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Estimating biophysical and geometrical parameters of grapevine canopies ('Sangiovese') by an unmanned aerial vehicle (UAV) and VIS-NIR cameras

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Summary

Three zones of different vine vigour were identified in a mature vineyard (*Vitis vinifera* 'Sangiovese') to test the potential of the Visible-Near Infrared (VIS-NIR) spectral information acquired from an unmanned aerial vehicles (UAV) in estimating the leaf area index (LAI), leaf chlorophyll, pruning weight, canopy height and canopy volume of grapevines. A significant linear correlation between the normalized differential vegetation index (NDVI) and LAI or between NDVI and leaf chlorophyll was found at day of the year (DOY) 162 and 190, whereas in August the relationship between NDVI and leaf chlorophyll was less evident. The canopy volume of low-vigour (LV) vines was 35 and 45 % of the high-vigour (HV) and medium-vigour (MV) ones, respectively. The pruning weight was linearly correlated with NDVI values of each vigour cohort. A good correlation between the measured canopy volume and UAV-estimated one as well as between measured and estimated canopy height was found. Our results indicated that the combined use of VIS-NIR cameras and UAV is a rapid and reliable technique to determine canopy structure and LAI of grapevine.

K e y w o r d s: canopy volume; greenness index; leaf area index; NDVI; remote sensing; structure from motion; *Vitis vinifera* L.

Introduction

Precision viticulture (PV) relies on the understanding of inter and within-field variability to define homogenous zones within the vineyard. This information is then used to optimize cultural practices with the objective to achieve uniformity of growth and yield (Bramley *et al.* 2005, Arnò *et al.* 2009). Zoning in heterogeneous vineyards can be conducted through the measurement and geo-referencing of vine biophysical parameters, such as leaf area, vine vigour and leaf chlorophyll content. These parameters are crucial for vineyard management as they are related to vegetative growth, nutrient concentrations and water status of the vines. The Leaf Area Index (LAI) is related to the surface responsible for solar radiation interception and gas exchange with the atmosphere determining vine carbon assimilation, water consumption and potential productivity of vines. On a practical level, LAI maps can be integrated and used in several agro-hydrological and crop models developed to predict crop evapotranspiration, productivity and irrigation scheduling at field and catchment scale (Vitale *et al.* 2016, Cammalleri *et al.* 2010). The LAI can be calculated by either destructive sampling or indirect measurements, based on either hemispherical photography or the transmittance of radiation through the vegetation (Lowell *et al.* 2003). Indirect methods are currently preferred as they are less expensive and time consuming than destructive ones.

Measuring vine canopy volume and its variability within the vineyard is also important to optimize canopy management (e.g. shoot positioning, shoot thinning, leaf removal, canopy hedging) and pest control (spray application), especially when the variable rate techniques (VRT) are used (Gil *et al.* 2007). Vine canopy volume can be calculated by manual measurements of height and width, but this method is labour intensive and time consuming. Alternatively, by the use of mobile terrestrial Light Detection and Ranging (Lidar) systems it is possible to create three-dimensional models of the vineyard and estimate the grapevine canopy volume (Rossel *et al.* 2009). However, these systems are still uncommon at the farm level due to their cost, especially when large areas are to be scanned.

Vine vigour can be also inferred from measurements of pruning weight. The weight of the pruned wood is related to the vegetative biomass produced during the growing season and, thus, to the vine vigour (Dobrowski *et al.* 2003, Taylor and Bates 2013). Pruning weight is also used to express vine size in the parameterization of vine balance, as in the calculation of the Ravaz index, commonly used by viticulturists to assess the relationship between vegetative and reproductive activity. However, the Ravaz method is time consuming as it is necessary to measure many samples and to interpolate data in order to draw a map of the vineyard vigour. The nitrogen (N) status is also a valuable indicator of vigour. Non destructive methods, based on either leaf reflectance or transmittance responses, have been developed to estimate the leaf N concentration (Porro *et al.* 2001, Brunetto *et al.* 2012). The greenness index calculated from SPAD readings

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using the Minolta SPAD-502 (Minolta Corp., Ramsey, N.J.) has been often related to the leaf chlorophyll concentration and to the total N content (UDDLING *et al.* 2007). Because of the tight correlation between chlorophyll and leaf nitrogen content, leaf chlorophyll can be used as an indirect index of the plant N status (TASKOS *et al.* 2015). The ability to rapidly monitor the leaf chlorophyll content during the entire growing season allows to promptly identify nitrogen deficiencies or excesses in vineyards. Since measurements are taken on single leaves, a drawback of this approach lies in the large number of samples that are to be taken in space and time to fully cover a vineyard during the growing season.

The Normalized Differential Vegetation Index (NDVI), one of the most commonly used spectral indices in precision agriculture (ROUSE *et al.* 1973), can also be used to estimate vigour. The NDVI is widely used in proximal (both leaf and canopy scale) and remote (farm, district and regional scale) sensing techniques (MATESE *et al.* 2015). There are several reports that show that LAI and vine size can be effectively estimated by using vegetative spectral indices derived from either satellite or airborne multispectral images (JOHNSON *et al.* 2003, HALL *et al.* 2008, DOBROWSKY *et al.* 2003) although with less accuracy than when proximal sensing tools were used in the field or direct measurements of pruning weight were taken (STAMATIADIS *et al.* 2006, TAYLOR and BATES 2012). It has been recently shown that vegetative spectral indices acquired from unmanned aerial vehicles (UAV) were very close to direct measurements of LAI and pruning weights in vineyards (REY CARAMÉS *et al.* 2015). The UAV technique implies great flexibility in flight scheduling and low operational costs (PRIMICERIO *et al.* 2012, MATESE *et al.* 2015), but there are few investigations so far exploring the correlation between vine size and LAI using UAV. The increasing availability of dedicated, low-cost, miniaturized sensors explain the interest in UAV for agricultural applications. For instance, UAV equipped with multispectral cameras have been used to estimate vine productivity and grape quality parameters (FIORILLO *et al.* 2012, REY CARAMÉS *et al.* 2015).

Recently, the acquisition of high resolution RGB images of the canopy from UAV joint to Structure from Motion (SfM) technique has proved to be an effective tool for estimating plant architecture through the computation of a Digital Surface Model (DSM) (ZARCO-TEJADA *et al.* 2014, TORRES-SÁNCHEZ *et al.* 2015, BALLESTEROS *et al.* 2015, MORIONDO *et al.* 2016). However, to the best of our knowledge no direct comparison between measured and estimated vine canopy volume has been reported so far. Previous studies have used the SfM technique to create a 3-D vineyard point cloud and to estimate vine canopy volume in order to predict vine LAI (MATHEWS *et al.* 2013, BALLESTEROS *et al.* 2015), but the cross-validation of the canopy volume estimates through actual field measurements was not conducted.

The general objective of this study was to test the ability of the VIS-NIR spectral information acquired from an UAV to identify vines with different vigour in a Guyot-trained, mature vineyard of 'Sangiovese' in Tuscany. Specific objectives were: a) to evaluate the capability of spectral indices derived from an NIR-RG camera to estimate the LAI, the leaf chlorophyll concentration and the vine pruning weight; b) to compare the values of canopy height and canopy volume estimated from RGB images joint to the Structure from Motion technique with actual values measured in the vineyard.

Material and Methods

P l a n t m a t e r i a l: The experiments were carried out in a commercial vineyard ('Sangiovese, the most widely grown cultivar in Italy) located at Suvereto in Tuscany (Italy, 43°04 N, 10° 41' E) in 2015-16. Vines were planted in 1999 in a clay-loam soil at a 0.8 x 2.4 m spacing (North-South row orientation) and trained according to the Guyot system. The vineyard was managed according to standard protocols for organic viticulture, whereby the soil was tilled six times at a depth of 0.15 m from budburst through harvest to control weeds. Composted sheep manure followed by the sowing of a cover crop (*Vicia faba* L.) was applied after grape harvest. The technique of sexual confusion was used to control the grapevine moth (*Lobesia botrana* Schiff.), whereas copper and sulphur compounds were sprayed eight times during the growing season to control downy mildew (*Plasmopara viticola* Berk. & G. Winter) and powdery mildew (*Uncinula necator* Schwein.), respectively. Shoot positioning and lateral shoot removal were done at the beginning of July and repeated at the beginning of August, when the crop was also manually adjusted to meet the standards for the local DOCG protocol for high quality wines. At harvest (18 September) the average grape yield per vine was 1.2 kg. Annual and summer (21 June - 21 September) precipitations were 809 and 39 mm, respectively. Summer mean temperature was 24.0 °C, and the highest daily mean temperature (29.1 °C) was recorded on 8 August.

Three homogeneous zones of high (HV), medium (MV) and low (LV) vigour were identified on the basis of the Normalized Different Vegetation Index (NDVI) calculated from multispectral images acquired during a preliminary UAV survey in May (DOY 149) (Fig. 1A). The Iterative Self-Organizing Data Analysis Technique (ISODATA), implemented in ArcGIS software (ESRI, Redlands, Ca, USA), was used to set the boundaries of the three zones within the vineyard.

Within each homogeneous zone a group of 75 vines, consisting in three adjacent portions of row (20 m each), was used for field measurements of the Leaf Area Index, leaf chlorophyll and canopy volume. All three rows were included in LAI measurements, as reported in the following section, while only the central row, consisting in four adjacent replicates of 4 m each (the first and the last 0.5 m of each replicate were excluded), was used for the determinations of canopy height, canopy width, canopy volume, leaf chlorophyll, and pruning weight.

L A I, l e a f c h l o r o p h y l l, c a n o p y v o l u m e, p r u n i n g w e i g h t: The LAI was measured not destructively at DOY 162 and 190 by a LAI-2000 optoelectronic sensor (LI-COR, Lincoln, Nebraska, USA). Due to the heterogeneous structure of the canopies arranged in rows, a tow-azimuth protocol was followed (WELLES and NORMAN 1991, LI-COR 1992). Initially, an ambient light standardization was carried out with the sensor extended

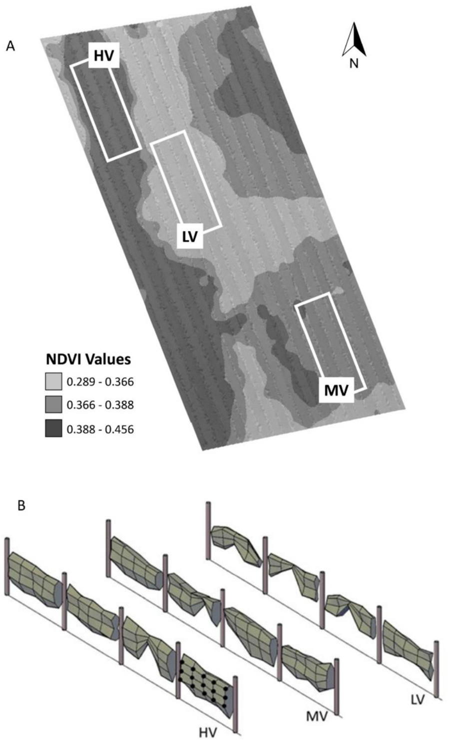

Fig. 1: Normalized difference vegetation index (NDVI) map (DOY 149) including the three groups of vines ('Sangiovese') used for field measurements (**A**) and three-dimensional canopy models of high (HV), medium (MV) and low vigor (LV) vines produced from measurement taken in the field at DOY 197 (**B**). Dots indicate the positions at which canopy width and leaf chlorophyll were measured.

upward and over the top of the canopy. Four below-canopy measurements were then recorded along a diagonal transect pointed toward the middle of the central row of each plot, with the instrument held a few centimeters above the soil. The first reading was taken directly beneath the mid-point of the central row, whereas the next three measurements were taken one-quarter, one-half and three-quarters of the distance from the adjoining row. This procedure was repeated for a total of four transects per plot in order to record both sides of the central row of the investigated plot. A physical cap was used to limit the azimuthal field-of-view to 180°, facing away from the operator and the adjoining row of vines.

A sample of 30 leaves with variable greenness index was selected at veraison (DOY 220) to determine the correlation between SPAD readings (greenness index) and the actual chlorophyll concentration. Chlorophyll was extracted using N,N-dimethylformamide according to the method described by Moran and Porath (1980), and total chlorophyll (a+b) concentration ($mg \cdot dm^{-2}$ of leaf area) calculated based on the equations provided by Lichtenthaler and Wellburn (1983). The greenness index was measured on 11 June (DOY 162), 9 July (DOY 190) and 12 August (DOY 224) on 15 fully-expanded leaves for each replicate using a Minolta SPAD 502 portable greenness meter (Konica Minolta, Inc., Osaka, Japan). In particular, measurements were taken on leaves (three measurements per leaf) inserted on the basal, median and apical shoot zone (located at a height from the ground of 0.90, 1.25 and 1.60 m, respectively) and repeated at regular intervals (1 m) along the block central row, excluding the first and the last 0.5 m of each of the four replicates (Fig. 1B). The greenness index confirmed to be a reliable proxy of chlorophyll concentration per unit of leaf area ($y = 0.002\ x^2 + 0.051\ x$; $R^2 = 0.90$) (suppl. Fig. 1). This equation was then used to convert the greenness index values into leaf chlorophyll concentrations. Following the same sampling protocol used for the greenness index determinations, the maximum canopy height, canopy height from the ground and canopy width were measured on 16 July (DOY 197). These data were used to create a 2-D canopy silhouette at 1 m intervals and then, the LOFT command implemented in AutoCAD (Autodesk Inc., McInnis Parkway, San Rafael, CA, USA) was used to obtain a 3-D canopy model of each replicate (Fig. 1B).

In February 2016 the pruning wood removed from each of the four replicates per vigour group was weighed and expressed as kilograms per linear meter of vine-row.

UAV setting and multispectral images collection: The acquisition campaign was performed using a S1000 UAV octocopter (DJI, Shenzhen, China) able to fly autonomously over a predetermined waypoint course. The S1000 was equipped with a 2-axis stabilized gimbal equipped with a consumer photo-camera (RGB) and a multispectral camera (NIR-RG). The RGB camera was a Coolpix P7700 (Nikon, Shinjuku, Japan) embodying a 12.2-megapixel CMOS sensor, whereas the NIR-RG multispectral camera was the Tetracam ADC-lite (Tetracam, Inc., Gainesville, FL, USA) equipped with a 3.2-megapixel CMOS sensor. Images were acquired at noon under clear sky conditions, the flight altitude was 100 m above ground level (AGL) at a UAV flight speed of 4 m s^{-1}, and the ground sample distance (GSD) was 4.02 cm. The image forward and side overlap (80 % and 70 %, respectively), guaranteed an optimal photogrammetric processing. Images were recorded in the visible green (G) and red (R) and near infrared (NIR) domain with nominal bandwidth of 520-600, 630-690, and 760-900 nm, respectively. Four flights were made at DOY 149 (29 May), DOY 162, DOY 190 and DOY 224, corresponding to the BBCH-scale stages 61 (beginning of flowering), 71 (fruit set completed), 77 (beginning of bunch closure) and 83 (veraison, berries developing color) (Lorenz *et al.* 1995). In order to standardize the radiation conditions, a white reference panel was acquired inside the target of the multispectral images just before each flight. An additional flight was made on 16 July (DOY 197) at an altitude of 50 m AGL and RGB images were acquired and processed for the 3D canopy reconstruction (GSD of 1.54 cm). At the same date, before the UAV flight, a set of sixty ground control points were placed in the vineyard and georeferenced using a Leica GS09 real time kinematic GPS (Leica Geosystems A.G., Heerbrugg, Switzerland) able to achieve a 3D resolution of 0.02 m.

Images processing: The multispectral images were first mosaicked using Autopano Giga 3.5 Software (Kolor SARL, Challes-les-Eaux, France), then georeferenced and orthorectified by using the known ground control points (ArcGIS software®, ESRI, Redlands, CA, USA). The absence of vegetation cover in the inter-row space, due to the periodic soil disking, allowed to obtain a clear separation of soil and canopy pixels in the orthomosaic and, thus, a precise extraction of the vegetation spectral information was possible. The Normalized Difference Vegetation Index (NDVI; Rouse *et al.* 1974), was calculated by means of the map algebra technique implemented in ArcGIS software (ESRI, Redlands, Ca, USA).

The three-dimensional canopy volume of grapevines was reconstructed starting from the digital surface model (DSM) obtained using a structure from motion approach (SfM). According to the SfM pipeline, in the first step an algorithm tracks a set of points common to several overlapping images. The 3D positions of every identified key points was then estimated along with camera position and its orientation for every picture. The estimated camera positions and digital images were further processed to retrieve the positions of non-feature point pixels that were finally combined into a single dense point cloud. In our specific case, RGB images acquired by UAV on DOY 197 were used as input Agisoft Photo-Scan® (Agisoft LLC). Three-dimensional structures were obtained as a point cloud and were further processed and rasterized to retrieve canopy height above the ground. The point clouds obtained were firstly rescaled and georeferenced using the spatial coordinates (UTM 32N) of the sixty ground control points previously placed on the study area and the relevant point clouds were then clipped strictly around the vineyard under study. The density of these point clouds was 8.500.000 points over a surface of 0.5 ha. The DSM generated from the point cloud was then processed in ArcGIS to obtain a digital terrain model (DTM) of the vineyard to retrieve the height of each three-dimensional axes of the canopy point above the ground.

The DSM generated from the point cloud was then processed in ArcGIS to obtain a digital terrain model (DTM) of the vineyard. A raster consisting only in the pixels of the canopy vines was obtained by subtracting the DTM to DSM using the map algebra technique. The maximum canopy height was obtained from the corresponding pixel of each replicate. The vine canopy volume was obtained by integrating the volume of all the pixel located below the canopy: the height and the area of each pixel was multiplied to obtain the pixel volume; the volume occupied by the vine was calculated by adding the volume of each pixel below the canopy. Canopy volume was calculated as the difference between total volume of each replicate and: a) the volume comprised between the ground and the first wire (0.9 m from the ground); b) the volume comprised between the ground and the measured distance from the ground of the canopy of each replicate.

S t a t i s t i c a l a n a l y s i s : Means of the various measured parameters of the three vines groups (HV, MV and LV) were separated by least significant differences (LSD) at $p \leq 0.05$ after analysis of variance (ANOVA). Where applicable, linear regression analysis was conducted using Costat (CoHort Software, Monterey, USA).

Results and Discussion

The leaf chlorophyll tended to increase between June (DOY 162) and July (DOY 190) in all the three groups of vine vigour. While this trend continued for LV vines in August (DOY 224), the leaf chlorophyll decreased (MV vines) or remained stable for HV ones (Fig. 2A). Leaf chlorophyll was significantly lower in LV vines than the other two vigour cohorts in June and July, whereas the MV vines showed the lowest values in August.

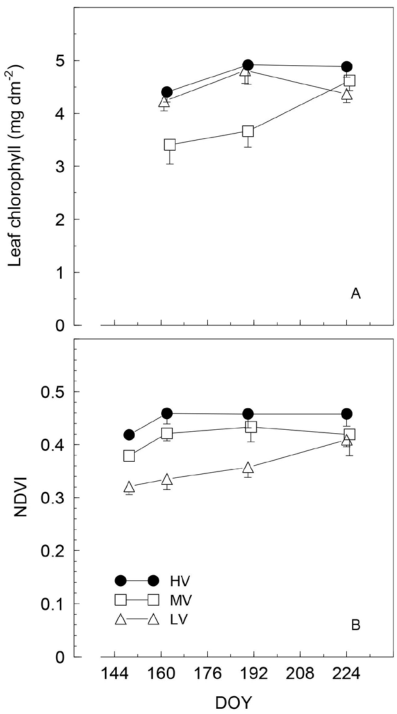

Fig. 2: Seasonal courses of leaf chlorophyll content (**A**) and NDVI (**B**) in high (HV), medium (MV) and low vigour (LV) grapevines ('Sangiovese'). Values are means – SD of four replicates for each group.

The NDVI of the three vigour cohorts were significantly different for NDVI at DOY 149, with the higher and lowest values measured in HV and LV vines, respectively. Starting from DOY 162 the NDVI of MV vines became similar to that of HV ones, and at DOY 224 differences between the three groups had disappeared (Fig. 2B). The lack of differences in NDVI values between groups in August was probably due to the canopy manipulations (shoot thinning and shoot positioning) performed in July. A similar pattern was observed for NDVI of the HV and MV vines, with values that increased between May (DOY 149) and June (DOY 162) and then remained approximately constant until August (DOY 224). The seasonal course of NDVI for HV and MV vines was similar to that reported by other authors (Johnson *et al.* 2003), with NDVI that progressively increased up to mid-June to remain stable, or slightly decreasing, in the summer. In contrast, an almost linear increase in NDVI values between May and August was observed in the LV vines (Fig. 2B), paralleling the course of SPAD readings. The pattern of NDVI for LV vines can be probably explained by the location was different because they were located in an area subjected to waterlogging during the winter, which depressed vegetative growth in spring and resulted in more prolonged vegetative activity in the summer than the other groups. The steady increase of leaf chlorophyll in LV vines between June and August seems to confirm this hypothesis.

Differences in leaf chlorophyll content reflecting differences in soil water availability conditions has been previously reported in grapevines (Bertamini *et al.* 2006).

A linear correlation between leaf chlorophyll and NDVI was found at DOY 162 and 190, whereas at DOY 224 there was no significant correlation (Fig. 3). Similarly, a wider range of leaf chlorophyll values was observed in June (from 3.0 to 4.7 mg dm^{-2}) and July (from 3.4 to 5.3) when the canopy was still actively growing, than in August (from 4.2 to 5.0), after the canopy had been hedged and grapes were beginning to ripe. The basal, median and apical leaves differently contributed to the general NDVI-leaf chlorophyll relationship at the canopy level. The chlorophyll-NDVI (whole-canopy) relationship was always tighter for basal leaves (R^2 = 0.66**, 0.66** and 0.37* at DOY 162, 190 and 224, respectively) than that for median or apical ones (suppl. Fig. 3). Since basal leaves are commonly sampled to determine whole vine nutrient status (Romero *et al.* 2010), the above relationships can be used to rapidly estimate the chlorophyll or the nitrogen status of vines at the field level (Steele *et al.* 2008, Taskos *et al.* 2015). The seasonal course of leaf chlorophyll in leaves located in the basal, median and apical part of the shoot were different. Regardless of the vigour cohorts, leaf chlorophyll tended to increase in apical leaves from June (DOY 162) through August (DOY 224), whereas an opposite trend was observed in basal leaves. Similar results were observed in previous studies conducted on the same cultivar as a result of leaf aging (Poni *et al.* 1994). At the last date of measurement (DOY 224) significant differences between basal, median and apical leaves were measured in LV vines, but in MV and HV ones (suppl. Fig. 2).

A significantly linear NDVI-LAI relationship (R^2=0.88) was found (Fig. 4), similarly to results reported in another study where NDVI values were calculated from multispectral satellite images (Johnson *et al.* 2003). Hall *et al.* (2008) reported a closer relationship between vine canopy area and LAI (R^2 = 0.83) than that between NDVI and LAI (R^2 = 0.74), when data of three phenological stages (post-budburst, post-flowering and verasion) were considered. Moreover, when the data were separated according to phenological stages the NDVI-LAI relationship was significant only at verasion.

The weight of pruning wood, commonly used as an estimate of vine vigour, matched the vegetative vigour initially identified on the basis of the NDVI determinations (0.54, 0.41 and 0.28 kg·m^{-1} for HV, MV and LV cohorts, respectively) and was indeed linearly correlated with NDVI values of each group (Fig. 5). The pruning weights in our study were consistent with those reported by Taylor and Bates (2013)

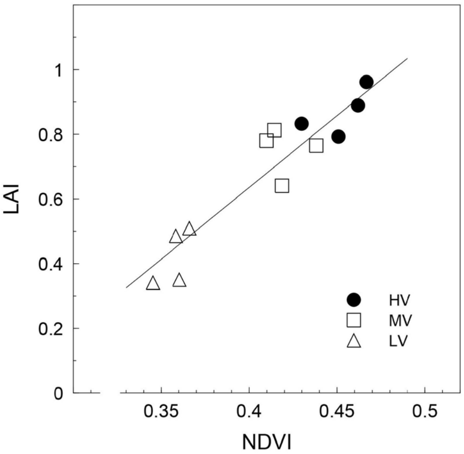

Fig. 4: The relationship between NDVI and LAI values in high (HV), medium (MV) and low vigour (LV) grapevines ('Sangiovese') at DOY 162 and 190. Each symbol represents one replicate. Linear regression equation: y = 4.62 x -1.22; R^2 = 0.88.

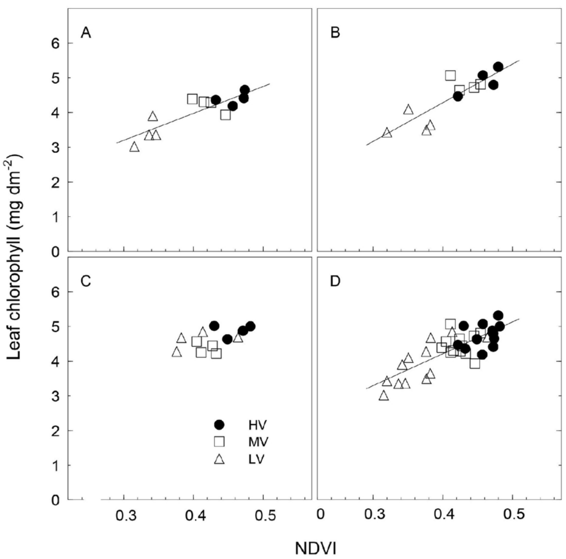

Fig. 3: The relationship between NDVI and leaf chlorophyll in high (HV), medium (MV) and low vigour (LV) grapevines ('Sangiovese') at DOY 162 (**A**), 190 (**B**) and 224 (**C**). In **D** data from all dates of measurement were pooled together. Each symbol represents one replicate. Linear regression equations: (A) y = 7.74 x + 0.88; R^2 = 0.73; (B) y = 11.1 x – 0.17; R^2 = 0.74; (D) y = 9.2 x + 0.55; R^2 = 0.61.

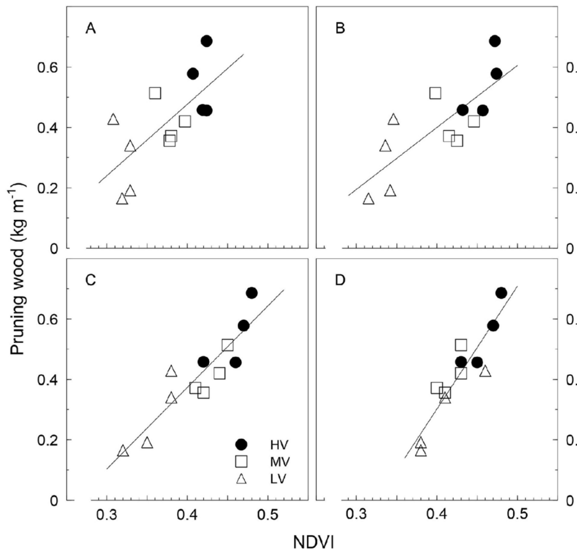

Fig. 5: The relationship between NDVI measured at DOY 149 (**A**), 162 (**B**), 190 (**C**) and 224 (**D**) in 2015 in high (HV), medium (MV) and low vigour (LV) grapevines and pruning wood weighted on 19 February 2016. Each symbol represents one replicate. Linear regression equations: y = 2.34x - 0.46, R^2 = 0.47, 0.015* (A); y = 2.04x - 0.41, R^2 = 0.62, 0.003** (B); y = 2.65x -0.69, R^2 = 0.82, 0.000*** (D); y = 4.00x - 1.30, R^2 = 0.83, 0.000*** (D).

(0.54, 0.46 and 0.39 kg·m^{-1} for HV, MV and LV, respectively) and slightly higher than those reported by Fiorillo *et al.* (2012) (0.39, 0.22 and 0.20 kg·m^{-1}). The correlation between the pruning wood and NDVI values measured at DOY 149, 162, 190 and 224 was always significant and the coefficient of determination increased from May to August (R^2 = 0.47, 0.56, 0.73 and 0.83 for DOY 149, 162, 190 and 224, respectively) (Fig. 5). Bonilla *et al.* (2015) also found a significant relationship between NDVI measured in August and pruning weight. Dobrowski *et al.* (2003) reported a positive and linear correlation between the ratio vegetation index (RVI = NIR/Red), calculated from multispectral airborne images acquired in August (post-veraison), and the pruning weight (values between 0.2 to 1.2 kg·m^{-1}).

The vine canopy volume reflected the vigour of each group. In particular, the canopy volume of LV vines was 35 and 45 % that of HV and MV ones, respectively. A good correlation between the measured canopy volume and the UAV estimated one was found. When a constant height of 0.9 m (the height of the first wire above ground) was used for the canopy volume estimation the data points were distributed along a 1:1 line (R^2 = 0.62 and RMSE = 0.08) and there was a linear relationship between estimated and measured canopy volume (Fig. 6A). The coefficient of determination increased (R^2 = 0.75) when the actual distance of the canopy from the ground was used in the calculations, but in this case the estimated canopy volume diverged from the 1:1 line (Fig. 6B). The variability of those relationships depends on the width and geometry of the canopy since the point cloud method includes an additional volume below the maximum width of the canopy: the higher the maximum width of the canopy, the larger the overestimation of canopy volume below that width. When the actual distance from the ground is used (Fig. 6C), the lowest portion of the canopy volume (grey area) is included in the canopy volume calculation, resulting in a higher value of R^2. Concomitantly, the approximation to a rectangular shape of the section comprised between the 0.9 m and the measured height from the ground leads to the inclusion of an additional volume (dotted area) which in turn, leads to an overestimation of canopy volume (Fig. 6C). Therefore, using a fixed height of the canopy from the ground (first wire) for canopy volume determination is a better option for applications at vineyard scale. The estimated values of the maximum canopy height were close to the ones measured manually in the field (RMSE = 0.15) and the relationship between measured and UAV-estimated values was linear (R^2 = 0.75) (Fig. 7). Zarco-Teiada *et al.* (2014) quantified the height of olive trees using high resolution images acquired from UAV and evaluated the effect of the spatial resolution of the input images on the RMSE of the measured/estimated tree height relationship. In particular, they reported RMSE values of 0.33 and 0.60 m when the

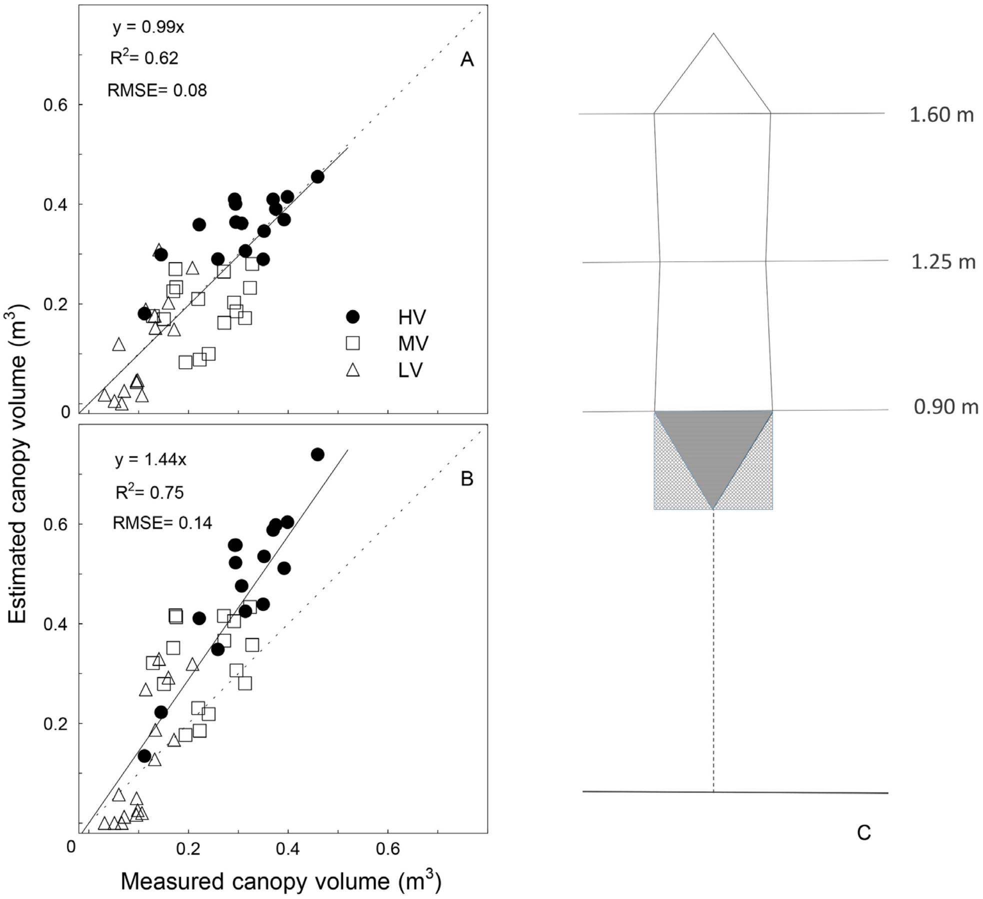

Fig. 6: Comparison between ground measured and UAV-estimated canopy volume (of a 1-m vineyard row) in high (HV), medium (MV) and low vigour (LV) grapevines at DOY 197. The UAV-estimated canopy volumes were obtained by considering a distance of the canopy from the ground of 0.9 m (height of the first wire) (**A**) or by using the distance measured for each replicate (**B**). Each symbol represents one replicate. The solid line is the fitted linear function and the dotted one is the 1:1 line. A simplified canopy longitudinal section is also reported (**C**). Horizontal lines (0.9, 1.25, 1.60 m) indicate the height of the three wires at which the canopy width was measured.

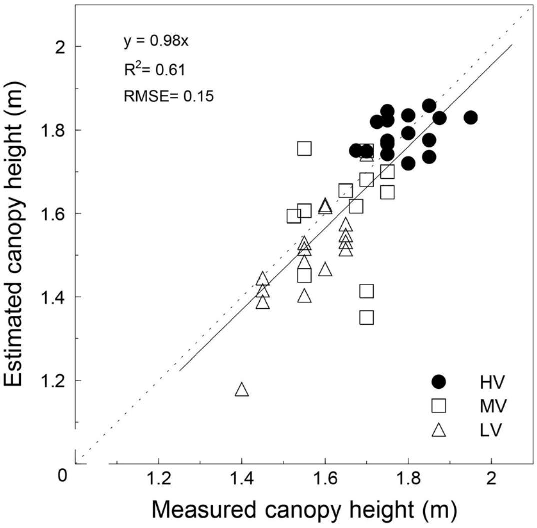

Fig. 7: Comparison between ground measured and UAV-estimated canopy height values in high (HV), medium (MV) and low vigour (LV) grapevines at DOY 197. Each symbol represents one replicate. The solid line is the fitted linear function and the dotted line is the 1:1 line.

images used for to generate the DSM had spatial resolution of 0.05 and 0.50 m·pixel^{-1}, respectively. Torres-Sánchez *et al.* (2015) reported a coefficient of determination of 0.65 (UAV flight altitude of 50 m) and 0.63 (UAV flight altitude of 100 m) for the relationship between measured and estimated canopy volume of olive trees.

The maps of pruning weight, LAI and canopy volume, derived from the specific relationships between NDVI and each of these variables, are important inputs for different variable rate applications concerning canopy, irrigation and pest management. The estimation of the pruning weight at field scale may facilitate pruning and thinning strategies and, thus, optimize the vine vegetative and reproductive balance. At the same time, LAI maps allow to better estimate vine water requirements and to increase water use efficiency. In fact, vine water use and crop coefficient, the latter used to calculate the crop evapotranspiration (ET_c), have been shown to be closely related to leaf area per vine and LAI (Wiliams and Ayars 2005, Netzer *et al.* 2008). The maps of canopy volume, as well as LAI maps, can be used in the variable rate spraying applications allowing to optimize the applied doses of pesticides or fertilizer according to the vine canopy volume in each area, with relevant benefits in terms of environmental sustainability, food security and cost reduction (Zaman *et al.* 2005, Gil *et al.* 2007).

In conclusion, the results presented in this work show the potential of the multispectral and RGB imagery from UAV to determine some biophysical and geometrical characteristics of grapevines. The NDVI derived from multispectral camera allowed to identify zones of different vine vigour within the vineyard and to estimate accurately leaf chlorophyll, LAI and pruning weight, with potential positive effects on grapevine nutrition, irrigation and canopy management. The major contribution of the basal leaves to the general NDVI (whole canopy)-leaf chlorophyll relationship confirms the potential in the use of the multispectral imagery from UAV for the determination of vine nitrogen status. We also showed that UAV-derived techniques can be used for low-cost, reliable determinations of canopy structure. The lack of information on canopy geometry and LAI is still the limiting factor to understand whole-vine physiological processes like photosynthesis and evapotranspiration in the field. In addition, optimizing cultural practices requires quick methods to determine spatial variability within the vineyard. Current management to modern vineyards is highly intense and, therefore, we need tools and techniques that allow to estimate and model functional activities at the whole vine and vineyard level rather than analysing processes in single leaves or canopy parts only. In this respect, we report that the RGB consumer camera mounted on UAV can be used to reconstruct a realistic 3-D model of the canopy in vertical training systems and estimate canopy volumes of vertically trained (Guyot) vines. However, further investigations are needed to verify the reliability of this technique for other training systems like GDC, Lyre or tendons where the canopy has a more horizontal display.

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