SD	0.16	0.08	0.06	0.10
RMSE	Mean	0.04	0.03	0.03	0.04
(cm^3 cm^{-3})	SD	0.03	0.03	0.01	0.01
r	Mean	0.67	0.80	0.93	0.87
	SD	0.55	0.17	0.10	0.17
Data (n°)		248	406	350	879

For CAM, the results obtained in both phases are not so different with an overestimation of SWC explained by CRM and RMSE. Compared to the CAL, the correlation index values (r) were better in both years in the CAM.

The RMSE values agree with those showed in previous studies as reported in the review of Sheikh and van Loon (2007). Then we can consider the performance of SWAP, in both soils, to be reliable in terms of the prediction of the soil water balance.

From the simulation results, the CWSI was calculated in the years 2011 and 2012 in both soils (Fig. 2). This functional parameter is very important to link the model application output to the grapevine responses in terms of grape quality.

On the other hand, it must be emphasized that if this water stress information must be employed for management purposes, a measurement of plant water status is required (Choné et al., 2001). Thus, a validation of CWSI-simulated was made comparing what really the plant has encountered in the field in terms of water stress (Ψ_l) and what the model has simulated.

In both soils and years, the CWSI simulated was compared with the Ψ_l measured in the field on plants. In particular, 13 measurements in the year 2011 (from 18 May to 22 September, average value CAL = −1.06 (±0.37) MPa; CAM = −0.86 (±0.26) MPa) and 14 in the year 2012 (from 1 June to 27 September, average value CAL = −1.20 (±0.28) MPa; CAM = −1.00 (±0.22) MPa) were compared. The results have shown a good correlation between the CWSI and Ψ_l in both soils and years at 0.05 level (2-tailed, Table 4).

The obtained results demonstrate that the model - once calibrated and validated on soil water content measurements - through the calculated CWSI, is also able to reflect what the plants effectively encountered in field in terms of water stress. Furthermore, it is important to stress that leaf water potential data are not involved in the calibration and validation procedures, and then the independence of the two procedures comparing data represent a further validation of the potentiality of process-based simulation model application in the viticultural sector.

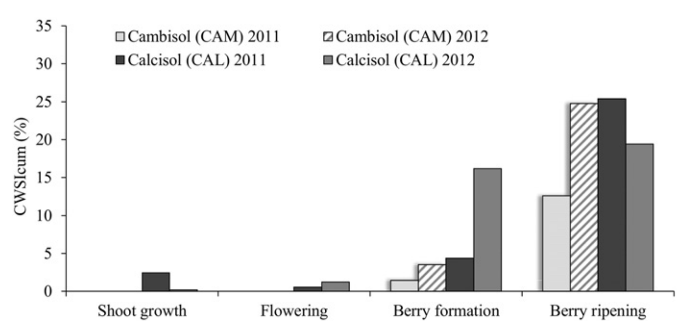

Fig. 2. Crop water stress index cumulated ($CWSI_{cum}$) during the phenological stages of grapevine in both soils for the seasons 2011 and 2012.

Table 4
Pearson correlation (r) between crop water stress index (CWSI) estimated and leaf water potential (LWP) measured.

Soil (fHZ)	Year	r
Calcisol (CAL)	2011	−0.80[a]
	2012	−0.55[b]
Cambisol (CAM)	2011	−0.76[a]
	2012	−0.69[a]

[a] Correlation significant at 0.01 level (2-tailed).
[b] Correlation significant at 0.05 level (2-tailed).

3.2. CWSI and bunch characteristics (grape quality)

The average values at harvest for the main quality bunch characteristics and plant responses in the three years of experiment (2011–2013) are reported in Table 5. Moreover, Fig. 3 shows the correlation (r) during the years 2011 (June to September: 5 measurements) and 2012 (August to October: 4 measurements) between simulated CWSI and berry characteristics for both soils (CAL and CAM).

For both soils and years, the CWSI was positively correlated (r from 0.50 to 0.98) with sugar, pH, color intensity and total anthocyanins measured on 100 berries. The density of berries correlation with CWSI was positive in both soils but with values >0.5 in CAL in both years (avg 0.81) and between 0.77 (2011) and 0.23 (2012) in CAM.

For both soils and years, the CWSI was negatively correlated (from −0.5 to −0.98) with: titratable acidity, color hue and total tannins in the grape skin. The total polyphenols, tannins and flavans measured in the grape seed show a positive or negative correlation driven by seasons. In the year 2011 (normal year) there was for all three seeds characteristics a positive correlation with CWSI, but in the 2012 (dry year) the correlation became negative.

The flavans in grape skin have shown a negative correlation in the CAM for both years (avg −0.92) and negative (−0.71) and positive (+0.55) correlation values for CAL in the year 2011 and 2012, respectively.

Taking into account that planting year, rootstock, cultivar and crop management were the same in CAM and CAL soils, the grape quality at harvest, in the three seasons monitored, can be considered a plant response to different levels of CWSI cumulated at harvest ($CWSI_{cum\text{-}h}$).

Further analysis has shown that on the thirteen grape characteristics measured, only five - very important for vinification and wine quality – such as tannins and flavans in the skin, total anthocyanins, color intensity and sugar content were linearly correlated to $CWSI_{cum\text{-}h}$ (Fig. 4). It may indicate also that CWSI can be used as a quantitative predictor of grape quality and then of wine quality.

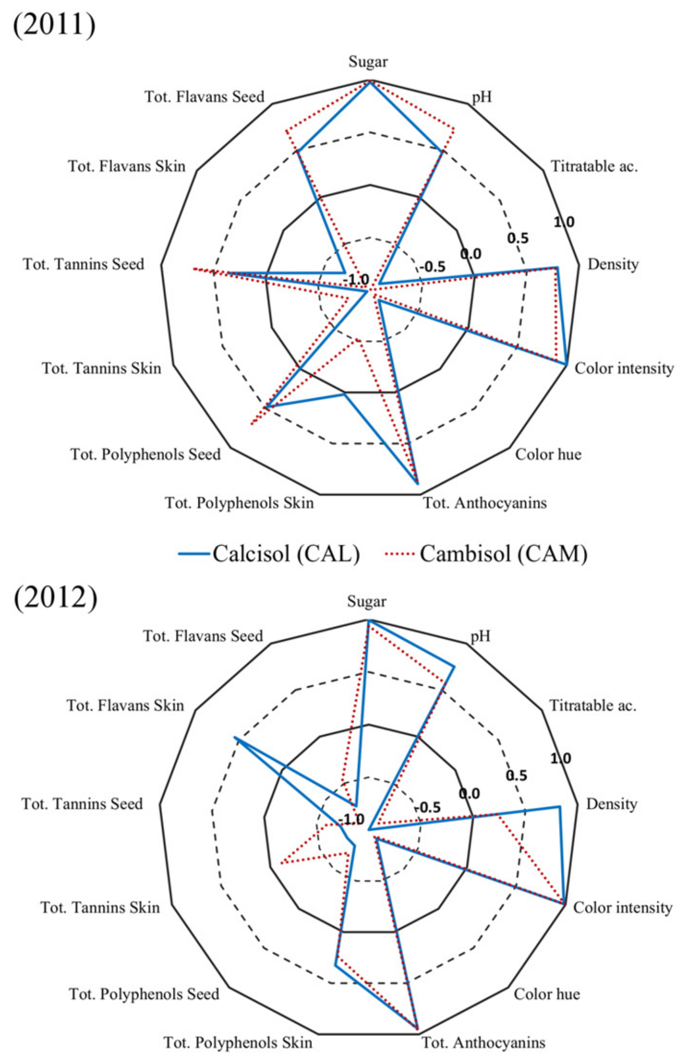

Fig. 3. Correlation coefficient (r) between CWSI and berry characteristics for both soils (CAL and CAM) during the years 2011 and 2012.

Moreover, findings are important for terroir resilience; in fact, berry quality variation between the two soils remains very important in all years analyzed. However, these linear relationships are specific for "Aglianico" cv. and can only be applied for this cultivar.

Table 5
Summary of plant responses and bunch characteristics at harvest in the vintages 2011, 2012 and 2013 (average value ± standard deviation).

Plant responses/bunch characteristics		CAL	CAM
Plant yield	(g)	972.5 (±336)	1807 (±290)
Cluster	Cluster/plant (pre-fruit thinning)	8.67 (±3.8)	14.58 (±3.8)
	Cluster/plant (post-fruit thinning)	4.17 (±1.34)	4.83 (±0.58)
	Weight (g)	241.8 (±77)	374.8 (±44)
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 (±0.6)	21.3 (±1.1)
	pH	3.4 (±0.10)	3.2 (±0.12)
	Titratable acidity (g/L)	6.6 (±1.1)	7.7 (±1.5)
	Color intensity	5.5 (±0.13)	4.1 (±0.08)
	Color hue	0.53 (±0.02)	0.51 (±0.01)
	Total anthocyanins ($mg\ kg^{-1}$)	628 (±67)	471 (±45)
Grape skin	Tot. polyphenols ($mg\ kg^{-1}$)	1971 (±400)	1745 (±259)
	Tot. tannins ($mg\ kg^{-1}$)	2617 (±303)	2454 (±239)
	Tot. flavans skin ($mg\ kg^{-1}$)	833 (±129)	743 (±119)
Grape seed	Tot. polyphenols ($mg\ kg^{-1}$)	1562 (±185)	1968 (±330)
	Tot. tannins ($mg\ kg^{-1}$)	1642 (±372)	1837 (±272)
	Tot. flavans seed ($mg\ kg^{-1}$)	1149 (±326)	1603 (±471)

3.3. Definition of CWSI thresholds for different grape quality of Aglianico

On the basis of recent literature on Aglianico wine in Campania region (Moio et al., 2004; Gambuti et al., 2014) Table 6 reports a classification of the ranges of twelve grape characteristics, strictly related to "Aglianico" grape quality and corresponding to four grape quality classes identified from literature (see Materials and methods section): UQG, SQG/WPQG and LQG.

By comparing data in Table 6 with observed grape quality in the three monitoring years it was possible to associate each class of grape quality with a $CWSI_{cum\text{-}h.}$ threshold.

UQG: $CWSI_{cum\text{-}h}$ values between 10 and 15%

SQG and WPQG: $CWSI_{cum\text{-}h}$ values between 5 and 10%

LQG = $CWSI_{cum\text{-}h}$ values less of 5%

Moreover, a class of UQG with uncertainty (UQG-u) for the $CWSI_{cum\text{-}h}$ > 15% was created. This last category represents the

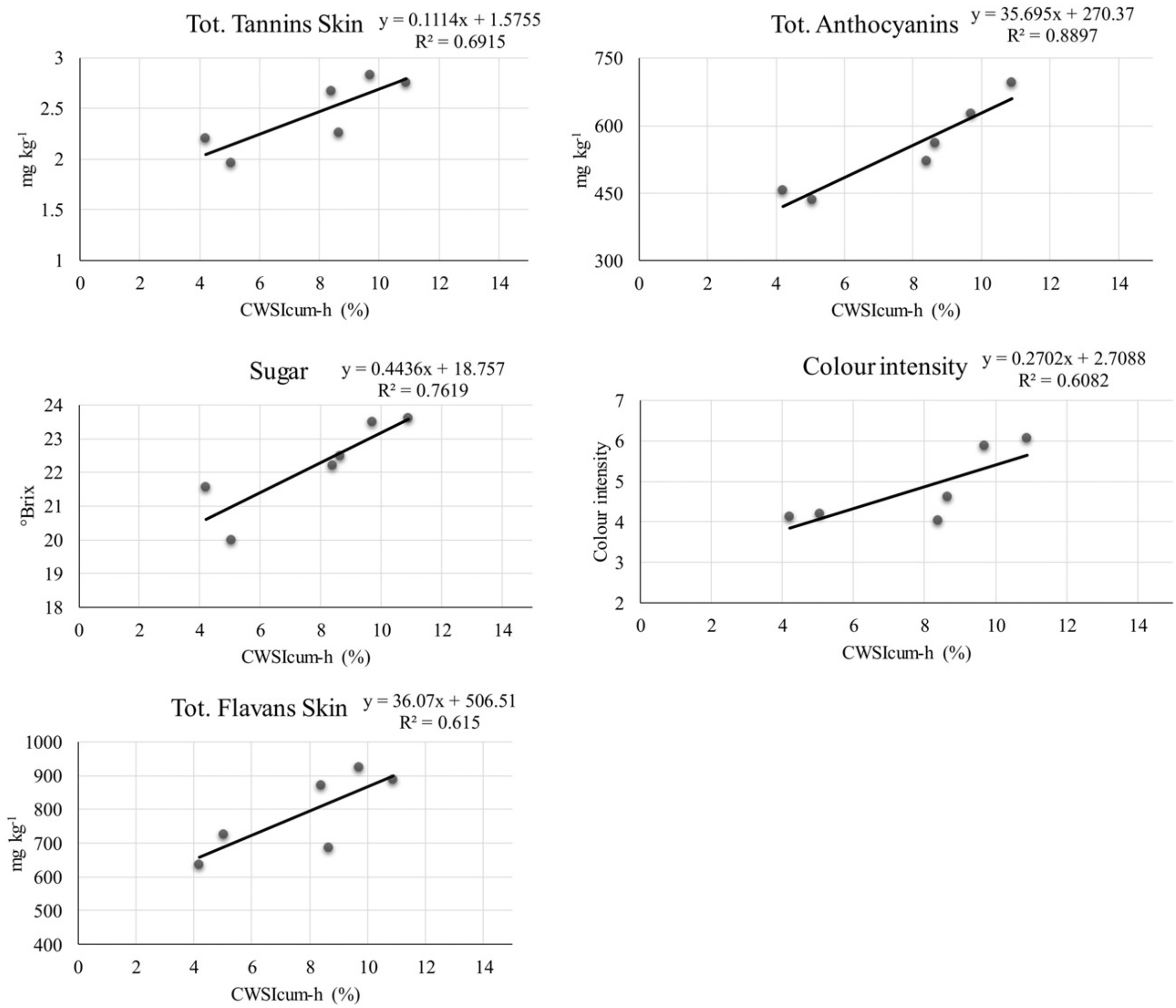

Fig. 4. Linear correlation between CWSI cumulated at harvest ($CWSI_{cum-h}$) in both soils in the three years (2011–2013) and bunches characteristics of Aglianico grapevine.

values of more severe stress to those recorded during the three years of monitoring. In fact, 2012 season represented a very dry vintage with value $CWSI_{cum-h}$ near 12%, the choice of maximum threshold of UQG fixed at 15% is due to the results obtained in the simulation of two dry years 2003 and 2007 where high grape quality was realized (data not shown) which were also in accordance with Bonfante et al. (2015a). In this case, the expected results cannot be defined with certainty. Considering the above, the grape quality classification of three monitoring years (2011, 2012 and 2013) is: CAM (LQG, SQG/WPQG and SQG/WPQG); CAL (SQG/WPQG, UQG and SQG/WPQG).

Table 6
Range of principal grape characteristics affecting the grape quality and the corresponding values of CWSI.

	LQG	SQG/WPQG	UQG
CWSI (%)	<5	5–10	10–15
Sugar (°Bx)	<22	22–23	23–24
pH	<3	3–3.6	
Ac. Tot (g/L)	>8	42,223.0	<7,5
Weight 100 berries (g)	>225	225–190	<190
Vol_100ac (mL)	>215	215–190	<190
Color intensity of skin extract	<4.3	5–4.3	>5
Color hue of skin extract	0.5	0.5	≤0.5
Total anthocyanins (mg kg^{-1})	<450	450–600	>600
Tot. polyphenols skin (mg kg^{-1})	<1700	1600–2000	>2000
Tot. polyphenols seed (mg kg^{-1})	>1700	>1700	<1700
Tot. tannins skin (mg kg^{-1})	<2300	2300–2600	>2600
Tot. tannins seed (mg kg^{-1})	<1700	1500–1800	>1700

3.4. Future CWSI and expected grape quality

The future climate conditions, obtained from the statistical downscaling procedure (50 equiprobable years representative of the period 2021–2050), were applied as upper boundary condition in the model simulation runs. The weather characteristics during the cropping season (1 April to 15 October) were:

- The average seasonal temperature was 20 °C (±0.4) with a minimum and maximum temperature of 14 and 26 °C (absolute min and max temperature of −0.7 and 39 °C, respectively).
- The average seasonal rainfall was 355 mm with a minimum and maximum seasonal values of 221 and 526 mm, respectively,
- The average seasonal ET_0 was 884 mm with a minimum and maximum seasonal values of 844 and 910 mm, respectively.

The calibrated and validated simulation model SWAP was run in both soils on future climate scenarios using the crop description derived from the three years of monitoring. In particular, the LAI development was considered specific for each soil, according to the measured data (Supplemental material, Fig. 1s).

This choice was necessary because in the future climate no information on global solar radiation was available to apply a crop growth engine (e.g. global radiation for crop model based on radiation use efficiency) in order to simulate the LAI development. Moreover, in alternative the use of other approaches based on the correlation between weather variables and LAI development (Cola et al., 2014) were not taken into account, because the future climate conditions are the same for the study area (and for both soils), and then, accordingly, LAI development. This is in contrast with the field evidences obtained from crop monitoring.

Finally, it is important to emphasize that usually the farmer tries to reach and maintain the same crop canopy dimension in the vineyard in each growing season through the leaf pruning, then the use of a unique description of LAI development in each soil, derived from the LAI monitored over three years, could be considered the best compromise to emphasize the future potentialities of soils.

From the output of the simulation, $CWSI_{cum\text{-}h}$ was determined in each soil in the future climate conditions (2021–2050) (Fig. 5). The CWSI differences at harvest between the two soils are not constant during the simulated years, showing a decrease in the wet years (e.g. year 20 Fig. 5) and an increase in the dry years (e.g. year 27 Fig. 5). The CAL average value of $CWSI_{cum\text{-}h}$ (14.3% ± 4.9) is 84% higher than the CAM (7.8% ± 2.7).

The differences of CWSI and grape quality between the studied soils are important because they show that the behavior recognized during the three years of monitoring were maintained also in the future climate scenario. Moreover, the average values of CWSI clearly evidence that while the CAL is oriented to UGQ, the CAM is moving towards SQG and WPQG (Fig. 6).

However, in our study we also seek to evaluate if under future climate conditions there will be any opportunity in the CAM to improve the quality of grapes for obtaining UGQ and in the CAL to maintain the high quality for producing UGQ.

The use of the identified $CWSI_{cum\text{-}h}$ thresholds for different grape quality coming from the simulation results allow one to define the expected probability of grape quality in the future climate condition for both soils. In particular, the $CWSI_{cum\text{-}h}$ predicted (2021–2050) have shown that (Figs. 5 and 6):

(i) The Calcisol (CAL) will maintain its status of best soil in relation with Aglianico plant also under climate change conditions (in 36% of cases it responds with a UQG, only in 8% with LQG, 46% with uncertainty of UQG, and 10% as SQG-WPQG).
(ii) The Cambisol (CAM) will behave as SQG in 68% of cases, as UQG in 18% of cases of and as LQG in 14%. None case of UQG with uncertainty is expected.

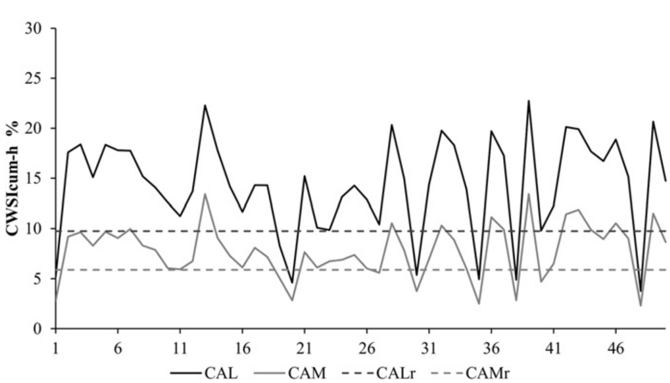

Fig. 5. The CWSI cumulated at harvest ($CWSI_{cum\text{-}h}$) simulated in the 50 equiprobable years representative of the future climate scenario (2021–2050) in the Calcisol (CAL) and Cambisol (CAM) and the average values over the three years of monitoring (2011–2012) in the Calcisol (CALr) and Cambisol (CAMr).

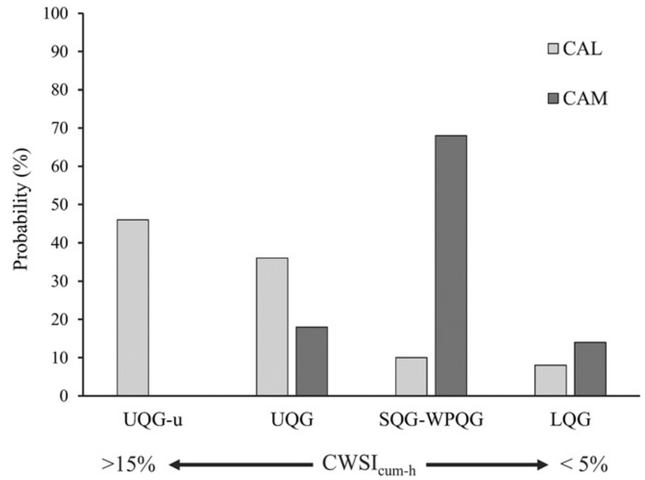

Fig. 6. The expected probability of grape quality (Ultra Quality Grapes – UQG; Standard Quality Grapes – SQG; Well Processed Quality Grapes – WPQG; Low Quality Grapes – LQG; and Ultra Quality Grapes with uncertainty -UQG-u), in the future climate conditions (2021–2050) in CAL and CAM soils.

The comparison between the expected future $CWSI_{cum\text{-}h}$ and then the grape quality with the $CWSI_{cum\text{-}h}$ obtained from crop monitoring in three different climatic years (2011 to 2013; CALr and CAMr Fig. 6) shows an average increase of 4.5% in the CAL (+46% of $CWSI_{cum\text{-}h}$) and 1.9% in the CAM (+32% of $CWSI_{cum\text{-}h}$) which means that the CAM will have more advantages in terms of grape quality in the future compared to the CAL, because the expected $CWSI_{cum\text{-}h}$ increase will be able to move from SGQ to UGQ without uncertainty.

4. Conclusions

Results confirm the potentiality of simulation modelling application in viticulture. The agreement between the CWSI estimated by the model and the measured crop water status (Ψ_l) strengthens the usefulness of simulation model application in the terroir analysis (in viticultural zoning procedures at different scales or to evaluate the effects of climate change).

The correlations identified between CWSI and the main berry characteristics allow to evaluate the "Aglianico" cv. response to climate change. The results have clearly supported the "Terroir concept" in terms of the resilient behavior of CAL (fHZ with Calcisol) to produce high quality wine, but also the improvement of potentiality of CAM (fHZ with Cambisol). Then, we can conclude that in our case study the future climate conditions could represent an opportunity for the CAM. However, there is a certain level of uncertainty in the ultra-quality grapes (UQG) for CAL due to high values of CWSI that could indicate a need of irrigation in the future, in order to preserve the UQG.

Obviously, the relationships identified between CWSI and grape quality are specific for the "Aglianico" cv. and they cannot be generalized for other grapevines. However, as demonstrated in the future climate impacts evaluation, they can be used in a different environmental context to predict the "Aglianico" grape quality responses, as well as in the viticultural zoning planning to identify the best areas to produce Aglianico wine. Moreover, these relationships may represent a new opportunity to support precision viticulture, quality production in irrigated vineyards and it can be usefully incorporated into Decision Support System (DSS) at farm scale (Terribile et al., 2015).

Finally, in viticulture, the future survival of farms will also depend on the link between quality and the dynamics of the soil-water-atmosphere system, which is the base of concept of terroir. In this sense, soil science plays a key role in providing the tools to understand the grapevine response under climate change for different types of soil.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.agsy.2016.12.009.

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