The potential of high spatial resolution information to define within-vineyard zones related to vine water status

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Abstract The goal of this study was to test the usefulness of high-spatial resolution information provided by airborne imagery and soil electrical properties to define plant water restriction zones within-vineyards. The main contribution of this is to propose a study on a large area representing the regions' vineyard diversity (different age, different varieties and different soils) located in southern France (Languedoc-Roussillon region, France). Nine non-irrigated plots were selected for this work in 2006 and 2007. In each plot, different zones were defined using the high-spatial resolution (1 m^2) information provided by airborne imagery (Normalised Difference Vegetation Index, NDVI). Within each zone, measurements were conducted to assess: (i) vine water status (Pre-dawn Leaf Water Potential, PLWP), (ii) vine vegetative expression (vine trunk circumference and canopy area), (iii) soil electrical resistivity and, (iv) harvest quantity and quality. Large differences were observed for vegetative expression, yield and plant water status between the individual NDVI-defined zones. Significant differences were also observed for soil resistivity and vine trunk circumference, suggesting the temporal stability of the zoning and its relevance to defining vine water status zones. The NDVI zoning could not be related to the observed differences in quality, thus showing the limitations in using this approach to assess grape quality under non-irrigated conditions. The paper concludes with the approach that is currently being considered: using NDVI zones (corresponding to plant water restriction zones) in association with soil electrical resistivity and plant water status measurements to provide an assessment of the spatial variability of grape production at harvest.

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Introduction

Many authors have shown that grapevine water status has a direct effect on grape quality through its influence on vegetative and fruit growth (Dry and Loveys 1998; Ojeda et al. 2002). This has led to the increased implementation of irrigated viticulture to alleviate grapevine water stress (Naor et al. 2001; Ortega-Farías et al. 2004; Girona et al. 2006). Yet, viticulture in the southern region of France is carried out using non-irrigated practices (Ojeda et al. 2005; Tisseyre et al. 2005) which adds to the challenges faced by wine producers when trying to maintain the high quality requirements in wine production *(AOC Appellation d'Origine Controlée)*. Thus, vineyard zoning based on relevant vine water status information could lead to a practical decision support tool. Such zoning would require the assessment of plant water status using high spatial resolution imagery to capture the vineyard scale.

Several researchers have proposed the use of pressure chamber methodology (Scholander et al. 1965) as an excellent tool to measure vine water status under irrigated and non-irrigated conditions (Naor et al. 2001; Ojeda et al. 2002; Tisseyre et al. 2005). Being a manual technique, vine water status assessment using Pre-dawn Leaf Water Potential (PLWP) or other plant water potential measurement is difficult to perform, time consuming and can only be done practically at low spatial and temporal resolutions. A more practical and representative tool would require an assessment of vine water status with high spatial resolution during the growing period, especially at the end of summer when significant water restrictions are experienced under non-irrigated conditions (Ojeda et al. 2005; Tisseyre et al. 2005, 2007).

Currently, no sensor providing direct assessment of plant water status with a high spatial resolution is easily available for wine-growers to monitor plant water status. The most promising technology is certainly based on thermal infra-red technologies to derive the plant water status and the stomatal conductance from the canopy temperature. Many authors have investigated these technologies at the leaf and the plant level (Idso 1982; Jackson et al. 1981; Moran et al. 1994; Sepaskhah and Kashefipour 1994). It was more recently applied to vine with infra-red cameras (Jones 1999; Jones et al. 2002; Fuentes et al. 2005; Stoll and Jones 2007). This approach is interesting to monitor plant water status over time, nevertheless it remains time consuming to provide information with a high spatial resolution. Other approaches based on satellite or airborne thermal images have been proposed (Tilling et al. 2007). However, applying these technologies to vineyards on large scales still raises scientific and technical problems like the incidence of bare soil and grass cover, the cost and the resolution of the data which does not necessary fit with co-operatives or winery requirements.

An alternative approach could then be based on the analysis of surrogate information that is easily available at high resolution, such as multi-spectral images and soil electrical properties mapping, to define different zones (Taylor and Bramley 2004; Tisseyre et al. 2005, 2007). An example of remote sensing has been the use of airborne imagery to map relative differences in vine canopies which is used to characterize grapevine canopy shape and vegetative expression throughout a vineyard (Hall et al. 2002). The combination of the two is taken as an estimate of vigour (Bramley 2001, Hall et al. 2002), whereas Johnson

et al. (2003) used high-spatial resolution imagery to map vine leaf area converting normalized difference vegetation index (NDVI) maps into leaf area index (LAI) maps. In non-irrigated conditions, vigour is strongly related to soil water availability, thus NDVI maps could constitute relevant information to propose different water restriction zones in the vineyard.

Studies of soil physical properties, such as soil texture and its relationship with the general condition of the vines have demonstrated that significant variations may exist within single vineyards (Hall et al. 2002; Taylor and Bramley 2004). Thus, Taylor and Bramley (2004) studied the spatial variability of soils, specifically in the adoption of soil apparent electrical conductivity and GPS-based elevation surveys prior to vineyard design. Barbeau et al. (2005) used soil electrical resistivity to compare the effect of rows with and without grass cover on soil water distribution. Bramley (2005) used such soil information to determine different soil zones within fields. This type of information can be considered relevant to characterize the spatial variability of plant water status at a within-vine field scale. It is important to note that there is no clear relation between soil electrical conductivity and soil depth or soil water availability. This is mainly due to the complexity of the relations between electrical soil properties and other soil parameters such as salinity, water content and texture, among others (Corwin and Lesch 2005; Samouëlian et al. 2005). However, In addition to airborne imagery, an electrical soil survey could provide relevant information to zone a vineyard according to water restriction.

In the light of previous research, the goal of the present study is to test the potential of high spatial resolution information provided by multi-spectral airborne imagery to define plant water restriction zones at a within-vineyard scale. The potential of soil electrical properties to provide supporting information was also considered in order to verify its relevance in delineating zones of different plant water restriction resulting from differences in soil characteristics. The originality of this study is to propose an approach which may be used by wine-growers and co-operatives in a very short timescale. Therefore, high resolution information used in this study fits with practical constraints in terms of cost, resolution and commercial availability. Another originality of this study is the scale of investigation; many experiments in precision viticulture have presented the use of high resolution information to provide within-field zones (Bramley 2001; Tisseyre et al. 2005) on particular fields. This study focuses on a decision scale which fits with the requirements of co-operatives and wineries. It aims to consider within-field variability but also the effect of different locations, different soil types and different training systems which may be met in the region. Finally, the originality of this approach is also based on the parameter that the zoning is based on. In our conditions, plant water status is one of the most important parameters which drive vigour, yield and quality. Potential of high spatial resolution information to define within vineyard zones related to vine water status has never been investigated in our conditions. As far as we know, many studies investigated the relation between high resolution information (NDVI and electrical soil survey) with vigour, LAI and yield, but not with plant water status.

Materials and methods

Experimental fields

Experiments were carried out on 41.7 ha in the experimental vineyard of Pech-Rouge (INRA-Gruissan), during the 1999, 2006 and 2007 growing seasons. The experimental

vineyard is located N $43°08'47''$, E $03°07'19''$ WGS84, in the Languedoc-Roussillon region (Aude department) of France. The experimental centre of Pech-Rouge produces white and red grapevine varieties (see Table 2) on three different soil units: (i) Colombier (Col), predominately characterized by calcareous soil, (ii) Clape (Cla), characterized by calcareous soil with an irregularly stony profile of 40 cm depth, and (iii) the Littorale (Lit), characterized by an arenosol (thick sandy soil). These soil types were not only chosen because they are representative of the vineyards in the area but because the Colombier (Col) and Clape (Cla) represent profiles with low soil water availability compared to the Littorale (Lit). Pech-Rouge vineyard has a Mediterranean climate with a strong maritime influence, the mean annual rainfall is about 600 mm. This climate is characterized by a dry summer.

Seasonal climatic characterization

Experiments were carried out during three different years with different climatic conditions. The dryness index (DI), proposed by Tonietto and Carbonneau (2004) was used to characterize the seasonal potential soil water balance. It is an indicator of the dryness level calculated on a 6-month period from April 1st to September 30th. Based on the DI value, four classes are usually considered: humid (wet climate with DI >150 mm), sub-humid (DI ∈] 50; 150 mm]), moderately dry (DI ∈] −100; 50 mm]) and very dry (DI < −100 mm). Last two classes represent conditions of medium to high levels of water restriction for the vine.

Table 1 presents accumulated precipitation (C.Pp), accumulated reference evapotranspiration (C.ET$_0$) and dryness index (DI) values calculated for each experimental year. Season 1999 presents the lowest DI (DI = 55 mm) corresponding to a sub-humid climate. Seasons 2006 and 2007 present DI corresponding to a moderately dry climate, with 2006 DI value close to very dry climate (DI = −82). The experiment covered years with different climatic conditions. Year 2006 and, to a lesser extent year 2007, should lead to high vine water restriction.

High-spatial resolution information

Airborne imagery

The methods used for image acquisition and image processing followed well-established methods for vines (Lamb et al. 2004). Three multi-spectral airborne images, with 1 m resolution, were acquired during the full vine canopy expansion period (July 1999, August

Table 1 Summary of the main climatic variables (period April-September) characterizing growing conditions during the three years of experimentation

Year	C.Pp (mm)	C.ET$_0$ (mm)	DI (mm)
1999	363	799	55
2006	144	869	−82
2007	242	801	−27

C.Pp: Cumulated precipitation

C.ET$_0$: Cumulated reference evapotranspiration

DI: Resulting dryness index

2006 and August 2007). The trial site image was collected by two different companies: *'IFN Inventaire Forestier National'* in 1999 and *'L'avion Jaune'* in 2006 and 2007. Images were acquired at 4000 m and 3200 m elevation respectively, under clear sky and dry soil conditions. The spectral regions contained in the images were: (i) blue (445–520 nm), (ii) green (510–600 nm), (ii) red (632–695 nm) and (iv) near-infrared (757–853 nm). The software package Matlab v7.0 (Mathworks, Inc.) was used for image processing and analysis. The image information was used to estimate the Normalised Difference Vegetation Index (NDVI) (Hall et al. 2002, 2003) and to generate relative biomass maps. This index was calculated by transforming each multi-waveband image pixel according to Eq. 1.

$$NDVI = \frac{(NIR) - (R)}{(NIR) + (R)} \tag{1}$$

where NIR = near infrared and R = red. Both variables corresponded to their respective reflectance in the light band (Rouse et al. 1973).

The three images (1999, 2006 and 2007) were used to check the time stability of the zones derived from the images.

Soil physical properties

Measurement of soil electrical resistivity (SE_Resistivity) with invasive electrodes was obtained using a SE_Resistivity survey sensor (Wenner 4 electrode device). The purpose of this sensor is to determine soil resistivity distribution from a determined soil volume. The method consists of the application of artificially generated direct electric currents to the soil and measuring the resulting differences in potential. The potential difference patterns were used to characterize sub-surface heterogeneities and electrical properties (Samouëlian et al. 2005), as the depth of exploration of the soil profile is proportional (for homogeneous materials) to the distance between probes. In this study, the soil information was obtained to a depth of 1 m. Measurements were made manually on specific zones defined according to NDVI information (see section sampling site determination). Five repetitions were systematically made on each measurement site and it was assumed that SE_Resistivity varies mainly with soil water availability.

Image processing

For each individual field, the image processing was performed using a Matlab script developed at the Agricultural Engineering University of Montpellier. The images were first geo-referenced using relevant points on the image such as field corners or obvious end of row. The co-ordinates of these features were determined using a DGPS (Differential Global Positioning System) (Leica Geosystems company, model GS 50 with differential correction OMNISTAR) according to the French system (Datum RGF93, projection Lambert93). Images were geo-referenced using a Helmert transformation. Considering the average slope of the fields and the elevation of the acquisition, image ortho-rectification was not necessary in this study. The next step consisted of selecting pixels belonging to the field; this was achieved using the field boundary as determined with a DGPS (see Fig. 1b). Finally, the calculation of NDVI was made pixel-by-pixel (Eq. 1) based on image digital numbers. Image calibration was not considered in the first approach since only relative differences in NDVI were considered for each field. To avoid the effect of canopy cover
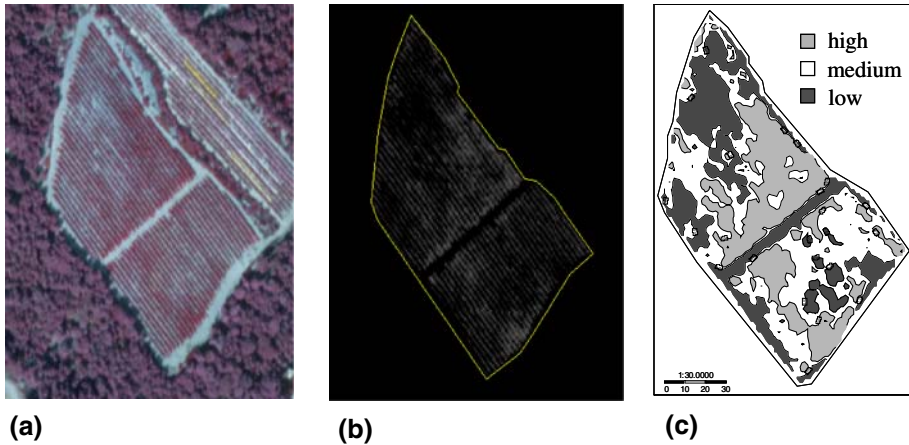
Fig. 1 Different steps of the image processing: (**a**) original image (B, G, R and NIR), (**b**) extraction of the boundary of the field and calculation of NDVI within the field, (**c**) NDVI map after applying a 3 × 3 pixel moving average window, with low (dark grey), medium (white) and high (light grey) NDVI values

discontinuity due to the vine training system (simple trellis), an averaged NDVI calculation was made using a 3 × 3 pixel-moving average window (area of 9 m^2). This 9 m^2 moving average window was chosen according to vine plantation density (1 × 2.5 m) in order to make sure to have NDVI values from plants. NDVI values from plants are significantly higher than from bare soil. Therefore, within-field variation of NDVI caused by soil variability was considered as insignificant compared to variation of NDVI values due to plant variability.

Spatial analysis and field selection

The NDVI calculation was performed on the whole vineyard, a set of 24 non-irrigated fields. However, only nine of these fields trained in a simple trellis system were selected (Table 2) on the basis of their spatial structure and their NDVI variation magnitude. For each field, NDVI values were used to compute geo-statistical information, such as: the variogram and its related parameters (nugget effect C0, sill C1 and range r), and the trend. This information was used to compute the Opportunity Index of site specific management (O$_i$) introduced by Pringle et al. (2003). The O$_i$ parameter provides separate measurements of magnitude of variation (CV$_a$) and the size of the spatial structure (S) of the within field variability (Pringle et al. 2003). Originally, Pringle et al. (2003) presented the problem of quantifying the opportunity of site-specific management based on yield monitor data. They suggested that a pertinent opportunity index has to take into account both the magnitude of the yield variation and the arrangement in space of this variation. They have proposed a SSCM (Site-Specific Crop Management) Opportunity Index (O$_i$) which takes into account these two components:

$$O_i = M \times S \tag{2}$$

where M = is the magnitude of data variation and S = is the spatial structure of data variation.

Table 2 Summary of the selected fields, crop variety, age, field area, vine and row spacing, areal coefficient of variation (CV_a), spatial structure statistic (S) and opportunity index (O_i) present in the dataset collected for this study

Soil unit	Field ID	Variety	Age (years)	Field area (ha)	Vine spacing (m)	Row spacing (m)	CV_a	S	O_i
Col	P90	MU	39	0.42	1.5	2.25	0.045	0.14	0.006
	P95	CA	40	0.81	1.5	2.25	0.033	0.20	0.007
	P96	GN	40	0.70	1.5	2.25	0.053	0.19	0.010
Cla	P63	SY	16	1.14	1.1	2.5	0.066	0.47	0.032
	P69	MO	17	1.65	1.0	2.5	0.026	0.46	0.012
	P76	SY	15	1.33	1.0	2.5	0.062	0.33	0.021
Lit	P11	PV	10	0.70	1.0	2.5	0.045	0.30	0.013
	P22	SY	11	1.72	1.0	2.5	0.054	0.62	0.034
	P61	CA	19	1.05	1.0	2.5	0.041	0.50	0.020

Soil unit: Col, Colombier; Cla, Clape; Lit, Littorale

Variety: MU, Muscat; CA, Carignan; GN, Grenache Noir; SY, Syrah; MO, Mourvèdre; PO, Portan; PV, Petit Verdot

In Eq. 2, the magnitude of field variation (M) is assessed by the areal Coefficient of Variation (CV_a). The spatial structure of field variation (S) is assessed by the proportion of total variance explained by a trend surface of field data and the integral scale of the trend surface residual. Pringle et al. (2003) have shown that O_i was reasonably successful in ranking the fields from the most suitable to the least suitable to site-specific management. In our case, the O_i was used to choose fields which present large zones with significant differences in NDVI values. It was then used as an objective information to select the most opportune fields for our experimentation and to avoid fields with only random variation. We used the O_i to rank the grape fields from the less opportune to the more opportune in each soil unit. Nine fields were chosen among the higher values of O_i, three in the Colombier (Col), three in the Clape (Cla) and three in the Littorale (Lit) in order to consider the different soil units. Table 2 presents a summary of the 9 grape-fields used in this study.

Note in Table 2, that O_i values are very low. The opportunity index was originally designed for yield values. In the case of NDVI information, the CV_a values are very low due to the small magnitude of variation (NDVI $\in$ [0, 1]) for all the fields. Conversely, the S components are spread over a wide range of values (from 0 to 62% of the within-field variability). Since the O_i results from a multiplication of both components (CV_a and S), observed O_i values are very low in the case of NDVI values. However, S remained very different depending on the considered field and the resulting O_i remained relevant in ranking the fields.

This result raises the problem of O_i as defined by Pringle et al. (2003), which could be adapted for other types of data such as NDVI. In this particular case, another recent index (Tisseyre and McBratney 2008) could have been more appropriate.

Sampling site determination

In each field, sampling site determination was based on the NDVI information. Fields selected according to the O_i were assumed to present significant spatial patterns. The field

zoning process aimed at considering two zones per grape field in order to verify whether NDVI variation was significantly related to other parameters, especially the plant water status. For each field, the zoning was carried out by considering three classes of NDVI; high, medium and low, where the low class corresponded to 0–33% quantile, the medium class corresponded to 33–67% quantile and the high class corresponded to 66–100% quantile. It is important to note that this classification is relative to each selected field from Table 2. Classes of NDVI were mapped. Two sampling sites per grape field were then determined taking into account two criteria: (i) they had to be located in two significant classes (zones) of NDVI (high and low), (ii) the zones of high or low NDVI had to present a significant area on the field (>100 m^2). The last criterion was considered mainly for practical reasons, to ensure the number of vines on each zone is relevant for further analysis. Medium zones of NDVI were never considered in this study, they were considered as transition zones (buffer zones) between low and high zones. Moreover, taking into account the inaccuracy of the geo-referenced data and the positioning system, the transition zone allowed us to confidently locate the sample sites within high and low NDVI zones.

Parameter measurement

Two ground-based measurement sites of 40 m^2 in high and low NDVI zones were chosen in each of the 9 fields. Several measurements were carried out to verify the relevance of the zoning (Table 3). In this table, a distinction is made based on the type of the variables, the

Table 3 Summary of the variables measured on the selected fields, number of acquisitions, date of acquisitions, number of repetitions per zones and name of the variable

Variables	# Acquisitions	Acquisition dates	# Repetitions	Nomenclature
High spatial resolution information				
NDVI	1	July 1999	1	NDVI_a
	1	August 2006	1	NDVI_b
	1	August 2007	1	NDVI_c
Soil electrical resistivity	1	March 2006	5	SE_resistivity
Quantitative measurement				
PLWP	1	July 2006	9	PLWP1
	1	August 2006	9	PLWP2
	1	August 2007	9	PLWP3
Vine trunk circumference	1	March 2006	40	–
Canopy height	1	August 2006	10	C_height1
	1	August 2007	10	C_height2
Canopy thickness	1	August 2006	10	C_thick1
	1	August 2007	10	C_thick2
Vine growth rate	1	March 2006	40	G_rate
Yield per plant	1	September 2006	10	Yield
Berry composition				
Sugar percentage (°Brix)	1	September 2006	–	Brix
pH	1	September 2006	–	pH
Titratable acidity	1	September 2006	–	T_acidity
Total polyphenols index	1	September 2006	–	TPI

number of acquisitions, the date of acquisitions and the number of repetitions (Number of vines per zone).

Although the soil electrical resistivity variable was measured manually (inter-row) with low spatial-resolution in this study, this parameter was treated as high resolution data since soil electrical survey is available and currently performed on many vineyards with embedded sensors.

Additional direct measurements were also made on the vines in each zone, including: pre-dawn leaf water potential (PLWP) at three different dates (July and August 2006 and August 2007), vine vegetative expression (canopy height (cm), canopy thickness (cm) and vine trunk circumference (mm)). In order to avoid vine age effects, the calculation of the trunk growth rate (G_rate) was considered using the ratio vine trunk circumference/age of the vine. At harvest, different variables were also measured to characterize the production (yield per plant) and berry quality parameters. Quality measurement was based on samples of 10 clusters (of different plants) collected in the center of each sampling site (high and low NDVI). Soluble solids concentration (using a thermo-compensated refractometer), total acidity (g l^{-1} of sulphuric acid) and pH were measured at berry maturity. To evaluate berry composition, measurements of total polyphenols index were assessed at harvest using the methodology proposed by Iland et al. (2000).

Data analysis and data mapping

Principal Component Analysis (PCA) was carried out on the data. This study allowed analysis of the whole data set, including all the sampling sites and all the parameters. Indeed, with the aim to check significant differences between both zones (high and low NDVI), a classical statistical analysis was undertaken. Thus, the comparison of mean values between NDVI zones was performed using the Kruskal-Wallis non-parametric test. This test was selected instead of the classical analysis of variance (ANOVA) because ANOVA normality assumptions were not met with our data.

Data mapping was performed using the 3DField software (Version 2.9.0.0, Copyright 1998−2007, Vladimir Galouchko, Russia). The interpolation method used in this study was based on a deterministic function (inverse distance weighting).

Results and discussion

General analysis

The PCA results are presented in Fig. 2 and for each zone (Lit, Col and Cla), the low NDVI sample sites are represented by the closed symbols (Cla_L, Col_L, Lit_L), while high NDVI sampling sites are represented by open symbols (Cla_H, Col_H, Lit_H). When several measurements were available on each sampling site, the average was computed. In the PCA, components 1, 2, and 3 represent 48%, 16% and 11% of the variation, respectively, accounting for 75% of the total variability. It can be seen in Fig. 2b, where component 1 is strongly correlated with NDVI for the three dates (NDVI_a, NDVI_b, NDVI_c), with canopy thickness (C_thick), canopy height (C_height), trunk growth rate (G_rate) and yield per plant. These last two variables constituted a smaller percentage in component 1. Conversely, component 1 is negatively correlated with pre-dawn leaf water potential (expressed in absolute values) at the three dates (PLWP1, PLWP2 and PLWP3)
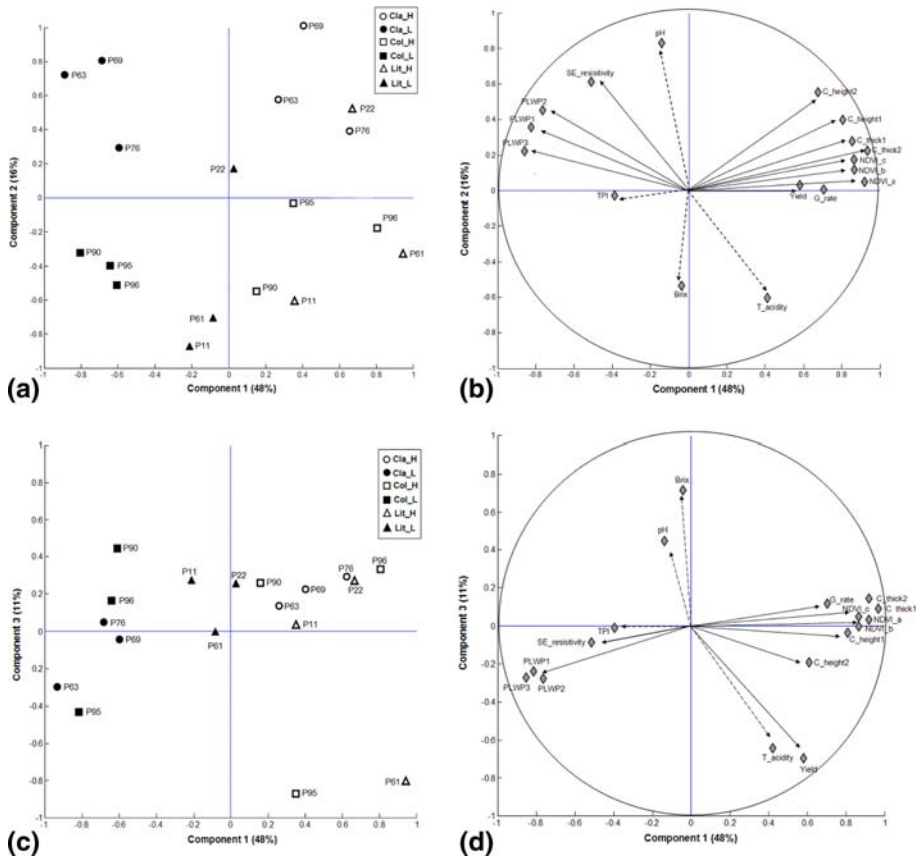
Fig. 2 Principal component analysis (PCA) performed on the data set from 1999, 2006 and 2007. Each point of the PCA represents a within plot measurement of high-NDVI (H) and low-NDVI (L) in each Colombier (Col), Clape (Cla) and Littorale (Lit) soil units. Projection of single individuals on the plane formed by the first and second component (**a**) and the plane formed by first and third component (**c**). Projection of variables on the plane made by the first and second component (**b**) and the plane made by first and third component (**d**). Dotted lines characterize vegetative expression and vine water potential variables, and dashed lines characterize berry quality variables. Variables are abbreviated as in Table 3

and with total polyphenols index (TPI). Low NDVI sites are located on the left part of the scatter plot while all the high ones are on the right side (Fig. 2a). Component 1 can be related to the plant vegetative expression differences driven by plant water status, underlying the relevance of NDVI information for vineyard zoning according to plant water status.

Component 1 shows a strong correlation between NDVI information measured in 1999, 2006 and in 2007. This indicates a relative temporal stability of this information which may be related to parameters such as soil depth, soil characteristics, elevation and the resulting soil water availability. Note that in this study, the temporal stability does not mean that zones present the same values over the years. It only means that low zones remain low and high zones remain high over the three years of the study (see Fig. 3). Figure 3 illustrates the temporal stability of NDVI zones observed on two fields in 1999 (3a, d), 2006 (3b, e) and 2007 (3c, f). For the six maps, NDVI data were mapped in 33%
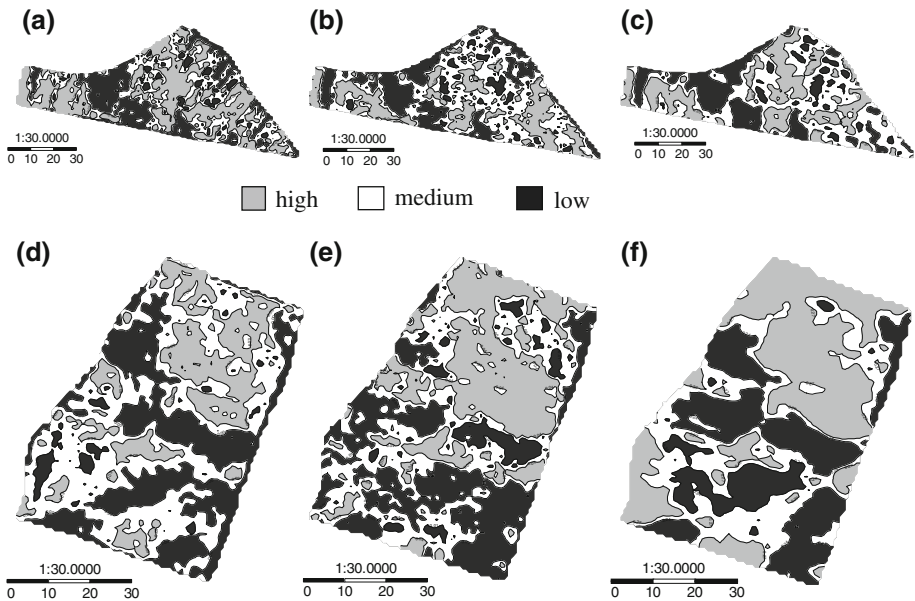
Fig. 3 Maps of normalised difference vegetation index (NDVI) estimated at different seasons: (**a**), (**b**), (**c**) July 1999, August 2006 and August 2007 in Mourvèdre (P69), respectively, and (**d**), (**e**), (**f**) July 1999, August 2006 and August 2007 in Syrah (P63), respectively. NDVI data were mapped in 33% quantiles. The class "very small" (dark grey) corresponds to the 0–33% quantile, the class "medium" (white) corresponds to the 33–67% quantile and the class "high" (light grey) corresponds to 67–100% quantile of the NDVI values

quantiles for each year which removes absolute differences between years due to climate, canopy management and conditions of image acquisition. For each map of the Fig. 3, the class "very small" (dark grey) corresponds to the 0–33% quantile, the class "medium" (white) corresponds to the 33–67% quantile and the class "high" (light grey) corresponds to 67–100% quantile of the NDVI values. Figure 3 shows that low or high NDVI are consistently located in the same part of the field in 1999, 2006 and 2007. These results highlight the incidence of perennial parameters like soil depth, soil texture and slope among others which drive NDVI within-field variability. However, depending on the climate of the year, significant differences in NDVI values, PLWP, yield and vigour were observed on the same zone from one year to another.

Figure 2b shows a correlation between trunk growth (G_rate) and NDVI. Considering G_rate as an indicator of average vine vigour since establishment, this result confirms the temporal stability of the zones under consideration.

Component 2 is strongly correlated with the pH and, to a lesser extent, with the berry total acidity (T_acidity) and Brix. Finally, Component 3 (Fig. 2d) is correlated with the berry composition parameters (pH, T_acidity and Brix). Thus, considering sampling sites (Fig. 2), most of the quality parameters (Brix, pH and T_acidity) did not show any linear relationship with the vegetative growth parameters and plant water status. These results are in accordance with those obtained by Peterlunger et al. (2002) and Ojeda et al. (2005) who found that a non-linear approach was required in order to relate the berry quality parameters with plant water status. This relationship requires a temporal approach which considers the level of water restriction in association with the variety and the phenological

stage of the vine. Indeed, considering sampling sites, the total acidity (T_acidity) and yield measurements are explained principally by the values obtained by the high NDVI values of P95 and P61 fields (Fig. 2d), which presented the higher yields and the higher berry total acidity with regard to the other sampling sites. Thus, the behaviour of these two variables were not observed in the rest of the sampling sites analyzed.

Figure 2 highlights obvious links between PLWP and quantitative parameters. As the water deficit increases (lower vine water potential values), the values of harvest parameters decrease. Regarding yield, this reduction is mainly due to a reduction in the individual berry weight. This means that severe water restrictions (particularly in the high water restriction zones) can cause a strong attenuation of the vine growth. In 2006, water stress occurred very early in the season reaching strong to severe levels for vines located in the Colombier and Clape zones. These results are in accordance with those by Schultz and Matthews (1988) and Ginestar et al. (1998) who found that vine growth is the first factor affected by water restriction. These results show the relevance of using NDVI to zone the vineyards according to water restriction. Results also showed that such a zoning seems to be stable over the years.

Considering Fig. 2a and b, SE_resistivity is a variable whose behaviour is peculiar to our conditions. It showed no significant representation in either component 1 or component 2: (i) it is correlated with the plant water status. This correlation shows that differences between plant water status are mainly explained by differences in soil conditions. (ii) it also explains the important extent of variation that exists between the Cla (positive values on PCA, Fig. 2a) from Lit and Col, both with negative values (on the PCA).

This result demonstrates the limitation of using SE_resistivity to zone the vineyard without any other considerations. SE_resistivity is an integrating parameter that characterises soil properties according to many different phenomena (such as salinity, water content, texture, amongst others) (Corwin and Lesch 2005, Samouëlian et al. 2005). In our conditions, variability due to the different soil types (Col, Cla and Lit soil units) is significant compared to the within-field variability. For example, presence of limestone layers on the Cla soil unit leads to high soil resistivity values for this part of the vineyard. To summarize, SE_resistivity can be used to delineate within-field plant water restriction zones, but this information needs to consider a previous expert delineation of the main soil types to be relevant.

Thus in our conditions, the soil (different zones of study) is the main influential factor on vine vegetative expression and plant water status. The soil hides even the influence of the variety maturity date. For example Syrah and Mouvèdre (P63 and P69 respectively, Fig. 2a) are two varieties which show very distinct behaviour in terms of date of maturity (early and late varieties, respectively). Nevertheless, both varieties appear in the same zone of the PCA (in the upper part of the scatter plot) which corresponds to the Clape zone, showing that the type of soil is the main factor to consider in this analysis.

The above ground biomass production and plant water status parameters are mainly influenced by soil water content. Therefore, NDVI information offers an accurate representation of growth behaviour of vineyards affected by water restriction in our conditions.

Vine water status

Figure 4 shows pre-dawn leaf water potential (PLWP) values measured at two different growing periods, post-setting (a) and post-veraison (b) (July and August 2006, respectively). Each bar represents a within-field measurement of high and low NDVI zones.
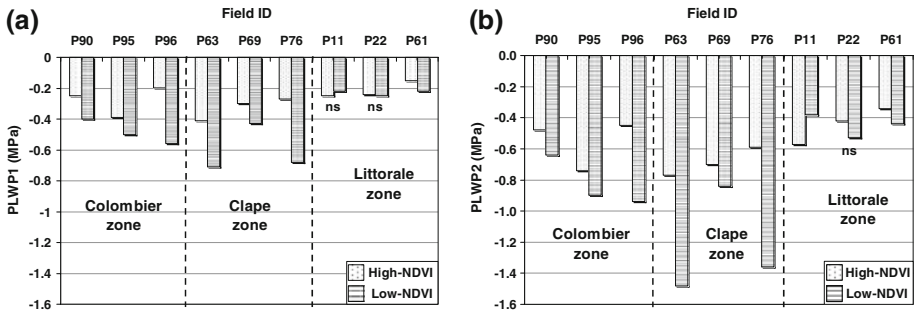
Fig. 4 Pre-dawn leaf water potential measurements (PLWP1 and PLWP2) for two different growing periods: (**a**) post-setting (July 2006) and (**b**) post-veraison (August 2006). Each bar represents a within-field measurement of high and low NDVI zones (Vine vegetative expression). Values followed by 'ns' are not significantly different (Kruskal-Wallis $P \le 0.05$). Each value represents an average of nine plants

Figure 4 shows that significant differences in PLWP occurred between high and low vegetative expression zones (NDVI), for almost all experimental fields. The exceptions were field P22 for both periods and field P11, which presented significant statistical differences only in post-veraison.

The lowest PLWP values found in the Cla soil unit were from vines subject to higher water restrictions, especially for the P63 and P76 fields; PLWP = −1.48 MPa and PLWP = −1.36 MPa, respectively, for post-veraison. These values are mainly explained by the limestone layers and the resulting low soil water availability. The highest PLWP values were found in the Lit soil unit (between −0.34 and −0.57 MPa for the post-veraison). The Col presented intermediary values. Similar results were observed with SE_resistivity. Thus, the Cla showed higher soil resistivity compared to Col and Lit.

The particular results observed for Lit can be explained. This soil unit presents particular conditions: deep sandy-loam soils with higher water storage capacity compared to Cla and Col soil units. This fact explains the low SE_resistivity values observed for the fields in the Lit soil unit. In these fields, water is not a limiting factor for vegetative growth. These fields developed the highest canopy area and also the highest evaporative demand. Later in the summer (August), sectors with the higher vegetative growth have the highest water consumption leading to water restriction symptoms (lower PLWP). This phenomenon can be seen as an induced water restriction.

This result is of importance since it demonstrates the limit of our approach. It shows that NDVI information and soil electrical resistivity may be relevant to define water restriction zones. However, such information needs to consider a previous delineation of the main soil types.

Other measured variables

The majority of the vegetative growth variables (canopy height, canopy thickness, canopy area and trunk circumference) showed significant differences between zones of high and low NDVI (Table 4). The major plant growth differences were observed in the fields located in the Cla and Col. These results are in agreement with PLWP values and soil electrical resistivity (Table 4). Large variations of vegetative expression are related with large differences in soil electrical resistivity.

Table 4 Summary of ground-based measurements in the dataset collected for this study (14 March, 04 July and 06 August 2006)

Fields ID	14 March		04 July			06 August		
	Trunk circumference (mm)	SE_resistivity (ohm)	Canopy height (cm)	Canopy thickness (cm)	Canopy area (m²/pl)	Canopy height (cm)	Canopy thickness (cm)	Canopy area (m²/pl)
Colombier								
P90								
Low	241.95	4.76	113.8	49.5	1.19	108.8	51.6	1.12
High	268.36	2.59	135.1	54.6	1.94	140.0	59.3	2.09
Sign.[a]	$P \leq 0.001$	$P \leq 0.01$	$P \leq 0.001$	$P \leq 0.05$	$P \leq 0.001$	$P \leq 0.001$	$P \leq 0.001$	$P \leq 0.001$
P95								
Low	228.81	1.70	115.2	45.4	1.34	108.7	44.5	1.09
High	291.50	1.85	138.4	62.5	2.49	133.5	62.0	2.52
Sign.	$P \leq 0.001$	n.s	$P \leq 0.001$	$P \leq 0.001$	$P \leq 0.001$	$P \leq 0.001$	$P \leq 0.001$	$P \leq 0.001$
P96								
Low	270.33	2.65	91.0	49.8	0.86	92.0	50.9	0.84
High	395.86	1.93	133.0	77.7	2.67	128.3	78.9	2.60
Sign.	$P \leq 0.001$	$P \leq 0.01$	$P \leq 0.001$	$P \leq 0.001$	$P \leq 0.001$	$P \leq 0.001$	$P \leq 0.001$	$P \leq 0.001$
Clape								
P63								
Low	107.16	59.50	97.0	46.0	1.89	91.5	41.7	1.38
High	133.97	16.44	143.0	64.5	3.03	149.5	69.9	3.20
Sign.	$P \leq 0.001$	$P \leq 0.01$	$P \leq 0.001$	$P \leq 0.001$	$P \leq 0.001$	$P \leq 0.001$	$P \leq 0.001$	$P \leq 0.001$
P69								
Low	142.1	72.36	105.5	47.2	2.23	103.5	49.1	2.04
High	210.03	10.76	160.5	67.3	3.72	152.0	68.6	3.39
Sign.	$P \leq 0.001$	$P \leq 0.01$	$P \leq 0.001$	$P \leq 0.001$	$P \leq 0.001$	$P \leq 0.001$	$P \leq 0.001$	$P \leq 0.001$

Table 4 continued

Fields ID	14 March		04 July			06 August		
	Trunk circumference (mm)	SE_resistivity (ohm)	Canopy height (cm)	Canopy thickness (cm)	Canopy area (m²/pl)	Canopy height (cm)	Canopy thickness (cm)	Canopy area (m²/pl)
P76								
Low	105.32	14.30	99.0	55.1	1.91	97.0	53.7	2.01
High	136.30	5.16	156.5	84.3	3.63	145.0	75.4	3.34
Sign.	$P \leq 0.001$	$P \leq 0.01$	$P \leq 0.001$	$P \leq 0.001$	$P \leq 0.001$	$P \leq 0.001$	$P \leq 0.001$	$P \leq 0.001$
Littorale								
P11								
Low	117.08	3.47	96	44.5	1.82	102.5	45.8	2.17
High	111.80	3.26	111.5	61.0	2.61	114.5	59.5	2.68
Sign.	n.s	$P \leq 0.05$	$P \leq 0.001$	$P \leq 0.001$	$P \leq 0.001$	$P \leq 0.05$	$P \leq 0.001$	$P \leq 0.001$
P22								
Low	115.04	3.39	130.5	50.3	2.45	89.3	43.6	1.79
High	128.24	3.81	146	64.7	3.36	113.5	57.3	2.68
Sign.	$P \leq 0.001$	n.s	$P \leq 0.01$	$P \leq 0.001$	$P \leq 0.01$	$P \leq 0.001$	$P \leq 0.001$	$P \leq 0.01$
P61								
Low	220.76	3.95	95.5	47.3	1.41	96.5	49.0	1.42
High	246.85	2.34	149.5	68.4	3.49	153.0	68.0	3.53
Sign.	$P \leq 0.001$	$P \leq 0.01$	$P \leq 0.001$	$P \leq 0.001$	$P \leq 0.001$	$P \leq 0.001$	$P \leq 0.001$	$P \leq 0.001$

[a] Values followed by 'ns' are not significantly different (Kruskal-Wallis $P \leq 0.05$)

It is important to mention that the major differences in vegetative growth variables (trunk circumference and plant canopy area) were observed in fields located in the Cla and Col, which were correlated to PLWP values (described previously). Furthermore, minor differences in both variables (vegetative growth and PLWP) were observed in the Littoral. Thus, Table 4 shows very similar results. Trunk circumference integrates information of vine growth from establishment, therefore, zones identified by trunk circumference can be considered as stable on this non-irrigated vineyard.

The results obtained in SE_Resistivity also presented strong similarities with trunk circumference measurements. This indicates that the variability in vegetative expression may often be stable and dependent on soil variability. This effect highlights the relevance of soil electrical resistivity for zoning purposes (but not on all the soil units considered).

Conclusions

This experiment showed that the information provided by airborne imagery and soil electrical resistivity is relevant to characterize the spatial variability of plant water status at a within-vineyard scale. However, it also highlights the necessity to consider each soil unit separately since NDVI or electrical resistivity may exhibit different spatial phenomena depending on the particular part of the vineyard. To be applied to the whole vineyard, this approach has to integrate additional information such as soil units based on expert analysis or auxiliary information (such as elevation, soil depth, soil colour or other knowledge).

The results showed that zones based on NDVI information either in 1999, 2006 or in 2007 exhibited significant differences in vine vegetative expression, yield and plant water status. Moreover, the results observed in soil electrical resistivity and vine trunk circumference prove the temporal stability of the zoning (at least over the 3 experimental years), its link with soil variables (soil depth, water availability) and its relevance to define vine water restriction zones. Unfortunately, quality differences were barely exhibited between the NDVI zones. This result shows the limits of this approach for grape quality assessment in non-irrigated conditions. It highlights the necessity to develop a more comprehensive approach to provide an assessment of the quality parameters based on this type of information. High spatial resolution information like airborne imagery and soil electrical resistivity offer great promise to characterize within-field variability in yield, vegetative expression and water restriction. Thus, this type of information constitutes relevant decision support to design zones of different water restriction.

References

Barbeau, G., Ramillon, D., Goulet, E., Blin, A., Marsault, J., & Landure, J. (2005). Effets combines de l'enherbement et du prote-greffe sur le comportement agronomique du Chenin [Combined effect of cover cropping and rootstock on agronomic behaviour of Chenin]. In H. R. Shultz (Ed.), *Proceedings of 14th GESCO Congress* (pp. 167–172). Geisenheim, Germany: Groupe d'Etudes des systèmes de Conduite de la Vigne.

Bramley R. G. V. (2001). Variation in the yield and quality of winegrapes and the effect of soil property variation in two contrasting Australian vineyards. In S. Blackmore & G. Grenier (Eds.), *Proceeding of the 3rd European Conference on Precision Agriculture* (pp. 767–772). France: Agro Montpellier, Ecole Nationale Superieure Agronomique de Montpellier.

Bramley, R. G. V. (2005). Understanding variability in winegrape production systems 2 Within vineyard variation in quality over several vintages. *Australian Journal of Grape and Wine Research, 11*, 33–45. doi:10.1111/j.1755-0238.2005.tb00277.x.

Corwin, D. L., & Lesch, S. M. (2005). Characterizing soil spatial variability with apparent soil electrical conductivity I. soil survey. *Computers and Electronics in Agriculture, 46*, 32–45.

Dry, P. R., & Loveys, B. R. (1998). Factors influencing grapevine vigour and the potential for control with partial rootzone drying. *Australian Journal of Grape and Wine Research, 4*, 140–148. doi:10.1111/j.1755-0238.1998.tb00143.x.

Fuentes, S., Conroy, J. P., Kelley, G., Rogers, G., & Collins M. (2005). Use of infrared thermography to assess spatial and temporal variability of stomatal conductance of grapevines under partial rootzone drying: An irrigation scheduling application. *Acta Horticulture, 689*, 309–316. (ISHS).

Ginestar, C., Eastham, J., Gray, S., & Lland, P. (1998). Use of sap flow sensor to schedule vineyard irrigation. I. Effect of post-verasion water deficit on water relations, vine growth, and yield of Shiraz grapevine. *American Journal of Enology and Viticulture, 49*, 413–420.

Girona, J., Mata, M., Del Campo, J., Arbone, A., Bartra, E., & Marsal, J. (2006). The use of midday leaf water potential for scheduling deficit irrigation in vineyards. *Irrigation Science, 24*, 115–117. doi:10.1007/s00271-005-0015-7.

Hall, A., Lamb, D. W., Holzapfel, B., & Louis, J. (2002). Optical remote sensing applications in viticulture—a review. *Australian Journal of Grape and Wine Research, 8*, 36–47. doi:10.1111/j.1755-0238.2002.tb00209.x.

Hall, A., Louis, J., & Lamb, D. (2003). Characterizing and mapping vineyard canopy using high spatial resolution aerial multi-spectral images. *Computers and Geosciences, 29*, 813–822. doi:10.1016/S0098-3004(03)00082-7.

Idso, S. B. (1982). Non-water-stressed baselines: A key to measuring and interpreting plant water stress. *Agricultural Meteorology, 27*, 59–70. doi:10.1016/0002-1571(82)90020-6.

Iland, P., Ewart, A., Sitters, J., Markides, A., & Bruer, N. (2000). *Techniques for chemical analysis and quality monitoring during winemaking.* (p. 111). Patrick II and Wine Promotions: Campbelltown, SA, Australia.

Jackson, R. D., Idso, S. B., Reginato, R. J., & Pinter, P. J, Jr. (1981). Canopy temperature as a drought stress indicator. *Water Resources Research, 17*, 1133–1138. doi:10.1029/WR017i004p01133.

Johnson, L. F., Roczen, D. E., Youkhana, S. K., Nemani, R. R., & Bosch, D. F. (2003). Mapping vineyard leaf area with multi-spectral satellite imagery. *Computers and Electronics in Agriculture, 38*, 33–44. doi:10.1016/S0168-1699(02)00106-0.

Jones, H. G. (1999). Use of thermography for quantitative studies of spatial and temporal variation of stomatal conductance over leaf surfaces. *Plant, Cell & Environment, 22*, 1043–1055. doi:10.1046/j.1365-3040.1999.00468.x.

Jones, H. G., Stoll, M., Santos, T., De Sousa, C., Chavez, M., & Grant, O. M. (2002). Use of infrared thermography for monitoring stomatal closure in the field: Application to grapevine. *Journal of Experimental Botany, 53*, 2249–2260. doi:10.1093/jxb/erf083.

Lamb, D. W., Weedon, M. M., & Bramley, R. G. V. (2004). Using remote sensing to predict phenolics and colour at harvest in a Cabernet Sauvignon vineyard: Timing observations against vine phenology and optimising image resolution. *Australian Journal of Grape and Wine Research, 10*, 46–54.

Moran, M. S., Clarke, T. R., Inoue, Y., & Vidal, A. (1994). Estimating crop water deficit using the relation between surface-air temperature and spectral vegetation index. *Remote Sensing of Environment, 49*, 246–263. doi:10.1016/0034-4257(94)90020-5.

Naor, A., Hupert, H., Greenblat, Y., Peres, M., & Klein, I. (2001). The response of nectarine fruit size and midday stem water potential to irrigation level in stage III and crop load. *Journal of the American Society for Horticultural Science, 126*, 140–143.

Ojeda, H., Carrillo, N., Deis, L., Tisseyre, B., Heywang, M., & Carbonneau, A. (2005). Precision viticulture and water status II: Quantitative and qualitative performance of different within field zones, defined from water potential mapping. In H. R. Shultz (Ed.), *Proceedings of 14th GESCO Congress* (pp. 741–748). Geisenheim, Germany: Groupe d'Etudes des systèmes de Conduite de la Vigne.

Ojeda, H., Kraeva, E., Deloire, A., Carbonneau, A., & Andary, C. (2002). Influence of pre and post-veraison water deficits on synthesis and concentration of skins phenolic compounds during berry growth of *Vitis vinifera* cv. Shiraz. *American Journal of Enology and Viticulture, 53*, 261–267.

Ortega-Farías, S., Duarte, M., Acevedo, C., Moreno, Y., & Córdova, F. (2004). Effect of four levels of water application on grape composition and midday stem water potential of *Vitis vinifera* L. cv. Cabernet Sauvignon. *Acta Horticulture, 664*, 491–497. (ISHS).

Peterlunger, E., Sivilotti, P., Bonetto, C., & Paladin, M. (2002). Water stress induces changes in polyphenol concentration in Merlot grape and wines. *Rivista di viticoltura e di enologia, 55*, 53–66.

Pringle, M. J., McBratney, A. B., Whelan, B. M., & Taylor, J. A. (2003). A preliminary approach to assessing the opportunity for site-specific crop management in a field, using yield monitor data. *Agricultural Systems, 76*, 273–292. doi:10.1016/S0308-521X(02)00005-7.

Rouse, J. W. Jr., Haas, R. H., Schell, J. A., & Deering, D. W. (1973). Monitoring vegetation systems in the great plains with ERTS. In S. C. Freden, E. P. Mercanti, & M. A. Becker (Eds.), *Proceedings of the Third ERTS Symposium, NASA SP-351 1* (pp. 309–317). Washington, DC, USA: US Government Printing Office.

Samouëlian, A., Cousin, I., Tabbagh, A., Bruand, A., & Richard, G. (2005). Electrical resistivity survey in soil science: A review. *Soil & Tillage Research, 83*, 173–193. doi:10.1016/j.still.2004.10.004.

Scholander, P. F., Hammel, H. T., Brandstreet, E. T., & Hemmingsen, E. A. (1965). Sap pressure in vascular plants. *Science, 148*, 339–346. doi:10.1126/science.148.3668.339.

Schultz, H., & Matthews, M. (1988). Vegetative growth distribution during water deficit in Vitis vinifera L. *Australian Journal of Plant Physiology, 15*, 641–656.

Sepaskhah, A. R., & Kashefipour, S. M. (1994). Relationships between leaf water potential, CWSI, yield and fruit quality of sweet lime under drip irrigation. *Agricultural Water Management, 25*, 13–21. doi: 10.1016/0378-3774(94)90049-3.

Stoll, M., & Jones, G. (2007). Thermal imaging as a viable tool for monitoring plant stress. *International Journal of Vine and Wine Research, 41*, 77–84.

Taylor, J., & Bramley, R. (2004). Precision viticulture: Managing vineyard variability. In R. Blair, P. Williams, & S. Pretorius (Eds.), *Proceeding of 12th Australian Wine Industry Technical Conference, Workshop 30B* (pp. 51–55). Australia: Melbourne Convention Centre.

Tilling, A., O'Leary, G., Ferwerda, J., Jones, S., Fitzgerald, G., Rodriguez, D., et al. (2007). Remote sensing of nitrogen and water stress in wheat. *Field Crops Research, 104*, 77–85. doi:10.1016/j.fcr.2007.03.023.

Tisseyre, B., & McBratney, A. (2008). A technical opportunity index based on mathematical morphology for site-specific management: An application to viticulture. *Precis Agriculture, 9*(1–2), 101–113. doi: 10.1007/s11119-008-9053-5.

Tisseyre, B., Ojeda, H., Carillo, N., Deism L., & Heywang, M. (2005). Precision viticulture and water status, mapping the pre-dawn water potential to define within vineyard zones. In H. R. Shultz (Ed.), *Proceedings of 14th GESCO Congress* (pp. 23–27). Geisenheim, Germany: Groupe d'Etudes des systèmes de Conduite de la Vigne.

Tisseyre, B., Taylor, J., & Ojeda, H. (2007). New technologies and methodologies for site-specific viticulture. *International Journal of Vine and Wine Research, 41*, 63–76.

Tonietto, J., & Carbonneau, A. (2004). A multicriteria climatic classification system for grape-growing regions worldwide. *Agricultural and Forest Meteorology, 124*, 81–97. doi:10.1016/j.agrformet.2003.06.001.