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Short communication

Multisensor approach to assess vineyard thermal dynamics combining high-resolution unmanned aerial vehicle (UAV) remote sensing and wireless sensor network (WSN) proximal sensing

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ABSTRACT

The progressive impact of global warming on viticulture requires enhancing knowledge of vine responses to summer abiotic stresses. The aim of this research is an evaluation of heat and radiative stress effects in terms of temperature at cluster and canopy level. A high-resolution thermal monitoring approach is presented, which combines remote and proximal sensing with an unmanned aerial vehicle (UAV) and wireless sensor network (WSN) respectively. Remote sensing was first used to drive the design of the WSN experimental plan, while both remote sensing and WSN provided a combined dataset that allowed statistically significant predictors of grape quality to be obtained at individual vine level.

1. Introduction

In most grape-growing areas worldwide, vineyards are typically characterized by natural spatial variability, responsible for different plant physiological responses, not only among different vineyards but also at smaller scales within the same vineyard (Bramley and Hamilton, 2004; Winkler et al., 1974). The management of this variability, within a context of climate change, is a challenge for wine growers who will have to adapt their agronomic strategies to varied environmental conditions (Palliotti et al., 2014). Climate change is, in fact, projected to increasingly impact thermal stresses of vines due mainly to higher temperature and radiation regimes as well as the low water availability, high leaf-to-air vapour pressure deficit and increased frequency and intensity of extreme weather events (Jones et al., 2005).

The occurrence of multiple summer stresses exerts a negative impact on grape composition and vine yield (Jackson et al., 1981; Palliotti et al., 2014). High light and temperatures often combined with insufficient water availability may accelerate grape ripening, with increased pH and sugar concentration in the must and a decrease in total acidity (Bindi et al., 2001). At the same time, intense radiative exposure may cause sunburn damage in the berries, with a consequent reduction in aroma compounds and anthocyanin accumulation: temperatures exceeding 35 °C can in fact impair their synthesis and enhance their degradation (Mori et al., 2007). In this context, the possibility of conducting accurate, timely and highly spatially resolved monitoring of water stress in vineyards could enable the optimal deployment of appropriate management strategies aimed at increasing vineyard resilience. A good measurable indicator of vine water stress is leaf water potential (Palliotti et al., 2009). Unfortunately, its measurement must be performed manually using a pressure chamber and requires lengthy operating times so is unsuitable for an accurate monitoring, especially in large vineyards. Precision viticulture has provided increasingly powerful tools, such as remote sensing by an unmanned aerial vehicle (UAV) equipped with multispectral and thermal cameras (Baluja et al., 2012; Zarco-Tejada et al., 2012; Bellvert et al., 2013; Matese et al., 2015b; Santesteban et al., 2017), or wireless sensor networks (WSN) for continuous microclimate monitoring during vine development (Vellidis et al., 2008; Matese et al., 2009; Fisher and Kebede, 2010; Matese at al., 2015a). Thermal infrared radiation emitted by the canopy, expressed as Land Surface Temperature (LST) is a well-explored proxy for water and heat stress conditions, which can be detected earlier than with conventional ground observations (Cohen et al., 2005; Sepulcre-Cantó et al., 2007). LST of the upper canopy is in fact directly related to leaf transpiration, through the regulation of stomata in order to prevent water loss and to favour heat dissipation. The heat stress interrupts the evaporative cooling process depressing the transpiration rate and causing an increase in leaf temperature (Miglietta et al., 2009), thus predisposing the leaves to

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irreversible photoinhibition phenomena (Palliotti et al., 2009). Therefore, the precise evaluation of the effects of heat and light stress effects on clusters and leaves is of great importance in vineyards for grape quality classification. However, the conventional remote sensing platforms, such as satellites or aircraft, are typically not capable of providing the high spatial resolution in the thermal bands that is necessary to resolve the inter-row effect in vineyards (Matese et al., 2015b).

This paper presents an integrated monitoring approach able to provide a spatially detailed assessment of thermal stress in vineyard, combining high resolution UAV remote sensing and WSN proximal sensing. The multispectral remote sensing data serve to drive the selection of the most adequate WSN surface nodes, while thermal and WSN data are used to develop vine stress and grape quality predictors.

2. Materials and methods

2.1. Experimental site

The experiment was carried out during 2014 in a 2.4 ha vineyard located in Montalcino (Siena, Italy) at Case Basse farm (43° 00′50.42 "N, 11° 27′5.82" E). The vineyard is approximately 330 m above sea level with a south-west exposure and gentle slope (5%). The vine variety is Sangiovese with 2.2 × 1.0 m spacing and northeast-southwest row orientation. Sixteen adjacent rows in the central part of the vineyard were used in the trial.

2.2. Flights features

During the season, two flights with UAV platform were made at 100 m altitude AGL. Flight 1 was at the beginning of the experiment (from 11:30 to 12:30 a.m. on 27 June) with the multispectral payload, to characterize the spatial variability of the vine vigour in the vineyard and identify homogeneous sub-areas where ground measurement nodes were to be placed. Flight 2 was later in the growing season (from 11:30 to 12:30 a.m. on 30 September) to confirm sub-areas vigour homogeneity and acquire thermal images.

2.3. UAV platform

The UAV platform (Fig. 1a) is a modified multi-rotor Mikrokopter-OktoXL (HiSystems GmbH, Moomerland, Germany) that can carry a 2 kg payload for 15 min flight time. It is controlled by an autopilot for autonomous flight to follow a planned waypoint route, which consists of a dual CPU controlling system based on a GPS board, 3-axis accelerometers, yaw-rate gyros and a 3-axis magnetometer. Flight parameters communication with the ground is provided by a radio link at 2.4 GHz; another channel at 5.8 GHz is used for remote sensing data transmission.

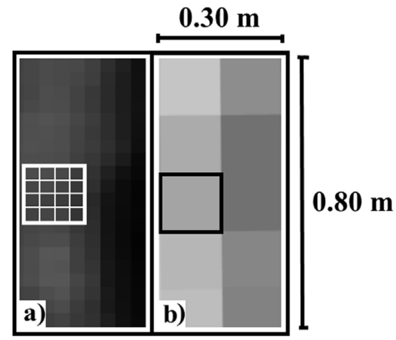

Fig. 2. Single plant remote data extraction with different resolutions at flight conditions: 0.04 m/pixel for multispectral (a) and 0.15 m/pixel for thermal (b) camera.

The aviation control and sensing system (sensors and camera mount) (Fig. 1b) were powered by two different power supplies, in order to protect the UAV from any electrical problems connected with the sensors.

2.4. Remote sensing payload and data processing

A Tetracam ADC Lite multispectral camera (Tetracam, Inc., Gainesville, FL, USA) was used (Fig. 1c), capable of sensing radiance in three bands in the visible and near infrared spectral regions. Multispectral image processing was applied to convert raw data into calibrated spectral reflectances (Matese et al., 2015b), leading to the computation of a vineyard vigour map based on the NDVI vegetation index (Rouse et al., 1973). During Flight 1, a ground resolution of 0.04 m/pixel (Fig. 2) was achieved, allowing the identification of two parcels with homogeneous vigour conditions (Fig. 3). A FLIR TAU II 320 (FLIR Systems, Inc., Wilsonville, OR, USA) was used alongside the multispectral camera on a custom-developed camera mount (Fig. 1d). This sensor, optimized for UAV application, is of minimal size (44.5 × 44.5 × 30.0 mm) and weight (72 g). Imaging sensor characteristics, i.e. 324 × 256 pixels and 24° × 18° FOV with fixed focal length of 19 mm, allowed images to be obtained of about 40 × 30 m at ground level, with a resolution of 0.15 m/pixel. The camera is equipped with an uncooled sensor able to measure longwave radiation in the spectral range 7.5–13 µm.

Radiometric calibration was first conducted in the laboratory, using blackbodies under varying target and ambient temperatures to develop radiometric calibration algorithms. It was then done in field conditions,

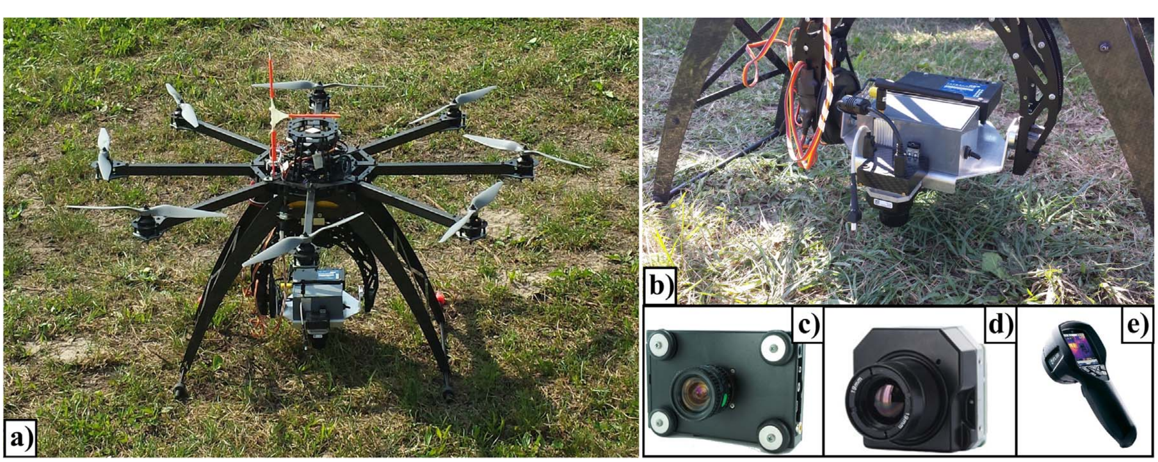

Fig. 1. UAV platform (a); ad-hoc developed camera mount for co-registered imaging (b); multispectral camera Tetracam ADC-Lite (c); thermal camera FLIR TAU II 320 (d); handheld device for proximal thermal measurements FlirI7 (e).

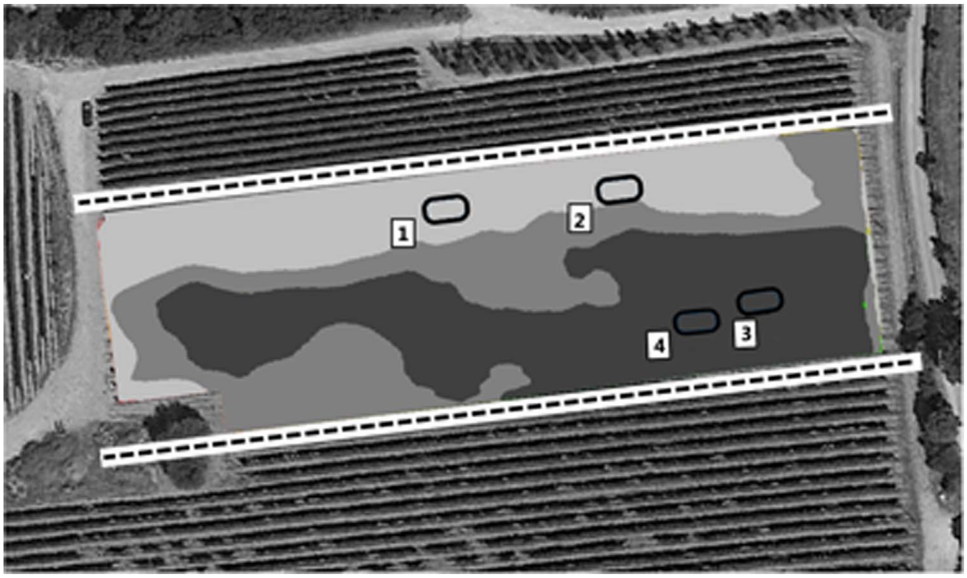

Fig. 3. Experimental design with the four nodes placed on the basis of the vigour map in highest (dark grey) and lowest (light grey) vigour zone.

by means of 3 different colour panels (1 × 1 m) at known temperature as reference. Those measurements were achieved continuously every 10 s during the flight, with a handheld thermal camera Flir i7 (FLIR Systems, Inc., USA) (Fig. 1e). Atmospheric corrections were made as described by Zarco-Tejada et al. (2012), while geometric corrections were accomplished as for the multispectral images. Individual vines were geo-referenced with a differential GPS Leica GS09 (Leica Geosystems AG, Heerbrugg, Switzerland) achieving a 0.02 m accuracy, which allowed manual data extraction of NDVI (Fig. 2a) and temperature (Fig. 2b) values acquired by the UAV at the single plant level with 0.80 × 0.30 m polygons.

2.5. Micrometeorological WSN monitoring

The proximal monitoring was conducted by a series of nodes developed and built with Arduino (Arduino project: http://arduino.cc/) open source technology. The core is a Seeeduino Stalker v.2 board (Seeed Technology Limited, Shenzhen, China). Node data are wireless transmitted to a coordinator unit, which collects and forwards data to a remote server. The system technical characteristics are described in Matese et al. (2015a). A node was placed in each parcel to monitor both internal temperature of two clusters in the south and two in the north part of the canopy using thermistor microprobes (GMR Strumenti Sas, Florence, Italy), and canopy microclimate with a shielded HTM2500LF sensor for measuring temperature and relative humidity (Humirel, Toulouse, France). The WSN acquired data in each parcel from 27 June to 30 September, monitoring the period between fruit-set and harvest. Proximal sensing data were used to calculate microbioclimatic indices, adapting classical bioclimatic indices to data acquired by each cluster temperature sensor during the monitoring period.

2.6. Meteorological data

Meteorological data covering the entire growing season were collected by an agrometeorological station A753 GPRS RTU SEN-R (Davis Instruments Corp., CA, USA), located at about 500 m from the study area.

2.7. Grape composition

Ripeness parameters related to grape composition (sugar, malic acid and pH) were measured on each sample cluster monitored by temperature probe.

2.8. Statistical analysis

Statistical analysis was performed by correlation matrix between remote, micrometeorological and quality data, using R software (R version 2.14.1 Copyright 2011 The R Foundation for Statistical Computing).

3. Results

In 2014, the sum of observed active temperatures, expressed in terms of the growing degree-days index (Winkler et al., 1974) was lower than in the previous seven years (Table 1). The 2014 summer

Table 1
Climatic characterization of the study area. Legend: Winkler index (WI); Huglin index (HI); Sum of daily excursion (ET); Mean, Max and Min Thermal Sum (Sum Tmean, Tmax, Tmin); Rainfall of the season (April-September) and summer (June- August); Number of days with temperatures over 35 °C (N° daysTmax ≥ 35 °C).

	Bioclimatic Index			Temperature (°C)			Rainfall (mm)		N° days
	WI	HI	ET	Sum Tmean	Sum Tmax	Sum Tmin	April-September	June-August	Tmax ≥ 35 °C
2007	1827	2442	1984	3955	5497	2750	309	153	11
2008	1913	2378	1990	4038	5410	2818	238	102	15
2009	2036	2591	1972	4169	5599	2910	302	139	18
2010	1859	2386	1974	3992	5349	2769	492	119	13
2011	2130	2682	2160	4267	5795	2900	291	209	21
2012	2098	2585	2082	4202	5642	2898	225	36	34
2013	1862	2351	1881	3919	5248	2740	366	182	8
2014	1766	2154	2391	3905	5138	2747	423	204	0

Table 2
Correlation matrix of remote sensing, proximal sensing and quality data of north (#_N) and south (#_S) cluster exposure. Legend: Remote sensing thermal data (LST); NDVI data (NDVI); Sum of daily excursions (TE_N, TE_S); cluster temperature at flight time (T_N, T_S); Winkler index calculated with cluster temperatures (WI_N, WI_S); Malic acid content (M_N, M_S); pH (pH_N; pH_S). No correlation value lower than ± 0.5 is presented in the table.

	LST	NDVI	TE_N	TE_S	T_N	T_S	WI_N	WI_S	M_N	M_S	pH_N	pH_S
LST	1	−0.66	0.57				0.6		−0.8	−0.86		
NDVI	−0.66	1		0.78		0.88						0.71
TE_N	0.57		1		0.53		0.74		−0.52			
TE_S		0.78		1		0.89						0.73
T_N			0.53		1		0.78					
T_S		0.88		0.89		1						0.55
WI_N	0.6		0.74		0.78		1		−0.75			
WI_S								1				

season was notable for lower monthly temperatures and higher precipitations than the previous years (Table 1). Moreover, in 2014 there were no days with temperature higher than 35 °C. The vigour map from Flight 1 (27 June) showed a rather low variability within the study area of the vineyard (mean NDVI equal to 0.46 ± 0.09), and the four WSN nodes were placed in two homogenous area with lowest and highest vigour

Proximal sensing data analysis did not show significant differences between temperatures among parcels characterized by different vigour; all data were thus gathered together as one dataset (Table 2). A positive correlation between LST and microclimatic parameters was found, as sum of daily excursions (TE_N) (R = 0.57) and Winkler index (WI_N) (R = 0.60), acquired in north clusters exposure; while a negative correlation was found with malic acid content, in both exposures (M_N, R = −0.8; M_S, R = −0.86), and with NDVI (R = −0.66). NDVI and south sample clusters were positively correlated both with microclimatic values, as sum of daily thermal excursions (TE_S, R = 0.78) and cluster temperatures for the flight time recorded on 30 September at 12.00 a.m. (T_S, R = 0.88); and for pH values (pH_S, R = 0.71). A positive correlation was also observed between pH_S and TE_S (R = 0.73), while a negative correlation was found between M_N and WI_N (R = −0.75).

4. Discussion

The combined use of a UAV remote sensing platform and differential GPS allowed high-resolution maps to be obtained with centimetre-level accuracy and data extraction to be performed at single vine level, going beyond the limits of the previous technologies such as common remote sensing platforms (satellite or aircraft) and traditional GPS. The environmental conditions in the 2014 season was characterized by low summer temperatures and high rains, compared to the previous extremely hot and dry seasons, like 2008, 2010 and 2012 (Table 1). It is likely that this pattern caused a strong vegetative phase associated with low vigour and thermal variability between zones. Coherently, no significant differences were found between the different homogeneous zones, and the vigour factor of the vine did not appear to affect cluster and leaf temperatures in these environmental conditions. Correlation analysis between remote sensing, proximal sensing and grape composition instead showed significant correlations: NDVI was correlated with cluster temperatures and pH values, and LST with Winkler index and malic acid content (Table 2). In line with previous studies, remote thermal sensing data analysis showed an inverse correlation with NDVI (Cohen et al., 2005; Jones et al., 2009) and malic acid content (Kliewer, 1971), due to the high temperature effect on both photosynthetic activity reduction and malic acid degradation. Given the high climatic variability in Mediterranean environments, repeatability of our results should be assessed under different seasonal effects, calling for further experiments and measurements to be performed in the next years, in order to fully explore and assess the relationship between remote sensing data, vine microclimate and grape quality, for different vine age and cluster exposure.

5. Conclusion

This paper reports the combination of thermal and multispectral UAV remote sensing with ground WSN monitoring in a vineyard. Imaging remote sensing provided an accurate detection of vigour heterogeneity within the vineyard to drive the proper identification of micro-zones for the experimental design. High spatial resolution imagery acquired simultaneously by thermal and multispectral sensors on the UAV enabled the identification and extraction of the mean reflectance and temperature for individual sample vines where WSN nodes were also installed. Significant correlations between remote and proximal parameters extracted from georeferenced vines were found both for microclimatic indices and cluster composition data. Although the 2014 season was not characterized by severe summer stress and the results of this study should be verified in different environmental conditions and different geographic areas, the proposed approach successfully combined technologies that are typically used independently, highlighting their mutual benefit. This level of integration of different technologies will provide innovative datasets to face the challenge of studying crops response to a changing climate. Recent advances in sensors and UAV technologies allow high spatial resolutions to be obtained not only on small study plots but also on large areas (Santesteban et al., 2017), making high-resolution thermal remote sensing an operational solution on commercially relevant acreage for abiotic stress monitoring.

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