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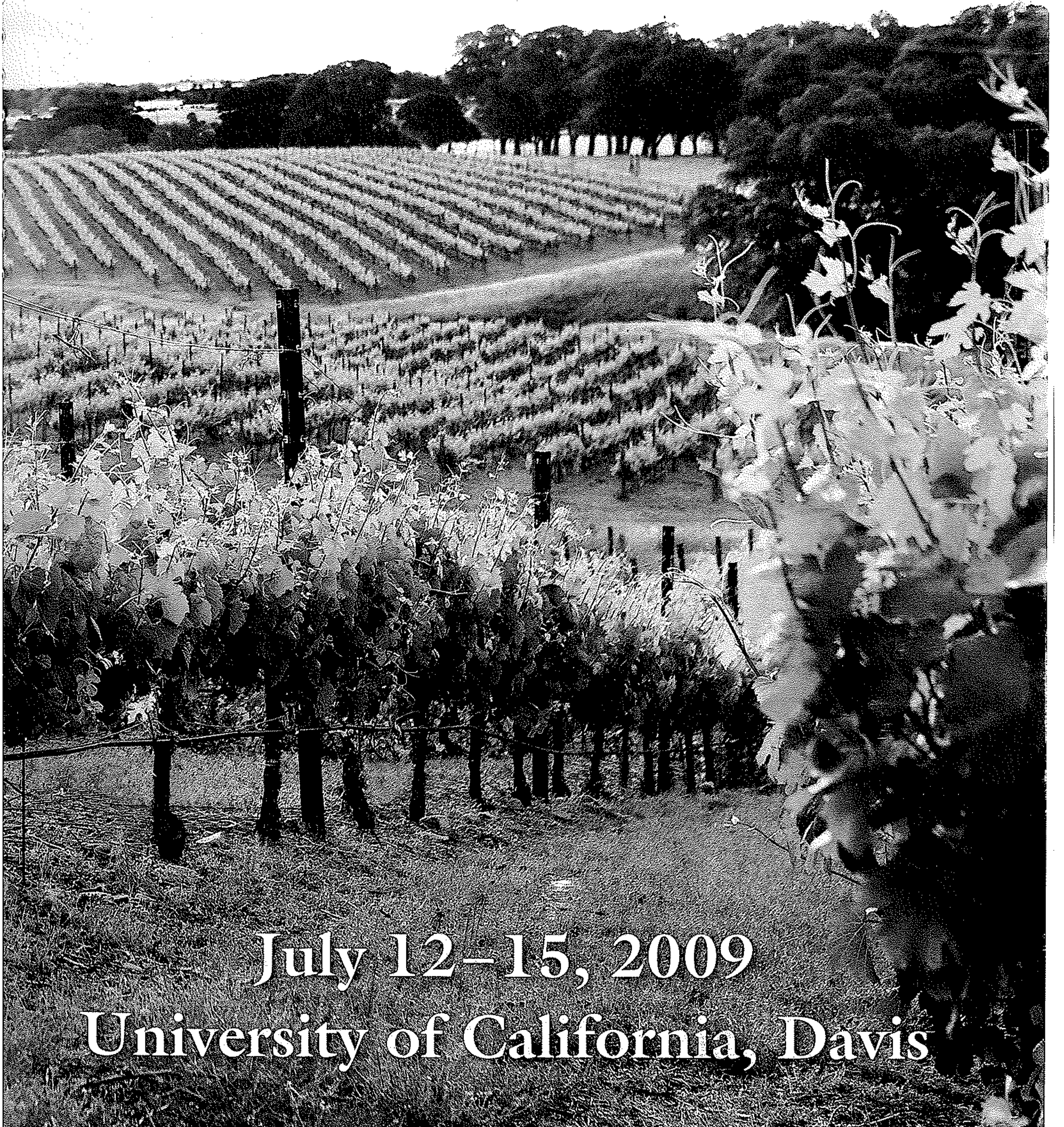

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MAPPING THE SPATIAL VARIABILITY OF VINEYARD CANOPY USING HIGH-RESOLUTION AIRBORNE MULTISPECTRAL IMAGES

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Abstract: Airborne remote sensing applied to vineyards is an innovative tool to obtain valuable information for viticulturists and vineyard managers. This contribution presents a method to collect and analyze high spatial resolution (0.3 m) airborne multispectral images, with the aim of deriving physical variables of the vineyard canopy and specific grape characteristics. Four vineyard experimental areas located in Tuscany (Central Italy) were monitored and images collected in three different periods during the 2007-2008 growing seasons were geometrically and radiometrically corrected and calibrated in order to obtain reflectance data. The normalized difference vegetation index (NDVI) was then calculated, and a semi-automatic procedure was applied to extract the image pixels corresponding to the vineyard canopy. The NDVI values of these pixels were analyzed to evaluate the spatial variability within the canopy and were then related with ground measurements of a set of grape quality parameters. This work is part of a larger project that aims at applying newest technologies to evaluate the influence of different agronomic and enological practices on the final product. The analysis confirmed the capacity of the NDVI high resolution images to provide useful information for driving vineyard management practices.

Vineyards, as other agricultural environments, show a high variability of their characteristics both in space and time (Brancadoro *et al*, 2006). The factors that define the vineyard environment can be classified as "static", like quantities that describe the soil properties (texture, pH, carbonates, soil depth, ecc...) and "dynamic", like soil temperature, moisture and nutrient content and canopy temperature. Such quantities are driven by the interaction between the atmosphere, the soil and the canopy, and are strictly related to cultural management practices; they show a high spatial and temporal variability which strongly affects the vegetative and productive levels of the vine plants. The cultural practices should therefore be modulated in relation with the spatial variability observed in the field, in order to be linked to the real cultural requirements. The concept of precision viticulture is based on the application of differential management practices based on the characteristics of the cultural environment.

Precision Viticulture (Cook and Bramley, 1998; Pierce and Nowak, 1999) involves the collection of large amounts of data relating to crop performance and the attributes of individual production areas at a high spatial resolution.

Implementation of a Precision Viticulture approach to vineyard management is a continual cyclical process (Bramley and Profitt 1999, Bramley 2001, Bramley *et al.* 2003, Bramley and Hamilton, 2004) which begins with observation of vineyard performance and associated vineyard attributes, followed by interpretation and evaluation of the collected data, leading to implementation of either targeted management of inputs and/or selective harvesting at vintage.

One of the most powerful tools in precision viticulture is the use of remote sensing (Hall *et al*, 2003) through its ability to rapidly provide a synoptic view of grapevine shape, size and vigour over entire vineyards. The use of satellite remote sensing, however, is often limited by the low time flexibility and by the inadequate spatial resolution of the main sensors.

The use of airborne multi-spectral remote sensing is quickly spreading, due to the fact that this technology is able to flexibly follow vine growing conditions and the phenological phases, allowing to support operational vineyard management decisions (Lamb, 2000).

Nowadays airborne remote sensing is able to fill in the lack of existing systems allowing to:

Work at high geometric resolutions, down to few centimeters with the possibility to discriminate the canopy information and separate it from the soil contribution of the inter-row space;

Choose the timing of the aerial passages with high accuracy and flexibility, improving the often inadequate sampling frequency of satellite surveys and allowing to avoid cloud cover conditions.

The research presented in this paper makes use of an airborne remote sensing system to monitor four experimental vineyards in the Tuscany region in central Italy. High spatial resolution vegetation index images were acquired and processed to provide information useful to precision viticulture. The results obtained from preliminary analyses of data taken in the 2007 and 2008 growing seasons are presented. New data acquisition technologies are tested to provide information useful for improving the wine quality in a context of integrated management of wine quality, environment and safety.

MATERIAL AND METHODS

THE STUDY AREA

Four vineyards in Tuscany (Central Italy), have been chosen as test sites (Fig.1): Donna Olimpia (Cabernet Sauvignon, 5.28 ha), Brolio (Sangiovese, 1.9 ha), Cortigliano (Sangiovese, 3.9 ha), Cacciagrande (Cabernet Sauvignon, 3.68 ha).

All vineyards are located between 43°30'N and 42°40'N in latitude; one of them (Brolio) is on a steep area with an elevation between 408 and 436 m a.s.l., all the others are on flat areas near the sea.

The region is characterized by a typical Mediterranean climate, mainly affected by Azores and Russian anticyclones and by Mediterranean depressions (Grifoni et al. 2006). Precipitation is concentrated in spring and autumn with a dry period in summer (annual rainfall between 620 and 860 mm). The growing season is characterized by a temperate spring and a hot summer (annual average temperature between 12.5 and 15°C). The soil type of Donna Olimpia is Typic Haploxerepts sandy, mixed, thermic; that of Brolio is Typic Haplustepts coarse-loamy mixed, mesic; that of Cacciagrande and Cortigliano is Aquic Haplustepts, fine, mixed, thermic (ref. : soil map of Tuscany).

EXPERIMENTAL DESIGN

A preliminary flight was carried out at the beginning of the research in order to obtain, for each vineyard, a characterization of the different vigor index areas, essential factor to create the experimental design. The project has been planned to investigate also the agronomic variables that can influence the final product and for this reason, inside each vigor block, experimental parcels were defined and characterized by a combination of different agronomic treatments: early defoliation of the first 6 basal nodes, 1-3 buds per spur thinning, bunch cutting.

AIRBORNE REMOTE SENSING

The current monitoring strategy is based on three flights per year (2007 and 2008), carried out in a period between June and September, which comprises important phenological stages like flowering, fruit set and veraison.

Airborne remote sensing is performed with SKY ARROW 650 TC/TCNS airplane (fig. 2). Simple operations allow lodging and removing the sensors that are positioned on proper plates. This airplane is completely built with carbon and Kevlar and has a 3.5 hours autonomy. It is extremely manageable, flexible and can take off and land from airports and airfields with airstrip length equal to 500 meters. The overflights can be carried out at an altitude between 300 and 400 m s.l.m. The system, that can acquire visible, near infrared and thermic bands, is composed of multispectral, thermic and real color digital cameras.

The images used in this work have been acquired with Duncan Multispectral Camera MS4100 (1920x1080 RGB colors CCD); they have 30 cm spatial resolution and record visible and near infrared bands. Each flight has been radiometrically and geometrically corrected. A radiometric correction process converts the digital number of each pixel (brightness value) into spectral radiance by the application of calibration functions specific for the cameras, derived from a laboratory spectral bench.

ELABORATION AND DATA PROCESSING

The high geometric resolution requires a more accurate orthorectification than usual, also due to the fact that images representing vineyards are difficult to be corrected. Problems are caused by the fact that usually vineyards are situated on morphologically complex areas and by the fact that there are few points suitable like Ground Control Points (GCP). For this reason a high precision survey was executed using a Differential GPS. At the beginning of each summer season, white panels (1*1 m dimension) were placed at known coordinates to facilitate the orthorectification. The orthorectification processes

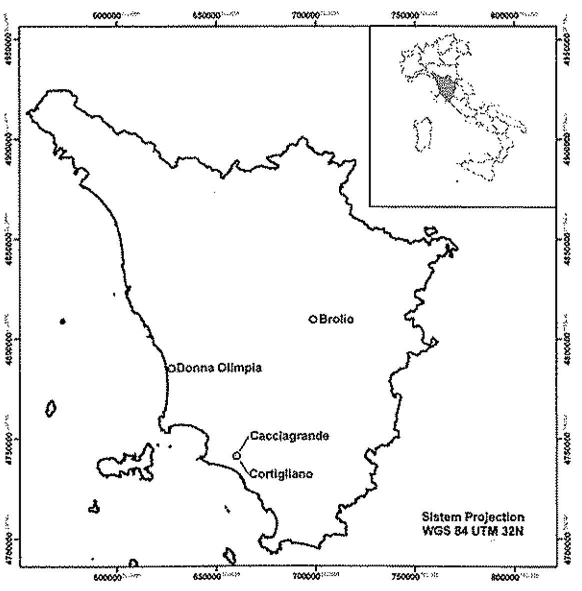

Fig.1 – Location of the experimental vineyards.

Fig.2 - SKY ARROW 650 TC/TCNS airplane.

made also use of a Digital Elevation Model (DEM) with a pixel size of 5*5m. This overall processing chain allowed to obtain a spatial accuracy of the processed images lower than 0.30 m, thus ensuring also an accurate multi-temporal comparison at pixel level between different flights.

Without considering the impact of topography and atmosphere, radiance values were converted into apparent reflectance values using the spectral solar irradiances provided by Iqbal (Iqbal, 1983).

The Normalized Difference Vegetation Index (NDVI) has been currently computed by the classical equation:

$NDVI = (R_{NIR} - R_{RED}) / (R_{NIR} + R_{RED})$

where R_{NIR} and R_{RED} are the reflectances in NIR and RED bands, respectively (Rouse *et al.*, 1973). Spectral vegetation indexes reduce multi-spectral values of each pixel to a single numeric value (index), and have been developed to show vegetative condition changes (Wiegand *et al.*, 1991; Price and Bausch, 1995).

The NDVI maps are processed to distinguish the canopy from inter-row space. In this research convolution filters with mobile windows were studied and evaluated. They extract the pixel value in the center of the mobile window if this is the maximum value between those inside the window. Four filters with different moving windows (3*3, 5*5, 7*7, 9*9 pixels), were considered. Average values per parcel were extracted from each NDVI map by the use of ArcGIS software.

Ground samples were collected for each experimental parcel by researchers of the Istituto Agrario di San Michele all'Adige (IASMA). The ground data collection was carried out every year following a previously defined experimental design. Chemical analyses were carried out on the obtained musts and skins to determine several wine quality parameters like pH, °Brix and polyphenols at the technological ripening and two weeks later.

STATISTICAL ANALYSIS

The investigation of the effects of environmental and/or agronomic practices on the recorded NDVI values was performed by applying SYSTAT 9 to compute an analysis of variance (ANOVA) and correlation matrices. Statistical analyses on the NDVI values for the two vine varieties were performed considering the flights of the same period in the two study years as "dependent" factors against "independent" factors like: year, locality, different levels of vigor, different agronomic practices and their interactions. Each flight was represented by 128 and 96 mean parcel values for Sangiovese and Cabernet Sauvignon vineyards, respectively. The first flight in the second year was not carried out due to technical problems. For this reason, the independent factor year and its interactions were not considered in the analysis of variance for this dependent factor. The significance of bunch cutting and its interactions was computed only for the third flight because this practice is carried out in August after the first two flights. Correlation matrices were constructed for each vineyard by computing conventional Pearson coefficients for continuous data.

RESULTS AND DISCUSSION

The application of the spatial filters to poorly grassed vineyards causes an increase of the vegetation index values by removing the signal from inter-row spaces (Tab.1). In general, the larger is the dimension of the filter moving window, the higher is the NDVI average value per parcel with a decrease in variation coefficient (Tab.2). One of the objectives of the whole research is to identify the variability of the production inside the vineyard and to understand if the canopy agricultural treatments influence the grape quality significantly; for this reason a spatial filter that maintains the highest variation coefficients is preferable. Thus, a filter with the smallest moving window (3*3 pixels), was chosen. No filter was found to be suitable to discriminate row from inter-row spaces when the latter are highly grassed, i.e. they have high vegetation index. This happened in the Donna Olimpia vineyard, where the inter-row space in the summer season is invaded by highly vigorous autochthonous weeds that can reach the height of 1 meter.

Block	Vigour	Treatment	Min	Max	Average
Br_1	Low	not filtered	0.161	0.621	0.337
Br_1	Low	filtered	0.201	0.621	0.399
Br_2	Mean	not filtered	0.157	0.737	0.381
Br_2	Mean	filtered	0.220	0.737	0.449
Br_3	Mean	not filtered	0.162	0.710	0.391
Br_3	Mean	filtered	0.213	0.710	0.461
Br_4	High	not filtered	0.249	0.811	0.546
Br_4	High	filtered	0.321	0.811	0.620

Tab.1 - NDVI statistics from filtered and non filtered images for the experimental blocks from the map of the Brolio Vineyard of 18-07-07.

	Filter 3*3	Filter 5*5	Filter 7*7	Filter 9*9
Blocks Average	0,533	0,688	0,717	0,721
Inside C.V.	0,112	0,072	0,061	0,060

Tab.2 - Average NDVI values and variation coefficients of the experimental blocks in the Cacciagrande vineyard of 16-7-08.

Sources Of Variation	Variables					
	Sangiovese			Cabernet Sauvignon		
	NDVI Flight 1	NDVI Flight 2	NDVI Flight 3	NDVI Flight 1	NDVI Flight 2	NDVI Flight 3
Y	-	0.000	0.000	-	0.146	0.000
L	0.000	0.000	0.000	0.053	0.000	0.000
BT	0.730	0.002	0.002	0.538	0.854	0.990
D	0.000	0.166	0.027	0.119	0.826	0.742
BC	-	-	0.005	-	-	0.733
L * Y	-	0.000	0.000	-	0.506	0.000
BT * Y	-	0.464	0.110	-	0.898	0.906
D * Y	-	0.924	0.327	-	0.541	0.900
BC * Y	-	0.831	0.631	-	0.782	0.791
BC * L	0.723	0.732	0.112	0.162	0.274	0.378
D * L	0.008	0.055	0.001	0.034	0.969	0.653
BT * L	0.784	0.938	0.019	0.366	0.981	0.254
D * BT	0.002	0.309	0.108	0.403	0.097	0.120
BC * BT	0.014	0.068	0.422	0.109	0.065	0.008
BC * D	0.021	0.775	0.384	0.594	0.830	0.690
B (L)	0.000	0.000	0.000	0.000	0.000	0.000
Y * B (L)	-	0.000	0.001	-	0.000	0.274

Tab. 3. – Results from the analyses of variance: significance values from the sources of NDVI variation in the Sangiovese and Cabernet Sauvignon vineyards. The sources of variation considered with relevant interactions are: year ([Y] 2007 and 2008), localities ([L] Brolio and Cortigliano in Sangiovese vineyards; Donna Olimpia and Cacciagrande in Cabernet Sauvignon vineyards), different kind of bud per spur thinning ([BT] 1 or 3 buds per spur), early defoliation of the first six basal leaves ([D] presence or absence of early defoliation), bunches cutting ([BC] presence or absence of bunch cutting), vigour ([B] blocks of the experimental design)

The results of the analysis of variance are summarized in Tab.3. The independent factors year, locality, vigour and their interactions were highly significant for the two varieties ($P<0.01$) indicating that in the study environment the climatic and geo-pedo-morphologic conditions play a basic role for plant development. Agronomic practices had a different effect on the NDVI values of the two grape varieties. Vineyards planted to Sangiovese were found to be sensitive to the agronomic practices and to their interactions with other factors, with the exception of the early defoliation practice that did not affect any NDVI vineyard mean value; this is due to the fact that aerial images are able to record differences on the high canopy and not differences due to practices that work on the basal nodes. This "sensitivity" of Sangiovese is one of the reasons for which it is the preferred grape variety in heterogeneous environments like that of Tuscany. NDVI values for vineyards planted to Cabernet Sauvignon were found to be not affected by agronomic practices, with the exception of the third flight that was influenced by the interaction of bunch cutting and bud thinning.

The results of correlation analyses between NDVI values and grape quality parameters are shown in Tab.4. These results were in accordance with what expected, with negative corre-

			Technological Vintage			Late Vintage		
			°Brix	pH	Polyphenols	°Brix	pH	Polyphenols
Sangiovese	Brolio	NDVI Flight 1	-0.408	-0.412	-0.379	-0.405	-0.113	-0.287
		NDVI Flight 2	-0.512	-0.504	-0.538	-0.457	-0.152	-0.407
		NDVI Flight 3	-0.547	-0.443	-0.546	-0.467	-0.093	-0.442
	Cortigliano	NDVI Flight 1	-0.439	-0.469	-0.483	-0.323	-0.158	-0.293
		NDVI Flight 2	-0.346	-0.48	-0.305	-0.425	-0.169	-0.359
		NDVI Flight 3	-0.306	-0.509	-0.294	-0.494	-0.316	-0.273
Cabernet Sauvignon	Donna Olimpia	NDVI Flight 1	0.186	0.113	0.178	0.093	0.379	0.147
		NDVI Flight 2	0.063	0.233	0.321	0.19	0.4	0.126
		NDVI Flight 3	0.133	0.152	0.408	0.258	0.38	0.219
	Cacciagrande	NDVI Flight 1	-0.263	-0.099	-0.363	-0.443	-0.249	-0.191
		NDVI Flight 2	-0.505	-0.387	-0.433	-0.567	-0.419	-0.173
		NDVI Flight 3	-0.513	-0.355	-0.435	-0.574	-0.368	-0.276

Tab.4 – Correlation matrix between the NDVI values and the grape quality parameters of each vineyard.

lations between the NDVI values and the grape parameters, except for the Donna Olimpia vineyard planted to Cabernet Sauvignon. This last result could be partially explained by the higher spatial homogeneity of the former vineyard with respect to the others. Such homogeneity causes small variations of the examined independent and dependent factors, which might reduce the "signal-to-noise ratio" of the applied analyses. The unexpected behavior of this vineyard can be due also to the previously mentioned spread of weeds, which reduces the efficiency in the observed NDVI values and introduces noise in the correlation analyses.

Another interesting aspect is that in most cases the correlation coefficient for °Brix and polyphenols tends to increase while approaching the vintage. This observation is not valid for pH, that has always the highest correlation coefficient with the second flight. On this basis we can suppose that July is the best period for the acquisition of NDVI images aimed at controlling wine pH.

CONCLUSIONS

The use of the Sky Arrow airplane and the DFR system was found to be flexible, cheap and not complex. The high geometric resolution of the images allows acquisition of important information about the vegetative condition of the single vine plants. In a complex environment like that of Tuscany, where the climatic and geo-morpho-pedologic characteristics are highly variable and affect the quality parameters, the Sky Arrow can be an efficient instrument to record the variability inside the vineyards and to monitor the seasonal NDVI trends related to different vigor areas.

The digital filters developed in this research allowed an efficient extraction of NDVI values relative only to the vine rows, increasing the value of the information obtained by aerial remote sensing.

The analysis of variance showed that the environment, the climatic seasonal trend and their interactions affect significantly both Sangiovese and Cabernet Sauvignon NDVI vineyard values. The agronomic practices were significant only in the vineyards planted to Sangiovese, with the exception of the early defoliation practice that did not affect any NDVI vineyard mean value.

Correlation matrices built between NDVI mean values and grape quality parameters indicated that there are logic correlations between these factors and that these correlations tend to increase with the advance of the season. This is less the case for vineyards which are grown in very homogeneous environmental conditions or are invaded by weeds, since in this case NDVI variations can be poorly representative for relevant variations in vine quality.

The next research activities will be oriented to better understanding the dynamics emerged in the first two study years by integrating remote sensing and quality grape indicators with agro-meteorological and pedologic parameters. Another objective of the research will be to define remote sensing indexes of vineyard enological capacities in a context of a "terroir" model (Fregoni *et al*, 2003)).

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