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Mapping vineyard vigor using airborne remote sensing: relations with yield, berry composition and sanitary status under humid climate conditions

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Abstract
The aim of this study was to assess the spatial variability of plant vigor in a vineyard in a humid climate. Normalised Difference Vegetation Index (NDVI) was used for relating the vigor level to grapevine performance and, as a new area, with the anthocyanin and organic acid compositions of the berries. The study was performed in a rain-fed vineyard with the Tannat cultivar, vertically trellised, during three consecutive vintages (2015–2017). NDVI was estimated from high-resolution images acquired using airborne sensors, which allowed differentiation of three vigor levels within the vineyard: high, medium and low. Three plots per vigor level were installed for performing samplings and field measurements. High vigor zones were associated with less water-stressed vines, higher yields, incidence of bunch rot, larger berries, total acidities and total anthocyanins concentrations. Low vigor zones corresponded to higher pH, soluble solids and phenolic contents in the berries. Medium vigor zones were associated with higher leaf surface, pruning weights, cluster average weights and greater extractable anthocyanins concentrations. The effect of weather conditions of each growing season on grapevine water status was a major factor influencing the analysed variables. NDVI values allowed for delineating areas with homogeneous vigor within the vineyard, which corresponded with different plant performance, showing the usefulness of this tool for site-specific management under the studied conditions.

Keywords Airborne imagery · Anthocyanins · Precision viticulture · Site-specific management · Spatial variability · *Vitis vinifera* L.

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Introduction

The spatial variability of grapevine (*Vitis vinifera* L.) performance within a single vineyard is a relevant issue for growers and winemakers (Bramley 2005; Baluja et al. 2013). Many factors, including soil (texture, water availability), climate, diseases, affect vine development and, consequently, grape yield and composition (Bramley 2010; King et al. 2014; Rey-Caramés et al. 2015; Ferrer et al. 2017). Some of these factors remain stable over time (Bramley 2005), and their assessment can provide wineries with a better understanding of grape quality coming from different sites within the vineyard and, then, plan winemaking protocols to obtain a better profit from each batch of grapes (Bramley et al. 2011; Bonilla et al. 2015). Moreover, this information allows for designing site-specific management of inputs (irrigation, fertilizing, spraying) and cultural practices (pruning, shoot and cluster thinning, canopy management); with the aim of homogenizing the whole vineyard (Bramley 2005; Tisseyre and McBratney 2008; Arnó et al. 2009; Urretavizcaya et al. 2014).

The spatial heterogeneity in grapevine vigor within a single vineyard causes a lack of uniformity in yield, sanitary status, berry ripening and composition (Cortell et al. 2007; Valdés-Gómez et al. 2008; Baluja et al. 2013; Filippetti et al. 2013). A balanced grapevine has a source (leaf surface) and sink (yield) ratio that surpasses a minimum threshold that ensures an appropriate ripening of the berries (Kliewer and Dokoozlian 2005). High vigor canopies have an excess in leaf area that results in excessive cluster shading and humidity (King et al. 2014). In contrast, light exposure favors the accumulation of phenolic compounds, such as anthocyanins, in the grapes (Spayd et al. 2002; Chorti et al. 2010). Moreover, several authors related high levels of vine vigor to high yields, low quality of grape and wine, expressed as a reduction in soluble solids and color intensity of wines and changes in the anthocyanin profiles of berry skins, in the organic acid contents (Lamb et al. 2004; Cortell et al. 2007). In fact, anthocyanins originate wine color, which is a sensory attribute of paramount importance, but anthocyanin profiles largely depend on the grapevine variety (González-Neves et al. 2007; Costa et al. 2014).

Nowadays, the spatial variability of plant vigor over a vineyard can be assessed by using multi-spectral cameras coupled to airborne remote vehicles, which can cover the whole vineyard area and obtain spectral vegetation indices (Tisseyre and McBratney 2008; Santesteban et al. 2013). The Normalized Difference Vegetation Index (NDVI), which relates red and near infrared wavelengths (Tarpley et al. 1984) and proved very convenient for multi-year studies (Fischer 1994), is the most used indicator. Furthermore, NDVI is strongly related to the state of development of the crop and has been widely used for defining areas with different vigor within a vineyard (Hall et al. 2002; Arnó et al. 2009; King et al. 2014). Several studies reported that NDVI not only provides information about vine vegetative vigor, but also about yield and grape composition, pH, acidity, sugar content or phenolic compounds (Lamb et al. 2004; Arnó et al. 2009; Fiorillo et al. 2012; Martínez-Casasnovas et al. 2012; Bonilla et al. 2015).

A strong correlation between NDVI and leaf area index (LAI) has been reported (Johnson et al. 2003; Rousseau et al. 2008; Rey-Caramés et al. 2015). In addition, the greatest incidence of bunch rot was observed in vines with a high vegetative vigor, as expressed by leaf surface and pruning weight (Valdés-Gómez et al. 2008; Calonnec et al. 2013; Guilpart et al. 2017). This is especially relevant for viticulture in humid climates, such as that of Uruguay, where vines develop large canopies that favor fungal attacks (Ferrer et al. 2017). Therefore, in these humid regions, it is especially important to assess grapevine vigor variability within a vineyard in order to schedule spraying and reduce the use of fungicides.

Tannat is the most planted red grapevine cultivar in Uruguay and, under the humid conditions of this region, its vegetative growth is favored, showing heterogeneity in vigor within a given vineyard and it is sensitive to bunch rot (Ferrer et al. 2017). Tannat grapes and wines have a deep color due to the high content of anthocyanins in berry skins, and are relatively rich in delphinidin, petunidin and non-acylated glucosides (González-Neves et al. 2007).

In this context, the aim of the current study was to detect within-vineyard differences in plant vigor using airborne images in a rain-fed Tannat vineyard over three successive growing seasons under humid climate conditions. The ranges of NDVI values were related to grapevine performance: vegetative growth, yield components, sanitary status, berry composition and, as a new area, to the anthocyanin and organic acid composition of the berries.

Materials and methods

Description of the study site

The study was conducted in a commercial vineyard of 1.8 ha planted in 1998 with *Vitis vinifera* L. cv. Tannat, located in Canelones, South Uruguay (34° 36′ S, 56° 14′ W). The vines were grafted on SO4 rootstock and were vertically shoot positioned on a double Guyot system. Spacings were 2.5 × 1.2 m (3333 vines ha^{-1}), the vineyard was not irrigated and it was managed uniformly by the owner. Soil at the study site is a typical Argiudoll, the terrain is relatively flat (27–29 m elevation) with 1–3% slope, the main one in the North–South direction and a slight one in the West–East direction.

Climate in the study area is temperate with an oceanic influence. Long-term (1973–2017) annual rainfall average is 1140 mm, evenly distributed over the year, although a water deficit might occur in summer. Average mean temperatures vary from 21.9 °C in January to 11.3 °C in July. In the current study, weather variables were taken from the agrometeorological station managed by INIA Las Brujas (34° 40′ S, 56° 20′ W, elevation 32 m, and 14.69 km away from the sea), which is less than 10 km from the study plot. Moreover, rainfall was recorded at the studied vineyard.

Dryness Index (DI) was calculated as a monthly soil water balance over a 6-month period, from 30 September to 31 March in the current case, which is acceptable for vineyards in the Southern Hemisphere. This index was computed month by month using the following equation (Tonietto and Carbonneau 2004):

$$\mathrm{DI} = \mathrm{W} = \mathrm{Wo} + \mathrm{P} - \mathrm{Tv} - \mathrm{Es} \tag{1}$$

where W is the estimate of soil water reserve at the end of a given period (in this case, month per month), Wo is the initial soil water reserve in the rootzone (therefore, W from a given month is the Wo for the previous one till the end of calculations in March), P is precipitation, Tv is potential transpiration in the vineyard and Es is the direct evaporation from the soil. Each year was classified according to the DI as proposed by Tonietto and Carbonneau (2004).

Image acquisition and vegetative index mapping

During the growing seasons of 2015, 2016 and 2017, multi-spectral airborne remote sensed imagery was acquired using manned flights in which the airplane was equipped with two digital cameras (1DS Mark II, Canon Inc., Tokyo, Japan); the first camera was set to capture images in the visible wavelength, whereas the other one was adapted to register the reflectance in the near-infrared wavelength. The flight campaigns were conducted by a commercial provider (2000 Aviation, Canelones, Uruguay) at véraison (code 35, Coombe 1995), in January. The flights were carried out under clear sky conditions and high solar elevation to reduce shadow effects on the ground. Flights were conducted at 620 m elevation and 50 m/s speed. Two lines of 4 km length each were followed during each flight.

The multi-spectral images obtained of high resolution on the ground (0.2 m), i.e. from images sized 4992 by 3328 pixels, pictures covered 874×583 m on ground. This allowed for filtering the green cover from the vineyard canopy, disregarding that from the spontaneous vegetation growing in the inter-row. A total of 18 images were taken per flight (60% forward overlap and 45% side overlap) that allowed for covering the whole study area. During the flights, Navcam software (www.ensomosaic.com) was used to control the navigation parameters and the cameras. The images obtained were processed to generate geo-referenced and ortho-rectified mosaics using the EnsoMOSAIC software (MosaicMill Ltd., Vantaa, Finland). From the generated mosaics, the spectral data retrieved from the red (R, 600–700 nm) and near-infrared (NIR, 700–900 nm) domains were used to compute the NDVI as an indication of the vegetation greenness. In the current study, NDVI was computed as

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{R})/(\mathrm{NIR} + \mathrm{R}) \tag{2}$$

using the ArcMap 9.2 suite from ArcGIS (ESRI Inc., Redlands, California, USA). The NDVI maps were processed to remove the reflectance generated by the cover crop in the inter-rows, using the algorithm described by Primicerio et al. (2015).

The 0.2 m resolution images captured during each flight were cut to a raster that covered the size of the vineyard. A regular grid with 7 m distance was defined within the studied vineyard. A 36 m^2 (6 m×6 m) buffer was associated with each point, covering between 350 and 450 pixels depending on the inter-row space between each buffer. A border area of 5 m surrounding the vineyard was excluded from the study. In the end, 171 grid points were obtained for spatial and temporal comparison (Fig. 1). In each flight, the average NDVI value was calculated at each grid point.

For each year studied, the NDVI values measured at véraison were classified into three different categories: high, medium or low. This allowed for separating nine plots (three per vigor level) within the vineyard.

Sampling and measurement of vegetative, yield and grape compositional traits

The experiment was conducted over three consecutive years: 2015, 2016 and 2017. Based on the vigor levels provided by the NDVI values, nine plots were defined within the vineyard (three per vigor category). Each plot consisted of 21 vines distributed in three rows. The vines were geo-referenced using a GNSS (Thales Navigation Inc., San Dimas, CA, USA) and re-checked in-field.

The véraison phenological stage (code 35) was determined according to Coombe (1995). Vine pre-dawn water status was determined using a pressure chamber (SoilMoisture equipment, Santa Barbara, CA, USA) on ten expanded and healthy leaves (five from the east side and five from the west side of the canopy) from five vines per plot. Leaf sampling and measuring were performed as suggested by Turner (1988). Briefly, leaf blades were

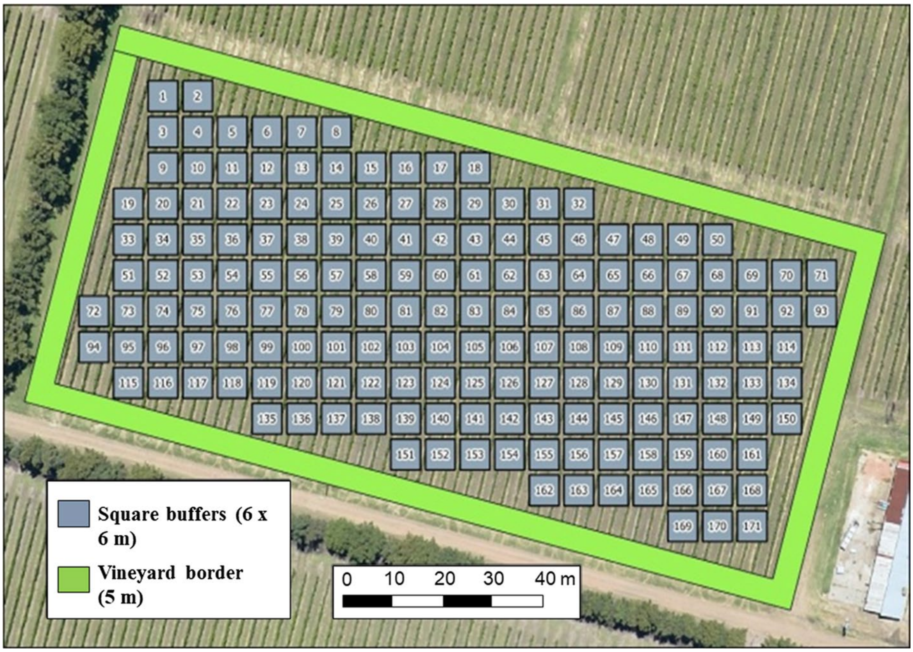

Fig. 1 Map of the studied vineyard displaying the border area and the 171 grid points used for NDVI calculations

covered with a plastic bag prior to severing the petiole, gas flow was limited to 20 kPa s^{-1} and the measurement was carried out within 1.5 min after detaching the leaf from the vine.

Potential exposed leaf surface (SFEp) was assessed at véraison on three vines per plot following the protocol described by Carbonneau (1995). Canopy height and width were determined with a measuring tape. Then, SFEp was estimated according to the following equation:

$$\mathrm{SFEp} = ((2 \times \mathrm{H} + \mathrm{W}) \times (1 - \mathrm{P}))/\mathrm{R} \tag{3}$$

where H is canopy height (m), W is canopy width (m), R is the distance between vine rows (m) and P is the percentage of porosity (%) within the canopy.

The percentage of porosity in the canopy was estimated from three photographs per plot taken against a white background and using the Image Color Extract software (www.coolphptools.com/color_extract). The ratio SFEp versus grape yield was calculated. During winter, pruning weight per vine and individual weight of the shoots were measured on all plants within each replication.

At harvest, the yield components were determined, including grape yield per vine (separating the healthy one and that affected by bunch rot), number and weight of clusters per vine. These measurements were carried out on all the vines within each replication. Those clusters that showed, at least, 5% of the berries affected by diseases (mainly bunch rot, *Botrytis* sp.) were counted and separately weighed. Berry weight was measured in duplicate samples of 250 berries.

The physical components of the berry (skin, flesh and seeds) were determined on samples of 50 berries, which were sliced in half with a razor blade. Skin was obtained by removing carefully the seeds and mesocarp from each berry-half using a small metal spatula and avoiding the rupture of pigmented hypodermal cells. The seeds were separated carefully from the remnants of flesh. Both skin and seeds were rinsed in deionized water and weighed after blotting off the excess of water. Flesh weight was estimated by the difference between the berry weight and the weights of skins and seeds. Skins were freeze-dried (LGJ-12, Labotec, China) for 7–10 days and stored in a freezer.

To determine berry composition at harvest, replicated 250-berry samples from all vines in each plot were collected. Berries were manually destemmed and the juice was obtained by crushing the pulp with an electric blender (HR2290, Phillips, Amsterdam, the Netherlands). According to official methods (OIV 2009), sugar contents (TSS) were measured using a refractometer (Atago N1, Atago, Tokyo, Japan); pH was determined with a pH meter (HI8521, Hanna Instruments, Villafranca Padovana, Italy) and acidity, expressed as g sulfuric acid/l juice, was measured by titration. The phenolic richness of the grapes (A280) and the potential in total (ApH1) and extractable anthocyanins (ApH 3.2) were measured using a spectrophotometer (Unico, S-2150, New Jersey, USA) according to Glories and Augustin (1993). The indices were calculated considering the respective dilution of the grape extracts (González-Neves et al. 2004a).

Organic acid (tartaric, malic and succinic) contents were quantified using high-performance liquid cromatography (HPLC). Samples were filtered through a 0.45 µm mesh and injected into the HPLC equipment. Elution and separation of organic acids was carried out using a CP18 column. Mobile phase consisted of ultra-pure water and pH was adjusted to 2.3 using H_3PO_4. Absorbances of organic acids were detected at 210 nm using a photodiode array detector (DAD). The peaks of the different organic acids were identified by comparison with elution times of each acid injected individually and, then, injected in mixed samples with other organic acids according to the official protocol (OIV 2009).

In order to reconstitute the freeze-dried skins, 7.5 g of skins were put into 40 ml of wine medium (5 g tartaric acid/l) and macerated for 3 h for the greatest extraction. On this material, the anthocyanin composition was determined by HPLC–DAD. A Merck equipment (Hitachi Ltd., Tokyo, Japan) was used; it consisted of a L-6200 pump, an automatic injector (model L-7200), a photodiode array detector (model L-7455) and a Nova-Pack C18 column (Waters ®, Milford, Massachussetts, USA) with an inner diameter of 3.9 mm and 300 mm length. Calibration curves were obtained at 280 and 520 nm. Individual anthocyanins were identified indirectly by comparing their absorption spectrum and retention time with respect to those of malvidin-3-glucoside. The 3-glucosides of delphinidin, cyanidin, petunidin, peonidin and malvidin were identified and quantified. The 6-acetyl and 6-*p*-coumaroyl esters from the aforementioned 3-glucosides were also determined. Data were expressed in mg of anthocyanidins per 100 berries.

Statistical analysis

Data were subjected to a two-way ANOVA considering vigor level, season and their interaction as factors. When significant differences were detected, the Tukey's test ($p \leq 0.05$) was used for mean separation. Moreover, a principal component analysis (PCA) was used for separating the variables associated with each vigor level. Pearson's r coefficient of correlation was employed to detect the possible relationships among the different variables considered. Statistical analyses were performed using the InfoStat software (www.infostat.com.ar).

Results and discussion

Soil water balance in the studied vineyard

The soil water balance for the grapevine growing cycle (September to February) showed DI values corresponding to the moderately dry class (Tonietto and Carbonneau 2004) for 2015 and 2017. By the end of the cycle, water stored in the soil was 12 mm in 2015, suggesting no water stress, whereas DI was −27.9 mm in 2017, indicating a certain level of water stress. In 2016, this index showed a value of −177 mm, corresponding to a severe drought. In accordance with these conditions, pre-dawn water potential values measured on the vines were around −0.2 MPa in 2015, between −0.58 and −0.65 MPa in 2016 and between −0.32 and −0.54 MPa in 2017, indicating that vines suffered from no water restrictions in 2015, from a moderate to severe water stress in 2016, and from a weak to moderate water stress in 2017, following the thresholds proposed by van Leeuwen et al. (2009).

Leaf area develops mainly during the first 3 months of the growing cycle, which are September to December in the conditions of the current study. When water availability is analyzed monthly, in 2015 soil was at field capacity during these first 3 months and under water-limiting conditions during the following three months. In 2016, water availability was limited during the first 3 months, but an important rainfall event occurred in December; the growing cycle finished under severe water deficit conditions. In 2017, soil was at field capacity in September and October; moderately dry in November and December and severe water deficit conditions occurred during berry ripening.

Vegetation index mapping and vigor zones delineation

The NDVI values allowed for delineating areas with homogeneous vigor within the vineyard (Fig. 2): high (H), medium (M) and low (L). The difference between the minimum and the maximum NDVI values were 0.05, 0.13 and 0.11 for 2015, 2016 and 2017, respectively (Fig. 2). These low values question the precision of NDVI measurements; however, fluctuations induced by low-accuracy measurements are prone to be low in view of the temporal stability of NDVI zones over the three-year period. Despite the low variability in NDVI values, in-field measurements proved that significant differences existed in vine size, pre-dawn leaf water potential and yield per plant, as explained in the following sections and reported for other grapevine varieties (Martínez-Casasnovas et al. 2012). The total range of NDVI values in a vineyard can be rather small and of the same order of magnitude as in the current study (Hall et al. 2002; Arnó et al. 2009; Martínez-Casasnovas et al. 2012; Santesteban et al. 2013; King et al. 2014). High values of NDVI corresponded to a greater vegetative growth, as expected.

Figure 2 shows that low or high NDVI values were consistently located in the same parts of the vineyard in 2015, 2016 and 2017. Although the absolute values of NDVI varied between the years studied, being higher in 2016, the zones within the vineyard classified as H, M or L were relatively stable over the study period (Fig. 2), as already observed in other vineyards (Fischer 1994; Acevedo-Opazo et al. 2008; Rousseau et al. 2008; King et al. 2014). This temporal stability may be related to characteristics such as soil depth, soil properties, elevation and the resulting soil water availability, among others that drive NDVI variability within the vineyard, as pointed out by Acevedo-Opazo et al. (2008).

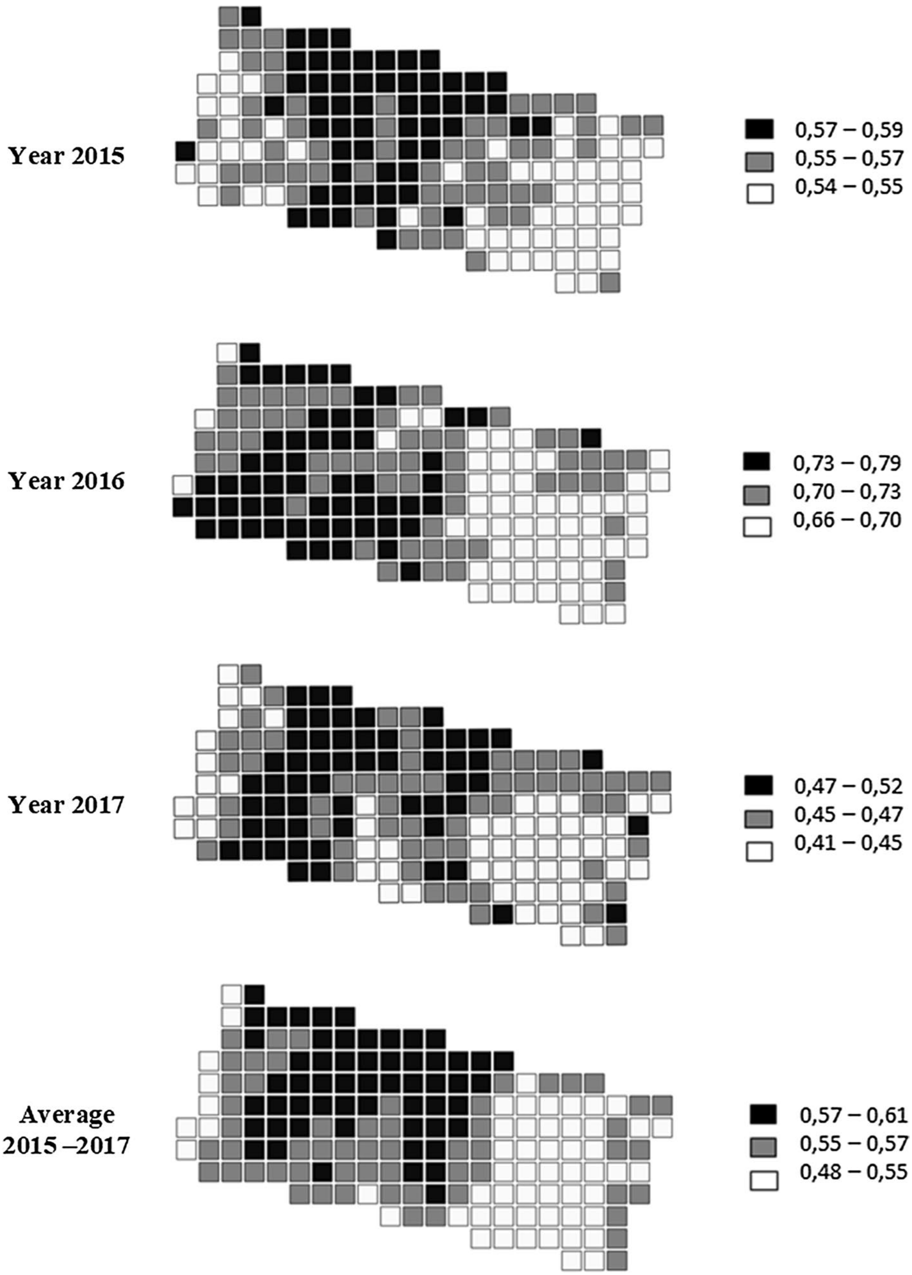

Fig. 2 Maps of NDVI values depicting the three vigor zones (white = low, grey = medium; black = high) for each year studied

Nevertheless, depending on the weather conditions of a given year, significant differences in NDVI, pre-dawn leaf water potential, yield and vigor were observed on the same zone from one year to another.

Effect of vigor level on vegetative growth, yield, health and berry compositional traits

A PCA allowed for a clear separation of the vigor classes according to the main factors characterizing them (Fig. 3), suggesting that even small differences in NDVI values might reflect changes in vine performance. The first two principal components (PC) explained 100% of the variation in the dataset; PC1and PC2 accounted for 81.7% and 18.3%, respectively. Basically, vigor zones were separated along PC1, which mainly reported differences in water status, berry composition and yield components. Hence, low NDVI sites are located on the right part of the PCA, whereas medium and high NDVI sites are located on the left-hand side of the PCA (Fig. 3). In addition, PC2 separated medium and high vigor zones by their differences in surface leaf area (SLA) and water status. Therefore, low NDVI zones were characterized for giving berries with greater contents in TSS, TPI and higher pH values when compared with vines from medium and high NDVI zones. In the case of vines in high NDVI zones, they were characterized for greater yields, berry weights and a less negative pre-dawn water potential. Surprisingly, vines from the medium NDVI zones were characterized for having the highest SLA and pruning weights.

Figure 3 displays a link between pre-dawn leaf water potential and yield components that can be integrated by NDVI, as previously suggested by Acevedo-Opazo et al. (2008). Less negative pre-dawn leaf water potential values increased the values of harvest parameters. The increase in yield was caused by a greater individual berry weight. This means that NDVI can reflect the well-known attenuation of vine growth caused by water restrictions (Schultz and Matthews 1988), even when these restrictions are weak to moderate as

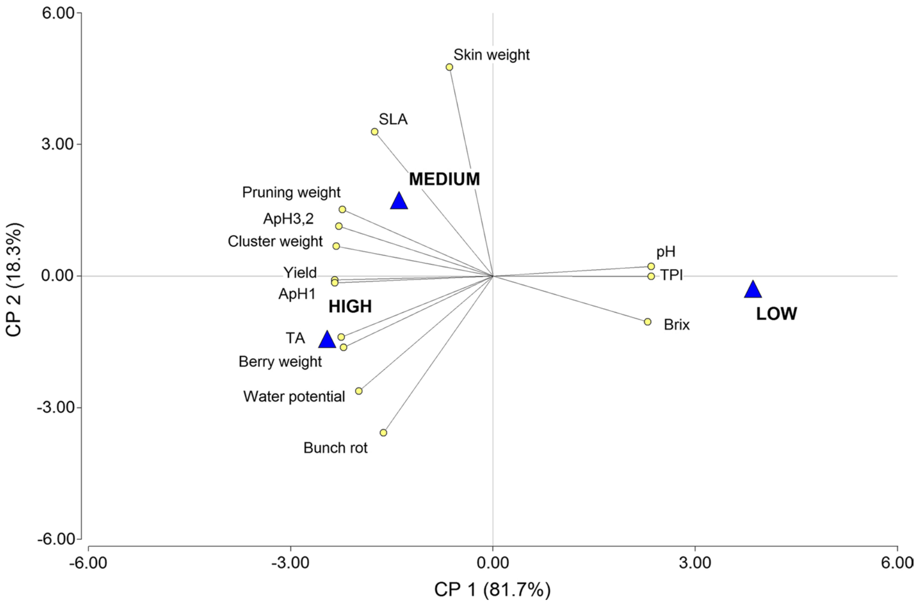

Fig. 3 Bi-plot from the principal component analysis discriminating the three vigor categories within the vineyard studied according to vegetative growth, yield, sanitary status and berry compositional traits (*TA* total acidity, *SLA* surface leaf area, *TPI* Total Phenolic Index)

in the current study, proving that vegetation indices are relevant for estimating vine vigor variability within a given field (Dobrowski et al. 2003). In contrast, high NDVI zones with vines not suffering from water constraints are prone to fungal attacks, as the PCA shows (Fig. 3), likely due to a greater leaf surface (Fermaud et al. 2008; Guilpart et al. 2017).

Moreover, berry composition was linked to NDVI as berries with greater TSS and TPI contents corresponded to low NDVI zones (Fig. 3). In the current study, this can be explained by the better conditions for maturation in vines from these zones in which pre-dawn leaf water potential showed a weak to moderate water stress and berry size was reduced, thus concentrating solutes. Similar observations were reported for Pinot Noir variety in the United States (Cortell et al. 2007) and Tempranillo in Spain (Bonilla et al. 2015). However, other components of the berries did not follow this trend, as high NDVI were related to greater contents in anthocyanins and higher total acidity (Fig. 3). These results suggest that a non-linear approach is required to relate berry quality traits to vine vigor and water status, as previously indicated (Peterlunger et al. 2002).

Response variables associated with NDVI levels standardized by year

Effect of vigor level on the vegetative growth and yield response of Tannat

Factorial analysis revealed that vigor level exerted a significant influence on pruning weight, SFEp and pre-dawn leaf water potential from véraison to harvest (Table 1), in accordance with Dobrowski et al. (2003), Johnson et al. (2003), Rousseau et al. (2008) and Bonilla et al. (2015). However, Table 2 shows that low vigor vines are characterized by lower pruning weights and more negative pre-dawn leaf water potential. In all cases, except for pruning weight, this influence depended on the year studied, as already indicated by other authors (Hall et al. 2011). A significant interaction between vigor level and year was observed only for the pre-dawn leaf water potential from véraison to harvest (Table 1).

During the years studied, low vigor vines, with lower leaf areas, were more stressed, namely pre-dawn leaf water potential values were more negative (Table 1) and likely this stress caused the reductions in leaf area. This suggests that soil water availability was different within the vineyard and those zones corresponding to low NDVI somehow had less water available in the soil and this was reflected in vine water status. Despite a smaller leaf area, and thus low transpiration surface, low vigor vines seemed to suffer from moderate water restrictions in 2016 and 2017 (Table 1). Therefore, it seems that soil water content was determinant for both reductions in plant transpiration surface pre-dawn leaf water potential of Tannat grapevines in accordance with King et al. (2014).

Moreover, the different vigor among vines within the same vineyard could have originated from the spatial heterogeneity in soil properties and water content, as already pointed out by other authors (Bramley et al. 2011; Tardáguila et al. 2011; Rey-Caramés et al. 2015). In the current case, gravimetric soil water content at 200 mm depth in the low vigor zones ranged from 0.2 to 0.22 g water/g soil, whereas in medium and high level zones, it ranged from 0.24 to 0.26 g water/g soil. The percentage of clay at 200–400 mm depth was 30.9–35.6% in low vigor zones and 35.7–45.6% in medium and high vigor zones (Alliaume et al. 2017).

Yield and berry weight were significantly affected by grapevine vigor level (Table 2), as already observed in other situations (Bramley, 2005; Rousseau et al. 2008; Bramley et al. 2011). In addition, year exerted a significant influence on all yield components considered in the current study. This response is usually detected

Table 1 Average values for the vegetative growth traits and the pre-dawn water potential of the Tannat cultivar according to the vigor level during each year studied

Vigor level	Pruning weight (kg vine^{-1})	SFEp (m^2 ha^{-1})	Shoot average weight (g)	Pre-dawn water potential (MPa)
2015				
High	0.51ab	6599ab	35.4ab	−0.22a
Medium	0.62a	7613a	44.5a	−0.20a
Low	0.41b	5971b	27.3b	−0.24a
2016				
High	0.52a	7188a	19.4a	−0.61a
Medium	0.59a	7534a	27.4a	−0.58a
Low	0.43a	7067a	29.7a	−0.65a
2017				
High	0.61a	5789a	37.2a	−0.32a
Medium	0.56a	5286a	39.5a	−0.43ab
Low	0.42a	4197a	33.7a	−0.54b
Factorial analysis				
Vigor	*	*	ns	**
Year	ns	***	*	***
Vigor × year	ns	ns	ns	*

The significances of the vigor and year factors, as well as their interaction, are also shown

Different letters in the column within a given year indicate significant differences among vigor levels according to the Tukey test ($p < 0.05$)

ns not significant, *SFEp* potential exposed leaf area

For the factorial analysis: ***$p < 0.001$; **$p < 0.01$; *$p < 0.05$

in vineyards, where inter-year variability in yield is rather common (Hall et al. 2011). The difference in yield between high and low vigor zones ranged from 18.6 to 40.5%, depending on the year. This suggests that the delineated zones, despite the low range in NDVI values, were able to capture significant differences in vine performance.

High vigor vines yielded significantly more and the berries they produced were significantly larger than low vigor vines in 2017 (Table 2), as already described in former studies (Rousseau et al. 2008; Filippetti et al. 2013). These differences might have been caused by an appropriate level of water availability during fruit set, when berry final size is determined (Ojeda et al. 2002) and by the spatial heterogeneity of soil properties within the vineyard (Tardáguila et al. 2011; Alliaume et al. 2017). No significant interactions between vigor level and yield were observed (Table 2).

In 2017, weather conditions (abundant rainfall in the month prior to harvest) and no water restrictions in the high vigor zone were determinant for *Botrytis* development. Thus, high vigor vines showed 46.5% clusters affected by bunch rot. In contrast, for low vigor vines (suffering from a moderate to severe water stress), bunch rot affected clusters were 19% (Table 2), an effect already observed under other conditions (Valdés-Gómez et al. 2008; Ferrer et al. 2017; Guilpart et al. 2017).

Table 2 Average values for yield and berry components of the Tannat cultivar according to the vigor level during each studied year

Vigor level	Yield (kg vine^{-1})	Bunch rot affected cluster (g)	Berry weight (g)	Skin (%)	Flesh (%)	Seed (%)	Skin/flesh
2015							
High	8.32a	0.33a	1.48a	17.10a	79.01a	3.88a	0.22a
Medium	7.79a	0.20a	1.49a	23.70a	71.82a	4.49a	0.33a
Low	5.36a	0.04a	1.43a	21.73a	73.65a	4.62a	0.29a
2016							
High	7.00a	6.61a	1.31a	15.39a	80.86a	3.75a	0.19a
Medium	7.22a	69.55a	1.31a	16.35a	80.41a	3.24a	0.20a
Low	5.67a	0.00a	1.11a	15.09a	81.16a	3.75a	0.18a
2017							
High	7.31a	3410.00a	1.58a	15.95a	78.92a	5.13a	0.20a
Medium	6.31ab	1583.33a	1.40ab	18.56a	75.90a	5.54a	0.24a
Low	5.27b	1035.00a	1.25b	16.83 a	77.67a	5.50a	0.22a
Factorial analysis							
Vigor	**	ns	**	ns	ns	ns	ns
Year	*	***	**	*	*	***	*
Vigor × year	ns	ns	ns	ns	ns	ns	ns

The significances of the vigor and year factors, as well as their interaction, are also shown

Different letters in the column within a given year indicate significant differences among vigor levels according to the Tukey test ($p < 0.05$)

ns not significant

For the factorial analysis: ***$p < 0.001$; **$p < 0.01$; *$p < 0.05$

Effect of vigor level on Tannat berry composition

Vine vigor level affected significantly the total acidity and the anthocyanin composition of the berries at harvest (Tables 3 and 4), as previously observed in other grapevine varieties (Bonilla et al. 2015) but not the organic acid concentrations in the berries (Table 3). The effect of the study year was significant for all compositional traits except for tartaric acid and total potential in anthocyanins (Table 3). Year exerted a significant influence on anthocyanin accumulation (mg per berry) and on anthocyanin composition (Table 4). Significant interactions between vigor level and year were observed for TSS, pH and anthocyanin composition (Tables 3 and 4). These results are in accordance with previous reports (Pereira et al. 2006) and reflect a highly significant effect of weather conditions on grapevine water status and, as a consequence, on berry composition, which in the current case affected TSS, AT, pH, TPI, anthocyanins and organic acids composition.

High-quality wines in Uruguay must have a minimum alcohol degree of 12.1 %vol. This threshold was assured for the wines from the three vigor levels in 2015; however, it was never reached in 2016 and it was only reached in high vigor vines in 2017. Water availability during maturation seemed to be the main cause for this fact, as already suggested in other areas (Medrano et al. 2003), since photo-assimilate supply seemed to be ensured by sufficient leaf area (Table 2). However, average photosynthetic rate per unit leaf area

Table 3 Average values of berry compositional traits of the Tannat cultivar according to the vigor level during each studied year

Vigor level	Soluble solids (ºBrix)	Total acidity (g L^{-1} sulfuric)	pH	Tartaric acid (g L^{-1})	Malic acid (g L^{-1})	Succinic acid (g L^{-1})	TPI	Total potential in anthocyanins (ApH1)	Potential in extractable anthocyanins (ApH3.2)
2015									
High	23.7a	4.2a	3.43a	5.6a	10.1a	6.03a	55.2a	1973a	1037a
Medium	24.1a	3.9ab	3.38a	5.8a	9.5a	5.40a	57.3a	2049a	1037a
Low	23.8a	3.7b	3.46a	5.0a	9.5a	5.11a	58.6a	1741a	894a
2016									
High	21.0a	4.8a	3.12 b	6.0a	6.7a	2.15a	46.4a	1710a	698a
Medium	20.9a	4.6a	3.17ab	4.8 b	6.5a	1.86a	47.0a	1649a	705a
Low	20.9a	3.9a	3.23a	4.7 b	6.4a	1.85a	51.3a	1944a	802a
2017									
High	22.2a	4.4a	3.13a	4.9a	6.2a	2.59a	51.1a	1806a	799a
Medium	20.8a	3.8ab	3.23a	4.5a	5.6a	2.06ab	52.1a	1757a	784a
Low	20.7a	3.6 b	3.20a	5.6a	5.5a	1.69 b	55.7a	1579a	702a
Factorial analysis									
Vigor	ns	***	*	ns	ns	ns	ns	ns	ns
Year	***	*	***	ns	***	***	**	ns	***
Vigor × year	*	ns	*	ns	ns	ns	ns	ns	ns

The significances of the vigor and year factors, as well as their interaction, are also shown

Different letters in the column within a given year indicate significant differences among vigor levels according to the Tukey test ($p < 0.05$)

ns not significant, *TPI* Total Phenolic Index

For the factorial analysis: ***$p < 0.001$; **$p < 0.01$; *$p < 0.05$

Table 4 Average values for the anthocyanin composition of the Tannat cultivar according to the vigor level during each year studied

Vigor level	Anthocyanins (mg berry^{-1})	Non-acylated glucosides (mg berry^{-1})	Acetylated glucosides (mg berry^{-1})	Coumaroylated glucosides (mg berry^{-1})
2015				
High	1.21b	0.91b	0.16a	0.14a
Medium	1.24b	0.96b	0.17a	0.11a
Low	1.92a	1.48a	0.26a	0.18a
2016				
High	1.06a	0.80a	0.15ab	0.11a
Medium	1.12a	0.83a	0.16a	0.13a
Low	1.09a	0.86a	0.13b	0.10a
2017				
High	1.06a	0.83a	0.16a	0.07ab
Medium	1.07a	0.82ab	0.16a	0.09a
Low	0.76b	0.60b	0.10b	0.06b
Factorial analysis				
Vigor	ns	*	ns	ns
Year	***	***	**	**
Vigor × year	***	***	**	*

The significances of the vigor and year factors, as well as their interaction, are also shown

Different letters in the column within a given year indicate significant differences among vigor levels according to the Tukey test ($p < 0.05$)

ns not significant

For the factorial analysis: ***$p < 0.001$; **$p < 0.01$; *$p < 0.05$

was not measured and it cannot be certain that near-zero rates of photosynthesis occurred because of drought. With the available data, the greatest leaf area was observed in 2016, but pre-dawn water potential reached values that could have restricted photosynthesis (−0.5 MPa) and maturation (−0.6 MPa), according to the reference thresholds proposed by Deloire et al. (2004). A vertically-trellised vine should have a minimum leaf area to fruit ratio that ensures berry ripening (Kliewer and Dokoozlian 2005). Echeverria et al. (2017) found that this minimum ranged between 0.30 and 0.40 m^2 kg^{-1} for Tannat. In the current study, this level was attained in 2016 (0.31–0.36 m^2 kg^{-1}) but grapes did not ripen properly, likely due to water restrictions. Moreover, wine quality might have also been restricted by bunch rot incidence, especially in medium vigor zones (Table 2).

The grapes produced in 2015 had the highest polyphenol richness and anthocyanin potentials (Table 3). In general, phenolic potential seems to be more dependent on water availability than on vine vigor level. The knowledge of the polyphenol richness and anthocyanin extractability of grapes allow for adapting winemaking techniques in order to obtain the best wine from grapes of a given quality (González-Neves et al. 2004b). Similar comments can be made regarding the composition of anthocyanins. Accumulation of anthocyanins (mg per berry) was greater in 2015 compared to 2016 and 2017. An increase in accumulation for all anthocyanins in fruit with a reduction in vine vigor can be expected (Cortell et al. 2007). However, water supply plays an essential role in the anthocyanin contents because late water deficit increases the biosynthesis of these compounds and their accumulation on berry skins (Ojeda et al. 2002).

Non-acetylated, acetylated and coumaroylated glucosides are usually related in Tannat grapes, as previously reported (González-Neves et al. 2004a). The effect of vintage on the anthocyanins was very important. Moreover, significant interactions between vigor level and year were observed for anthocyanin composition (Table 4).

In 2016, low vigor vines produced berries with higher pH than those from high vigor vines. However, in 2017, high vigor vines produced berries with higher total acidity than low vigor vines (Table 3). In general, high vigor vines generate an excessively high leaf surface, which generates an excessive shading that does not favor malic acid degradation, as reported by Spayd et al. (2002), Cortell et al. (2007) and King et al. (2014). This was confirmed by the positive correlation between SEFp and malic acid concentration (r = 0.46, *p* value = 0.02), which was also highly correlated with pH (r = 0.85; p-value = 0.000). Pereira et al. (2006) reported that in those years without water restrictions during berry ripening, grapes were characterized by higher concentrations in organic acids. In the present case, malic and succinic acid concentrations were greater in 2015, when DI was positive (+ 12 mm) and pre-dawn leaf water potential values reflected a moderate water stress. In contrast, in 2016 and 2017, the DI values were negative (− 27.9 mm and − 177 mm, respectively) and pre-dawn water potential values reflected severe water restrictions, organic acid concentrations were lower (Table 5). Moreover, significant correlations between water potentials and organic acid concentrations were detected (r = 0.7 and p-value = 0.00 for malic acid and r = 0.82 and p-value = 0.00 for succinic acid), as already observed by Shellie and Bowen (2014). In addition, year did not affect tartaric acid concentrations in Tannat

Table 5 Pearson's coefficients of correlation (r) between the NDVI values and those of the different vegetative growth, yield components and berry compositional traits for the Tannat cultivar

Explanatory variable	Response variable	Coefficient of correlation (r)	p-value
NDVI	Beginning of véraison (code 35)	− 0.67	0.00021
	Ψmaturation	− 0.71	0.000031
	SFEp	0.60	0.00085
	SFEp/kg grape	0.49	0.04
	% Bunch rot	− 0.40	0.04
	Berry weight	− 0.43	0.02
	% skin	− 0.37	0.06
	% flesh	0.50	0.01
	% seed	− 0.76	0.000007
	Skin/flesh	− 0.37	0.04
	Soluble solids	− 0.44	0.02
	Total acidity	0.62	0.00053
	pH	− 0.46	0.04
	Malic acid	− 0.34	0.08
	Succinic acid	− 0.52	0.01
	ApH3.2	− 0.41	0.03
	TPI	− 0.60	0.0008

Only the significant correlations are shown grapes due to the fact that this acid is less sensitive to weather conditions during the maturation period (Poni et al. 2018).

NDVI correlations with vegetative, yield and berry compositional traits

Significant correlations between NDVI values and the variables measured in the field were detected, although their signs depended on the considered trait (Table 5). Vegetative growth variables such as SFEp and its ratio to yield were positively correlated with NDVI (Table 5).

These results proved the usefulness of NDVI to discern the spatial heterogeneity in vegetative growth within the vineyard, as well as for delineating areas with different vigor, as previously reported (Dobrowski et al. 2003; Hall et al. 2011; Baluja et al. 2013; Bonilla et al. 2015; Rey-Caramés et al. 2015).

Rey-Caramés et al. (2015) suggested that, for vertically-trellised vineyards, NDVI would not correlate with yield components due to the fact that clusters are on the lower part of the trellis system. However, in the current study, significant correlations were found for NDVI and berry weight and percentage of flesh (Table 5). The positive correlation observed between NDVI and the percentage of clusters affected by bunch rot (Table 5) is also noteworthy. In this sense, Fermaud et al. (2008), Calonnec et al. (2013) and Guilpart et al. (2017) associated vines with high vigor with fungal disease development due to favorable micro-climate conditions (i.e. excessive shading associated with poor ventilation) at the cluster zone, the low water stress combined with the characteristic bunch compactness of the Tannat cultivar (Ferrer et al. 2017). The last vegetative growth indicator, pruning weight, was significantly correlated with the percentage of clusters affected by bunch rot ($r=0.43$, p-value$=0.03$) as already observed by Valdés-Gómez et al. (2008) and Guilpart et al. (2017).

In addition, significant correlations between NDVI and berry compositional traits were detected (Table 5). Soluble solids content, TPI, anthocyanins, malic and succinic acid were negatively correlated with NDVI, whereas total acidity was positively correlated (Table 5), confirming previous findings for other grapevine cultivars (Rousseau et al. 2008; Filippetti et al. 2013; Bonilla et al. 2015). These relations were a consequence of cluster shading caused by either an increased vegetative growth, the retard in berry ripening or the influence of vine water status on berry chemical components (Medrano et al. 2003; Lamb et al. 2004; Chorti et al. 2010; Fiorillo et al. 2012; Martínez-Casasnovas et al. 2012). According to Poni et al. (2018), the precocity of véraison is a major source of variation for acidity at harvest, which in the current work correlates significantly with NDVI ($r=-0.67$, p-value 0.00021). In this study, no significant correlations between NDVI and anthocyanin composition were detected, in contrast with the results reported by García-Estévez et al. (2017).

The results suggest that NDVI could be a useful tool for defining and categorizing zones with homogeneous vigor in vineyards under humid conditions in order to establish site-specific management practices according to the grapevine needs for each defined zone (Tisseyre and McBratney 2008; Arnó et al. 2009; Santesteban et al. 2013; Rey-Caramés et al. 2015). In the case of humid conditions such as those of Uruguay, site-specific management would be directed to the design of more efficient spraying according to plant vigor, to rationalize nitrogen fertilization or supplementary irrigation, to define canopy management practices that favor aeration or identifying zones within the vineyard that are more sensitive to bunch rot. From the point of view of berry quality, NDVI would allow for site-specific harvests according to the desired type of wine (Fiorillo et al. 2012; Urretavizcaya et al. 2014; Bonilla et al. 2015).

Conclusions

The results from this study suggest that the delineation of NDVI zones within the vineyard was relevant to characterize the spatial variability of vine water status, vegetative growth, yield and berry composition. This indicates that NDVI information allows for the implementation of site-specific management practices that would permit to reduce production costs and improve quality of the grapes.

During the 3 years of study, vigor zones selected by NDVI values within the vineyard remained relatively stable, although weather conditions occurring each year modified the absolute values of NDVI. In the current study, NDVI was positively correlated with leaf area, leaf area to yield ratio and juice acidity, whereas most of the variables describing grapevine performance and berry composition were negatively correlated with NDVI (berry weight, skin to flesh ratio, TSS, pH, anthocyanins and TPI). Some of these relations have been previously reported by other authors; however, environmental influences and complex relationships between plant vigor and grape composition made the values of these correlations different from those from other studies. Therefore, the performance of a given agro-ecosystem largely depends on environmental factors and, in view of the results from the current study, airborne imagery could be a useful decision support tool for a dynamic analysis of plant physiological and productive processes, as well as for designing site-specific management zones within a vineyard under humid climate conditions.

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