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The use of multispectral and thermal images as a tool for irrigation scheduling in vineyards

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Abstract. Multispectral and thermal imagery were studied to evaluate the relationship between grapevine water status and "Plant Cell Density" index (PCD) and "Crop Water Stress" index (CWSI). Grapevine water status was determined with a pressure chamber by measuring the leaf water potential (Ψ_{leaf}) of 184 grapevines distributed homogeneously within a 11 ha vineyard. Image acquisitions and Ψ_{leaf} measures were obtained simultaneously at noon. Results showed that PCD could be useful to discriminate well-watered zones in a vineyard. However the relationship between PCD *vs* Ψ_{leaf} seemed to vary between different zones of the vineyard. This inconvenient did not exist with CWSI. The relationship between Ψ_{leaf} and "crop-air temperature differential" was strong and presented a high coefficient of determination (r^2 = 0.714; $P < 0.0001$) at noon. Accordingly, this methodology showed potential to be used as a tool for irrigation scheduling. Further studies should be directed to explore the convenience of CWSI measured at other moments of the day and the optimal thermal image resolution to obtain the best results.

Keywords. *Multispectral imagery – Thermal imagery – Crop water stress index – Leaf water potential.*

L'utilisation des images multispectrales et thermiques comme outil pour la programmation de l'irrigation chez les vignobles

Résumé. *Des images multispectrales et thermiques ont été étudiées pour évaluer la relation entre l'état hydrique de la vigne et le "Plant Cell Density" index (PCD) et le "Crop Water Stress" index (CWSI). L'état hydrique de la vigne est déterminé en mesurant le potentiel hydrique de la feuille (Ψ_{leaf}) avec une chambre à pression. Sur une vigne de 11 ha on a étudié 184 plantes distribuées régulièrement dans l'espace. La prise des images et le potentiel hydrique ont été pris simultanément à midi. Les résultats ont indiqué que, bien que le PCD s'est montré utile pour discriminer les zones les plus favorables d'état hydrique, on a trouvé que la relation PCD vs Ψ_{leaf} peut varier d'une zone de la vigne à une autre. Par contre, cet inconvénient n'a pas apparu quand on a utilisé le CWSI. En effet, la relation entre Ψ_{leaf} et le différentiel de température entre l'air et la culture était très étroite et présentait un coefficient de détermination (r^2=0,714 ; P<0,0001) très élevé à midi. Or, cette méthodologie du CWSI a montré un grand potentiel pour être utilisé dans la programmation d'irrigation dans le vignoble. Afin d'obtenir les meilleurs résultats, les prochains travaux chercheront à identifier le meilleur moment de la journée pour calculer le CWSI et définir la résolution optimale des images thermiques.*

Mots-clés. *Images multispectrales – Images thermiques – Crop water stress index – Plant cell Density – Potentiel hydrique de la feuille.*

I – Introduction

Vineyards present a natural spatial variability. Different responses of grapevines are commonly found in different zones, and these can be explained by a number of parameters either physical (topography, soil properties, etc.) or management (pruning, training system, irrigation, fertilization, etc.). Thus, there exist a wide range of variation in yield and also in different berry composition parameters within-vineyard. One of the main priorities for wine grapegrowers, is to obtain uniform yields and batches of berry composition. Until now, this has been achieved by *zonal vine-*

yards management in which, individual blocks are split into zones of similar characteristics and managed and harvested differentially (Bramley and Hamilton, 2004a).

Many authors have shown the direct effect of grapevine water status on both yield and berry composition (Ojeda *et al.*, 2002; Girona *et al.*, 2009; Esteban *et al.*, 1999; Basile *et al.*, 2011). This general concept has led to the use of irrigation to help solving heterogeneity problems into blocks. Regulated Deficit Irrigation (RDI) is a technique that can improve berry composition parameters without affecting yield. However, an adequate management of RDI in each zone of the vineyard is not easy and has to be determined individually as a function of vine water status. In fact, speaking in terms of precision viticulture (PV), the ideal would be to apply the necessary water for each vine of the plot by knowing its water status. A good indicator for irrigation scheduling is the leaf water potential (Ψ_{leaf}) (Girona *et al.* 2006). However, this method presents the inconvenience that has to be measured manually with a pressure chamber in a reduced span of time at noon and thus it results impractical in large commercial blocks. This is the reason why other alternatives which could replace Ψ_{leaf} have to be investigated. Remote sensing technology for crop-management applications which has increased considerably during last years, can be a candidate to explore.

Multispectral images have been widely used for studying qualitative and quantitatively the vegetative status of different crops. Normalized Differences Vegetation Index (NDVI) or Plant Cell Density (PCD) can be obtained by combining mathematically different wavebands. Acevedo-Opazo (2008) used high resolution multi-spectral images to define different irrigation zones and to relate NDVI with plant water status.

On the other hand, thermal images are currently presented as a promising technology to derive plant water status. In fact, in 1970’s Gates (1964) and Jackson *et al.* (1977) demonstrated that leaf temperature (T_{leaf}) could be used as plant water status indicator. Jackson *et al.* (1988) and Idso *et al.* (1981) obtained a normalized index denominated "Crop water stress" index (CWSI) to overcome the effects of other environmental parameters affecting the relation between stress and plant temperature.

Although there are a number of studies that have related CWSI or NDVI with plant water status, no study have found sound relationships between Ψ_{leaf} and either vegetative indices or temperature within the whole block. The objective of this study was to evaluate both methods (multispectral and thermal imagery) as an indicator of Ψ_{leaf}.

II – Materials and methods

A case study was carried out on a 16-years old `Pinot noir´ wine grape (*Vitis vinifera* L.). The 11-ha commercial vineyard was located at 41º39’58"N, 00º30’10"E (WGS84, UTM zone 31N) in Raïmat, Lleida, Catalonia, Spain.

In 2008, four flights were done with a four waveband multispectral camera (DMS2C-2K System) corresponding to the infra-red, red, green and blue wavelengths. The camera image resolution was 2048 x 2048 pixels with 14-bit digitization and optical focal length of 24-28 mm, yielding a ground-based spatial resolution of 50 cm at 1 km altitude. Flights were done by the company RS Teledetección by using a light aircraft (CESSNA C172S EC-JYN). The ratiobased vegetation index PCD was obtained according to Equation 1:

$$PCD = \frac{\varphi_{NIR}}{\varphi_{RED}} \tag{1}$$

where φ_{NIR} and φ_{RED} are spectral reflectance measurements acquired in the near-infrared (760-900 nm) and red (630-690 nm), respectively.

Therefore, in 2009 a thermal image was acquired the 31st july at noon, with a thermal sensor Miracle 307 KS (Thermoteknix Systems, UT) installed on board an unmanned aerial vehicle (UAV) (Quantalab, IAS-CSIC Córdoba, Spain). Image resolution was 640 x 480 pixels and spectral response in the range 7.5-13 µm. The camera was equipped with 45º FOV lens, yielding 30-40 cm spatial resolution at 150 m altitude.

During all 2009 season, four infrared temperature (IRT) sensors (model PC151HT-4; Pyrocouple, Calex Electronics) were placed 1 m above the grapevines with different irrigation treatments (well-watered and stressed) (Sepulcre-Canto *et al.*, 2006), recording mean leaf temperature every 5-min with a datalogger (model CR200X,Campbell Scientific, Logan, UT). This data was used to calculate the CWSI as follows:

$$CWSI = \frac{(T_c - T_a) - (T_c - T_a)_{LL}}{(T_c - T_a)_{UL} - (T_c - T_a)_{LL}} \qquad (2)$$

where (Tc-Ta) is the difference between canopy and air temperature, $(T_c\text{-}T_a)_{LL}$ is the expected lower limit of $(T_c\text{-}T_a)$ in the case of a canopy which is transpiring at the potential rate, and $(T_c\text{-}T_a)_{UL}$ expected differential in the case of a non-transpiring canopy. The lower and upper limits of Tc-Ta were obtained following the methodology of Idso *et al.* (1981).

1. Leaf water potential (Ψ_{leaf}) measurements

At the same time of the images acquisitions, 184 Ψ_{leaf} were measured in a regular grid around the vineyard. Determinations of Ψ_{leaf} were performed with a pressure chamber (Scholander *et al.*, 1965) (Soil Moisture plant water status console 3005 Corp. Sta. Barbara, CA, USA) following the recommendations of Turner and Long (1980). All measurements were done at noon (less than 1 hour) selecting one wee-lit leaf.

2. Image processing

Thermal imagery acquisition and geometric, radiometric and atmospheric corrections were processed by Quantalab, IAS-CSIC of Córdoba. The methodology for obtaining surface temperature by removing atmospheric effects using a single-channel atmospheric correction is explained in Berni *et al.* (2009). Pixel data from each measured vine was extracted and averaged avoiding obtaining pure soil pixels. Analysis for multispectral images was carried out in ArcMap (version 9.3; ESRI Inc. Redlands, CA, USA) using the Spatial Analyst extension. On the other hand, thermal images were processed with ENVI 4.7 (ITT Visual Information Solutions, 2009).

III – Results and discussion

1. Multispectral images

Table 1 showed a high variability of vine water status within-vineyard which increased along the season. The most stressed grapevines were found in the last day of measurement (beginning August), reaching minimum values of -1.4 MPa. A previous study carried out in this same plot, indicated that spatial heterogeneity of grapevine water status was stable and followed very similar patterns over the time. It also demonstrated that the more stressed grapevines were localized in zones with shallower soils and with less soil water holding capacity.

Similarly to Ψ_{leaf}, PCD index also presented high variability within-vineyard, although this variability remained stable along the season. The highest differences between maximum and minimum PCD values were found at the end of the vegetative growing period (end July). This was

Table 1. **Descriptive statistical analysis and relationships between leaf water potential (Ψ_{leaf}) and plant cell density (PCD) index measurements in a vineyard of 11 hectares in Raïmat (Lleida, Spain). Significant differences among Ψ_{leaf} and PCD based on Duncan's test at P < 0.05**

2008	Average	Stand. Desv.	Min.	Max.	C_v
Ψ_{leaf}					
Day 1	-0.81	0.15	-1.15	-0.48	19.01
Day 2	-0.69	0.12	-1.08	-0.45	17.25
Day 3	-0.62	0.11	-0.94	-0.41	17.69
Day 4	-0.79	0.20	-1.42	-0.44	25.63
PCD					
Day 1	130.50	43.09	44.50	229.18	33.02
Day 2	129.15	43.08	48.58	216.54	33.36
Day 3	126.93	46.81	33.37	222.97	36.87
Day 4	120.96	39.41	44.56	213.59	32.58
	Day 1	**Day 2**	**Day 3**	**Day 4**	
r^2	0.215	0.105	0.196	0.046	
Pr>F	<.0001	<.0001	<.0001	n.s	

explained because at that moment, the most stressed vines throughout the season had less vigour than fully irrigated grapevines. Visually, from maps as showed in Fig. 1, it seemed that there was a relationship between both analyzed parameters, except for the fourth day. However, statistical analysis did not indicate this perception.

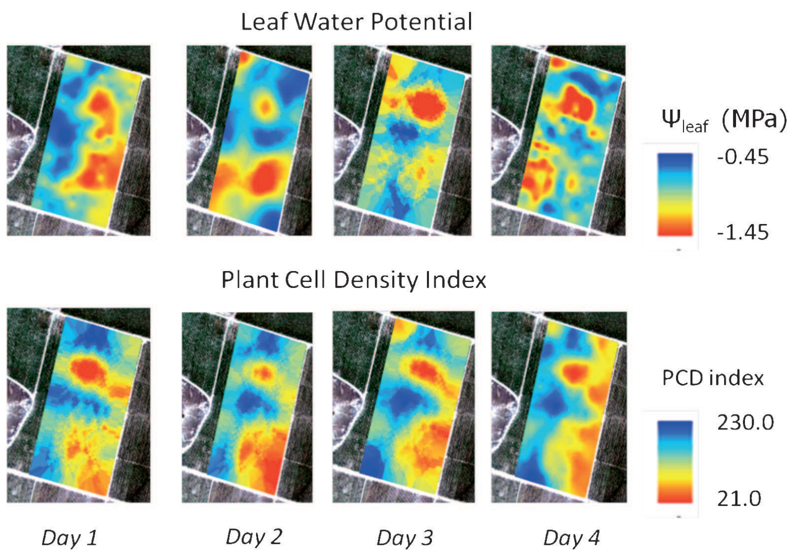

Fig. 1. Leaf water potential (Ψ_{leaf}) measured with pressure chamber and plant cell density (PCD) maps obtained in four different days during 2008.

Relationships were slightly low in all cases, although significant (P<0.0001), with the exception of the 4th day which presented a non-significant relationship (Table 1). This was explained due to grapevine pruning management. It is well-known that these vegetative indices obtained from airborne multispectral imagery are very sensitive to crop cultural practices (Bramley *et al.*, 2011). For instance, in our studied block, a mechanical pruning was made in half part of the block two days before of the 4^{th} image acquisition. Then, PCD values were considerably reduced in that zone due to the lower reflected near infrared by leaves because of less canopy vigor. On the other hand, an improvement of grapevine water status was achieved in that zone, obtaining maximum values of Ψ_{leaf} of -0.44 MPa.

Results of this study demonstrated that structural vegetative indexes are not always related to plant water status indicators because they are mainly giving information about the canopy size. Well-watered grapevines along the season will be more vigorous, but is also possible that vines with higher vigour may have increased transpiration, and consequently this would lead to lower Ψ_{leaf} due to increased water loss though transpiration (Rossouw, 2010). Then, these indices demonstrated to be highly stable in detecting water stress variations on time but also very sensitive to the intersection of cultural practices and pathogen effects.

2. Thermal images

In 2009, vine water status variability was slightly high at moment that Ψ_{leaf} were measured. Spatial distribution of vine water status was shown in the two maps of Fig. 2. Coefficient of variation (C_v) was 20.97, ranging from -0.6 MPa to -1.7 MPa. High image resolution was showed in the thermal mosaic, where was possible to distinguish pure crown temperature pixel from grapevines and soil pixels. Visually, it seems clear the relationship between both parameters. Blue color zones of Ψ_{leaf} map represented zones with well-watered grapevines, which in theory had a higher stomatal conductance and a major transpiration which is directly affected by lower leaf temperatures. On the other hand, more stressed grapevines (represented in red color), depending on the variety, close the stomata to avoid water losses and consequently, T_{leaf} increases.

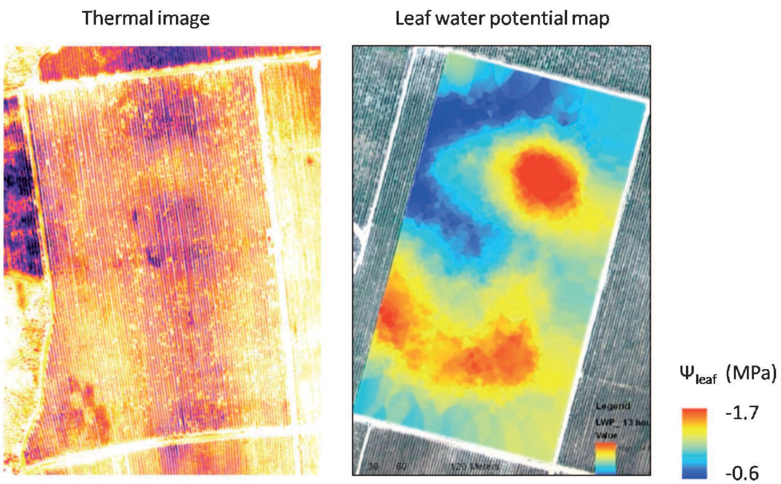

Fig. 2. Thermal mosaic from the overlapping of thermal images obtained from an UAV at noon. Leaf water potential (Ψ_{leaf}) map measured at noon.

Relationship between Ψ_{leaf} and crop-air temperature differential in the whole block presented a high significant degree of determination (r^2 = 0.714, P < 0.0001) at noon. According to the most recent literature [Grimes and Williams (1990); Peacock *et al.* (1998); Choné *et al.* (2001); Williams and Araujo (2002) and Girona *et al.* (2006)], a reasonable threshold of Ψ_{leaf} for well-irrigated grapevines would be around -0.8 MPa, -1.2 MPa for moderately stressed vines, and -1.5 MPa for severe stress conditions. Then, maximum differences of (Tc-Ta) which reached until 8ºC, corresponded with the most stressed grapevines within the block, which presented Ψ_{leaf} values around -1.6 MPa. On the other hand, small differences of (Tc-Ta) corresponded with well-watered grapevines. Bearing in mind that moderately stressed grapevines starts with Ψ_{leaf} values below -1.2 MPa, results indicated that grapevine stress starts when (Tc-Ta) values are above 3ºC.

CWSI equation was obtained from IRT sensors data. Thus, relationship between CWSI and Ψ_{leaf} measurements in the whole block showed that well-watered grapevines corresponded with CWSI values below 0.5, whereas the most stressed grapevines of the block, reached until values around 1.0.

IV – Conclusions

In the present study it was demonstrated the viability of high resolution thermal imagery for detecting the level of water stress in grapevines. Further studies will be performed to develop applications useful to improve irrigation efficiency at parcel scale. However, this work showed the feasibility of this tool only at noon. In future studies we will investigate the time-window of the day in which relationships between CWSI and Ψ_{leaf} would be useful.

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