TEMPORAL STABILITY OF WITHIN-FIELD PATTERNS OF NDVI IN NON IRRIGATED MEDITERRANEAN VINEYARDS

M. KAZMIERSKI[1], P. GLEMAS[2], J. ROUSSEAU[2] and B. TISSEYRE[1]*

1: UMR ITAP, Montpellier SupAgro/Cemagref, Bât. 21, 2 place Viala,
34060 Montpellier, France
2: Groupe ICV Institut Coopératif du Vin

Abstract

Aims: The objective of this paper is to study the temporal stability of within-field spatial variability of the Normalised Difference Vegetative Index (NDVI) at two time scales: intra-annual and inter-annual. This study aims to provide answers to the practical use of NDVI and, in particular, to determine whether it is possible (i) to advance the date of image acquisition in order to increase the time required for image analysis and interpretation before harvest and (ii) to verify if an image acquired in one year can be used to manage the vineyard in the following years.

Methods and results: The study was conducted on 17 individual fields. The analysis of the intra-annual stability was performed with four images in 2007 and two images in 2006 that were acquired at different stages of vine development. The analysis of the inter-annual stability was performed with five images taken around veraison on five different years over a period of 10 years (from 1999 to 2009). For the 17 fields of the study, a sampling grid was defined to take into account the characteristics of image processing and the particular shape of each field. A rank coefficient of correlation (Spearman) was used to characterize the correlation between dates of acquisition (images). A Kendall test was implemented to individually characterize and identify the source of the observed temporal stability.

Conclusion: In Mediterranean conditions, this study highlighted the temporal stability of within-field NDVI patterns both within a season or between seasons. Regarding the intra-annual scale, an image acquired from 15 to 20 days before veraison had a significant correlation ($p < 0.05$) with an image acquired at harvest. For earlier images (i.e., taken around flowering), the strength of the correlation decreased as the time lag between two images increased. This decrease was probably linked to summer pruning operations, the presence of an inter-row cover crop or a spring vigour that differed from the final vigour in some fields. Regarding the inter-annual scale, images acquired at veraison were all significantly correlated ($p < 0.05$) over the 10 year period regardless of the time lag between image acquisition. The degree of the correlation decreases continuously with time. For the 17 fields of the experiment, a decrease in the stability of NDVI between years was noticeable when significant changes in vine training (irrigation, replanting) occurred. For fields that did not undergo major changes, the spatial patterns of NDVI could be considered relatively stable over time for periods up to 3 to 5 years according to the age of the vineyard.

Significance and impact of the study: This study showed that in Mediterranean conditions it is possible (i) to advance the date of image acquisition to at least 20 days before veraison if the objective is to highlight the spatial variability at harvest, (ii) to use information from an image acquired at veraison over several subsequent years if the field does not undergo major changes in management practices and (iii) to use early-season images (around flowering) as a potential source of information for managing other operations.

Key words: *Vitis vinifera*, NDVI, within-vineyard variability, temporal stability, precision viticulture

Résumé

Objectif: L'objectif de ce travail est d'étudier la stabilité temporelle de la variabilité spatiale du NDVI à deux échelles de temps : intra-annuelle et interannuelle. Cette étude a pour objectif d'apporter des réponses pour une utilisation pratique du NDVI, en particulier vérifier s'il est possible (i) d'avancer la date d'acquisition des images afin d'en permettre une analyse et une interprétation bien avant la récolte et (ii) de voir si une image acquise l'année ne peut-être utilisée pour aider à la conduite du vignoble les années suivantes.

Méthodes et résultats: L'étude a été conduite sur 17 parcelles. L'analyse de la stabilité intra-annuelle a été réalisée avec quatre images acquises à des dates différentes en 2007 et deux images en 2006. L'analyse de la stabilité interannuelle a été réalisée avec cinq images correspondant à cinq années différentes réparties sur une période de 10 ans, de 1999 à 2009. Pour les 17 parcelles de l'étude, une grille d'échantillonnage a été définie de manière à prendre en compte les caractéristiques du traitement des images ainsi que la forme particulière des parcelles. Un coefficient de corrélation de rang (Spearman) a été utilisé pour caractériser la corrélation entre les différentes dates d'acquisition (images). Un test de Kendall a été mis en œuvre afin de mettre en évidence le caractère plus moins stable de chaque parcelle et d'évaluer l'origine de la stabilité temporelle observée.

Conclusion: Cette étude a permis de mettre en évidence, en condition méditerranéenne, une stabilité des motifs spatiaux de NDVI que ce soit au cours d'une même année ou entre plusieurs années. Au niveau intra-annuel, une image acquise jusqu'à 15 à 20 jours avant la véraison présente une corrélation significative ($p < 0.05$) avec une image acquise à la vendange. Toutefois, cette corrélation se dégrade régulièrement au cours du temps. Cette dégradation est vraisemblablement liée aux opérations en vert, à la présence d'enherbement ou d'une vigueur printanière différente de la vigueur finale sur certaines parcelles. Au niveau interannuel, les images à la véraison présentent toutes une corrélation significative ($p < 0.05$) jusqu'à un intervalle de temps de 10 ans entre deux images. Le niveau de cette corrélation décroît avec le temps de manière continue. Sur l'ensemble des 17 parcelles testées, cette diminution de la stabilité du NDVI semble s'expliquer par des modifications de conduite (irrigation, replantation) sur certaines parcelles. Pour les parcelles qui ne font pas l'objet de changements majeurs, les motifs spatiaux du NDVI peuvent être considérés comme relativement stables dans le temps sur des périodes allant de trois à cinq ans en fonction de l'âge du vignoble.

Signification et impact de l'étude: En condition méditerranéenne, cette étude montre que (i) il est possible d'avancer la date d'acquisition des images avant la véraison lorsque l'objectif est de mettre en évidence la variabilité spatiale à la vendange, (ii) l'information d'une image acquise à la véraison peut, à condition que la conduite du vignoble ne fasse pas l'objet de changements majeurs, être utilisée sur plusieurs années, (iii) les images précoces (autour de la floraison) sont potentiellement source d'information pour la gestion d'autres opérations.

Mots clés: *Vitis vinifera*, NDVI, variabilité spatiale intra-parcellaire, stabilité temporelle, viticulture de précision

manuscript received 18th May 2010 - revised manuscript received 24th May 2011

J. Int. Sci. Vigne Vin, 2011, **45**, n° 2, 61-73

*Corresponding author: tisseyre@supagro.inra.fr

INTRODUCTION

Many authors have shown the benefits of using remote sensing in viticulture (Hall *et al.*, 2003; Johnson *et al.*, 2003; Dobrowski *et al.*, 2003; Lamb *et al.*, 2004; Bramley *et al.*, 2005; Acevedo-Opazo *et al.*, 2008). Remote sensing applications are currently dominated by either aerial- or satellite-mounted multispectral (Blue, Green, Red and Near Infra-Red wavelengths) sensors according to cost and operability. Aerial/satellite images are generally processed to produce vegetative indices, such as the Normalised Difference Vegetative Index (NDVI) (Rouse *et al.*, 1973) or Plant Cell Density (PCD) (Metternicht *et al.*, 2000), on a per pixel basis. These indices are often used as an estimate of vine vigour and/or canopy characteristics. In viticulture, vigour generally refers to the vine (shoot) growth rate (Champagnol, 1984) and the canopy spatial development, which is usually described by shape measurements (Carbonneau, 1976 and 1995) or by an analysis of the distribution between primary, secondary and tertiary leaves (Champagnol, 1984). Some authors also use a visual evaluation of leaf colour (Smart, 2003). In remote sensing, vigour is viewed as a combination of plant biomass (vine size) and photosynthetic activity termed the 'photosynthetically active biomass' (PAB) (Bramley, 2001). Therefore, indices computed from remote sensing are more related to vegetative expression, since vigorous vines are characterized by larger and denser canopies than less vigorous vines. Many authors have shown relationships between NDVI and vine parameters including Leaf Area Index (LAI) (Johnson, 2003), annual pruning weight (Dobrowski *et al.*, 2003), water restriction zones (Acevedo-Opazo *et al.*, 2008) or other vine parameters (Lamb *et al.*, 2004) at a within-vineyard level. This explains why imagery is currently used in Chile (Best *et al.*, 2005), California (Scholasch *et al.*, 2005) and Australia (Hall *et al.*, 2002; Lamb *et al.*, 2004; Bramley *et al.*, 2005) to delineate zones that differ in vegetative expression.

Vegetative indices, such as NDVI, derived from airborne images show great opportunities to characterize vineyards and the spatial variability in vine vegetative expression. Most applications to date are based on images acquired at veraison. This stage is of interest since the grapevine has reached its final size and is switching from vegetative to reproductive development. Spatial variability in vigour at this stage results from interactions between the grapevine and the climatic events of the year. It also incorporates the effect of within-season management practices, such as summer pruning. Therefore, veraison is considered by many authors (Lamb *et al.*, 2004; Bramley *et al.*, 2005; Acevedo-Opazo *et al.*, 2008) as the optimum stage to link NDVI with production parameters (yield, quality) or environmental parameters (soil, water availability, etc.). The majority of current commercial applications of NDVI are oriented toward characterizing the spatial variability of vigour/yield and differential harvesting.

However, for most commercial vineyards, information at veraison is too late to consider other site-specific operations in the vineyard. Depending on the provider, the time between image acquisition and practical use in the field may take one to several weeks. Several factors may also cause a delay in the delivery of images to the end user including: i) weather conditions (clouds), which, depending on the region, may be more or less important and may cause delays in image acquisition and ii) the availability of the company or platform for the acquisition, which, according to the demand, the weather conditions or other technical problems can affect the timeliness of image acquisition. Information may become available only a few days or weeks before harvest, which sometimes leaves very little time to properly analyse and interpret the information, leading to misuse of the information.

The practical use of NDVI in vineyards therefore raises two questions that this paper deals with. The first question refers to the within-year temporal stability of NDVI patterns. Considering the NDVI response at harvest as the reference, to what extent can the date of image acquisition be advanced before harvest without altering the spatial variability observed at harvest. In the literature, the reference image is regarded as the image at veraison. This question is justified from a practical standpoint as it allows the maximum time before harvest for image analysis and for making and implementing management decisions. In the intra-annual study, the image at harvest is considered as the reference image since it shows the spatial variability of the canopy observed at the end of the production cycle.

The second question refers to the inter-year temporal stability of the NDVI patterns. This question is particularly relevant given the perennial nature of grapevine cultivation. If NDVI is temporally stable over several years then it would be possible to use the information obtained in year « n » as a decision support to manage operations in a subsequent year « n + k » (k = 1,2,…,*K*). The temporal stability of the spatial pattern in vigour in consecutive years in irrigated vineyards (Bramley and Hamilton, 2004) and in vigour and yield parameters in non irrigated vineyards (Tisseyre *et al.*, 2008) has already been highlighted. However, the temporal stability of NDVI over a large number of fields and over a long time period has not previously been reported.

It may seem odd to focus on both questions simultaneously. Indeed, if the spatial variability of a vegetative index shows a significant inter-annual stability, it may seem futile to try to advance the date of acquisition to use the information in the same year. However, from a practical standpoint, image acquisition is a significant investment and the end user expects the shortest return on investment. Therefore, growers expect to use the image during the year of acquisition if possible and in the following years if necessary. For this reason it is important to study both questions simultaneously.

This paper proposes to use a database of airborne images to study the intra-year and the inter-year temporal stability of NDVI patterns on a single vineyard. Note that the goal of this paper is to study the temporal stability of the NDVI patterns and not the temporal stability of the NDVI values. This observation is important since it accounts for the fact that the raw value in NDVI may shift due to annual changes in climate and/or management or differences in image acquisition/analysis. The objective is to check if the temporal NDVI patterns observed are the same, that is, if the areas with highest, medium and lowest NDVI values are always at the same locations over time.

The first part of this paper will present the experimental fields, the sampling scheme and the methods used to process and analyse the data. The second part will present the main results and discuss the potential of choosing both a relevant date of acquisition and the frequency needed for image acquisition.

MATERIALS AND METHODS

1. Experimental fields

The experiment was conducted in the research vineyard of INRA at Domaine de Pech Rouge (Gruissan, Aude, France) (RGF93 datum, Lambert93 coordinates: E:709800, N:6226840) on 17 fields representing a total area of approximately 16 ha. Table 1 presents information on the different fields including field size, training system, age of vines and grape variety. The selected fields are all very representative of Mediterranean vineyards in Southern France.

The study intentionally considered two different training systems that are common in this part of France: vertical shoot positioning (VSP) and gobelet. The consideration of these two training systems generated two field populations of different ages. The oldest fields (>10 years) are traditionally in gobelet while new or newly replanted fields are preferably trained in VSP to facilitate mechanisation. To take into account this peculiarity in the database, these two classes of fields were identified during the analysis (Table 1).

Image acquisition occurred in 5 years (1999, 2006, 2007, 2008 and 2009) spread over a period of 10 years. Management practices (pruning, fertilisation, trimming, etc.) were very similar for all the fields over these 10 years. Note, however, that significant changes occurred on three

Table 1 - Description of the physical condition and management practices employed in the 17 fields used in the study.

Field (Id)	Area (ha)	Variety	Date of plantation	Age class	Training system	Row spacing (m)	Vine spacing (m)	Pedological Unit	Change in practices (1999-2009)
P11	0.69	Petit Verdot	1996	1	VSP	2.5	1	PU3	no
P22	1.72	Syrah	1995	1	VSP	2.5	1	PU3	yes
P78	0.75	Muscat	1997	1	VSP	2.5	1	PU2	no
P67	1.64	Mourvèdre	1991	1	VSP	2.5	1	PU2	no
P69	1.65	Mourvèdre	1989-1990	1	VSP	2.5	1	PU2	no
P72	1.41	Mourvèdre	1996	1	VSP	2.5	1	PU2	no
P76	1.33	Syrah	1993	1	VSP	2.5	1	PU2	no
P63	1.24	Syrah	1990	1	VSP	2.5	1	PU2	no
P92a	0.44	Grenache	1990	1	Gobelet	2.25	1.5	PU1	yes
P79	0.70	Carignan	1980	2	Gobelet	2.5	1	PU1	no
P80	0.69	Syrah	1974	2	VSP	2.5	1	PU2	no
P90	0.42	Muscat	1961	2	Gobelet	2.25	1.5	PU1	no
P91	0.32	Muscat	1961	2	VSP	2.25	1.5	PU1	no
P61	1.05	Carignan	1977	2	Gobelet	2.5	1	PU1	no
P92b	0.42	Grenache	1961	2	Gobelet	2.25	1.5	PU1	yes
P95	0.81	Carignan	1961	2	Gobelet	2.25	1.5	PU1	no
P96	0.70	Grenache N	1961	2	Gobelet	2.25	1.5	PU1	no

VSP: Vertical Shoot Positioning, PU1: depressions on marls and marlstones, PU2: Orbitolina limestones and marls, PU3: deep sandy soils.

fields during this period: for field P22, irrigation trials were performed in 2007 and 2008, while for fields P92a and P92b, additional vines were planted in 2008 to replace the dead vines.

The 17 fields (except field P22 in 2007 and 2008) were non irrigated. The Pech Rouge vineyard has a Mediterranean climate with a hot dry summer. Precipitation occurs mainly in autumn and spring. A high evaporative demand usually leads to significant water restrictions in summer. The average water constraint over the vineyard, estimated by predawn leaf water potential measurements, was -0.75 MPa in August 2003 (dry year) and -0.60 MPa in August 2006 (wet year) (Taylor *et al.*, 2010).

On this vineyard, previous work (Acevedo-Opazo *et al.*, 2008; Taylor *et al.*, 2010) has shown that i) water restriction is the main factor affecting the growth of the vines, ii) vegetative indices, like the NDVI, derived from airborne images are a good surrogate to highlight within-field zones of water restriction and iii) soil variability is the main factor explaining the spatial variability of the vine water status near harvest.

As indicated in Table 1, the 17 fields are spread over three pedological units (PU1, PU2 and PU3). Taylor *et al.* (2010) showed that PU1 and PU2 both have significantly higher water restrictions than PU3. There is also significant soil variability within each PU (Coulouma *et al.*, 2010), which explains a significant variability in vine vigour and vine water status at the within-field level (Taylor *et al.*, 2010).

2. Measurements

a) Airborne imagery

Nine multispectral airborne images were available (Table 2). For each of the five years when imagery was acquired, there was an image taken at veraison. In addition, in 2006 and 2007 there were images acquired at different stages of the season. Because of the diversity of the varieties, terms like veraison or harvest refer to a date that matches the majority of the varieties.

Images of 1 m resolution were collected by Inventaire Forestier National (IFN) (Nogent sur Vernisson, Loiret, France) in 1999 and Avion Jaune (Montpellier, Hérault, France) in 2006, 2007, 2008 and 2009. The spectral regions contained in the images were: (i) blue (445-520 nm), (ii) green (510-600 nm), (iii) red (632-695 nm) and (iv) near-infrared (757-853nm). The Normalised Difference Vegetative Index (NDVI) was derived for each image (Rouse *et al.*, 1973).

b) Image processing

The 1 m square image pixels were aggregated into 3 m square pixels using the methodology outlined in Acevedo-Opazo *et al.* (2008), which approximates the « mixed pixel » row spacing approach of Lamb *et al.* (2004). The calculation of NDVI was then made on the 3 m pixels (area of 9 m^2). The software package Matlab 7.0 (Mathworks, Inc.) was used for image processing and analysis.

c) Sampling scheme

The goal of the sampling scheme was to overlay a sampling grid to allow comparison of NDVI values from

Table 2 - Date of acquisition of the multispectral images.

Acquisition year	Acquisition date	Stage
1999	end of July	around Veraison
2006_1	30/06/2006	around 30 days before Veraison
2006_2	30/07/2006	around Veraison
2007_1	12/06/2007	around 45 days before Veraison
2007_2	11/07/2007	around 20 days before Veraison
2007_3	31/07/2007	around Veraison
2007_4	27/08/2007	around 30 days after Veraison (1-2 weeks before harvest)
2008	31/07/2008	around Veraison
2009	01/08/2009	around Veraison

one image to another. A regular 10 m grid was defined for each field, and the NDVI values were extracted to the grid points from each associated image. Given the inaccuracy of image geo-referencing (+/- 2 m.) and the smoothing of 3*3 m introduced with image processing, the spatial footprint of a measurement site has been set at 6*6 m (36 m^2). Therefore at each grid node the mean NDVI value was computed over this spatial footprint (36 m^2). The grid spacing of 10 m was used to avoid spatial correlation caused by the image smoothing. Finally, to avoid any border effect, a 5 m space on each side of each field was excluded from the sampling scheme. The average sampling rate was approximately 65 sites per hectare, however, depending on the shape and the area of the field, the number of sampling sites per field was different. The highest number of sites was consistently obtained for the larger field (P22) with 108 sampling sites and the lowest number of sites was obtained for the smaller field (P91) with 21 sampling sites. Figure 1 shows an illustration of the sampling sites obtained on four fields differing in size and shape.

For each field, the same grid of sites was applied to all the images acquired, and the mean NDVI value was extracted at each site. To analyse the within-field variability on all fields for each date, the NDVI data were normalised on a per field and per year basis. This standardization helped focus the analysis on the within-field variability and eliminate differences in NDVI associated with the field (training system, plantation density) or vintage (climatic conditions of the year). The resulting data base was used to test the temporal stability of the spatial variability in the NDVI values.

3. Data analysis

a) Temporal stability analysis

- Temporal stability between pairs of images

Temporal stability analysis was performed to verify whether the same part of the vineyard systematically presents the highest, medium or lowest NDVI values within a year or from year to year. Testing the temporal stability of a parameter can be summarized by a correlation analysis of the values observed on all the sites in date 'n' versus the values of the same parameter observed in date 'n + k'. To conduct such an analysis, a rank correlation analysis based on the Spearman rank method was chosen over a classical linear correlation (e.g., Pearson). This choice was made in order to limit the assumptions on the type of relationship between different dates. The Spearman rank method doesn't require any assumptions on the linearity of the relationship or on data distribution. The Spearman coefficient (r_s) was computed according to Equation 1 (see Saporta, 1990 for more details). The r_s was used to test the intra-annual and the inter-annual stability. Note, however, that in this last case, the data were stratified into young and old vines leading to the computation of two series of r_s values.

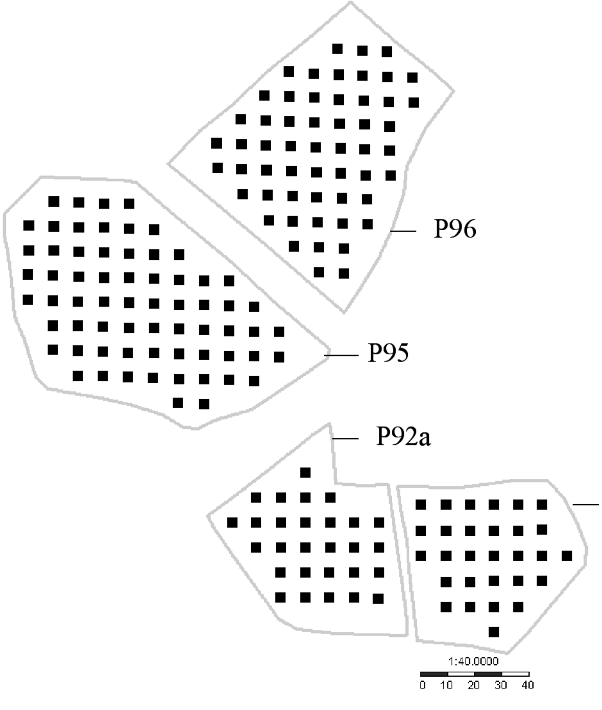


Figure 1 - Example of sampling grids defined specifically on four different fields. Each sampling site has a spatial footprint of 36 m^2.

For the analysis of the intra-annual stability, only images acquired around veraison were considered for this analysis. For a time lag of one or two years, it was possible to calculate several r_s values; that is, for a time lag of one year there were three possibilities considered: 2009-2008, 2008-2007 and 2007-2006. When several values of r_s were available, the mean has been computed.

$$r_s = 1 - \frac{6.\sum_{i=1}^{n}\left(R\left(X_{k,t_1}\right) - R\left(X_{k,t_2}\right)\right)^2}{n.\left(n^2 - 1\right)} \qquad \text{[eq. 1]}$$

Where:

n: is the number of sampling sites on the vineyard (all the fields),

X_{k,t_1}: is the NDVI value on the site *k* and the date t_1 for all the fields,

X_{k,t_2}: is the NDVI value on the site *k* and the date t_2 for all the fields,

$R(X_{k,t_1})$: is the rank of X_{k,t_1} among all the values of the date t_1, and

$R(X_{k,t_2})$: is the rank of X_{k,t_2} among all the values of the date t_2.

The r_s varies from -1 to 1. An r_s value of 1 implies that all the values present exactly the same rank in both series, which would denote, in our case, a strong temporal stability of the NDVI patterns between two successive dates. The significance of r_s is given by a probability law. The level of significance considered was 5%.

As a standard regression coefficient, the implemented Spearman coefficient does not permit calculation of whether a site has the same actual NDVI value from one date to another. Rather it indicates if the NDVI values are spatially ordered in the same way from one date to another. In this sense, the question is not whether the NDVI values are stable over time but if the spatial patterns of NDVI are stable over time.

An arbitrary threshold $Tr_s = 0.60$ was considered on the values of r_s in order to define the approximate date (DTr_s) from which the patterns of NDVI could be considered stable. This threshold value does not correspond to any agronomic indicator, but it is a statistical threshold that corresponds to 80% of the magnitude of variation of r_s.

- Temporal stability of a field over several dates

An analysis was conducted in order to quantify the strength of temporal stability for each considered field. The goal of this analysis was to rank the fields according to their temporal stability. This analysis was conducted with Kendall's coefficient of concordance (W). The W coefficient was originally developed to quantify the agreement between several judges in their assessments of a given set of n objects. Such a test was used in this study as it does not require any assumptions either on the distribution of the values or on the type of relationship (i.e., linearity) between data series. The W statistic only focuses on the rank of the values and provides an assessment of how the rank given by several judges fits between the different objects. For each field, in this study, the n objects were the n sites of measurement, and the 'judges' were the different images (dates of acquisition). The analysis was then conducted on a matrix where the lines refer to the sites of measurement and the columns refer to the year. The W statistic varies from 0 in case of total disagreement (i.e., no temporal stability) to 1 in the case of total agreement. The equation to compute W is given by Equation 2 (after Saporta, 1990).

$$W = \frac{\sum_{i=1}^{n}(R_i - \overline{R})^2}{\frac{1}{12}k^2(n^3 - n)} \qquad \text{[eq. 2]}$$

with

$$R_i = \sum_{t=1}^{k} R(X_{i,t})$$

and

h

$$\overline{R} = \frac{\sum_{i=1}^{n} R_i}{n}$$

Where:

n: is the number of sites of measurement,
k: is the number of year, and
$\overline{R}$: is the average rank of the measurement site over all the considered year.

- Field clustering according to their temporal stability

To simplify the analysis, the fields were grouped into three classes of temporal stability according to their W values: very high, high or moderate level of temporal stability. Classification into the three classes was performed with an ascendant hierarchical classification (Saporta, 1990).

b) Data mapping

Data mapping was performed using gvSIG (v1.1, Generalitat Valenciana, IVER T.I.). Three classes of NDVI were created (high, medium and low), where the low class corresponded to the 0-33% quantile, the medium class corresponded to the 34-67% quantile and the high class corresponded to the 68-100% quantile. Note that this classification is relative to each selected field from Table 1. Finally, maps have only been used to visualize the results of the analysis. To this end, three classes were considered sufficient.

RESULTS

1. Analysis of the within-year spatial stability of NDVI

Figure 2 shows the evolution of Spearman's rank correlation between the NDVI measured a few days before harvest and the NDVI measured at different dates within a year (years 2007 and 2006). In 2006, the image 10 days before harvest was not available. The value of r_s has been corrected by considering the decrease of r_s observed in 2007 between harvest and veraison.

Over the study period for image acquisition (80 to 10 days before harvest) and the 17 fields, the spatial patterns of NDVI can be considered relatively stable since the r_s remains relatively high ($r_s > 0.54$) and statistically significant ($p < 0.05$) in all cases. However, Figure 2 shows that the correlation coefficient increases regularly when advancing from veraison to harvest. It is only 0.54 in June (80 days before harvest) while it is 0.87 at veraison (38 days before harvest). The use of $Tr_s = 0.60$ as threshold, as defined previously in Materials and Methods, suggests that up to 75 days before harvest, an image presents the same spatial patterns as an image at harvest.

Several factors may explain the observed decrease of r_s: (i) the early vigour may be different from final vigour, for example, some vines may have a rapid vegetative growth in spring followed by an early cessation of vegetative growth. This is often the case with vines on superficial calcareous soil with a quick increase in spring soil temperature and good spring soil moisture followed by a severe drought from July onwards. Other vines may have a more moderate but longer growth in summer, (ii) management practices such as trellising and trimming may alter the expected temporal stability of NDVI patterns. This is not related to the physiological development of the plant, but rather because trellising and trimming tends to homogenize the shape of the canopy presented to the sensor. When the image is taken just after trimming, the shape of the canopy of vigorous vines is very similar to that of less vigorous vines. In this case, it is harder to identify clear spatial patterns and the correlation between images is affected, (iii) finally, on some fields, an inter-row cover crop, either natural or sown, may still be present and photosyntheticaly active in June, whereas it tends to be destroyed by soil tillage or by dry climatic conditions in mid-late summer.

Figure 3 illustrates one of these problems on field P76. The practice of cover cropping in every third row leads to an increase in biomass, resulting in an increase in NDVI over vegetated rows and the emergence of spatial patterns in the row direction (Figure 3 date 2007_1). This effect decreases from 85 to 10 days before harvest as the cover crop dies due to the high evaporative demand in summer. Note, however, that the spatial patterns associated with the grass seem superimposed to the spatial patterns associated with the development of the vine. This feature suggests the possibility of eliminating the effect of the grass by image processing algorithms (Hall *et al.*, 2003).

From 60 days before harvest, the spatial patterns of the NDVI remain relatively stable in both 2006 and 2007 (Figure 3). It is also noteworthy to observe the stability of spatial patterns between 2006 and 2007 in this field.

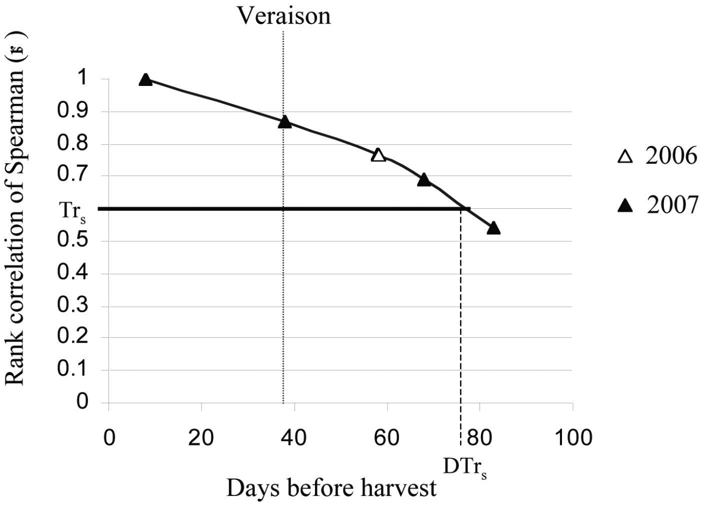
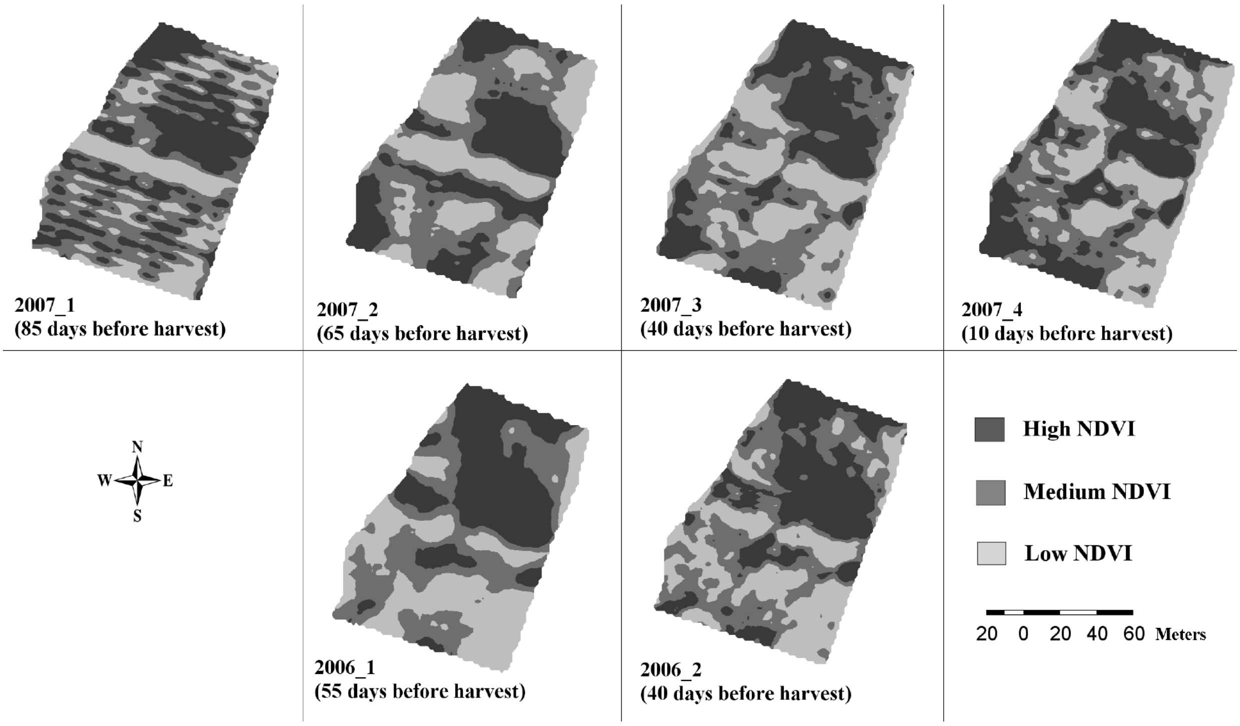


Figure 2 - Change in Spearman's rank correlation between NDVI measured a few days before harvest and NDVI measured at different dates within a year (2007 and 2006), Tr_s (0.60) is an arbitrary threshold considered to define the approximate date (DTr_s) from which the patterns of NDVI could be considered stable.


2007_1 (85 days before harvest)

2007_2 (65 days before harvest)

2007_3 (40 days before harvest)

2007_4 (10 days before harvest)

2006_1 (55 days before harvest)

2006_2 (40 days before harvest)

Figure 3 - NDVI maps of a field (P76) at four dates in 2007 and two dates in 2006. Each of the three greyscale classes corresponds to 33% of the data.

Spearman's rank correlation between images at veraison and harvest is particularly high ($r_s = 0.87$) for all the fields of the experiment together. This highlights a high temporal stability of the spatial patterns of NDVI between any two dates. Indeed in this region (Mediterranean climate), during this period, vegetative development has slowed or ceased and the foliage has reached its final size. Furthermore, there are no operations, such as summer pruning, to change the canopy shape. Similarly, due to the dry summer, the shallow-rooted cover crop is dry and does not interact with the NDVI response. Under these conditions the NDVI pattern remains relatively stable.

This result is in agreement with several authors (Lamb *et al.*, 2004; Bramley *et al.*, 2005; Acevedo-Opazo *et al.*, 2008) that have identified veraison as a particularly relevant stage for image acquisition. This stage helps to highlight the same spatial patterns as those corresponding to the final development of the vine. This result also shows that it is possible to obtain imagery much earlier without significantly affecting the quality of information. Under non irrigated Mediterranean climatic conditions, Spearman's rank correlation remains high ($r_s \geq 0.6$) even 20 to 30 days before veraison, showing that a significant proportion of the spatial pattern of NDVI remains stable from the period just before veraison to harvest.

2. Inter-annual temporal stability of the within-field variability of NDVI patterns

Figure 4 shows the results of r_s in relation to the inter-annual time lag between two images. The data were stratified by age (Table 1) prior to analysis. Figure 4a presents the results for the younger fields, mainly trained in VSP, and Figure 4b shows the results for the older fields, mainly trained in gobelet. The r_s values were all significant ($p < 0.05$) and greater than 0.45. This result shows the relative temporal stability of NDVI spatial patterns on all the fields together for the considered time lag (10 years). Knowing that in our conditions the main factor which affects the growth of the vines is soil water availability (Acevedo-Opazo *et al.*, 2008), it is therefore logical to find a temporal stability of NDVI patterns.

Figure 4a and b show that the evolution of r_s presents very similar characteristics for both populations. The r_s decreases as the time lag between two images increases. The decrease of r_s is linear ($R^2 > 0.95$) and steady over time. On average, the r_s values decrease by 0.02 per year whatever the age class of the field. The two populations, which cover different ages of plantation and training systems, therefore present a very similar evolution of the temporal stability of NDVI. Note, however, that the r_s values are on average slightly higher for aged fields trained in gobelet. Although small, this difference is consistent over the ten years of the experiment. It can be explained by the training system; on VSP, the trellising is an operation that changes the shape of the canopy. Since the gobelet system does not alter the vine shape, the spatial patterns identified from an aerial image may be clearer with this training system.

Application of the Trs threshold ($Tr_s = 0.60$) defined previously suggests that for periods up to five years, two images will present very similar spatial patterns of NDVI independently of the training system (Figure 4).

3. Temporal stability of the within-field variability field by field

Table 3 summarises the Kendall's coefficient of concordance (W) for each field computed over the five images that correspond to veraison. The W statistic illustrates to what extent a field can be considered as time stable relative to the other fields. The W varies from 0.49 for field P92a to 0.89 for field P96, however, all the coefficients were found to be statistically significant ($p < 0.05$). The cluster analysis (ascendant hierarchical classification) highlighted three classes of fields. Class 1 fields exhibit a very high temporal stability ($W \geq 0.8$), Class 2 fields have a high temporal stability ($0.66 \leq W \leq 0.78$) and Class 3 fields are characterized by a moderate temporal stability ($0.49 \leq W \leq 0.59$). The class boundaries considered here are related to the classification results. They are defined in relative terms compared to the field database being tested. Note that the boundary between Class 1 and Class 2 is unclear as these two classes encompass a continuous distribution from W = 0.89 to 0.66. In contrast, Class 3 corresponds to a particular class whose values of W are clearly distinct from the other two classes.

The first important observation from the results in Table 3 is that the temporal stability classes are not linked to the variety, the training system, the date of plantation or the pedological unit.

To illustrate the results presented in Table 3, the NDVI maps of four fields belonging to different classes are presented (Figure 5). The northern field (P96) belongs to Class 1 and is characterized by spatial patterns that are highly temporal stable regardless of the year. The western field (P95) belongs to Class 2 and also exhibits stable spatial patterns. Both southern fields (P92a and P92b) belong to Class 3 and show relatively stable spatial patterns, however, these patterns vary between years. Most notably, a significant change between 2008 and 2009 can be seen, which corresponds to a change in training system and the replacement of dead or diseased vines (Table 1).

The examples presented in Figure 5 are fairly representative of the 17 fields used in this study. The fields in Classes 1 and 2 have significant within-field soil variability, which affects the spatial variability of water restriction and consequently vine vigour. The vigour variability related to soil is stable and explains the presence of recurrent NDVI spatial patterns from year to year. Among this group of fields, the most stable fields (Class 1) corresponded to cases where the occurrence of severe and recurring water restriction led to a weakening of the vines and a higher mortality in low NDVI areas, which is the case in the field P96 presented in Figure 4. The Class 3 fields have undergone significant change (Table 1) either through irrigation trials (P22) or through changes in training system (P92a and P92b).

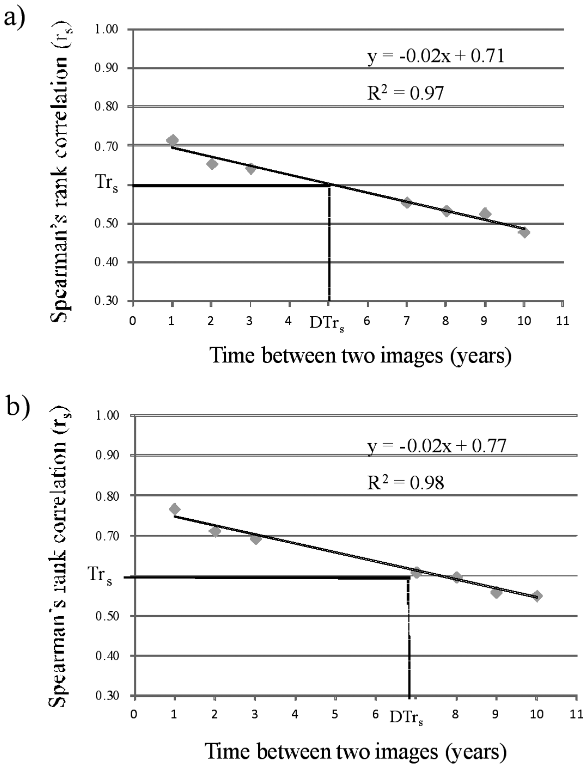


Figure 4 - Spearman's rank correlations (r_s) according to the inter-annual time lag between two images a) for fields belonging to Age class 1 (see table 1) and b) for fields belonging to Age class 2.

DISCUSSION

1. The within-year variability of NDVI

This study has highlighted the temporal stability of spatial patterns of NDVI within the year. A previous study has shown the potential value of imagery at veraison for grape quality management (Rousseau *et al.*, 2008). From a practical standpoint, this study showed that, in Mediterranean conditions, the acquisition of an image 20 to 30 days before veraison (according to the presence of green cover grass at this stage) can produce spatial patterns in vigour that are highly correlated to the vine vigour at

Table 3 - Rank coefficient of concordance (W) of Kendall for each field and class derived from a hierarchical classification.
The fields are listed by decreasing value of W (all W values are statistically significant, $p < 0.05$).

Field identification	Kendall coefficient of concordance (W)	Class derived from a cluster analysis	Age class	Pedological Unit
P96	0.89	1	2	PU1
P63	0.86	1	1	PU2
P90	0.83	1	2	PU1
P11	0.81	1	1	PU3
P76	0.80	1	1	PU2
P95	0.78	2	2	PU1
P79	0.77	2	2	PU1
P69	0.75	2	1	PU2
P72	0.73	2	1	PU2
P61	0.70	2	1	PU2
P78	0.70	2	2	PU1
P67	0.67	2	1	PU2
P80	0.66	2	2	PU2
P91	0.66	2	2	PU1
P92b	0.59	3	2	PU1
P22	0.53	3	1	PU3
P92a	0.49	3	1	PU1

harvest. This time period is interesting because it allows sufficient time to process and analyse any images if the goal is to make use of the image for within-season vine management of the harvest in that year. Note, however, that image at veraison presents in all cases a higher correlation with image at harvest. Therefore, in the case of vineyards that do not have a history of image acquisition, image at veraison may be better to be sure to maximize the correlation between the image data and fruit attributes.

Beyond 30 days prior to veraison, although statistically significant, the correlation between the observed spatial patterns and spatial patterns at harvest decreases. Several factors may explain this phenomenon such as the presence of a cover crop/grass or the existence of a spring vigour response that differs from the final vigour. This last point has already been hypothesised by Hall *et al.* (2011) on the basis of a single field. From a large database, this study also identified an interesting question concerning the evolution of spatial patterns during the year. Obviously, if they are different and not only due to cover crops, then the spatial patterns revealed in early-season images could possibly be relevant to manage other operations such as fertilization, pruning or bunch thinning. This issue deserves further study, which must be done on a field by field basis with a complete characterization of each field (soil and climate conditions, cover crops, management practices, etc.).

Cover crops can create abnormal spatial patterns in early-season images (around flowering), when the cover crop is still vigorous and the vine canopy is only half grown. The cover crop therefore has a high impact on the NDVI response (and variability). Under Mediterranean conditions, the incidence and vigour of cover crops in the period between flowering and grape closure is dependent on yearly climatic conditions (e.g., incidence of spring rainfall). By veraison, the cover crop is dessicated due to the high evapotranspiration demand in summer in this region.

2. NDVI maps before flowering

Very early-season image acquisition (from budburst to flowering) was not considered in this study. At this stage, the canopy is very small and the incidence of winter grass/cover crops would be dominant in the NDVI response. High-resolution multispectral images (i.e., 0.1-0.2 m) and a segmentation algorithm to measure specifically the NDVI on the vine rows would be necessary to overcome this problem. This possibility has already been investigated by some authors (Hall *et al.*, 2003). Another solution would be to use an ATV or a tractor on board sensors to measure NDVI corresponding only to the vine canopy (Drissi *et al.*, 2009). These solutions raise other issues related to the cost of acquiring high-resolution imagery, such as the time required to process larger datasets and the possibility to obtain complete information over large vineyards at a given date with the same sampling precision (embedded sensors). In light of economic constraints and the area to cover at any given date, these solutions may be of interest to advance the date of acquisition, however, changes in

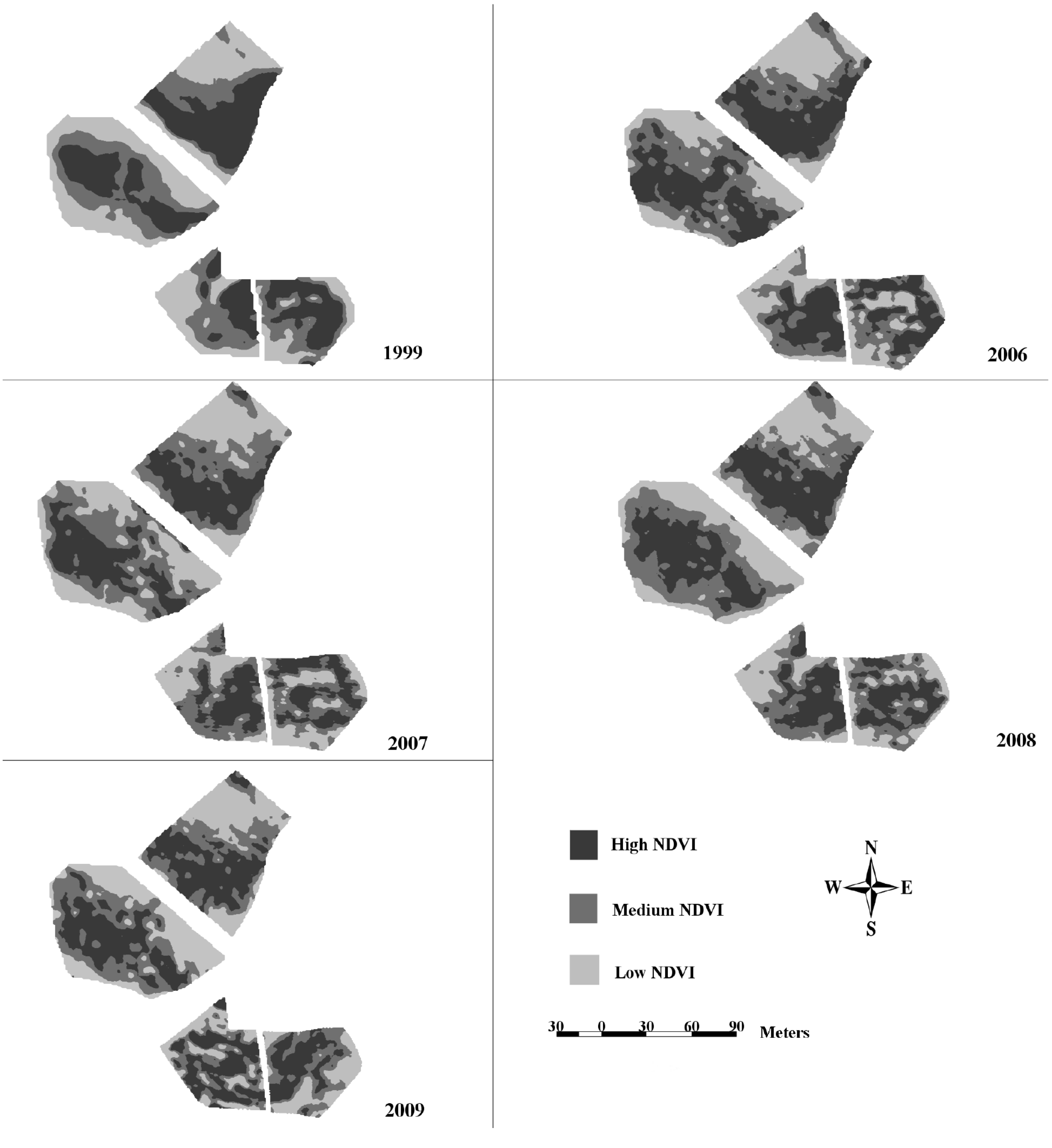


Figure 5 - NDVI maps at veraison of 4 fields belonging to different classes of stability for the 5 years of the study.
Three levels of NDVI corresponding to tiertiles were considered. The northern field (P96) corresponds to Class 1 (very high temporal stability), the western field (P95) corresponds to Class 2 (high temporal stability) and the southern fields (P92a and P92b) correspond to Class 3 (moderate temporal stability).

vegetative indices related to canopy management (summer pruning) remain problematic when analysing the information regardless of the sensor.

3. Inter-annual NDVI stability

In non irrigated Mediterranean situations, this study showed a temporal stability in spatial patterns of vine vigour, highlighted by a vegetative index such as the NDVI, at veraison and at a within-field level. In a context where the training/management of the vineyard does not undergo major changes, the inter-annual temporal stability of spatial patterns showed that images acquired at veraison (and up until 30 days before veraison) may well be used to consider site-specific management over a period of 5 years. However, this study also showed that significant changes in the vineyard would disrupt the temporal stability of these spatial patterns. In a context where a variable rate of inputs (fertilizer, irrigation, pruning, etc.) is implemented, the images should be regularly renewed.

As such, imagery and associated vegetative indices may be an excellent tool for validating the effect of site-specific management practices in a vineyard.

These results can be directly compared with the study by Tisseyre *et al.* (2008) on the same experimental site. On a single field (P76) and over 5 years, Tisseyre *et al.* showed that the spatial variability of vine vigour estimated by the weight of pruning wood had a strong temporal stability. It is interesting to note that Kendall's coefficient for the weight of pruning wood showed approximately the same value (W = 0.76) as that found in this study for NDVI (W = 0.80) for the same field. Considering that the NDVI is a good indicator of vegetative expression (Johnson *et al.*, 2003; Dobrowski *et al.*, 2003), this study confirmed the temporal stability of spatial variability of vegetative expression on a larger number of fields and a longer period.

On a larger scale (denomination area or cooperative), a time series of images may be of interest to perform a field typology. Indeed, it is possible to identify vine fields with very high temporal stability (Class 1), which may correspond to extreme cases where the environmental factors affecting vine growth are significant or to areas with missing plants. It is also possible to identify fields with moderate to low temporal stability (Class 3), which may indicate fields that have undergone recent significant changes in management practices (change in training system, implementation of irrigation, etc.). At larger scale, the analysis of a time series of images may then constitute a dynamic and comprehensive tool to control the practices of growers over the intake area of the harvest.

CONCLUSION

This study provides answers about the practical use of vegetative indices, such as NDVI, in non irrigated Mediterranean conditions. The results are based on a database with (i) 17 single fields with different varieties and training systems studied simultaneously, (ii) a time series of 5 images over a period of 10 years used to test the inter-annual stability and finally (iii) two time series of 2 and 4 images used to test the intra-annual stability in two different years. Such a study has not previously been reported in the literature. The results are based on non-parametric methods allowing the objective quantification of the temporal stability of spatial patterns of NDVI.

The study demonstrated the temporal stability of the spatial variability of NDVI at both an intra-annual and inter-annual scale. The inter-annual stability showed that the information provided by an NDVI image may be used for 3 to 5 years depending on the training system and the age of the vines, providing that the fields are not subject to significant changes in management. Note, however, that inter-annual stability regularly decreases with increasing time lag showing that an image of year remains the best information source to highlight properly the spatial variability of the year. The intra-annual stability observed is interesting since it allows the advancement of the date of image acquisition within-season to a point 20 days before veraison, providing that no operation affect the canopy of the vineyard. From a practical standpoint, this makes it possible to have more time for processing, analysing and using the NDVI information within-season. The results also showed that an image taken too early in the season may be affected by canopy management and/or cover crops. Another source of instability which has been hypothesised is a physiological difference between early (spring) and final (harvest) vigour at a site. Finally, it is important to note that these results are specific to non irrigated Mediterranean climates and that similar studies should be conducted on irrigated vineyards or vineyards in different climatic regimes where water restriction is less significant in order to ascertain whether the spatial variability of NDVI exhibits the same temporal stability in these different conditions.

Acknowledgements : The authors would like to acknowledge the French FUI (Fond Unique Inter-ministériel), the Conseil Regional Languedoc-Roussillon and the European regional development fund for funding this work within the framework of the Collaborative Research Project Vinnotec. We are grateful to James Taylor (University of Sydney) for his advice and comments.

REFERENCES

ACEVEDO-OPAZO C., TISSEYRE B., GUILLAUME S. and OJEDA H., 2008. The potential of high spatial resolution information to define within-vineyard zones related to vine water status. *J. Precision Agric.*, **9**, 285-302.

BEST S., LEON K. and CLARET M., 2005. Use of precision viticulture tools to optimize the harvest of high quality grapes. *Proc. 7th Fruit, nut and vegetable production engineering - TIC (Frutic05) Conference*, Montpellier, 249-258.

BRAMLEY R.G.V., 2001. Variation in yield and quality of winegrapes and the effect of soil property variation in two contrasting Australian vineyards. *Proc. 3rd European conference on precision agriculture*, Montpellier, 2, 767-772.

BRAMLEY R.G.V. and HAMILTON R.P., 2004. Understanding variability in winegrape production systems 1. Within vineyard variation in yield over several vintages. *Australian J. Grape Wine Res.*, **10**, 32-45.

BRAMLEY R.G.V., PROFFITT A.P.B., HINZE C.J., PEARSE B. and HAMILTON R.P., 2005. Generating benefits from precision viticulture through selective harvesting. *Proc. 5th European Conference on Precision Agriculture*, Uppsala, 891-898.

CARBONNEAU A., 1976. Analyse de la croissance des feuilles du sarment de vigne : Estimation de sa surface foliaire par échantillonnage. *Connaissance Vigne Vin*, **10** (2), 141-159.

CARBONNEAU A., 1995. La surface foliaire exposée potentielle - guide pour sa mesure. *Progrès Agric. Vitic.*, **112** (2), 204-212.

CHAMPAGNOL F., 1984. *Éléments de physiologie de la vigne et de viticulture générale*. B.P. 13, Prades-le-Lez, 34890 Saint-Gély-du-Fesc.

COULOUMA, G., TISSEYRE, B., and LAGACHERIE, P., 2009. Is a systematic two dimensional EMI soil survey always relevant for vineyard production management? A test on two pedologically contrasting Mediterranean vineyards. Chapter 24 *In: Proximal soil sensing: Eds. R.A. Viscarra Rossel, A.B. McBratney and B. Minasny*. Progress in Soil Science series. Springer. Heidelburg, Germany (In press) ISBN 978-90-481-8858-1.

DOBROWSKI S.Z., USTIN S.L. and WOLPERT J.A., 2003. Grapevine dormant pruning weight prediction using remotely sensed data. *Australian J. Grape Wine Res.*, **9**, 177-182.

DRISSI R., GOUTOULY J.P., FORGET D. and GAUDILLIÈRE J.P., 2009. Non-destructive measurement of grapevine leaf area by ground normalized difference vegetation index. *Agronomy Journal*, **101**, 226-231.

HALL A., LAMB D.W., HOLZAPFEL B. and LOUIS J., 2002. Optical remote sensing applications in viticulture - a review. *Australian J. Grape Wine Res.*, **8**, 36-47.

HALL A., LOUIS J. and LAMB D., 2003. Characterising and mapping vineyard canopy using high-spatial-resolution aerial multispectral images. *Computers & Geosciences*, **29**, 813-822.

HALL A., LAMB D.W., HOLZAPFEL B.P. and LOUIS J.P., 2011. Within-season temporal variation in correlations between vineyard canopy and winegrape composition and yield. *Journal Precision Agriculture*, **12** (1), 103-117.

JOHNSON L.F., ROCZEN D.E., YOUKHANA S.K., NEMANI R.R. and BOSCH D.F., 2003. Mapping vineyard leaf area with multispectral satellite imagery. *Computers and Electronics in Agric.*, **38**, 33-44.

JOHNSON L.F., 2003. Temporal stability of an NDVI-LAI relationship in a Napa Valley vineyard. *Australian J. Grape Wine Res.*, **9**, 96-101.

LAMB D.W., WEEDON M.M. and 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 J. Grape Wine Res.*, **10**, 46-54.

METTERNICHT G.I., HONEY F. and BEESTON G., 2000. Video-based Precision Farming. *Geo Asia Pacific*, June-July Issue, pp. 23-26.

ROUSE J.W., HAAS R.H., SCHELL J.A. and DEERING D.W., 1973. Monitoring vegetation systems in the Great Plains with ERTS. *Proc. 3rd ERTS Symposium*, NASA SP-351 1. US Government Printing Office, Washington DC. pp 309-317.

ROUSSEAU J., DUPIN S., ACEVEDO-OPAZO C., TISSEYRE B. and OJEDA H., 2008. Imagerie aérienne : application à la caractérisation des potentiels viticoles et œnologiques. *Bull. OIV*, 932-934, 507-517.

SAPORTA G., 1990. Probabilités, *analyse de données et statistique*. Ed. Technip Paris.

SCHOLASCH T., DAWSON T., BELLON-MAUREL V. and RUBIN Y., 2005. Role of vapor pressure deficit and soil moisture at different depths on stomatal conductance regulation. Insufficience of midday stem water potential for explaining stomatal conductance (Cabernet-Sauvignon-Napa Valley). *Proceed. 7th Fruit, Nut and Vegetable Production Engineering* - TIC (Frutic05) Conference, Montpellier, 279-288.

SMART R.E., 2003. The mother of all scorecards. Practical Winery & Vineyard, 03/04 2003, 76-78. San Rafael (California - USA).

TAYLOR J., ACEVEDO-OPAZO C., OJEDA H. and TISSEYRE B., 2010. Identification and significance of sources of spatial variation in grapevine water status. *Australian J. Grape Wine Res.*, **16**, 218-226.

TISSEYRE B., MAZZONI C. and FONTA H., 2008. Within-field temporal stability of some parameters in viticulture: potential toward a site specific management. *J. Int. Sci. Vigne Vin*, **42** (1), 27-39.