DETECTING WATER STRESS IN ORCHARD CROPS USING PRI FROM AIRBORNE IMAGERY

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ABSTRACT:
The Photochemical Reflectance Index (PRI) has been used to assess light use efficiency, photosynthesis, and more recently, water stress in crops. Nevertheless, vegetation stress cannot be readily assessed spatially without considering leaf and canopy structural effects on PRI. Reflectance from bands at 531 and 570 nm is affected by both leaf and canopy parameters such as chlorophyll content, dry matter, leaf thickness, leaf area index, and leaf angle distribution function, among others. A new modelling method is presented here, accounting for leaf biochemical and canopy structural inputs to simulate the PRI-based threshold for non-stress conditions, therefore enabling the comparison between non-stress (modelled) and stress (imagery) levels. The results presented suggest that: i) PRI can be used as an indicator of water stress when using modelling approaches to characterize non-stress conditions as function of canopy structure; ii) PRI values acquired over the growing season can be used as an indicator of fruit quality.

1. INTRODUCTION

PRI was proposed by Gamon et al. (1992) as an indicator of the de-epoxidation state of the xanthophyll pigments related with photosynthetic processes. It has been used to assess light use efficiency, photosynthesis, and more recently, water stress in crops (Thenot et al, 2002 y Winkel et al, 2002). Canopies with variable structure, chlorophyll content and dry matter affect the sensitivity of PRI to stress, which in such case would mostly track the spatial variation of the canopy leaf area density and structure (Barton and North, 2001; Suárez *et al.*, 2008). Consequently, modelling work at leaf and canopy scales is needed to enable an operational use of PRI to map water stress in non-homogeneous canopies where structural variation play the main role in the reflectance signature. A new modelling method is presented in this paper based on radiative transfer simulation to estimate a theoretical PRI baseline for non-stress conditions in two tree species, olive and peach. The method compares canopy-level imaged PRI with theoretical non-stress PRI obtained through model inversion for existing structural and background conditions, defining a within field threshold to detect stressed vegetation. As part of the research of regulated deficit irrigation effect on fruit quality parameters, some authors demonstrated that stem water potential (SWP) time series measured along the fruit growing season would potentially indicate fruit quality (Myers, 1988; Moriana et al., 2007). In this study, similar approach is undertaken using PRI instead of SWP as water stress indicator to assess fruit quality using a time series of imagery acquired over the fruit growing period.

2. MATERIALS AND METHODS

2.1 Study areas

The study sites used in this work are located in Córdoba (Spain). The first study site is an irrigated 4 ha-orchard established in 1997 with olive trees (*Olea europaea* L. cv. "Arbequino") in a 3.5x7 m grid. Drip irrigation permitted the use of different water treatment amounts within the same field. The experiment was designed in an area of six rows with three different water treatments: 2 deficit-irrigation treatments and one block of full-irrigated trees used as control (see Suárez *et al*. (2008) for a full description). The second study site was within a commercial peach orchard (*Prunus persica* cv. "BabyGold8") planted in 1990 in a 5x3.3 m grid. A subset of 6 lines x 30 peach trees each were irrigated differently than the rest of the orchard. The non-stressed trees were drip irrigated starting in mid May with an application rate equivalent to 80% of calculated crop ET. Three different deficit irrigation treatments were applied starting irrigation at Stage III of fruit development (rapid growth stage) and over-irrigating afterwards until tree water status (by means of stem water potential, SWP) was fully recovered.

2.2 Field Data

Stomatal conductance (G) and stem water potential (Ψ) were measured with a leaf steady-state porometer (model SC-1, Decagon Devices, Washington, DC, USA) and a Scholander pressure bomb (PWSC Model 3000, Soil Moisture Equipment Corp., California) respectively. Leaf reflectance measurements were also conducted in the study sites at the time of the flights with an ASD Field Spectrometer (FieldSpec Handheld Pro, ASD Inc., CO, USA) with a leaf clip probe. In the peach orchard, a subset of 18 trees was monitored during the fruit growing period and harvested independently. All the fruits of the trees of this subset were weighted and their diameters measured. Later, 8 fruits per tree were selected for a physiochemical and organoleptic characterization: Total Soluble Solids (TSS) and Total Acidity (TA) used to calculate the ratio (TSS/TA), which is considered the best indicator of fruit taste.

2.3 Imagery

Two airborne campaigns were conducted in collaboration with the Spanish Aerospace Institute (INTA) using the Airborne Hyperspectral Scanner (AHS) developed by Sensytech Inc. (Argon St. Inc., USA) over the first experimental field to acquire six images corresponding to three flight times (7:30, 9:30 and 12:30 GMT) on two consecutive years (25th July 2004 and 16th July 2005). The flight height was set to 1000 m above ground level, acquiring imagery with a 90º field of view (FOV) and 2.5 mrad instantaneous FOV, produced a spatial resolution of 2 m. In the 2004 campaign, imagery was collected at 38 bands over the 0.430-1.550 μm and 8.20-12.70 μm spectral regions. In the 2005 campaign, 80 bands were available in the 0.430-2.49 μm and 8.20-12.70 μm ranges. Atmospheric correction and radiometric calibrations were applied as can be found in Sobrino *et al.* (2006).

In the summers of 2007 and 2008, a 6-band multispectral camera (MCA-6, Tetracam, Inc., California, USA) onboard an Unmanned Aerial Vehicle (UAV) flying at 150 m above ground level (Berni *et al*, 2009) was used to acquire a total of 11 images from the two study sites. The characteristics of the camera and images acquired as long as the calibration procedures applied can be found in Berni *et al.* (2009) and Suárez *et al.* (2009). The bandsets used in each of the study sites comprised bands centered at 530, 550, 570, 670, 700 and 800 nm used to calculate the PRI (Gamon *et al.*, 1992). The thermal camera installed on board the airborne platform was the Thermovision A40M (FLIR, USA). The camera, imagery characteristics, and calibration methods can be found in Berni *et al.* (2009).

2.4 Radiative Transfer Modelling

Radiative transfer simulations were conducted with PROSPECT (Jacquemoud and Baret, 1990) linked to the 3D radiative transfer FLIGHT model (North, 1996) for two crops (olive and peach trees). The FLIGHT model was first used in this study to simulate complex canopy scenes to understand the directional effects on narrow-band indices such as PRI. Crown spectra were then extracted from both the AHS imagery and simulation scenes, and vegetation indices calculated for the three acquisition times. Diurnal variations of indices as compared with modelled changes as function of the viewing geometry and water stress condition were assessed. The suggested new methodology to assess water stress in vegetation consisted on simulating a non-stress PRI value for a crop field (sPRI) by model inversion using the canopy reflectance from airborne imagery. The difference found between the image PRI (per tree or block level) and the non-stress simulated PRI by model inversion (sPRI), calculated as PRI-sPRI, would be associated with xanthophylls absorption levels at 530 nm. The methodology applied for orchards through PROSPECT-FLIGHT model inversion was based on generating look-up tables independently for each crop and imagery conditions. The method consisted on targeting pure crowns under non-water-deficit conditions, and inverting the coupled leaf-canopy models for Cab and LAI. Model inversion was conducted using other input values from the literature (Kempeneers *et al.*, 2007 for peach trees; Zarco-Tejada *et al*, 2004 for olive trees). Cab and LAI were allowed to vary in the leaf- and canopy-level model inversion step, respectively. The parameter ranges used to build the look-up tables can be found in Suárez et al. (2009). Simulated PRI obtained by model inversion for each crop field (sPRI) was compared with PRI extracted from the canopy reflectance for each pure crown. In addition, simulated PRI and image-extracted PRI from each orchard tree were compared against crown temperature and water potential measurements acquired at the time of each flight.

2.5 Assessment of fruit quality parameters using PRI

Individual crown PRI values extracted from the 10 images acquired over the fruit growing period were normalized with the instantaneous irradiance (E). The integral of PRI/E along the fruit growing period was calculated for each individual crown and compared with fruit quality parameters after harvesting at crown scale following the approach of previous authors (Myers, 1988; Moriana *et al.*, 2007).

3. RESULTS AND DISCUSSION

High determination coefficients between PRI and crown temperature (T) (used here as a water stress indicator) were obtained for peach and olive trees, yielding r^2=0.8 and 0.84, respectively. After simulating the influence of the type of soil, sun angle and leaf area index, the sensitivity of PRI is presented in Figure 1. To assess the sensibility of PRI to the three inputs, both resolutions: high (by means of individual crowns) and medium (by means of the mixture crown-soil-shadows) were studied separately. Once the influence of external parameters on PRI was demonstrated, a methodology based on radiative transfer modelling is undertaken to separate the effects of such parameters and water stress on the spectral signal.

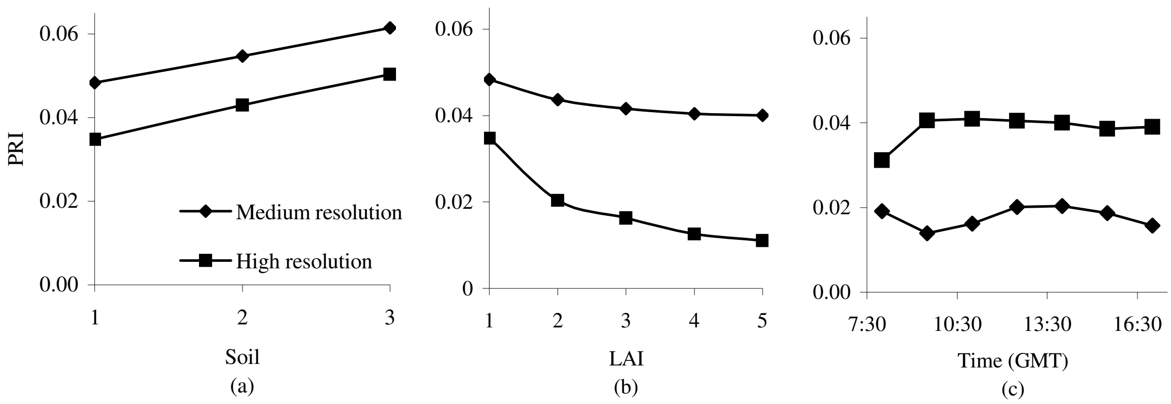


Figure 1. PRI values from simulated spectra for three different types of soil (a), for five leaf area index (LAI) values ranging from 1 to 5 (b) and for seven different times of the day from 8 AM to 5 PM (GMT) (c).

Figure 2 shows the simulation of xanthophylls absorption at leaf scale using PROSPECT RTM, together with the spectra corresponding to the leaves of a well-watered tree and a water-stressed tree. The simulation of this absorption at leaf scale is the basis for the methodology at canopy scale. The results of applying a methodology to assess water stress at canopy level based on simulating a theoretical PRI value (sPRI) corresponding to non-stress crowns are presented in figure 3 for peach and olive trees.

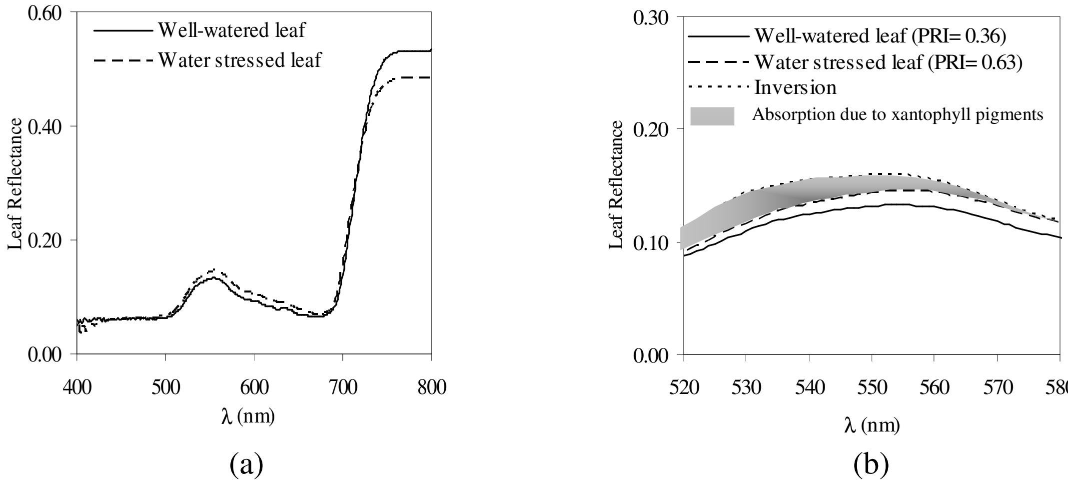
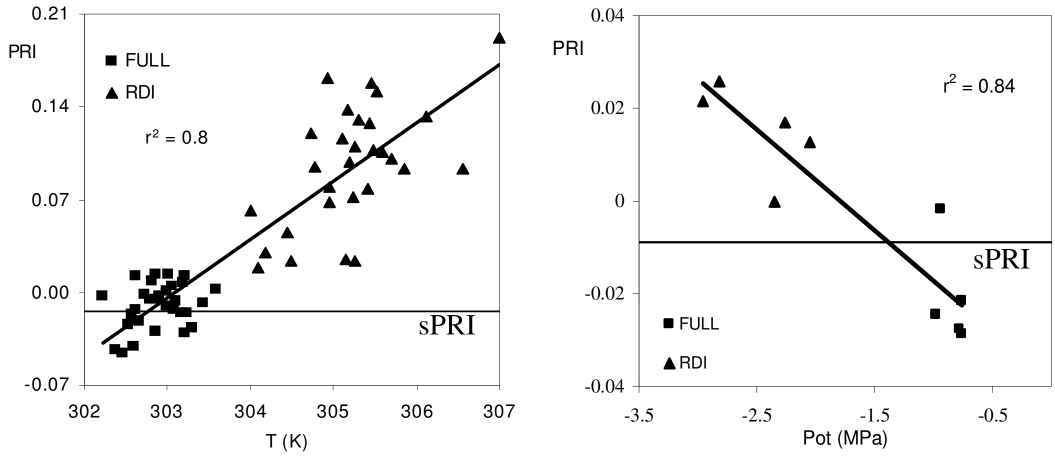


Figure 2. (a) Peach leaf reflectance measured in the field for a stressed and an unstressed each leaf. (b) Leaf spectra on the PRI region and inverted spectrum of the stress leaf showing the effects of xanthophylls absorption.

The integral of the PRI/E calculated with ten images acquired during the fruit growing period was correlated with the ratio Total Soluble Sugars/Total Acidity (TSS/TA) yielding a determination coefficient of r^2=0.72. The same method using crown temperature minus air temperature (Tc-Ta) yielded r^2=0.21, suggesting the superior sensitivity of PRI/E to fruit quality.



(a) (b)

Figure 3. Relationship between PRI and temperature for peach trees (a), PRI with stem water potential for olive trees. The relative position of individual crown PRI as compared with the calculated PRI from the theoretical spectrum is shown.

4. CONCLUSIONS

Results demonstrated that PRI is a good indicator of crops water stress. Nevertheless the effect of external parameters such as soil type, sun angle and leaf area index, require the use of radiative transfer modelling to assess water stress using PRI. The methodology presented for the assessment of water stress at crown scale using PRI and RTM have been validated in two tree species: olive and peach. The results show that PRI can be used as a water stress indicator, being able to characterized trees under water stress with the use of RTM. Moreover, the image-based crown PRI/E time-series acquired along the fruit growing period was demonstrated to yield insights into the TSS/TA fruit quality parameter due to its relationship with water stress levels.

5. REFERENCES

Barton, C.V.M. & North, P.R.J. (2001). Remote Sensing of canopy light use efficiency using the photochemical reflectance index. Model and analysis. *Remote Sens Environ*, 78, 264, 273.

Berni, J.A.J., Zarco-Tejada, P.J., Suarez, L., Fereres, E. Thermal and Narrow-band Multispectral Remote Sensing for Vegetation Monitoring from an Unmanned Aerial Vehicle. (In press). *IEEE T Geosci Remote*, December, 2008.

Gamon, J.A., Peñuelas, J. & Field, C.B. (1992). A narrow-wave band spectral index that track diurnal changes in photosynthetic efficiency. *Remote Sens Environ* 41, 35-44.

Haboudane, D., Miller, J.R., Tremblay, N., Zarco-Tejada, P.J. & Dextraze, L. (2002). Integrated narrow-band vegetation indices for prediction of crop chlorophyll content for application to precision agriculture. *Remote Sens Environ* 84 (2-3), 416-426.

Jacquemoud S. and Baret F. (1990), PROSPECT: a model of leaf optical properties spectra, *Remote Sens Environ*. 34:75-91.

Kempeneers, P., P.J. Zarco-Tejada, P.R.J. North, S. De Backer, S. Delalieux , G. Sepulcre-Cantó, F. Morales, J.A.N. Van Aardt, R. Sagardoy, P. Coppin, P. Scheunders, Model inversion robustness under changing viewing conditions for chlorophyll estimation from hyperspectral imagery. *Int J Remote Sens* (in press, April 2007).

Myers, B.J. (1988). Water stress integral-a link between short-term stress and long-term growth. *Tree Physiology* (4), 315-323.

Moriana, A., Pérez-López, D., Gómez-Rico, A., Salvador, M.D., Olmedilla, N., Ribas, F., Fregapane, G. (2007). Irrigation scheduling for traditional, low-density olive orchards: Water relations and influence on oil characteristics. *Agr Water Manage* (87). 171-179.

North, P.R.J. (1996). Three-dimensional forest light interaction model using a montecarlo method. *IEEE T Geosci Remote* 34 (5), 946-956.

Rouse, J.W., Haas, R.H., Schell, J.A., Deering, D.W. & Harlan, J.C. (1974). Monitoring the vernal advancements and retrogradation of natural vegetation in Nasa/Gsfc Final Report (ed. MD, U.G.) p. 371.

Sobrino, J.A., Jiménez-Muñoz, J.C., Zarco-Tejada, P.J., Sepulcre-Cantó, G. and de Miguel, E. (2006). Land Surface Temperature derived from Airborne Hyperspectral Scanner Thermal Infrared data. *Remote Sens Environ*, 102, 99–115.

Suárez, L., Zarco-Tejada, P. J., Sepulcre-Cantó, G., Pérez-Priego, O., Miller, J.R., Jiménez-Muñoz, J.C., Sobrino, J. (2008). Assessing Canopy PRI For Water Stress Detection With Diurnal Airborne Imagery. *Remote Sens Environ*, 112, 560-575.

Suárez, L., Zarco-Tejada, P.J., Berni, J.A.J., González-Dugo, V., Fereres, E., (2009) Modelling PRI for Water Stress Detection using Radiative Transfer Models, *Remote Sens Environ 113 730-744*.

Thenot, F., Méthy, M. & Winkel, T. (2002). The Photochemical Reflectance Index (PRI) as a water-stress index. *Int J Remote Sens*, 23(23), 5135-5139.

Winkel, T., Méthy, M. & Thénot, F. (2002). Radiation use efficiency, chlorophyll fluorescence , and reflectance indices associated with ontogenic changes in water-limited Chenopodium quinoa leaves. *Photosynthetica*, 40(2), 227-232.

Zarco-Tejada, P.J., Miller J.R., Morales A., Berjón A., & Agüera J. (2004) Hyperspectral Indices and Model Simulation for Chlorophyll Estimation in Open-Canopy Tree Crops, *Remote Sens Environ,* 90(4), 463-476.