Analysis of micrometeorological conditions in Piedmontese vineyards

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Abstract: *Grapevine environment has been studied, in recent years, to provide useful information to support and improve crop management and wine–making. In order to investigate vineyards micrometeorological factors and microclimate, an experimental campaign was carried out during the 2008, 2009 and 2010 vegetative seasons in three Piedmontese vineyards, each one characterized by same climatic but different microclimatic conditions, in which measurements of a wide number of variables were performed. Energy and mass exchange processes were analyzed over these vineyards located in complex terrain, providing a complete dataset of observations not commonly performed within vineyards. The results have evidenced that most variables exhibit similar behaviors, from a general point of view, but peculiar differences exist, when the three sites are compared with each other. These differences are small, in general, but sufficient to significantly affect energy and hydrological budgets. Considering also terrain differences, micrometeorological variables may strongly affect grape ripening and quality. In the actual context of changing climate, such kind of observations can constitute a starting point for assessing climatic effects on grapevine production.*
Keywords: *Vineyards, meteorological stations, experimental measurements, statistical analysis.*

Riassunto: *L'ambiente dei vigneti è stato recentemente studiato per fornire informazioni utili a supportare e migliorare la gestione della coltura e la produzione del vino. Durante le stagioni vegetative 2008, 2009 e 2010 si è svolta una campagna sperimentale in cui sono state effettuate misure di diverse variabili per studiare il microclima di tre vigneti piemontesi, caratterizzati dallo stesso clima ma da diverse condizioni microclimatiche (progetto MASGRAPE). Sono stati analizzati i processi di scambio di energia e massa avvenuti nei vigneti, caratterizzati dalla presenza di un terreno complesso, fornendo un archivio di osservazioni non comunemente effettuate all'interno di vigneti. I risultati hanno evidenziato che la maggior parte delle variabili presenta un andamento simile ma, confrontando i dati dei tre siti, emergono differenze peculiari. Queste differenze sono generalmente piccole ma sufficienti per influenzare i bilanci energetici e idrologici. Considerando anche le differenze nelle caratteristiche del terreno, le variabili micrometeorologiche possono fortemente influenzare la maturazione e la qualità dell'uva. Nell'attuale contesto di cambiamento climatico, questo tipo di osservazioni può costituire un punto di partenza per valutare gli effetti del clima sulla produzione di uva.*
Parole chiave: *Vigneti, stazioni meteorologiche, misure sperimentali, analisi statistica.*

1. INTRODUCTION

Grapevine agroecosystem represents an interesting environment to be investigated, since grape and wine production is a great economic activity, with Europe possessing the largest area planted with vines among continents (~38%), despite its not large area. This is also true both for Italy and for its Piedmont region, in which famous and high–quality wines are produced.

Grapevine productivity depends on several factors, including soil fertility, management practices, climate and meteorology. It is thus particularly important to study the effects of a changing climate on the vineyard's yield and quality. More precisely, it is essential to understand how and how much climate and meteorology affect grape productivity and quality. Vineyards micrometeorology could be evaluated by examining thermodynamic variables and studying exchange processes between soil, canopy, and atmosphere.

In recent years, several studies and experimental campaigns were carried out in the world, with the aim to improve the understanding of grapevine agro-ecosystem and the quality of both fruit and wine production. Some studies were related to the evaluation of the phenological phases of different cultivars (Cortazar-Atauri *et al.*, 2009; Mariani *et al.*, 2013; Tomasi *et al.*, 2011); other studies concern the estimation of yield, dry matter, and sugar accumulation (Poni *et al.*, 2006; Cortazar–Atauri *et al.*, 2009; Cola *et al.*, 2014), or the evaluation of different vineyards management strategies (Valdes-Gomez *et al.*, 2009; Rossi *et al.*, 2014). As also indicated by Caffarra and Eccel (2010), phenological models are certainly

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Submitted 11 January 2018, accepted 1 February 2018

DOI:10.19199/2018.2.2038-5625.027

important tools for planning viticultural practices in the short term, but are also important for projecting the impact of climate change on grapevine in the long term. In this respect, the availability of multiple data at vineyard's site could allow the implementation of sophisticated phenologic algorythms, less dependent on parameters to be tuned for each variety.

Other investigations were related to the understanding of the grapevine response to atmospheric carbon dioxide and water consumption through experimental measurements and flux modeling (Spano *et al.*, 2008; Castellvi and Snyder, 2010; Oliver *et al.*, 1992). Energy fluxes were also estimated from sloping crops using standard agrometeorological measurements and topography (Rana *et al.*, 2007), and the method of energy balance models for assessing surface energy fluxes in vineyards was used also by Gonzalez-Dugo *et al.* (2012) for estimating evapotranspiration in vineyards. In this respect, net radiation is the main energy budget component, controlling evapotranspiration processes, and was considered by several authors, such as Carrasco *et al.* (2008), in their analyses.

Other authors (Nicholas *et al.*, 2011) studied the relationship between climate statistics derived from hourly temperature measures in individual vineyards and key phenolic compounds, inferring important correlations for determining premium wine quality when instantaneous measurements are used.

In any case, the importance of considering grape temperature, instead of the commonly measured screen-level temperature, is considered fundamental in order to understand, and possibly model, the wide variety of biochemical and physiological processes taking place during the berry ripening (Cola *et al.*, 2009). Matese *et al.*, (2013) monitored some agrometeorological variables directly in the vineyard, with the aim to support management practices. In this respect, the study of Asproudi *et al.*, (2016), on individual Nebbiolo grapes in Italy, revealed that primarily temperature, but also other microclimatic conditions, such as radiation, both intended as measured on the berries, affect the final content of some aroma precursors. Radiation exposure and berry temperatures resulted also the most important parameters influencing berry quality, according to the study of Pereira *et al.*, (2006), who analyzed a specific Merlot vineyard in France. Also the study of Sanna *et al.*, (2014), which assessed the improvement of the models capability in forecasting grapevine infections when more precise and calibrated data are available in input, can be considered as a confirmation about the importance of data quality in vineyard's management. And a similar conclusion was reached also by Matese *et al.*, (2014), which provided information about spatial variability at different scales from a statistical point of view: these authors pointed out that data taken from agrometeorological stations may not be fully representative of actual field conditions.

Taking into account these premises and those findings, in the territory object of this study, Piedmont region, vineyards are located on the hills of Monferrato, Langhe and Roero, often characterized by not negligible inclination (which, according to wine experts, ensures the best microclimate for wine production). Over this complex terrain, exchange processes were explored in three vineyards located on different slopes by means of measurements and numerical simulations carried out with a land surface model (Francone *et al.*, 2012) originally developed by one of the authors (Cassardo *et al.*, 1995a) and subsequently refined and adapted for agrometeorological purposes (Cassardo, 2006; Cassardo, 2015) with the inclusion of carbon budget and photosynthetic activity evaluation.

Microclimate conditions within the vineyards may differ consistently from the conditions existing externally to the vineyards, due to the presence of vertically-oriented vegetation, and because vineyards can be differently organized in terms of size, aspect, declivity and row orientation, particularly in hilly regions, where viticulture is mainly widespread. Moreover, when vineyards surfaces are tilted, soil texture and parameters can differ in different zones of the vineyard.

Thus, in principle, standard weather and agrometeorological monitoring networks could be not immediately suitable for characterizing the microclimate within vegetation, because the sensors are usually placed outside the rows and, in any case, positioned above the canopy level, and thus they are not representative of the real physical conditions at which the plants are subjected. Despite these problems, these data can be used as references, in order to find eventual relationships with variables measured within vineyards, or be used as ancillary data where and when such specific within-canopy measurements are not available.

Thus, during the measurements campaigns, special sets of conventional instruments, with

10 minutes acquisition rate, for monitoring the meteorological conditions above and within the vine canopy and in the soil, were installed. Other fast response instruments (sonic anemometers, and hygrometers), and radiometers, ordinarily not used for conventional measurements in vineyards, were also installed in order to perform turbulence measurements with high acquisition rates (> 10Hz), and then evaluate surface turbulent fluxes of momentum and heat.
The variables sampled during the experimental campaign were selected among those of agronomic interest: air temperature and solar radiation (measured above and within the vegetation), soil temperature, soil water content, and turbulent heat fluxes between soil or vegetation and atmosphere.
The main aim of the measurements campaign was to create a database of data suitable to perform the analysis of exchange processes between soil, vegetation and atmosphere, with a particular focus on the influence of terrain morphology and vineyards system. A secondary aim of such database of micrometeorological parameters was to allow to perform correlations of those data with the grape quality and productivity. This paper deals with the first objective.

2. MATERIALS AND METHODS

Measurements were collected during 2008, 2009 and 2010 vegetative seasons (e.g. from May to September) in three hilly sites, in which Barbera and Nebbiolo grapevines were planted. Such measurements were performed in the frame of a wide regional project, named MASGRAPE (adoption of a Multidisciplinary Approach to Study the GRAPEvine agroecosystem: analysis of biotic and abiotic factors able to influence yield and quality; Francone *et al.*, 2012a) and aimed to assess several factors related to grape productivity. The detailed analysis was performed in the frame of project MACSUR2 (the second phase of the project MACSUR – Modelling European Agriculture with Climate Change on Food Security, whose full proposal is available here[1]).
The above mentioned three experimental sites are: Cocconato (45°05′ N; 8°03′ E; 311 m a.s.l.), Fubine (44°58′ N; 8°26′ E; 210 m a.s.l.) and Castiglione

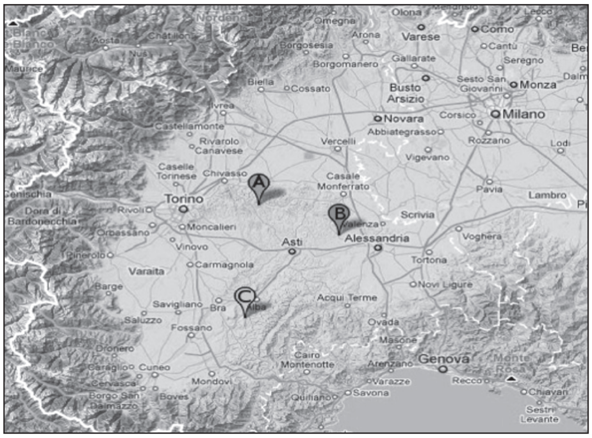

Fig. 1 - Location of the three sites: Cocconato (A), Fubine (B), and Castiglione Falletto (C).
Fig. 1 - Posizione dei tre siti: Cocconato (A), Fubine (B) and Castiglione Falletto (C).

Falletto (44°37′ N; 7°59′ E; 275 m a.s.l.) (Fig. 1), all located in the most important productive wine zones of Piemonte region, in North-western Italy. The climate of the experimental area is continental, mitigated by the relative vicinity of the Ligurian-Mediterranean Sea (about 50-70 km on straight line, southwards). The three sites are characterized by heterogeneous properties, in terms of geomorphology and vegetation cover. In these sites, the vineyards were placed in rows 2.5 m apart from each other, and trained on vertical shoot–positioned system (VSP), perpendicular to the contour lines (*ritocchino*) at Cocconato and aligned with them (*giropoggio*) at Fubine and Castiglione Falletto. The three vineyards were oriented southwards (Cocconato), south–eastwards (Fubine), and eastwards (Castiglione Falletto). The soil texture of the top layer was classified as silty clay loam for Cocconato, loam for Fubine, and silty loam for Castiglione Falletto. The soil surface below the vines was bare, while between the rows there was short grass. The canopy structure was changing along the seasons, due to the vine physiology and to specific management practices (lopping and thinning of the canopy).
In the analyzed vineyards, meteorological data were monitored continuously (10 minutes acquisition rate). However, due to technical reasons (electric blackouts, failure of acquisition system, etc.), some discontinuities in the recorded data are present.
Air temperature and relative humidity were measured above and within the canopy in a shelter (H08–032–IS, Hobo Pro RH and Temperature Data Logger). The photosynthetically active

[1] MACSUR phase 1: https://macsur.eu/images/download/fullproposal.pdf
MACSUR phase 2: https://macsur.eu/images/download/MACSUR2%20Proposal.pdf

radiation (PAR) was recorded above and within the canopy (S–LIA–M003, Photosynthetic Light Smart Sensor, Hobo), while the solar global radiation (GR) was estimated from the PAR above the canopy, by assuming that the ratio between PAR and GR is constant and equal to 0.4 (Prino, 2007; Prino *et al.*, 2009).

The list of slow–response instruments is completed by the sensors to monitor soil temperature (S–TMA–M006 8–Bit Temp Smart Sensor) and volumetric water content (S–SMA–M005 Dielectric Aquameter EC–20, Decagon), installed into the top layer of the soil, 15 cm below the surface.

In addition, limited only to the 2009 and 2010 vegetative seasons, three fast response 3–D ultrasonic anemometers (Solent R2, gill Instruments, data acquisition rates > 10Hz) were installed 3 m above the soil surface, and one fast response hygrometer (Krypton lamp KH20) was installed only in one site (Fubine), very close to the ultrasonic anemometer. Finally, since July 2009, also a net radiation transducer (t056 TRADNT, SIAP+MICROS) was positioned on a meadow near to the vine rows.

Raw data were visualized and stored on a laptop with a dedicated software; the laptop and power supply connection were hold on a dedicated cabinet, located along the vine rows. Data were transferred on portable disks approximately every two weeks. Collected data were stored in a database and processed in order to obtain hourly data series.

Fast response data obtained using 3–dimensional ultrasonic anemometers and a fast response hygrometer were elaborated by employing eddy covariance method to evaluate sensible (SHF) and latent (LHF) heat fluxes, which are important physical variables related to water and energy exchange processes at biosphere/atmosphere interface. In particular, eddy covariance method was proven also by other studies to be the best way to give realistic estimates of turbulent sensible heat flux (Consoli and Papa, 2012) and evaporation flux (Shapland *et al.*, 2013; Papa and Consoli, 2013) over vegetated terrain, even if, in case of sparse high vegetation, other approaches based on different techniques could give more precise values (Cammalleri *et al.*, 2014). In any case, the errors in the estimation of turbulent heat fluxes using eddy covariance can be approximately quantified in about 50 Wm^{-2}, in agreement with the considerations expressed by Masseroni *et al.*, (2013) in their studies.

To address the problem of terrain inhomogeneity and slope disuniformity, particularly evident in hilly vineyards, and that could force the air to flow over a plane not parallel to the terrain, the planar fit method (PFM – Wilczak *et al.*, 2001; also detailed in Richiardone *et al.*, 2008) was employed, which consists in taking a two-dimensional linear regression of the vertical component versus the horizontal ones over long time periods (weeks or more) during which the anemometer position did not change. This method proved to produce better results over complex terrain than the triple rotation method (Mc Millan, 1988; referenced also more clearly in Cassardo *et al.*, 1995b), in which, during each short period (about 30-60 minutes) when the turbulent fluxes are evaluated, the imposition of having the mean wind oriented alng te streamlines, $-\overline{w}=0$ and $-\overline{v'w'}=0$ could produce a wrong estimation of the fluxes.

The LHF was evaluated using the signal of the Krypton lamp and combining its fluctuations, proportional to those of water vapor content q′, with those of the vertical wind speed w' (corrected by the PF), in order to give $-\overline{w'q'}$. when Krypton lamp was unavilable, "sonic" SHF ($-\overline{w'T_s'}$) (T_s being the sonic temperature) was convrted into "real" SHF ($-\overline{w'T'}$) by using humidity measured by conventional hygrometers (Cassardo *et al.*, 1995b).

3. RESULTS

The present section contains a summary of main results obtained by the analysis of all experimental measurements collected in the campaign performed during 2008, 2009 and 2010 vegetative seasons. The data are presented frequently as daily mean, but sometimes also the typical day (obtained by averaging all observations carried out at same hour in different days) is shown.

3.1. Temperature measurements

Temperature measurements were performed above and within the canopy vineyards, in a shelter, at Castiglione Falletto and Fubine, while at Cocconato vineyard measurements were performed only above the canopy. Most measurements were performed during the vegetative season (from March to October, on average). Since there are some missing data that are making difficult a direct comparison between the three sites, the data of some relevant meteorological variables (air temperature, humidity, and pressure; precipitation; wind speed; radiation) were interpolated by using the data collected in the stations belonging to the

AGRO and ARPA Stations	Stations coordinates		
	Lon (g.dddd)	Lat (gg.dddd)	Quote (m a.s.l.)
Asti	8.1131	44,5509	175
Barolo	6.9576	44,6606	360
Baldissero d'Alba	7.5521	44.4512	265
Bra	7.5109	44,4208	298
Bra Isola	7.5026	44.4136	290
Buttigliera	7.5602	45.0115	290
Carmagnola	7.4115	44.5314	232
Casale Monferrato	8.3019	45.0759	136
Castagnole Monferrato	8.3025	44.9650	220
Castelnuovo Don Bosco	7.9575	45.0614	352
Castiglione Falletto	7.9772	44.6289	309
Cocconato	8.0568	45.0819	321
Crea	8.1643	45.0541	385
Cuccaro	8.4528	44.9800	230
La Morra	7.9433	44.6289	326
Montechiaro	8.0608	45.0029	200
Murisengo	8.1447	45.0786	340
Occimiano	8.5033	45.0592	114
Pino Torinese	7.4558	45.0232	608
Quargnento	8.5158	44.9403	108
Rosignano	8.4169	45.0664	207
Serralunga d'Alba	8.9890	44.6398	289
Treiso	8.0459	44.4042	376
Verolengo	8.0043	45.1110	163
Vezzolano	7.9608	45.0819	420

Tab. 1 - Coordinates (longitude East and latitude North, respectively, in degrees and decimals, and elevation, in m a.s.l.).
Tab. 1 - coordinate (longitudine Est e latitudine Nord, rispettivamente, in gradi e decimali, e quota, in m s.l.m.).

regional networks of Environmental Protection Agency (ARPA Piemonte, hereafter simply called ARPA) and Agrometeorological Service (hereafter called AGRO). (Tab. 1) reports the coordinates of all stations used.

For each variable, the regression and the correlation coefficient between each experimental site and each station were evaluated, considering daily mean values (or cumulated for precipitation). Subsequently, missing data were interpolated as

Variables and stations	bias	rmse
Castiglione Falletto global radiation above the canopy (W m^{-2})	-9	4
Castiglione Falletto global radiation within the canopy (W m^{-2})	-7	2
Cocconato global radiation above the canopy (W m^{-2})	-3	3
Cocconato global radiation within the canopy (W m^{-2})	-10	6
Fubine global radiation above the canopy (W m^{-2})	>6	2
Fubine global radiation within the canopy (W m^{-2})	0	4
Castiglione Falletto air temperature above the canopy (° C)	0.00	0.02
Castiglione Falletto air temperature within the canopy (° C)	0.00	0.06
Cocconato air temperature above the canopy (° C)	0.00	0.03
Fubine air temperature above the canopy (° C)	0.00	0.02
Fubine air temperature within the canopy (° C)	0.00	0.03
Castiglione Falletto wind speed ux (m s^{-1})	0.00	0.01
Castiglione Falletto wind speed uy (m s^{-1})	0.20	0.01
Cocconato wind speed ux (m s^{-1})	0.00	0.01
Cocconato wind speed uy (m s^{-1})	-0.30	0.02
Fubine wind speed ux (m s^{-1})	0.00	0.01
Fubine wind speed uy (m s^{-1})	-0.10	0.03
Cocconato dew point above the canopy (° C)	0.0	0.1
Fubine dew point above the canopy (° C)	0.0	0.2

Tab. 2 - Bias and root mean square error for each site and variable reconstructed.
Tab. 2 - Bias ed errore quadratico medio per ogni sito e variabile ricostruita.

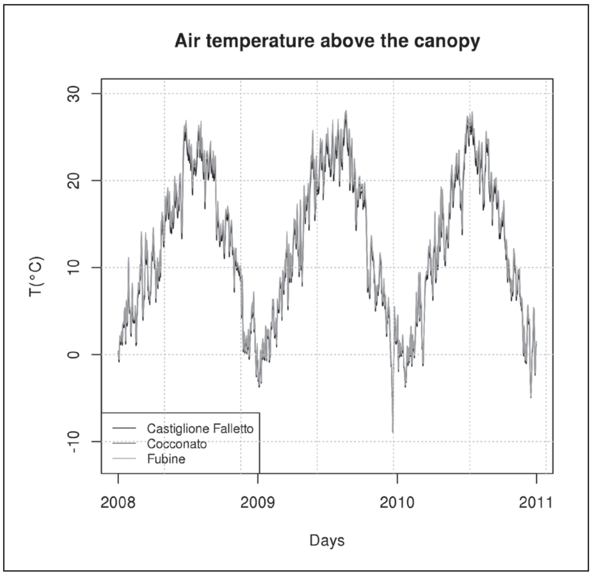

Fig. 2 - Mean daily air temperature above canopy measured or reconstructed in the three sites.
Fig. 2 - Temperatura media giornaliera sopra la vegetazione misurata o ricostruita nei tre siti.

weighted averages of all station data reconstructed using regression lines. Weights were taken proportional to correlation coefficients.
The method was tested by evaluating the bias between measured data and interpolated data. Such values are reported in (Tab. 2) for each variable and station. An alternative method of reconstruction was tested, in which, instead of considering daily mean values, daily minimum and maximum values were used for making two separate regressions with their correlation coefficients. In this way, for each day both minimum and maximum temperature were reconstructed separately, and then each instantaneous values was interpolated between them. However, the error of the reconstructed method based on daily mean values was lower for each variable and in each station, thus this method was selected. The reconstructed data show small errors for temperature and pressure, medium errors for relative humidity and radiation, and relatively large errors for wind speed, humidity and precipitation. (Fig. 2) shows the values of air temperatures from the database of reconstructed data.
In (Fig. 3), the comparison between temperature data above and within canopy, during spring 2009 in Fubine site, is shown. The period was chosen in order to have both data measured contemporary, without missing data. To make the plot more visible and to evidence the respective daily trends, data corresponding to the same hour of different days were averaged, thus this plot represents the "typical day". It is evident that the thermometer within the vineyard detects a higher value one hour earlier, while minima timings almost coincide, the temperature within the canopy being slightly colder. Thus, daily thermal excursion within the canopy is about 3 °C larger than the one above the vineyards. This behavior is not surprising, and can be explained by considering that the instrument within canopy is closer to the soil surface, and is thus more influenced by soil heating, during day time, or cooling, during night time. The data shown in (Fig. 3) refer to spring time; in other seasons, temperature behaviors are different, because the canopy layer is more or less dense or active, but the differences can always be interpreted using considerations similar to those above mentioned.
(Fig. 4) shows the comparison between temperature data collected above the canopy in the three vineyards. Also in this case, the "typical day" was evaluated, in order to evidence the daily trend.

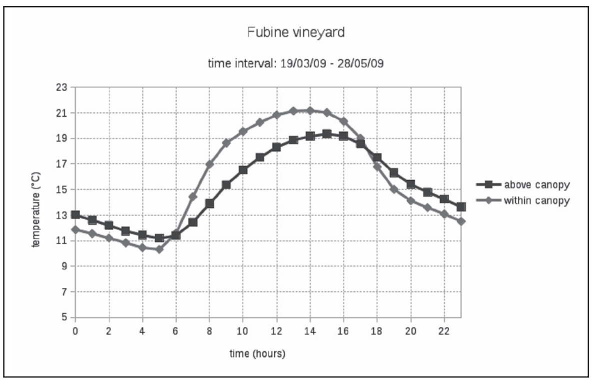

Fig. 3 - Comparison of temparature data above and within the canopy at Fubine vineyard.
Fig. 3 - Confronto fra i dati di temperatura sopra e in mezzo alla vegetazione nel vigneto di Fubine.

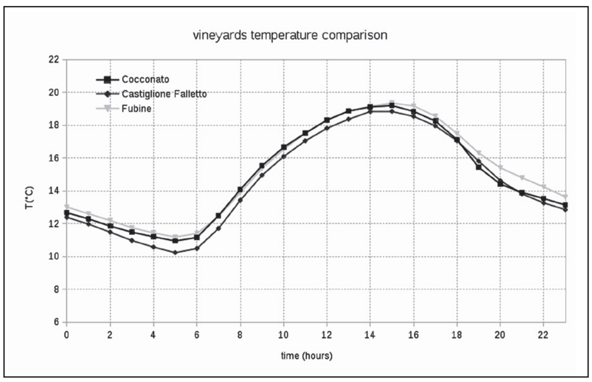

Fig. 4 - Comparison of temperature data, above canopy, measured in the three sites during spring 2009.
Fig. 4 - Confronto dei dati di temperatura, sopra la vegetazione, nei tre siti durante la primavera 2009.

	Mean	Standard deviation	Median	Min	Max	Range	Standard error
Air temperature above the canopy, Castiglione Falletto (°C) (reconstructed data)	12.3	8.2	12.3	-8.9	27.0	35.9	0.3
Air temperature above the canopy, Cocconato (°C) (reconstructed data)	12.7	8.3	12.8	-8.8	27.7	36.5	0.3
Air temperature above the canopy, Fubine (°C) (reconstructed data)	13.0	8.4	13.0	-8.9	28.1	36.9	0.3
Air temperature difference (above minus within canopy) Castiglione Falletto (°C) (recorded data)	-0.6	0.4	-0.6	-1.5	0.5	1.9	0.0
Air temperature difference (above minus within canopy) Fubine (°C) (recorded data)	-0.3	0.5	-0.2	-2.1	0.7	2.9	0.0

Tab. 3 - Statistical analysis of mean daily value of air temperature of reconstructed data and of difference between temperature measured above and within the canopy, during 2008, 2009 and 2010 seasons.
Tab. 3 - Analisi statistica dei valori medi giornalieri di temperatura dell'aria dei dati ricostruiti e della differenza tre la temperatura misurata sopra e in mezzo alla vegetazione, durante il 2008, 2009 e 2010.

All sites show a similar trend, but a closer inspection reveals small but significant differences, attributable to specific characteristics, such as different sites altitude or exposure. However, minima and maxima timings are coincident, in the three sites, meaning that the different orientation of the exposition (South at Cocconato, South–East at Fubine, and East at Castiglione Falletto) do not affects daily mean temperature.
(Tab. 3) shows the statistical analysis of mean daily air temperature reconstructed data over 2008 – 2010 time period, in the three sites, and the analysis of mean daily air temperature differences between the values recorded above and within the canopy, in Castiglione Falletto and Fubine.
The inspection of the values shown in (Tab. 3) shows that the warmest site is Fubine, on average, and that this difference is evident during daytime, but is limited to only 1 °C. Regarding the difference between above – and within – canopy temperatures, on average the difference is about 0.5 °C or less, but the former is higher (lower) during daytime (nighttime) by 2-3 °C.

3.2. Radiation measurements

PAR radiation is the portion of solar radiation, within the spectral range of 400 – 700 nm, absorbed by plants for photosynthesis; shorter and higher wavelengths are reflected by leaves epidermis.
Usually, the plants use more red and blue wavelengths, and less green wavelengths, thus maximizing the green portion of radiation in the reflection. For a given incoming radiation above the canopy, the radiation within the canopy is determined by the plant structure and the radiative properties of the various canopy elements and the ground surface, as well as the leaves density.

The transmission of incoming radiation into the plant canopy shows an approximately exponential decay with an attenuation following the Beer law $I=I_0e^{(-LAI.k)}$, in which k is an extinction coefficient equal to 0.55 for grapevine (Prino *et al.*, 2009) and LAI is the leaf area index (the area of total leaves per unit of ground area).
Global radiation was estimated from PAR data by means of spectral considerations, by assuming the following equation

$$GR=\frac{PAR}{0.4}$$

(Prino *et al.*, 2009). PAR measurements were performed above and within the canopy vineyard in all three experimental sites.
The comparison between PAR above and within the vine canopy, during summer 2009, is shown in (Figs. 5-7), where the different patterns are evidenced in the graphics by plotting the "typical day". The amount of radiation intercepted by the canopy varies from site to site and from season to

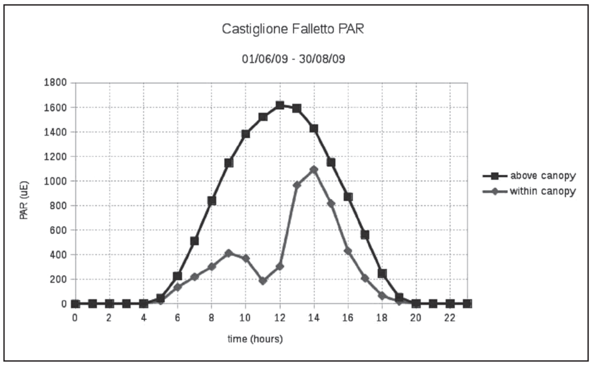

Fig. 5 - Typical day of PAR measured above and within Castiglione Falletto vineyard in summer.
Fig. 5 - Giorno tipico di PAR misurata sopra e dentro il vigneto di Castiglione Falletto d'estate.

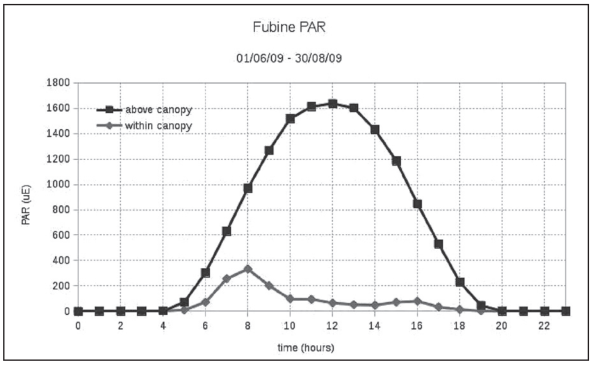

Fig. 6 - Typical day of PAR measured above and within Fubine vineyard in summer.
Fig. 6 - Giorno tipico di PAR misurata sopra e dentro il vigneto di Fubine d'estate.

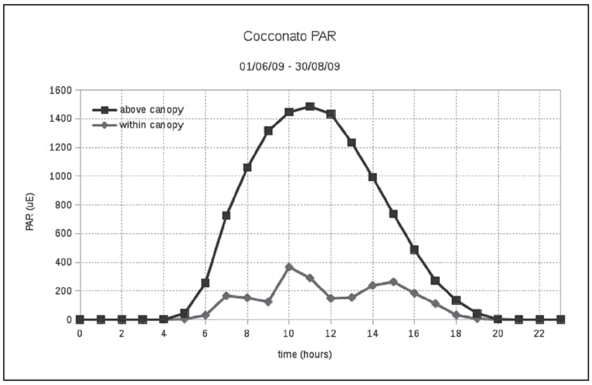

Fig. 7 - Typical day of PAR measured above and within Cocconato vineyard in summer.
Fig. 7 - Giorno tipico di PAR misurata sopra e dentro il vigneto di Cocconato d'estate.

season, and it is also depending on how and where the vegetation has covered the sensor, as well as on vineyards structure and its management.

The differences between the PARs are greater during summer, when leaf area index (LAI) reaches its maximum annual value, and for this reason we have decided to show PAR values during this season in (Figs. 5-7).

Both above- and within-canopy radiation show some differences in the daily trend. Cocconato shows both maxima before noon, while in the other two sites the maximum of above-canopy radiation is at noon, and those of within-canopy radiation are in the morning (Fubine) and in the afternoon (Castiglione Falletto). Considering the combined effect of the different orientation of the exposition (South at Cocconato, South-East at Fubine, and East at Castiglione Falletto) and the different vertical shoot-positioned system (VSP), perpendicular to the contour lines (*ritocchino*) at Cocconato and aligned with them (*giropoggio*) at Fubine and Castiglione Falletto, it may be concluded that such differences impact in a detectable way on the radiation received by the vegetation (and, consequently, by the grape), even if this does not have particular effects on air daily mean temperature.

The comparison between the estimated global radiation above the canopy, in three sites, shown as monthly average to decrease the large daily variability of the data, is shown in (Fig. 8). This figure evidences the differences among the three sites in the summer values, larger at Fubine and lower at Cocconato, with an average difference,

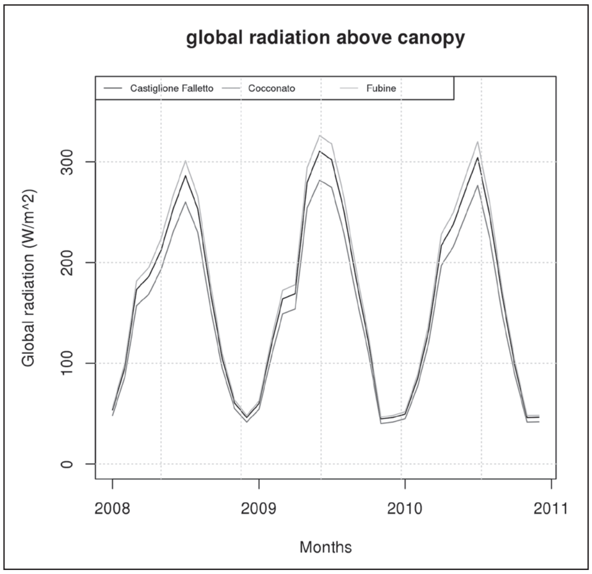

Fig. 8 - Mean monthly global radiation values of reconstructed data in the three sites.
Fig. 8 - Valori medi mensili di radiazione globale ricostruiti nei tre siti.

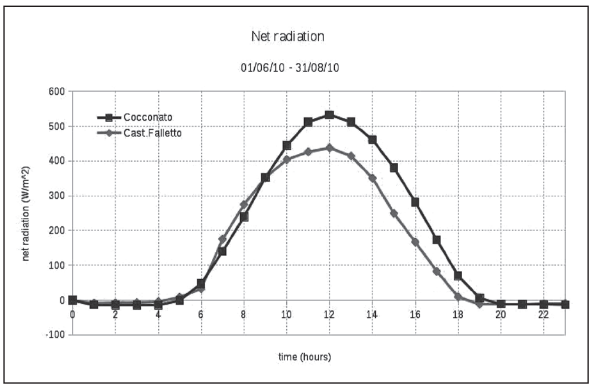

Fig. 9 - Net radiation measured at Castiglione Falletto and Cocconato vineyards.
Fig. 9 - Radiazione netta misurata nei vigneti di Castiglione Falletto e Cocconato.

	Mean	Standard deviation	Median	Min	Max	Range	Standard error
Global radiation above the canopy Castiglione Falletto (W m^{-2}) (reconstructed data)	163	106	153	1	364	363	3
Global radiation above the canopy Cocconato (W m^{-2}) (reconstructed data)	148	96	140	1	331	330	3
Global radiation above the canopy Fubine (W m^{-2}) (reconstructed data)	171	111	161	1	383	382	3
Global radiation difference (above minus within canopy) Castiglione Falletto (W m^{-2}) (recorded data)	118	101	123	-8	356	364	4
Global radiation difference (above minus within canopy) Cocconato (W m^{-2}) (recorded data)	77	107	33	-84	332	416	5
Global radiation difference (above minus within canopy) Fubine (W m^{-2}) (recorded data)	177	109	181	-12	384	396	5

Tab. 4 - Statistical analysis of mean daily values of global radiation of reconstructed data and of difference between radiation recorded above and within the vine canopy during 2008, 2009 and 2010 seasons.
Tab. 4 - Analisi statistica dei valori medi giornalieri di radiazione solare globale ricostruiti e della variazione tra i valori registrati sopra e dentro la vegetazione, durante le stagioni 2008, 2009 e 2010.

in July, of about 50 W m^{-2}. Despite this difference could appear large, considering the propagation of error in the formula used to derive global radiation from PAR (the variable effectively measured), it is compatible with the typical measurement error of the instrument (usually some tenths of Wm^{-2}).
The measurements of net radiation were carried out only at Castiglione Falletto and Cocconato sites. In (Fig. 9) the typical day of the net radiation, measured during summer 2010, is shown. The maxima occur at 12 a.m. and their values differ by about 100 *W/m²*. Also the shape of curves is different, because after the similar growth in the morning, the net radiation at Castiglione Falletto increases less after 9 a.m. and maintains a gap also in the afternoon. Such behavior is also present in the global radiation curve (not shown as direct comparison of typical day as in (Fig. 9), but understandable by comparing time trends of the typical days of global radiation in (Figs. 5-7), or looking at (Tab. 4), and may be caused by the different tilting and exposition of the surface in the two vineyards, rather that by albedo differences.

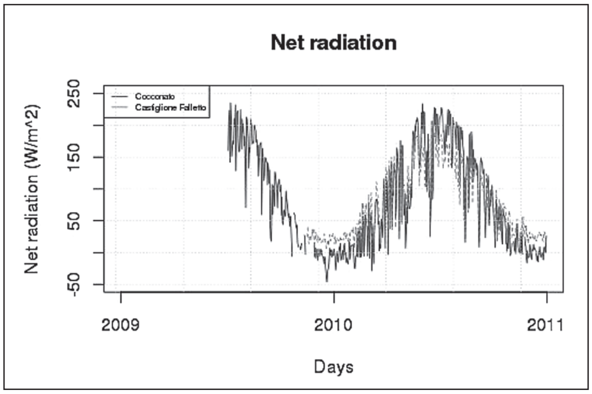

Fig. 10 - Mean daily net radiation values recorded in Cocconato and Castiglione Falletto.
Fig. 10 - Valori medi giornalieri di radiazione netta misurati a Cocconato e Castiglione Falletto.

(Fig. 10) shows the time trend of daily mean values recorded in the same two stations, while in (Tab. 5) the statistical analysis of mean daily net radiation data are shown.
Cocconato station globally records about 10 Wm^{-2} than Castiglion Falletto, but there are some seasonal differences (in winter Cocconato values are the lowest, while in Castiglion Fal-

	Mean	Standard deviation	Median	Min	Max	Range	Standard error
Net radiation Castiglione Falletto (W m^{-2}) (recorded data)	76	55	60	6	208	202	2
Net radiation Cocconato (W m^{-2}) (recorded data)	85	77	69	-46	235	281	3

Tab. 5 - Statistical analysis of mean daily value of net radiation of recorded data in Castiglione Falletto and Cocconato during 2009 and 2010 seasons.
Tab. 5 - Analisi statistica dei valori medi giornalieri di radiazione netta misurata a Castiglione Falletto e Cocconato durante le stagioni 2009 e 2010.

letto, also during winter time, the daily mean net radiation is positive; in summer, Castiglion Falletto daily means are much higher than Cocconato ones). These differences may be attributed to a series of different causes that involve soil variables (temperature and moisture) and characteristics (such as albedo and soil type), and eventually also the surface tilting. However, the fact that daily mean values are always positive in Cocconato may suggest some sensor malfunction.

3.3. Soil temperature and water content measurements

Measurements of soil temperature (ST) and volumetric water content (VWC) were performed only at Cocconato and Fubine vineyards (ST at both, VWC only at Cocconato), where the soil texture of top layer was classified as silty clay loam and loam, respectively. The sensors were installed 15 cm below the soil surface. Measured values of ST and VWC are shown in (Fig. 11, 12).
The analysis of behavior of soil temperature allow to define as warm season the period from the beginning of May to the end of September. The inspection of data of soil water content shows a general decrease during the warm season: the VWC frequently falls below the wilting poin (0.21 $m^3_{water} m^{-3}_{soil}$ for the type of soil at Cocconato) already at the beginning of June. The peaks shown in the graphic occur only in occasion of relevant rainfalls, and the minimum value of VWC is reached in September, during 2009 summer. The steep decrease of VWC during the periods without rainfall in summer is caused by the strong evapotranspiration and the relevant drainage caused by the high hydraulic conductivity when VWC is high.
(Tab. 6) shows the statistical analysis of the soil temperature and volumetric water content.

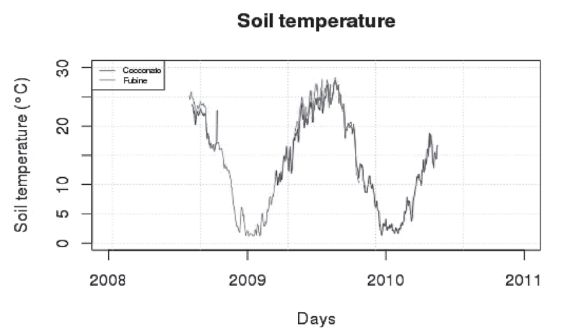

Fig. 11 - Mean daily soil temperature values recorded at 15 cm underground in Cocconato and Fubine.
Fig. 11 - Valori medi giornalieri di temperatura nel terreno misurati 15 cm sottoterra a Cocconato e Fubine.

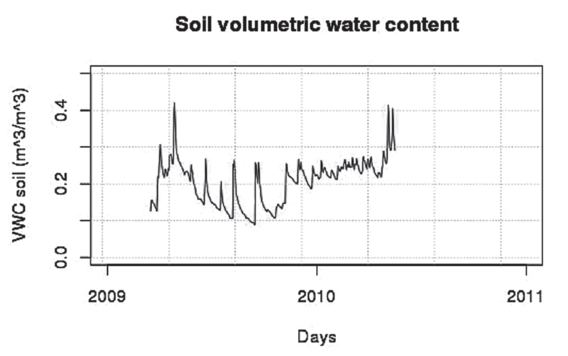

Fig. 12 - Mean daily soil volumetric water content values (in m^3_{water} m^{-3}_{soil}) recorded at 15 cm underground in Cocconato.
Fig. 12 - Valori medi giornalieri di contenuto volumetrico di acqua nel suolo (in m^3_{acqua} m^{-3}_{suolo}) misurati 15 cm sottoterra a Cocconato.

3.4. Heat fluxes measurements

Sensible (SHF) and latent (LHF) heat fluxes were evaluated during 2009 and 2010 seasons: SHF in all three sites (Fig. 13), and LHF only in Fubine (Fig. 14). The SHF values, shown in (Figs. 13, 14, 15), evidentiate an increase of the flux during

	Mean	Standard deviation	Median	Min	Max	Range	Standard error
Soil temperature at 15 cm (°C) Cocconato	15.1	7.5	15.8	1.3	27.8	26.5	0.3
Soil temperature at 15 cm (°C) Fubine	16.2	8.8	19.1	1.2	28.3	27.1	0.4
Soil volumetric water content (m^3_{water} m^{-3}_{soil}) at 15 cm – Cocconato	0.20	0.06	0.22	0.09	0.42	0.33	0.00

Tab. 6 - Statistical analysis of mean daily value of soil temperature and volumetric water content measured 15 cm underground during the period 2008-2010 seasons at Cocconato and Fubine.
Tab. 6 - Analisi statistica dei valori medi giornalieri di temperatura nel suolo e contenuto volumetrico di umidità misurati 15 cm sottoterra durante il periodo 2008-2010 a Cocconato e Fubine.

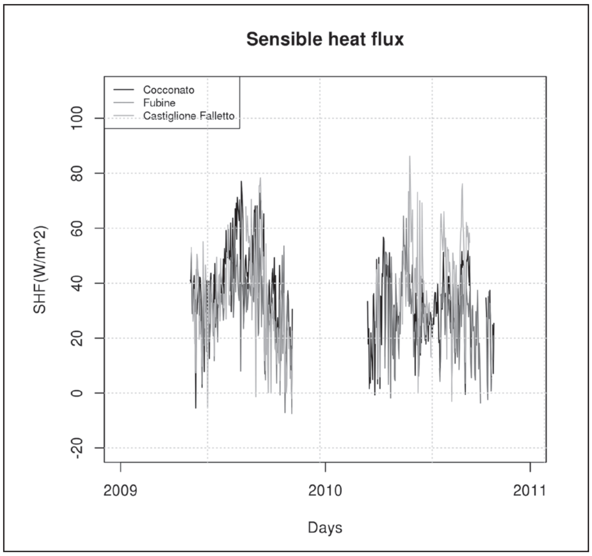

Fig. 13 - Mean daily values of sensible heat flux recorded in the threesites during 2009 and 2010 seasons.
Fig. 13 - Valori medi giornalieri di flusso di calore sensibile misurati nei tre siti nelle stagioni 2009 e 2010.

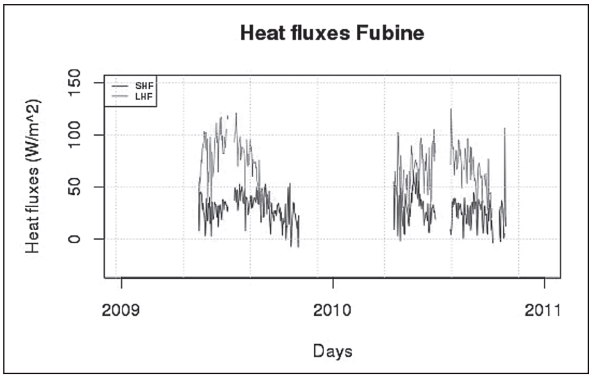

Fig. 14 - Mean daily values of sensible and latent heat fluxes recorded in Fubine during 2009 and 2010 seasons.
Fig. 14 - Valori medi giornalieri di flusso di calore sensibile e latente misurati a Fubine nelle stagioni 2009 e 2010.

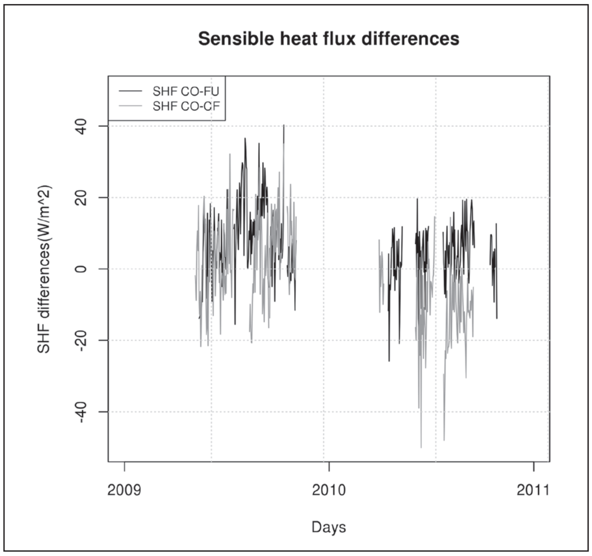

Fig. 15 - Mean daily sensible heat flux differences (Cocconato values minus Fubine and Castiglione Falletto values) recorded during 2009 and 2010 seasons.
Fig. 15 - Differenze medie giornaliere di flusso di calore sensibile (calcolaticome valori di Cocconato meno valori di Fubine e Castiglione Falletto) misurati nelle stagioni 2009 e 2010.

the warm season of 2009, while 2010 vegetative season shows values larger than 2009 during early (March to May) and late (August and September) months.

More in detail (Tab. 7), during 2009 values in Cocconato are higher than in other two sites, especially Fubine, with daily mean differences of about 20 W m^{-2}, larger in August. On the contrary, during 2010, Cocconato and Fubine SHF values are similar, while Castiglion Falletto values are larger by 10-20 W m^{-2}. Regarding LHF, which is the physical measure of the evapotranspiration, and was measured only in Fubine, this value

	Mean	Standard deviation	Median	Min	Max	Range	Standard error
SHF (W m^{-2}) Cocconato	34	16	34	-5	77	83	1
SHF (W m^{-2}) Fubine	29	13	30	-8	64	72	1
LHF (W m^{-2}) Fubine	68	24	70	11	125	114	1
SHF (W m^{-2}) Castiglione Falletto	37	18	36	-5	86	91	1
SHF difference (CO - FU) (W m^{-2})	7	10	6	-26	40	66	1
SHF difference (CO - CF) (W m^{-2})	-2	14	-2	-50	35	85	1

Tab. 7 - Statistical analysis of mean daily value of sensible (SHF) and latent (LHF) heat fluxes recorded during 2009 and 2010 seasons.
Tab. 7 - Analisi statistica dei valori medi giornalieri di flusso di calore sensibile (SHF) e latente (LHF) misurati nelle stagioni 2009 e 2010.

appears larger than SHF during the warmest months, with a numerical value almost double (meaning a Bowen ratio of about 0.5 or less in this location).

4. CONCLUSIONS

This paper describes the detailed analysis of the data measured during 2008, 2009 and 2010 vegetative seasons (from May to September) in three vineyards located on hilly sites in Piemonte region (northern Italy).

The instruments installed included conventional instruments, for monitoring the meteorological conditions above and within the vine canopy and in the soil, and fast response instruments and radiometers, to evaluate energy balance.

The results of the analysis confirmed that microclimate conditions within the vine-yards may differ consistently from the conditions existing externally to the vineyards, particularly in hilly regions, as those we analyzed. As a corollary, the use of data coming from conventional meteorological and agro-meteorological monitoring stations located at a certain distance from the vineyard could not allow to directly characterize its microclimate or micrometeorological conditions, because the measures are not representative of the real physical conditions at which the plants are subjected. These differences emerge when hourly data are investigated, while generally daily or monthly data tend to attenuate such differences. In particular, radiation and energy balance components are the variables showing the largest differences among the three experimental sites, while air temperature show large differences between above-canopy and within-canopy values at hourly basis. The possess of such kind of measurements could allow the reconstruction of short periods of missing data using conventional meteorological or agrometeorological stations as ancillary data.

The result of this experimental campaign is the creation of a database suitable to perform the analysis of exchange processes between soil, vegetation and atmosphere, with a particular focus on the influence of terrain morphology and vineyards system. Such data may also be useful for performing correlations with the grape quality and productivity, since the knowledge of the environmental conditions is fundamental to understand how climate can influence the vine development and grape productivity and quality.

The performed evaluation could also be useful to the calibration and validation of numerical model applied to the vineyard system.

ACKNOWLEDGMENTS

This study was performed within the international research project "MACSUR – Modelling European Agriculture for Food Security with Climate Change, a FACCE JPI knowledge hub" funded for the Italian partnership by the Italian Ministry of Agricultural Food and Forestry Policies (D.M. 24064/7303/15) and, in the initial experimental phase, within the MASGRAPE project (regione Piemonte).

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