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RESEARCH ARTICLE

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Vine vigor, yield and grape quality assessment by airborne remote sensing over three years: Analysis of unexpected relationships in cv. Tempranillo

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Abstract

The prediction of grape composition is becoming more important due to the need of reducing the current levels of alcohol and pH of the wines, a problem that is exacerbated by climate change. This work presents a 3-year study of the spatial variability of grape composition in a rainfed Tempranillo vineyard located in Rioja (Spain). It is based on the acquisition of multispectral imagery at *véraison* (start of the ripening process); and zoning based on NDVI, to assess its performance for zonal management. The results reveal a high spatial variability within the plot, with a stable pattern over the years, even with very different climate conditions. NDVI was a good predictor of vegetative growth variables. However, the prediction of grape composition was more complex. Unexpectedly, anthocyanins were found to be higher in the highest vigor zone, which is probably related to the effects of climate change. This unexpected relationship is particularly discussed in the article.

Additional key words: precision viticulture; spatial variability; airborne imagery; anthocyanins; NDVI.

Abbreviations used: CV (Coefficient of Variation); NDVI (Normalized Difference Vegetation Index); NIR (Near Infrared).

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Introduction

Spatial variability in vineyards is an important issue that affects both farmers and winemakers, especially when trying to obtain the best potential out of their vines. Land (topography and soil), climate and diseases affect crop development and, therefore, grape yield and quality throughout a single vineyard. Some of these sources of variation remain stable along time, as observed by Bramley & Hamilton (2004). The study of these patterns can lead wineries to a better understanding of the different qualities of batches, in order to plan different winemaking procedures and get a better profit from the grapes (Proffit *et al.*, 2006; Bramley *et al.*, 2011). Furthermore, this information allows targeted crop management in terms of inputs (irrigation, fertilizers, spraying) and cultural practices (pruning, shoot and grape thinning, canopy management); with the aim to achieve more uniform parcels (Bramley, 2005; Proffit & Malcolm, 2005; Arnó *et al.,* 2009).

The concern about grape composition is increasing among winemakers, since most vineyards all over the world produce high sugar content grapes. This is mostly because of viticultural practices, which have usually been designed to this aim. Climate change has also contributed to increase the berry ripeness process naturally. Therefore, wines present higher alcohol content and also there is a trend towards a pH increase (Schultz & Jones, 2010). Generally, for the most part of winemaking regions, the warming trend from the last decades to date has led to higher quality wines, with higher concentrations in anthocyanins and polyphenols, especially in northern regions. However, predictions reveal an average trend of +2 °C by 2049 (Schultz & Jones, 2010). This considerable increase will affect very likely grapevine phenology, leading to high-temperature ripening processes and to technological, phenolic and aromatic ripeness mismatch (Schultz & Jones, 2010). In addition, anthocyanin synthesis is highly related to temperature. Whilst sugar activity ranges from 18 to 33 °C, pigment producing enzymes is limited to 17-26 °C (Iland & Gago, 2002; Sadras *et al.,* 2007). Temperatures above 30 °C after *véraison* can inhibit anthocyanin formation (Kliewer & Torres, 1972; Mori *et al.,* 2007).

Microclimate in the leaf and bunch area depends on leaf density and bunch and leaf arrangement, and affects light reaching the vine, as well as leaf and bunch temperature and humidity (Smart & Robinson, 1991). It is assumed that, the higher bunch exposure to light, the better the grape quality (Kliewer, 1970; Smart *et al.,* 1985). In addition, grapes show higher concentrations in sugar, phenolics or anthocyanins, and less acidity and malic acid. Generally, it is agreed that an increase in light exposure favours polyphenolic accumulation, mainly flavonoids, like anthocyainins and flavonols (Haselgrove *et al.,* 2000; Spayd *et al.,* 2002; Tarara *et al.,* 2008). Also, when there is enough and moderate light getting to the bunches, the limiting factor in anthocyanin synthesis is temperature. However, some authors have reported that over-exposure and therefore high temperatures in grape bunches may lead to reducing anthocyanin accumulations (Kliewer *et al.,* 1967; Haselgrove *et al.,* 2000; Spayd *et al.,* 2002). In this sense, vine vigor can affect vine microclimate, light reception and/or temperature in the bunches.

To assess vineyard variability, one of the most powerful tools is the airborne remote sensing through the translation of reflectance into a single number or index. This index can be related to shape, size and photosynthesic activity of the vines. Usually, spectral vegetation indexes are ratios including red and near-infrared (NIR) reflectance: red wavelengths are absorbed by leaf chlorophyll and NIR wavelengths by the mesophyll tissues. The most basic vegetation index is RVI (Ratio Vegetation Index), which is simply the coefficient between NIR and red reflected light. In order to avoid the influence of the light intensity reflected by objects (whether they are shadowed or fully exposed), other normalised indexes have been developed, such as the Normalized Difference Vegetation Index (NDVI). Since this ratio diminishes atmospheric and luminous variations, it is very convenient in multi-temporal studies (Fischer, 1994) Several studies demonstrate that NDVI can provide information not only about vine vegetative status, but about yield and grape composition, pH, acidity, sugar content or phenolic compounds (Lamb *et al.,* 2004; Arnó *et al.,* 2011; Fiorillo *et al.,* 2012; Martínez-Casasnovas *et al.,* 2012). Nevertheless, latest technology developments have improved the spectral resolution of remote sensors, allowing for calculating new indexes based in other narrow wavelengths capable to detect chlorosis, water stress or nutrition deficiencies in grapevine. Some of them are TCARI (Transformed Chlorophyll Absorption in Reflectance Index) based on 550, 670 and 800 nm wavelenghts, OSAVI (Optimised Soil Adjusted Vegetation Index) at 670 and 800 nm, or PRI (Photochemical Reflectance Index) at 570 and 539 nm (Zarco-Tejada *et al.,* 2005).

In this respect, the purpose of this paper was to study the feasibility of using airborne remote sensing to assess spatial variability of vine vigor and its relation to grape composition traits (*e.g.* anthocyanins, polyphenols, etc.), and consequently delineate differential management zones for precision viticulture purposes. Unexpected relationships between vine vigor and some grape composition traits are analysed and are particularly discussed.

Material and methods

Study area

The study was carried out in a commercial vineyard of 14 ha planted with *Vitis vinifera* cv. Tempranillo, located in Laguardia, Alava, Rioja Appelation, North Spain (ETRS89 UTM 30N, coordinates 531930, 4712532). The field was planted in 1985 and the vines were grafted on 41B, within a 2.80×1.20 m pattern. The canopy was vertically shoot positioned. The field is not irrigated. Rioja-typical spatially uniform management was carried out in the whole vineyard: cordon-pruning (12 buds/vine) and shoot thinning to 12 shoots/vine. An experimental area of 1.2 ha in the vineyard, which comprised different topography, soils and vine response was selected. Climate data for the three years of study is shown in Table 1.

Sampling and measurement of vegetative, yield and grape composition traits

The experiment was carried out over three consecutive years, 2010, 2011 and 2012. Forty-two vines were selected for sampling in the experimental area, based on differences in "on-the-field" observations. The same target vines were sampled in the three years. In 2012, twelve additional vines were considered for sampling. The vines were geo-referenced and re-checked on-field. Sampling was carried out three times per season: at *véraison*, immediately before harvest and after leaf falling. At *véraison*, total shoot length and total leaf area were measured twice in each target vine. Total shoot length was measured as the sum of length of the main shoot plus laterals. Total leaf area per shoot was calcu-

Table 1. Average, maximum and minimum temperatures, rainfall and average air relative humidity for the three seasons of study

		Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	*Avg*	*Max*	*Min*	*Sum*
Avg. Temperature (°C)	*Avg Year*	*8.4*	*5.6*	*5.1*	*6.5*	*9.1*	*10.4*	*14.9*	*18.6*	*20.7*	*21.1*	*17.4*	*13.4*	*12.6*			
	2009/10	9.7	4.5	3.6	4.4	7.4	12.3	12.7	16.9	21.4	20.8	17.5	12.3	*11.9*			
	2010/11	8.8	3.9	5.1	6.7	8.2	13.8	16.3	17.9	17.3	22.0	19.0	14.5	*12.8*			
	2011/12	10.4	6.6	5.7	3.5	10.2	9.0	15.4	19.3	19.4	22.2	17.5	13.1	*12.7*			
Max. Temperature (°C)	2009/10	20.8	15.8	12.2	15.1	18.9	27.9	27.4	30.8	34.7	36.6	32.6	28.1	*25.1*	*36.6*		
	2010/11	*nd*	15.5	15.9	19.4	22.6	29.9	31.6	35.7	31.9	37.7	34.4	30.5	*27.7*	*37.7*		
	2011/12	18.4	15.6	14.8	20.1	24.4	21.3	30.4	35.2	36.8	39.1	32.2	28.5	*26.4*	*39.1*		
Min. Temperature (°C)	2009/10	0.8	–6.9	–7.0	–3.5	–3.2	1.1	2.6	6.6	8.4	9.0	4.8	1.6	*1.2*		*–7.0*	
	2010/11	–8.3	–5.9	–4.5	0.0	0.1	2.0	5.5	7.4	9.7	8.6	9.3	1.8	*2.1*		*–8.3*	
	2011/12	–0.1	–2.3	–4.5	–3.5	0.0	1.3	4.7	8.8	6.2	10.2	6.9	1.1	*2.4*		*–4.5*	
Rainfall (mm)	*Avg Year*	*68.5*	*59.2*	*44.2*	*36.0*	*36.8*	*52.9*	*59.9*	*44.3*	*24.6*	*19.9*	*38.1*	*62.2*				*546.3*
	2009/10	98.8	94.1	41.3	12.5	14.1	6.9	39.4	72.8	4.2	0.2	19.0	37.4				*440.7*
	2010/11	46.4	34.1	21.5	39.7	67.5	46.3	26.6	32.3	20.5	11.0	13.0	14.5				*373.4*
	2011/12	78.3	21.7	14.0	34.6	7.0	60.8	39.1	23.1	14.4	11.3	36.9	86.6				*427.8*
Avg. Rel. Humidity (%)	2009/10	74	74	74.0	74.0	74.0	74.0	74.0	74.5	71.6	59.5	64.3	69.3	*71.4*			
	2010/11	*nd*	75.5	78.6	73.8	75.1	67.2	66.9	63.6	75.0	58.4	74.4	63.3	*70.2*			
	2011/12	81.4	76.5	80.2	67.1	57.5	71.4	63.2	57.6	57.0	52.8	61.1	75.3	*66.7*			

lated as the sum of main shoot leaf area and laterals leaf area. Leaf area was calculated by weighting leaf discs of a known area, as proposed by Smart & Robinson (1991). Exposed leaf area per vine was calculated after Smart & Robinson (1991) too, by measuring the vegetative wall and considering that the vine width was 1.20 m. At pre-harvest, yield and grape traits were measured. Grape yield was measured as kilograms per vine, and two representative bunches of each vine were packed to subsequent analysis in the laboratory. Berry weight was determined by weighting 50 berries randomly selected from each sample. Potential alcoholic degree, as a quantification of sugar content, juice pH and total titratable acidity were determined following the International Organisation of Vine and Wine. Part of the sampled grapes were frozen (–20 °C) for colour analysis (mg/L of total anthocyanins) and phenolics at a later date by the Glories method (Glories & Augustin, 1993). In each year, in winter, pruning weights were measured on the same target vines after pruning them by hand.

Vegetation index mapping and analysis

Multi-spectral airborne remote sensed imagery (0.50 m resolution) was acquired at *véraison* (Lamb *et al.,* 2004) in the three years of study: 20th Aug 2010, 19th Aug 2011 and 13th Aug 2012. The spectral bands were pre-processed by the provider to compensate for misregistration due to lens distortion (< 0.2 pixels). Relative radiometric correction of the images was implemented in order to minimize the image artefacts and bias across each individual band, reducing the effects of lens light fall-off and variable pixel response. Reflectance correction among the images of the mosaic was applied by an algorithm that eliminated the effects of reflectance variations and unlike common colour balancing routines, preserving spectral integrity. Imagery was calibrated to "Like Values" in order to ensure that images are comparable on the same relative scale (Furby & Campbell, 2001).

The NDVI formula was applied to the corrected bands as an indicator of vine vigor (Rouse *et al.,* 1974). Pixels corresponding to soil were removed by means of a threshold NDVI value. Thereafter, an interpolation process was run in order to create a continuous NDVI map and blur noise data. To extract individual NDVI values of the target vines, a buffer (circular area) of 1.20 m, around each sample point (equivalent of the inter-vine spacing) was created. Then, average NDVI value was extracted from the pixels in each vine buffer. Spearman correlation coefficients were calculated for all measured variables. Furthermore, the NDVI values along the vine rows were interpolated to create a continuous NDVI map for further clustering analysis. Therefore, the study area was classified into three zones by an ISODATA algorithm applied to the continuous NDVI map (Fig. 1). The distinction of three zones was a better adaptation for the requirements of the winemaking and commercial strategies of the winery. This clustering method was preferred since it has been positively assessed by other researchers (Bramley & Hamilton, 2004; Martínez-Casasnovas *et al.,* 2012). Analysis of variance (ANOVA) and LSD-Fisher comparison was performed for all variables in order to verify the differences between the three management zones.

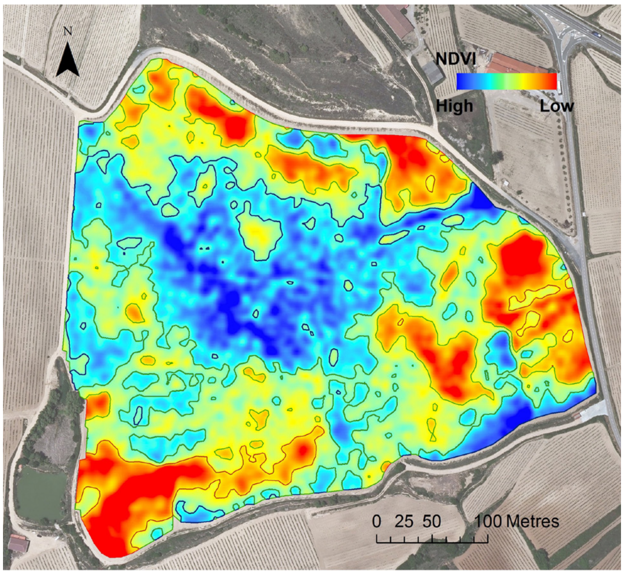

Figure 1. Pseudocolor image of the continuous NDVI map and delineation of the three vigor zones (red=low; green=medium; blue=high) for year 2010.

Equipment

Target vines where geo-referenced by using a Thales Mobile Mapper GPS (Thales Navigation Inc., San Dimas, CA, USA) (accuracy <1 m after post-processing).

NDVI images were supplied by a commercial provider (SpecTerra Services Pty Ltd, Leederville, Australia) using the "HiRAMS system": a high resolution airborne multispectral four channel camera mounted on a plane. The sensor bandpass filters were adjusted to 450nm (blue, band one), 550 nm (green, band two), 670 nm (red, band three) and 780 nm (NIR, band four). This sensor also allows, for specific applications, the installation of filters within the range of 400-950 nm. The plane was a single engine Cessna 172 Skyhawk (Cessna Aircraft Co., Wichita, KS, USA) of about 11 m wingspan and flying at 1800 m above ground level.

The geographic information acquired was analyzed with ArcGIS Desktop 10.0 (ESRI, Redlands, CA, USA) and the statistical analysis was carried out with Infostat software (Infostat v.2012, Córdoba, Argentina).

Results

Variability of vegetative, yield and grape composition traits

Summary statistics of the variables measured are reported in Table 2. Year within-field variability was very high, with coefficients of variation (CV), up to 56% in total shoot length (in 2012), or yield, up to 52% (in 2012). Grape maturity characters (pH, sugar content and total acidity) had the lowest CV (< 14%). Anthocyanins and phenolics had higher variability (20-30%). Variability over time was especially significant for anthocyanins and phenolics, with CV across years of 20-30%. Yield characters remained more similar over the three years.

NDVI correlations with vegetative, yield and grape composition traits

Table 3 shows that the strongest correlations with NDVI were related to vegetative variables (total shoot

Table 2. Summary statistics of vegetative, yield and grape traits for the years 2010, 2011 and 2012

Traits	Mean ± SD			CV %			Mean CV %
	2010	2011	2012	2010	2011	2012	
	n=42	*n=42*	*n=54*				
Total shoot length (cm)	351 ± 179	345 ± 175	323 ± 180	51.0	50.6	55.8	4.4
Exposed leaf area (m^2/vine)	3.26 ± 0.66	3.41 ± 0.58	3.12 ± 0.65	20.1	17.1	20.9	4.4
Total leaf area (m^2/shoot)	0.77 ± 0.24	0.69 ± 0.24	0.5 ± 0.11	31.5	34.3	21.3	21.2
Pruning weight (kg)/vine	1.10 ± 0.49	1.12 ± 0.39	1.07 ± 0.43	44.5	35.0	40.5	1.3
Yield (kg)/vine	3.98 ± 1.67	3.38 ± 1.68	3.83 ± 2.00	41.8	49.6	52.2	8.4
Average bunch weight (g)	234.8 ± 76.9	263. 6 ± 83.0	282.7 ± 104.1	32.7	31.5	36.8	9.3
Berry weight (g)	2.3 ± 0.4	2.4 ± 0.4	2.2 ± 0.5	16.6	18.0	21.1	5.0
Sugar content (ºal)	13.6 ± 1.2	14.4 ± 1.2	14.2 ± 1.3	8.9	8.6	9.2	3.1
Total acidity (g/L tartaric acid)	7.92 ± 0.99	6.20 ± 0.84	5.31 ± 0.57	12.9	13.6	10.8	20.9
pH	3.07 ± 0.11	3.29 ± 0.11	3.14 ± 0.17	3.6	3.5	5.3	3.6
Total anthocyanins (mg/L)	403 ± 141	451 ± 109	683 ± 206	34.9	24.1	30.1	29.2
Total phenolics (AU)	40.2 ± 9.9	40.7 ± 6.8	56.7 ± 12.5	24.5	16.6	22.1	20.4

AU = absorbance units.

Table 3. Correlation coefficients between NDVI and vegetative, yield and grape composition traits

Traits	2010	2011	2012
Total shoot length	0.81***	0.70***	0.70***
Exposed leaf area	0.80***	0.67***	0.73***
Total leaf area (shoot)	0.65***	0.49**	0.73***
Pruning weight	0.73***	0.5***	0.62***
Yield/vine	0.27	0.02	0.03
Average bunch weight	0.29*	0.38*	0.18
Berry weight	0.34*	0.51***	0.38**
Probable degree	–0.29*	–0.44**	–0.32*
Total acidity	0.12	0.11	–0.05
pH	0.43**	0.09	0.33*
Total anthocyanin	0.4*	0.24	0.09
Total phenolics	–0.13	–0.41**	–0.29*

$^*p<0.05$, $^{**}p<0.01$, $^{***}p<0.001$

length, exposed leaf area, pruning weight). The amount of yield per vine was found to be not significantly related with NDVI, and presented poor relationship in 2011 and 2012. However, the relationship between NDVI and bunch weight was significant in 2010 and 2012. Berry weight exhibited a significant relationship with NDVI for the three years of study (r=0.34, r=0.51 and r=0.38, respectively).

Sugar content was negatively related to NDVI. Although total acidity was not significantly correlated with NDVI, juice pH was significantly correlated in years 2010 and 2012. Unexpectedly, anthocyanins were positively related to vigor, although with low significance (Table 3). Total phenolics were found to be negatively related to the NDVI, with significant coefficients of r=0.41 and r=0.29 in 2011 and 2012, respectively.

Performance of NDVI - based zones

Table 4 shows the result of the ANOVA test, with the mean of each variable for every year within the zones resulting from the unsupervised clustering of NDVI interpolated data. Most variables related to vigor showed significant difference within the three zones (total shoot length, leaf areas, pruning weight). Some exceptions, however, occurred, where the distinction was only between two zones: low vigor and medium-high vigor. The three zones presented also a stable pattern through time.

Yield variables presented more diverse results. Differences in yield per vine were only significant in 2010 between the low vigor zone and the others. The trend in the three years was low yield in the low vigor zone but similar yield in the medium and high vigor, being slightly lower in the high vigor zone. Bunch weight presented statistical significance only between two zones, normally between the low vigor zone and the rest, but there was a trend towards an increase of bunch weight with higher vigor. In general, berry weight increased with vigor. There were significant differences between the means only in 2011, whilst in 2010 and 2012 the test only differentiated the means in two zones.

Regarding grape composition traits, sugar content decreased as vigor increased, being significant only in 2011 and 2012. The means were separated only in two different groups. No differences were found in total acidity, although juice pH was lower in low vigour zones, being significantly different to medium and high vigor zones in years 2010 and 2011.

Concerning anthocyanins, significant differences were only found in 2011 between the low vigor and the

Table 4. Analysis of variance for vegetative and grape yield and composition traits for every year within the zones (low, medium and high vigor)

Traits	2010				2011				2012			
	Low	Medium	High		Low	Medium	High		Low	Medium	High	
	n=14	*n=15*	*n=13*		*n=7*	*n=7*	*n=28*		*n=9*	*n=18*	*n=27*	
Total shoot length (cm)	171a	397b	491c	***	130a	247b	423c	***	118a	260b	433c	***
Exposed leaf area (m^2/vine)	2.57a	3.42b	3.80c	***	2.61a	3.41b	3.61b	***	2.27a	2.84b	3.59c	***
Total leaf area (m^2/shoot)	0.56a	0.87b	0.90b	***	0.50a	0.61ab	0.75b	*	0.44a	0.64b	0.91c	***
Pruning weight (kg)/vine	0.66a	1.17b	1.51c	***	0.60a	1.14b	1.25b	***	0.43a	1.06b	1.28b	***
Yield (kg)/vine	3.22a	4.54b	4.29b	*	2.53	3.48	3.56	ns	2.67	4.13	4.04	ns
Avg. bunch weight (g)	192.6a	261.5b	254.2b	*	179.4a	213.0a	297.2b	***	202.4a	303.5b	296.9b	*
Berry weight (g)	2.1a	2.4ab	2.5b	*	1.8a	2.3b	2.6c	***	1.8a	2.2b	2.3b	**
Sugar content (ºal)	14.1	13.5	13.3	ns	15.6b	14.8ab	14.0a	**	15.4b	14.2a	13.7a	**
Total acidity (g/L tartaric acid)	8.31	7.63	8.08	ns	6.55	5.68	6.28	ns	5.65	5.09	6.87	ns
pH	3.00a	3.10b	3.12b	**	3.19a	3.34b	3.29ab	*	3.03a	3.15ab	3.18b	*
Total anthocyanins (mg/L)	308	440	430	ns	341a	440ab	474b	**	542	741	670	ns
Total phenolics (AU)	42.0	38.7	39.3	ns	43.5	38.1	40.2	ns	62.7	61.0	53.0	ns

$^*p<0.05$, $^{**}p<0.01$, $^{***}p<0.001$. ns = no significant. AU = absorbance units.

high vigor zone. Nevertheless, a trend was observed towards lower anthocyanin levels in the lower vigor zone than in the high or medium vigor zone. Total phenolics presented no significance differences over the three years. Yet, phenolics trended to higher contents in the low vigor zone, and lower contents in the high vigor zone.

Discussion

In view of the summary statistics, the high year within-field variability shows the great importance of differential management and selective harvesting, as described by Bramley & Hamilton (2004). Relevant grape composition variability was observed, as reported previously by other authors (Bramley, 2005; Fiorillo *et al.,* 2012; Martínez-Casasnovas *et al.,* 2012). Lower values of variables expressing vigor, lower acidity and higher sugars and phenolic compounds, reflected that, generally, 2010 could be considered as an average year while 2011, and especially 2012, were extremely dry.

Both Pearson correlations and ANOVA suggested that NDVI is a good indicator of vine vegetative development, as found by Acevedo-Opazo *et al.* (2008). The three zones presented also a stable pattern through time.

Yield variables exhibited a trend towards less yielding in the low vigor vines. Berry weight, which is a very important factor for phenolic concentration on the basis of the skin/pulp ratio (Coombe & Iland, 2004), was significantly lower in the three years of study. Smaller berries lead to lighter bunches and therefore less yield. However, for the vine yield variable, the Pearson correlations were poor and ANOVA test showed that high vigor vines yielded lower or similar than medium vigor vines. This could be explained by an excess of vigor on some of those vines, which originated a poor fruit setting and/or reduced bud fruitfulness, as observed by Cortell *et al.* (2005).

Regarding grape composition traits, sugars were found higher in the low vigor vines. These results agree with reported reductions in sugar accumulation due to fruit shading and vegetative growth (Kliewer *et al.,* 1967).

No great differences or relationships with vigor were found in terms of total acidity, although pH presented a positive relation with NDVI, showing higher values in the low vigor zones. For equivalent total acidity, this trend can be explained by a reduction in malic acid concentration, and higher proportion of tartaric acid, which has more acidic power. Low vigor vines usually have less malic acid contents (Smart *et al.,* 1985), due to a decreasing synthesis and also because high exposed bunches experience high temperatures, that lead to malic combustion.

Concerning anthocyanins, the results showed a positive relationship with vigor, and the trend towards less concentration in the low vigor zone, disagree with most part of studies on the subject, where low vigor zones tended to exhibit the highest levels of anthocyanins (Lamb *et al.,* 2004; Stamatiadis *et al.,* 2006; Cortell *et al.,* 2007; Martínez-Casanovas *et al.,* 2012; Filippetti *et al.,* 2013). Most part of these studies have been conducted under cool climates and/or other grape varieties. Fiorillo *et al.* (2012), however, found that, in some years, the highest values of anthocyanins were found in the medium vigor block. They reported that medium vigor vines may experience moderate water deficit and moderate-high light exposure in the fruiting zone compared with the other zones. Conversely, low vigor vines may suffer from strong water deficit, resulting in a severe photosynthesis restriction and ripening downshift (Hardie & Considine, 1976). Zarrouk *et al.* (2012) have reported lower anthocyanin concentrations in Tempranillo vines in stress conditions, claiming a bunch over-exposure to sunlight and excess of temperature. In this sense, Tempranillo seemed to present a different behaviour as other grape cultivars (Teixeira *et al.*, 2013), due to a different genotypic expression of the biosynthetic pathways of anthocyanins.

Vegetation/yield ratios, commonly used to evaluate grape quality, were calculated and compared (data not shown), finding no differences within the zones, and being always above the minimum requirements for a proper ripening. For this reason, differences in anthocyanin contents may be explained by exposure effects. As explained before, several studies have reported that high sunlight exposures may lead to high berry temperatures and reduction of anthocyanin accumulation (Kliewer *et al.,* 1967; Haselgrove *et al.,* 2000; Spayd *et al.,* 2002). In warm climates, grapes reach enough sugar levels for high quality winemaking, but it is not the same regarding colour (Iland & Gago, 2002). This decoupling between sugar and anthocyanins during grape ripening in high temperature environments has already been stated by Sadras & Moran (2012), proving that anthocyanin synthesis trigger occurs later than sugar's. Then, vigorous vines create more shading effects in the bunch area, protecting grapes from high temperatures in August and September (data not shown), and leading to higher anthocyanin and colour contents. The positive effect of bunch shading on anthocyanins has been explained by De la Fuente *et al.* (2007). This suggests that vigor influence on anthocyanin accumulation depends, basically, on environmental factors and especially, on maximal temperatures. This means that both macroclimate (occurrence of high maximal temperatures) and microclimate (vigor level and its influence in leaf shading in the bunch area) are involved in the process, in addition of Tempranillo particular gene expression. In a hot year, vigorous vines may protect bunches from overexposure producing more coloured grapes, and oppositely, in a cool year, the more exposed grapes may present the highest anthocyanin contents.

Total phenolics presented negative correlations with vigor, as stated by Cortell *et al.* (2005), due to reduced phenolic synthesis. The lower vigor zone presented always the lower values, according to most part of studies on this subject (Lamb *et al.,* 2004).

The present research confirms the great spatial variability in vineyard response in all the studied variables, suggesting an opportunity for differential management. NDVI was shown to be good indicator of vine vigor. NDVI-based zonification in three areas showed significant differences of yield variables, specially bunch and berry weight, without any ambiguity. Grape composition traits, as pH, anthocyanins and sugar content, seemed to be more variable but, largely related to NDVI variation. In this respect, particularly relevant was the unexpected relationship between NDVI and anthocyanin content, which showed a positive correlation. This was due to important environmental influences and complex relationships between vigor and grape composition, involving vine microclimate and the specific Tempranillo cultivar genotypic expression. Although some authors have found a negative correspondence between anthocyanin content and vigor by NDVI-based zones, in this study the relationship was found to be positive, opening a new issue in the field of vegetation indexes applications in viticulture. Moreover, under a climate change scenario, it may be interesting to consider the NDVI zones for a selective harvesting on the basis of grape juice pH. Finally, most part of the analysed traits was not significant for the three defined areas, suggesting that only two zones are recommended for a practical differential management. In any case, NDVI mapping remains at the moment, the most affordable way to obtain vineyard spatial information easily and objectively.

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