EFFECTS OF FUTURE CLIMATE CHANGE ON GRAPE QUALITY: A CASE STUDY FOR THE AGLIANICO GRAPE IN CAMPANIA REGION, ITALY

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Abstract
Water deficits limit yields and this is one of the negative aspects of climate change. However, this applies particularly when emphasis is on biomass production (e.g. for crops like maize, wheat, etc.) but not necessarily for plants where quality, not quantity is most relevant. For grapevine water stress occurring during specific phenological phases is an important factor when producing good quality wines. It induces in the red wine the production of anthocyanins and aroma precursors. On this base, in some terroirs the future climate constrictions could represent an opportunity to increase winegrowers' incomes.
This study was carried out in Campania region (Southern Italy), an area well known for high quality wine production. Growth of the Aglianico grapevine cultivar, with a standard clone population on 1103 Paulsen rootstocks, was studied on two different types of soil: Calcisols and Cambisols. The agro-hydrological model SWAP was calibrated and applied to estimate soil-plant water status at the various crop phenological phases for three vintages (2011-2013). Then, the Crop water stress index (CWSI), as estimated by the model, was related to physiological measurements (e.g. leaf water potential), grape bunches measurements (e.g. sugar content) and wine quality (e.g. tannins). For both soils, the correlation between grape quality characteristics and CWSI were high (e.g. 0.895* with anthocyanins in the skins).
Finally, the model was applied to future climate conditions (2021-2051) obtained from statistical downscaling of Global Circulation Models (AOGCM) in order to estimate the effect of the climate on CWSI and hence on grape quality. Results show that in the study area the effects of climate change on grape and wine quality are not expected to be significant for Aglianico grapevine when grown on Calcisols and Cambisols.

Keywords: climate change, grape quality, SWAP, Crop Water Stress Index (CWSI), Leaf Water Potential (LWP), Calcisols, Cambisols.

1 INTRODUCTION
In the 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 crop yield and quality. For food crops (e.g. maize), water scarcity will produce a reduction in yield and thus in farmer income. This relation is clearly expressed in the literature by the concept of Water Productivity -WP (Steduto et al., 2009). On the contrary, for grapevine, water scarcity could represent an advantage because grape quality is strongly related to the degree of water stress suffered during the cropping season (Van Leeuwen et a., 2009; Intrigliolo and Castel, 2011).
Therefore, the evaluation of climate impact on grapevine should be primarily addressed on grape quality and not on the yield. In recent years, several papers were published on the effects of climate change on grapevine (Moriondo et al., 2013; Leibar et al., 2015), berry and wine quality (Lorenzo et al., 2013, Barnuud et al., 2014) climate oriented, based on the evaluation of climate variables effects on crop adaptation in terms of bioclimatic indexes (e.g. phenological modelling, Amerine and Winkler, Huglin, ..etc..) and not on an integrated analysis such as those addressing .
Nevertheless, in viticulture, the concept of terroir is strongly based on the interactions between plant, soil and climate to produce specific conditions able to achieve a quality wine. This means that changes in climate can modify these interactions by acting on the processes involved in the soil-plant and atmosphere systems, and then producing an improvement or a worsening of wine quality.
In using these approaches, it is crucial to identify and to test a functional property of the simulated SPA system related to plant water stress and highly correlated to grape quality response.
Based on the scientific literature, it is known that one of functional properties is the Crop Water Stress Index (CWSI), which is the ratio between the actual and potential crop transpiration. CWSI was previously used and tested on grapevine in Italy and in the same Campania Region (Bonfante et al., 2011, 2015).
Water deficit can influence the grape berry composition resulting in improved wine quality by enhancement of color, flavor and aromas. While some pathways and physiological processes affected by water deficit have been clearly identified, no information is known about the global effect of water deficit on grape berry (Deluc, 2009).

However, the relation between water deficit and grape quality can be described in synthetic way by CWSI calibrated on the specific plant cultivar (Bonfante et al., 2015).
In this work, a simulation model of the SPA system (SWAP) was applied to analyze the correlation between CWSI and grape quality (e.g. contents of tannins and anthocyanins) and to evaluate the expected grape quality responses in the future climate conditions (2021-2050), in a case study of southern Italy, where the terroir analysis was previously realized by Bonfante et al., 2015. More specifically we aimed: i) to identify the correlation between grape quality for a specific red wine and CWSI, the latter obtained from physically based simulation model application, and ii) to evaluate the effects of future climate change on the expected grape quality.

2 MATERIALS AND METHODS

Methodology applied (Bonfante et al., article submitted for publication, 2016)
The methodology applied consists of five steps:
1) Calibration and Validation of SWAP model on soil water balance
2) Evaluation of CWSI on plant Leaf Water Potential (LWP)
3) Correlation between grape quality and CWSI
4) Definition of CWSI thresholds for different grape quality
4) Simulation of future CWSI and evaluation of expected grape quality responses.

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 a.s.l.), in a farm oriented to high quality wine production named Quintodecimo. The studied vineyard was the 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). Pedological and hydrological soil characterization of study area, as the functional homogeneous zones (fHZs) definition, were reported and largely explained in Bonfante et al. (2015). From this viticultural zoning study (Bonfante et al. 2015), two soils representative of fHZs were identified and SWAP model (Kroes et al., 2008) tested and used to forecast the Soil Plant and Atmosphere system behaviour to climate change : CAL : Cambic Calcisol (Clayic, Aric) and CAM : Eutric Cambisol (Clayic, Aric, Colluvic)
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.
The SWAP model was previously used and tested in Italy and in the Campania Region and is very often used in viticulture by different authors (Ben-Asher et al., 2006; Minacapilli et al., 2009; Bonfante et al., 2011; Rallo et al., 2012). For the simulation of the future climate conditions, LAI was defined along the cropping season in according to the LAI measurements during the three years in both soils.
The soil water balance solved by SWAP was used to calculate the daily crop water stress index (CWSI) (Bonfante et al., 2011 and 2015) which was defined as follows:

$$CWSI = \left[1 - \left(T_r/T_p\right)\right] \cdot 100$$

where Tr is the daily actual water uptake ant Tp is the daily potential transpiration.
The sum of daily CWSI in the required period represents the cumulated stress $CWSI_{cum}$:

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

The SWAP model performance was evaluated through the agreement between observed and predicted soil water content at different soil depth, expressed by using the indexes proposed by Loague and Green (1991): the root mean squared error (RMSE), the coefficient of residual mass (CRM) and the parameters of the linear regression equation between observed and predicted values.
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) through a statistical downscaling model (SDM, Tomozeiu et al., 2007) starting from coupled atmosphere–ocean global climate models (AOGCMs) under emission scenario 1A (ENSAMBLE, Van

der Linden and Mitchell, 2009) (50 realizations of the daily values representative of the period between 2021 and 2050). Further details about the procedure were given by Tomozeiu et al. (2013). Daily reference evapotranspiration (ET_0) was evaluated according to the equation of Hargreaves.

Crop measurements and Must/wine characteristics.

The crop monitoring was conducted within each fHZ (CAL and CAM) on 27 plants, for two years during the season (2011 and 2012) and at harvest in the 2013. In this last year only the crop information needed for the model application were collected during the season (e.g. LAI). The crop 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 fHZ on an individual set of 10 plants using a Scholander type pressure bomb (SAPS II, 3115, Soil moisture Equipment Corp., Santa Barbara CA, U.S.A). For further detail on procedure applied see Bonfante et al., 2015.

3 RESULTS AND DISCUSSION

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.

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). The validation of SWAP model through these two climatic years represents a lucky condition in order to obtain a proper estimation of SPA system behavior under climate change.

The results of the overall performance of SWAP, for both soils CAL and CAM, in the calibration (year 2011) and validation procedure (year 2012) have shown a good agreement between the measured and estimated SWC. The average statistica indexex values of both years were reported in table 1.

Table 1: Main performace indexes of SWAP application in the two soils over the two years (2011-2012)

Indexes	Calcisol (CAL)	Cambisol (CAM)
CRM	-0.04 (±0.12)	-0.06 (±0.08)
RMSE (cm^3 cm^{-3})	0.03 (±0.03)	0.03 (±0.01)
r	0.74 (±0.30)	0.90 (±0.13)
Data (n°)	654	1229

In both soils and years, the CWSI simulated was compared with the LWP measured in field on plants. In particular, 13 measurements in the year 2011 (from 18 May to 22 September) and 14 in the year 2014 (from 1 June to 27 September) were compared. The results have shown a good correlation between the CWSI and LWP in both soils and years with an average value of 0.67 and 0.72 for CAL and CAM respectively. The correlations were highly significant 0.05 level (2-tailed, Tab.5).

The obtained results demonstrate that the soil water balance simulations, and consequently the calibration and validation of SWAP, were correctly performed and that the CWSI obtained from the output of model reflects what the plants effectively encountered in field in terms of water stress.

The daily CWSI estimated in the years 2011 and 2012 and validated on the base of LWP measurements in both soils (CAL and CAM), was correlated with several grape bunch characteristics that directly affect the wine quality.

For both soils and years, the CWSI was positively correlated (>0.5 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 (>- 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 the 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. This behavior could be strictly climate dependent not directly from water stress.

The flavans in the 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 the crop, rootstock and crop management were the same in CAM and CAL soils, the grape must quality at harvest, in the three seasons monitored, can be considered a plant response to different levels of CWSI cumulated at harvest ($CWSI_{cum-h)}$.

Further analysis has shown that on the thirteen must 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 $CWSI_{cum-h}$.

The grape bunch characteristics values assumed at harvest that directly affect the wine quality, are a result of a dynamic equilibrium between the plant and the environment during the season. Currently, no numerical model is

able to handle simultaneously the biochemical and biological appearance of the plant. Then, the only way to predict the grape quality according to the water stress, on the base of SPA system behavior, is to identify cultivar specific CWSI thresholds. These values must be defined by using measured data and calibrated models results.
Thus, an effort was done to synthesize the information collected in terms of grape quality, over the three years of grape monitoring and $CWSI_{cum-h}$, in order to identify the CWSI thresholds able to differentiate the grape must quality for Aglianico cv. (Bonfante et al., article submitted for publication, 2016).

Definition of CWSI thresholds for different must quality of Aglianico (Bonfante et al., article submitted for publication, 2016).

Starting from literature (Ritchey and Waterhouse 1999, Hunter et al., 1995, and Kennedy et al., 2002) and considering the 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 UQW
2) Standard Quality Grapes (SQG) that could be easily processed to obtain UQW and SQW 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 and,
4) Low Quality Grapes (LQG), which cannot be used to produce good quality wines.

On the base of literature produced in the last years on Aglianico wine in Campania Region (Moio 2004, Gambuti et al.,2014) a classification of different levels of grape qualities on twelve grape's characteristics strictly related to Aglianico grape quality were realized and used to classify the Aglianico grape quality responses over the three years of monitoring on both soils.
This classification allowed to define the $CWSI_{cum-h}$ threshold for each grape quality class.
UQG: $CWSI_{cum-h}$ values between 10 and 15%
SQG and WPQG: $CWSI_{cum-h}$ values between 5 and 10%
LQG= $CWSI_{cum-h}$ values less of 5%

Moreover, a class of UQG with uncertainty (UQG-u) for the $CWSI_{cum-h}$ > 15% was created. This last represents the values of more severe stress (2012 season represented a very dry vintage) to those recorded during the three years of monitoring. 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) are: CAM (LQG, SQG /WPQG and SQG and WPQG); CAL (SQG /WPQG, UQG and SQG /WPQG).

Future CWSI and expected grape quality.

The calibrated and validated simulation model, SWAP, was run in both soils on future climate scenarios (50 equiprobable years representative of the period 2021-2050) using the crop description derived from the three years of monitoring.

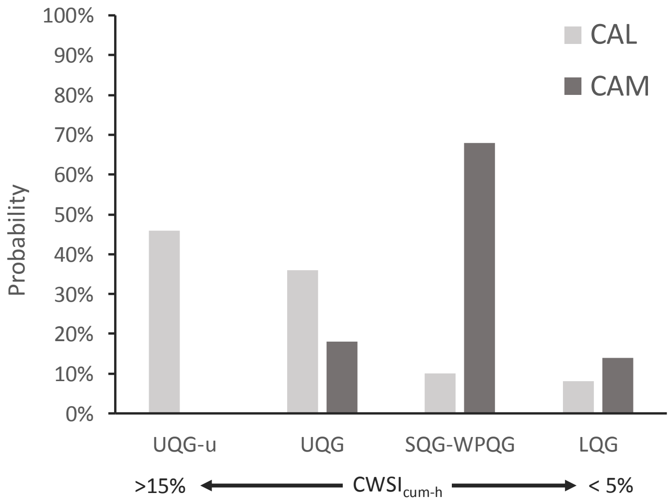

Figure 1: The expected probability of grape quality (Ultra Quality Grapes – UQG; Standard Quality Grapes – SQG; Well Processed Quality Grapes – WPQG; Low Quality Grapes – LQG; and Ultra Quality Grapes with uncertainty -UQG-u), in the future climate conditions (2021-2050) in CAL and CAM soils. (Bonfante et al., article submitted for publication, 2016)

In particular, the LAI development was considered specific for each soil, according to the measured data. From the output of the simulation, $CWSI_{cum-h}$ were determined in each soil in the future climate conditions (2021-

2050). The use of the identified $CWSI_{cum-h}$ thresholds for different grape quality coming from the simulation results allow to define the expected probability of grape quality in the future climate condition for both soils. In particular, the $CWSI_{cum-h}$ predicted (2021-2050) have shown that (Fig. 1) (Bonfante et al., article submitted for publication, 2016):

(i) The Calcisol (CAL) will maintain its status of best soil in relation with Aglianico plant also under climate change conditions (in the 36% of cases it responds with a UQG, only in the 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.

4 CONCLUSION

The results on the Aglianico grapevine responses to water stress are very important for the winegrowers of Campania Region because this vineyard represents the most important Campanian red vine. It is also important to emphasize that the study based on the use of SPA models allows to predict crop responses to climate change and then to give information about how to cope with climate change risks in the near future. In this way, SPA models allow to know if for some soils there will be the necessity to use the drip irrigation to control the plant water status, in order to maintain or improve the quality of grape most. Obviously, the relationships identified between CWSI and grape quality are specific for the Aglianico cv and they cannot generalized for the other grapevines. However, as demonstrated in the future climate impacts evaluation, they can be used in different environmental contest to predict the Aglianico grape quality responses, as well as in the viticultural zoning planning to identify the best areas to produce Aglianico wine. The correlations identified between CWSI and the main berry characteristics allow to evaluate the Aglianico cv. response to climate change. The results have clearly showed the “Terroir concept” in the resilient behavior of CAL (HZ with Calcisol) to produce high quality wine, but also the improvement of potentiality of CAM (Hz with Cambisol). Then, we can conclude that in our case study the future climate conditions could represent an opportunity for the CAM. However, from results a certain level of uncertainty in the UQG for CAL, not demonstrable in terms of worsening in grape quality through our dataset comes out. This last condition is due to high values of CWSI that could indicate a need of irrigation, in order to preserve the UQG.

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