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Remote sensing detection of nutrient uptake in vineyards using narrow-band hyperspectral imagery

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Summary

This manuscript delves further into the assessment of narrow-band vegetation indices derived from hyperspectral imagery acquired at 1 m spatial resolution with the Compact Airborne Spectrographic Imager (CASI). Narrow-band indices proposed in this study were assessed as indicators of biochemical and structural parameters in *Vitis vinifera* L., observing their relationships with foliar variables such as N, P, K, Ca, Fe, Mg and chlorophyll a+b concentration (C_{a+b}). Hyperspectral indices were assessed to study their capability for vegetation condition monitoring as a function of fertilization treatments applied (basically extracts of Ascophyllum nodosum seaweed and chelates), showing associations with field variables. Narrow-band vegetation indices displayed sensitivity to vineyard growth and condition as a function of seaweed fertilization and other supplementary mineral correctors, such as chelates. This work shows the interest of using new narrow-band hyperspectral remote sensing indices for vineyard monitoring due to their potential to indicate physiological condition.

K e y w o r d s : hyperspectral, remote sensing, reflectance, active limestone, grapevine, vineyards, iron chlorosis, Ascophyllum nodosum.

A b b r e v i a t i o n s : chlorophyll content (C_{a+b}), dry matter (C_m), water content (C_w), indices (G, MCARI, TCARI, TVI, ZM, GM_2, GM_1, $MTVI_1$, $MTVI_2$, RDVI, $MCARI_1$ and $MCARI_2$), treatment (T1-T4) and study area (ALG1-ALG4).

Introduction

New narrow-band vegetation indices calculated from leaf-level spectroscopy and multispectral-hyperspectral imagery have been shown as potential indicators of vegetation status and photosynthetic condition in vineyards (Zarco-Tejada *et al.* 2005). These new indices are calculated from narrow-band multispectral or hyperspectral imagery that allows for the discrimination of background effects and shadows due to the optimum pixel size in the range of 1-2 m. High-spectral resolution sensors enable the calculation of other narrow-band vegetation indices related to specific light absorptions or band shapes caused by leaf biochemical and canopy biophysical processes or conditions, such as chlorophyll (Vogelmann *et al.* 1993, Carter 1994, Gitelson and Merzlyak 1996, Zarco-Tejada *et al.* 2001, Haboudane *et al.* 2002, 2004) and carotenoids (Fuentes *et al.* 2001, Sims and Gamon 2002). Recent studies demonstrate the validity of several hyperspectral indices for quantifying chlorophyll concentration (Vogelmann *et al*. 1993, Carter 1994, Gitelson and Merzlyak 1997, Zarco-Tejada *et al*. 2001, 2004, 2005), enabling the application of remote sensing methods in precision agriculture for vegetation stress and field mapping into different stress classes.

Leaf chlorophyll concentration is used as an indicator of vegetation stress condition because of its direct role in photosynthetic processes. Stressed vegetation is affected by various physiological perturbations in the light-dependent reactions of photosynthesis, including structural damage to photosynthetic pigments. Total chlorophyll content (C_{a+b}) and other leaf biochemical constituents such as dry matter (C_m) and water content (C_w) may be used as indicators of plant stress and nutritional deficiencies caused by macro and micro elements (Chen and Barak 1982, Marschner *et al.* 1986, Tagliavini and Rombolà 2001).

New trends in crop fertilization methods are directed towards the use of natural sources of nutrients. Marine algae species such as *Macrocystis*, *Eklonia, Sargassum*, *Durvillia, Porphyra, Fucus* and *Ascophyllum* are identified as potential fertilizer agents in crops. Among these species, *Ascophyllum nodosum* is the most widely investigated in agriculture (Blunden 1991). Algae extracts have a suitable content of N and K, but are much lower in P than traditional animal manures and typical NPK ratios in chemical fertilizers. This manuscript deals with narrow-band vegetation indices from airborne hyperspectral imagery calculated on spectral bands sensitive to canopy structure and pigment concentration to detect the effects caused by nutrient uptake in vineyards (*Vitis vinifera* L.). The study conducted shows the sensitivity of the proposed indices for assessing the effects of fertilizer treatments (*A. nodosum* and chelates) on vegetation status.

Material and Methods

S t u d y s i t e s e l e c t i o n a n d e x p e r i m e n t a l d e s i g n : Research work was

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conducted in the summer of 2003 in a vineyard (*Vitis vinifera* L. 'Tempranillo') located in Roturas, Valladolid (Spain), within the Ribera del Duero Denomination of Origin. The soils are calcareous, very basic, and have textures ranging from silt to silty clay. Calcium is the cation which dominates the exchange complex, causing carbonates to predominate (48.97 %, higher than the average of the control plots of Ribera del Duero: 38.40 %; standard deviation of 18.08), and the pH is in the range of 7.0-8.5. The area has a continental climate, with average annual rainfall between 430 and 550 $L \cdot m^{-2}$. Temperatures range between -20 ºC and 42 ºC, with an average temperature of 11 ºC and a frost-free period of 115 d. The number of sunshine hours per year is 2300. The field study site selected for this experiment was 4.69 ha^{-1}. The vineyard was planted in 1999 in a 3 m x 1.30 m pattern (2777 $stocks \cdot ha^{-1}$) and a north-east to south-west row orientation (N-S + 45º), Ellipsoid SGR80 (Datum ETRS89) UTM zone 30N X: 405799, Y: 4613796. 'Tempranillo' is well adapted to the extreme climatic conditions of the region, producing opulent wines rich in fruit, body and color, not requiring blends with other varieties, and an optimal production of 5000 $kg \cdot ha^{-1}$. Fig. 1 shows the field study site and the vineyard field imaged by the Compact Airborne Spectrographic Imager (CASI) airborne sensor used in this study.

The fertilizer applied in this experiment was extracted from the marine algae *Ascophyllum nodosum* by acid hydrolysis processes (Bioalgeen®, Schulze and Hermsen GmbH). The experimental design consisted of four fertilization treatments (T1, T2, T3 and T4) applied on four study sites within the field (ALG1, ALG2, ALG3 and ALG4). The different treatments were carried out by means of direct application, in liquid form and spray, to all the leaves and randomly selecting the study areas. Each study plot included four subsites corresponding to the four different treatments, with a subplot consisting of two rows of 10 vines. The composition of the treatments per 1000 L was: (T1) 2.5 L of Talosint® with 10 L of Bioalgeen®; (T2) 2.5 L of Talosint® with 20 L of Bioalgeen®; (T3) 10 L of Bioalgeen® + 5 kg Karentol Mix®; and (T4) the control treatment. Talosint® is a broad spectrum organo-cupric fungicide/bactericide for control of soil endoparasite fungi and esca in vineyards; Karentol Mix of KenoGard® is a corrector for multiple deficiencies of Mn, Mg, B, Cu, Fe, Mo, Zn, S in chelated form. Algae and Talosint® were used in all treatments except in the control. The dose was 0.125 % (via foliar), with foliar application recommended for the start of vegetative growth and in the presence of stress conditions due to deficiencies.

Leaf samples (n = 80) were collected from the study areas (10 x 10 m^2), using 50 leaves to assess dry matter and the elements N, P, K, Ca, Mg, Fe, 20 leaves for chlorophyll C_{a+b} determination, and 10 leaves to measure leaf reflectance and transmittance, as in ZARCO-TEJADA *et al.* (2005).

Chlorophyll *a* (C_a), chlorophyll *b* (C_b), and total carotenoids (C_{x+c}) concentration were calculated as in WELLBURN (1994), with a Jasco V-530 UV-VIS spectrophotometer (Jasco Inc., Great Dunmow, UK). Structural measurements on each study site consisted of grid size, number of vines within the 10 x 10 m^2 site, trunk height, vegetation height and width, and row orientation. Three soil samples within each subplot were collected at a depth of 30 cm for laboratory analysis.

Grape harvesting took place on September 29, 2003, and clusters were gathered from each study site. Selected parameters were measured on each study site from 100 berries collected from the clusters of that area, obtaining a representative sample. Methods for foliar and soil analysis were based on standard methods of analysis (ASTM, EPA), measuring acidity, conductivity, carbonates, active limestone, soluble phosphorus, total nitrogen, interchange capacity, organic matter, texture, chlorophyll, nutrients (nitrogen, phosphorus), and cations (sodium, potassium, magnesium, calcium and iron). Correlation matrix and factorial and cluster analysis were run in SPSS (v. 5) to analyze the relationship between foliar contents, treatment approaches and soils.

Airborne Campaign with the CASI hyperspectral sensor: Airborne image acquisition campaigns were conducted in July 2003 with the Compact Airborne Spectrographic Imager (CASI) sensor in collaborative research with York University (Canada) and the Spanish Aerospace Institute, Instituto Nacional de Técnica Aeroespacial (INTA). CASI imagery were collected on two airborne missions, each with a specific sensor mode of operation: i) the Mapping Mission, with 1 m spatial resolution and 8 user-selected spectral bands placed in the spectrum to enable the calculation of specific narrow-band indices sensitive to pigment concentration (bands at 490, 550, 670, 700, 750, 762, 775 and 800 nm with full-width 192 at half maximum (FWHM) ranging be-

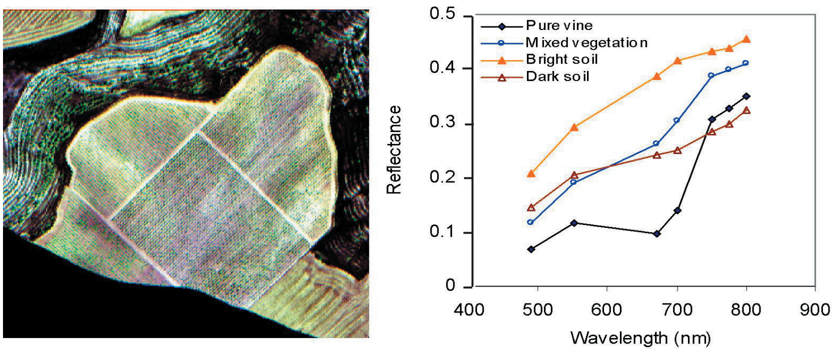

Fig. 1: Hyperspectral CASI image collected on the vineyard field of study, acquired at 1 m spatial resolution with 7 spectral bands, showing reflectance spectra extracted from different scene components.

tween 7 and 12 nm); and the Hyperspectral Mission, with 4 m spatial resolution, 72 channels and 7.5 nm spectral resolution. The 12-bit radiometric resolution data collected by CASI were processed to at-sensor radiance using calibration coefficients derived in the laboratory by the Earth Observations Laboratory (EOL), York University. Atmospheric correction was applied to CASI imagery via the CAM5S atmospheric correction model (O'NEILL *et al.,* 1997) using field-measured aerosol optical depth data collected at 340, 380, 440, 500, 670, 870, and 1020 nm by means of a Micro-Tops II sunphotometer (Solar Light Co., Philadelphia, PA, USA) at the time of data acquisition. Reflectance data were geo-referenced using GPS data collected onboard the aircraft. Soil reflectance spectra were used to perform a flat-field correction that compensated for residual effects on derived surface reflectance estimations in atmospheric water and oxygen absorption spectral regions. The multispectral images were analyzed to extract the mean reflectance spectra from each study site. In order to avoid mixed pixels due to the influence of soil and shadows, mean reflectance spectra were extracted from pure vine pixels as a function of an image-based threshold based on NDVI. Fig. 1 shows vegetation and soil spectra extracted from a CASI mapping mission image on selected sites after processing to surface reflectance, observing the spectral patterns for pure vine pixels, mixed soil-vegetation pixels, and bright and dark soil spectra.

Narrow-band indices calculated from hyperspectral reflectance and leaf and canopy levels are demonstrated to be related to specific light absorptions caused by leaf biochemical constituents, such as chlorophyll *a* and *b*, carotenoids/chlorophyll and anthocyanins/chlorophyll ratios, dry matter, and water content. A large number of vegetation indices are currently proposed for C_{a+b} estimation in crop and forest species, exploiting the differences in reflectance between healthy and stressed vegetation in the visible and red edge spectral region (VOGELMANN *et al.* 1993, CARTER 1994, CARTER and SPIERING 2002, ZARCO-TEJADA *et al.* 2001, SIMS and GAMON 2002). A full review of these chlorophyll indices can be found in ZARCO-TEJADA *et al.* (2001, 2004, 2005).

A total of 17 narrow-band vegetation indices (see ZARCO-TEJADA *et al.* 2005) were calculated from the reflectance imagery collected by the airborne hyperspectral CASI sensor. The indices were calculated on all study sites, enabling monitoring of the fertilizing treatments on the vegetation status. Assessment of the fertilizing effects on vine vigor and structure was conducted through vegetation indices sensitive to physiological condition and canopy structure, such as: (i) chlorophyll indices, related to pigment content and therefore to plant physiology; (ii) structural indices, related to external structure parameters of the plant; and (iii) combined indices, calculated as a function of chlorophyll and structural indices to minimize background and shadow effects. The high spatial resolution of the CASI sensor used in this study, with 1 m pixel size, enabled separation of the scene components, without spectral mixing of pure vegetation, shadow and background on the pixel spectrum (see Fig. 1 for examples of pure components extracted from the imagery). Relationships were obtained between vegetation indices and foliar determination of nitrogen, phosphorus, potassium, calcium, iron and magnesium from the study sites, as well as with vine production as a function of fertilization treatments applied.

Results and Discussion

Study of foliar mineral and chlorophyll content: The foliar content of mineral elements and chlorophyll in each study area is shown in Tab. 1. Statistical analysis with SPSS for these data shows that the sampling adequacy through the Kaiser-Meyer-Olkin (KMO) measure (0.58) is significant. The sphericity data, 32.3, measured by Bartlett's test, is also significant (its associated probability is less than 0.05).

Table 1

Foliar content of mineral elements and chlorophyll in each treatment (T1-T4) and study area (ALG1-ALG4)

Identif	Treatment	N %	P %	K %	Ca %	Mg %	Fe ppm	C_a (µg·cm^{-2})	C_b (µg·cm^{-2})	C_{a+b} (µg·cm^{-2})
1	T1 ALG1	2.57	0.15	0.78	2.44	0.44	79.2	32.10	9.77	41.87
2	T1 ALG2	2.78	0.16	0.84	2.48	0.39	67.7	27.63	7.49	35.12
3	T1 ALG3	2.74	0.16	0.78	2.59	0.38	87.9	34.28	9.34	43.61
4	T1 ALG4	2.64	0.15	0.67	2.61	0.42	74.3	36.59	9.58	46.18
5	T2 ALG1	2.59	0.15	0.65	2.47	0.45	81.2	32.39	9.15	41.53
6	T2 ALG2	2.66	0.16	0.73	2.69	0.47	79.0	33.16	9.51	42.67
7	T2 ALG3	2.54	0.15	0.57	2.82	0.46	79.5	30.56	8.23	38.79
8	T2 ALG4	2.65	0.15	0.57	2,81	0.50	80.0	37.70	10.31	48.01
9	T3 ALG1	2.68	0.16	0.67	2.48	0.43	89.0	30.29	9.43	39.72
10	T3 ALG2	2.72	0.16	0.70	2.40	0.39	64.3	34.51	9.49	44.00
11	T3 ALG3	2.70	0.15	0.56	2.84	0.46	74.9	36.13	10.14	46.28
12	T3 ALG4	2.64	0.15	0.62	2.42	0.43	104.1	30.48	8.35	38.83
13	T4 ALG1	2.63	0.15	0.57	2.50	0.37	73.0	33.36	9.20	42.56
14	T4 ALG2	2.76	0.15	0.65	2.47	0.36	72.7	30.69	7.94	38.62
15	T4 ALG3	2.60	0.14	0.51	2.64	0.38	74.4	33.92	9.37	43.29
16	T4 ALG4	2.84	0.15	0.66	2.22	0.38	66.7	36.27	10.06	46.33

This means that the correlation matrix in Tab. 2 is not an identity matrix and that the strength of the relationship among variables is good. The correlation matrix shows that the most closely associated variables are P-K (r = 0.726) and Ca-Mg (r = 0.608). C_{a+b} concentration correlated inversely with phosphorus levels (r = -0.249; $p < 0.05$) and potassium levels (r = -0.346; $p < 0.05$) in the blades, in line with the observations of other researchers (Martín *et al.* 2007). In situations where there was iron chlorosis, when P leaf concentration increased, the P/Fe ratio also increased, without any correlation between soil and leaf phosphorus content (Fregoni 1998).

From the factorial analysis we found that a cumulative 78 % of total variance can be explained with three principal components. A 3D graphic with these components (Fig. 2) shows P and K clustered separately from Ca and Mg, and chlorophyll is a variable that is separate and independent of each of the other variables (N, P, K, Ca, Mg, Fe). Another 3D graphic (Fig. 3) shows the T4 treatment data grouped in a cluster, clearly differentiated from the data for other treatments.

As seen in Tab. 3 (comparison of mean values for variables), the T1, T2 and T3 treatments supply more P, K, Ca, Mg and Fe nutrients than the T4 control treatment. Differences among the mean values are moderately significant for K, Ca, Mg and Fe and non-significant for P. As for chlorophyll, although the C_{a+b} average concentration in the sampling leaves collected in the field trial was determined, it was impossible to recognize differences between treatments. This finding is similar to that previously reported by Martín *et al*. (2007). On the other hand, the most closely associated treatments are T2 and T3 (r = 0.89 for K; r = 0.61 for Fe), whereas T1 appears closer to T4 (r = 0.75 for K; r = 0.98 for C_{a+b}).

In Tab. 2, an inverse, non-significant relationship was detected between iron concentration and chlorophyll concentration (r = -0.214) of the sampling leaves. It is well known that iron concentration in leaves is not a valid indicator for diagnosing iron chlorosis (Martín *et al*. 2007).

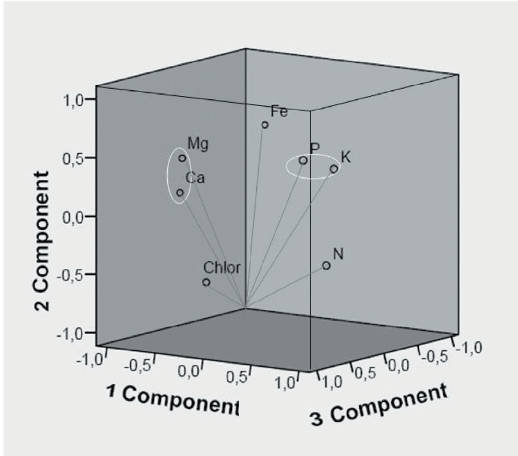

Fig. 2: 3D principal components plot for data of Tab. 1 showing the spatial distribution of the variables (foliar nutrients). Short Euclidean distances between points indicate similarity (e.g. P and K, Ca and Mg).

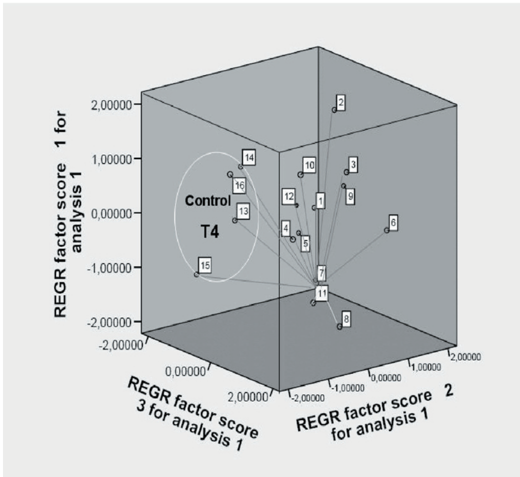

Fig. 3: 3D principal components plot for data of Tab. 1 showing the spatial distribution of the foliar nutrients (1-16). The four T4 control treatments on each study area (13-16) are grouped in a cluster, clearly differentiated from the other treatments.

Table 2

Correlation matrix for foliar mineral and chlorophyll content (Pearson's r values)

	N	P	K	Ca	Mg	Fe	Chlorophyll
Pearson correlation							
N		0.377	0.388	-0.417	-0.493	-0.389	0.131
P	0.377		0.726	-0.148	0.007	0.018	-0.249
K	0.388	0.726		-0.406	-0.170	-0.072	-0.346
Ca	-0.417	-0.148	-0.406		0.608	0.105	0.229
Mg	-0.493	0.007	-0.170	0.608		0.347	0.238
Fe	-0.389	0.018	-0.072	0.105	0.347		-0.214
Chlorophyll	0.131	-0.249	-0.346	0.229	0.238	-0.214	
Sig. (Unilateral)							
N		0.075	0.069	0.054	0.026	0.068	0.314
P	0.075		0.001	0.292	0.490	0.474	0.176
K	0.069	0.001		0.059	0.264	0.396	0.094
Ca	0.054	0.292	0.059		0.006	0.349	0.197
Mg	0.026	0.490	0.264	0.006		0.094	0.187
Fe	0.068	0.474	0.396	0.349	0.094		0.213
Chlorophyll	0.314	0.176	0.094	0.197	0.187	0.213	

Table 3

Comparison of treatments: foliar nutrient concentration response to different treatments (top); and relationship between treatments (bottom)

	%N		% P		% K		% Ca		% Mg		Fe (ppm)		C_{a+b} ($\mu g \cdot cm^{-2}$)	
Treatment	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
T1	2.68	0.09	0.155	0.006	0.77	0.07	2.53	0.08	0.41	0.03	72.3	8.5	41.7	4.73
T2	2.61	0.06	0.152	0.006	0.63	0.08	2.7	0.16	0.47	0.02	79.9	0.9	42.7	3.87
T3	2.68	0.03	0.155	0.006	0.64	0.06	2.53	0.21	0.43	0.03	83.1	17.3	42.2	3.53
T1-T2-T3 (pool)	2.66	0.07	0.15	0.005	0.68	0.09	2.59	0.16	0.44	0.04	78.5	10.4	42.2	3.55
T4 (control)	2.71	0.11	0.147	0.005	0.6	0.07	2.46	0.17	0.37	0.01	71.7	3.4	42.7	2.44
	r	Sig.	r	Sig.	r	Sig.	r	Sig.	r	Sig.	r	Sig.	r	Sig.
T1 vs T4	0.48	-0.2	-	-	0.75	0.05	-0.29	0.7	0.03	0.05	0.42	0.3	0.98	0.05
T2 vs T4	0.90	0.3	0.58	0.4	0.62	0.1	-0.16	0.8	-0.66	0.3	-0.08	0.02	0.47	0.1
T3 vs T4	-0.46	0.6	1.00	0.8	0.38	0.5	0.73	0.2	0.88	0.4	-0.78	0.03	-0.5	0.2
T1 vs T2	0.09	0.5	0.58	0.4	0.77	0.2	0.92	0.1	-	-	0.27	0.2	0.3	0.2
T1 vs T3	0.69	0.3	-	-	0.44	0.1	0.41	0.1	-0.05	0.1	0.09	0.2	-0.39	0.2
T2 vs T3	-0.17	0.3	0.58	0.4	0.89	0.05	0.38	0.2	-0.16	0.2	0.61	0.05	-0.75	0.1

The so-called iron chlorosis paradox (Bavaresco *et al.* 1999) is manifested when chlorotic plants have higher leaf Fe concentration than green ones. The imbalance between foliar iron levels and chlorosis intensity necessitates the use of alternative methods to diagnose the disease. One such method is the interpretation of relationships between nutrients rather than absolute iron content in tissues. Thus, the mean values of the K/Ca 0.26 and Ca/Mg 6.15 relationship compared with reference values provided by Martín *et al.* (2007) in Ribera del Duero (K/Ca 0.18 for healthy plants and 0.35 for chlorotic plants; Ca/Mg 6.58 for healthy plants and 4.57 for chlorotic plants) confirm that cultivars are slightly affected by iron chlorosis, usually associated with high pH values in soil (in the 7.0-8.5 range) and active limestone (10 %). Consequently, the estimation of C_{a+b} concentrations in leaves before veraison could be a useful viticultural management tool for predicting grape quality at harvest in vineyards affected by iron chlorosis (Martín *et al.* 2007).

A detailed assessment of yield as a function of the treatments applied, carried out by way of example for site ALG2, shows that the T4 control treatment is the one with the lowest yield, the one with the smallest alcoholic degree (1.0 kg, 4 bunches of grapes, 25.4 ºBrix) and the greatest total acidity (4.47 $g \cdot L^{-1}$). T1 is the treatment whose parameters are closest to those obtained for the T4 control treatment (1.8 kg, 8 bunches of grapes, 24.2 ºBrix, and 4.34 $g \cdot L^{1}$ of total acidity). However, T2 and T3 were, on average, the treatments with the largest yields and alcoholic degree (2.3 kg, 8 bunches of grapes, 26.3 ºBrix and 4.2 $g \cdot L^{-1}$ of total acidity). These results are consistent since the T2 and T3 treatments were provided with more nutrients than T1 (and T4) due to the higher concentrations of Bioalgeen® or Karentol Mix®.

Study of hyperspectral indices: The relationships obtained between narrow-band vegetation indices calculated from the airborne imagery and the concentration of leaf mineral elements are classified as a function of the type of indices calculated: i) chlorophyll indices; ii) structural indices; and iii) combined indices. Among the chlorophyll indices used, the best relationships with nitrogen were obtained for the G, MCARI, TCARI and TVI indices, resulting in a correlation coefficient of r ± 0.5 for all of them. The best correlations with calcium were obtained with the ZM and GM_2 indices (r = 0.51), yielding a correlation coefficient between magnesium and GM_1 of r = -0.58.

Among the structural indices calculated, $MTVI_1$, $MTVI_2$, RDVI, $MCARI_1$ and $MCARI_2$ were the best indicators of nitrogen concentration, yielding a correlation coefficient of r ± 0.5 in all cases. Relationships between structural indices and calcium showed superior results than with the chlorophyll indices, obtaining correlation coefficients of r = -0.59 (NDVI), r = -0.58 (SR), r = -0.58 (MSR), r = -0.56 (OSAVI), and r = -0.50 (MSAVI). The best relationships for structural indices were obtained with magnesium, probably due to the effects on crop growth, yielding r = -0.62 for NDVI, SR and MSR, and r = -0.57 with OSAVI. Combined ratios between chlorophyll and structural indices showed the best results with nitrogen and magnesium. The best correlations with nitrogen were attained for $MCARI_2$·(TCARI/OSAVI) (r = -0.58) and NDVI·(TCARI/OSAVI) (r = -0.53). The $MCARI_2$/(TCARI/OSAVI) index obtained the best correlations with magnesium (r = -0.69), with TCARI/OSAVI and MCARI/OSAVI yielding r = 0.57.

The best relationships between indices and chlorophyll content were obtained for the MCARI, TCARI, TVI, ZM, GM_1, and GM_2 indices, yielding the best correlation with G (r = -0.46). The correlations between chlorophyll content and concentration of mineral elements showed that the best result was obtained for nitrogen concentration (r = 0.51).

Results of the narrow-band indices calculated from the CASI imagery consistently showed that the indices were able to capture the effects of the fertilization treatments (Fig. 4). The T1 and T2 treatments, containing seaweeds, consistently showed higher index values related to chlorophyll concentration and canopy structure than the T4 control treatment. The G (Fig. 4 a) and MCARI (Fig. 4 b) chlorophyll indices, the $MTVI_2$ (Fig. 4 c) and $MCARI_1$

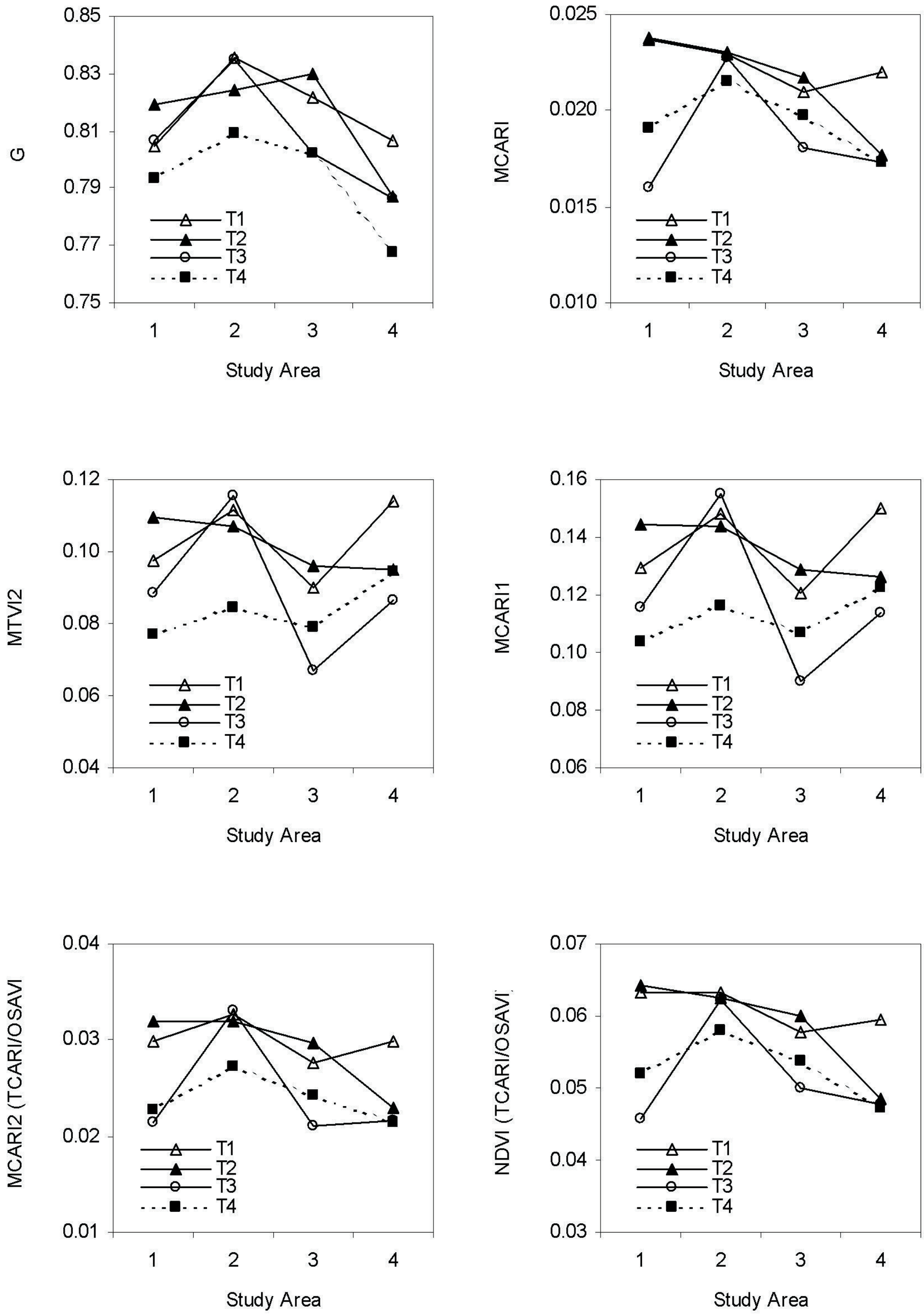

Fig. 4: Values of the G, MCARI, MTVI2, MCARI1, MCARI (TCARI/OSAVI) and NDVI (TCARI/OSAVI) indices calculated from hyperspectral CASI imagery on each study area and treatment level. Study areas: 1 = ALG1; 2 = ALG2; 3 = ALG3; 4 = ALG4.

(Fig. 4 d) structural indices, and the MCARI (TCARI/OSAVI) and NDVI (TCARI/OSAVI) combined indices were shown to be sensitive to the T1 and T2 treatments, obtaining higher values than T4. These results suggest the validity of the treatments applied and the successful detection of fertilization effects on remote sensing imagery using hyperspectral indices, demonstrating the sensitivity of narrow-band indices to vineyard condition.

Potential yield increments as a function of fertilization treatments applied were also assessed, studying the relationships between yield and remote sensing vegetation indices. Results obtained as a function of treatment and study site (Tab. 4) showed correlation coefficients up to r = 0.81 for the $MTVI_2$ and $MCARI_2$ indices. Consistently, the results indicate that structural indices were sensitive to yield, in line with studies showing an increase of quality and weight in grape growth in soils with an elevated active limestone content (calcium carbonate extractable with ammonium oxalate). An exhaustive examination of the set of indices in different fertilization treatments and grape production concludes that the algae was a good releasing agent and a relationship exists between sites with active limestone content fertilized with the seaweed and elevated yield values, successfully captured by vegetation indices sensitive to structure and physiological condition. Application of physiological condition monitoring in vineyards as part of precision viticulture practices enables the generation of chlorophyll concentration maps using the TCARI/

Table 4

Correlation coefficients obtained between airborne hyperspectral indices and chlorophyll content

Chlorophyll indices	r
G	-0.69
TVI	-0.76
ZTM	-0.56
G_M1	0.60
G_M2	-0.56
MCARI2 / (TCARI / OSAVI)	-0.52
Structural indices	r
MTVI1	-0.79
MTVI2	-0.81
MCARI1	-0.79
MCARI2	-0.81

In all cases, significance Pearson´s r is under 0.05.

OSAVI index. Another study conducted in vineyards in Ribera del Duero (Martín *et al.* 2007) showed that the TCARI/OSAVI combined index has a higher sensitivity for C_{a+b} estimation at canopy level than the traditionally accepted NDVI index for vegetation condition monitoring.

The TCARI/OSAVI index has allowed us to generate classes of potentially high, medium and low quality as a function of estimated chlorophyll concentration. Within-field spatial variability observed on the calculated chlorophyll map could be used to define variable-rate fertilization strategies.

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