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Modelling PRI for water stress detection using radiative transfer models

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ABSTRACT

This paper presents a methodology for water stress detection in crop canopies using a radiative transfer modelling approach and the *Photochemical Reflectance Index* (PRI). Airborne imagery was acquired with a 6-band multispectral camera yielding 15 cm spatial resolution and 10 nm FWHM over 3 crops comprising two tree-structured orchards and a corn field. The methodology is based on the PRI as a water stress indicator, and a radiative transfer modelling approach to simulate PRI baselines for non-stress conditions as a function of leaf structure, chlorophyll concentration (Cab), and canopy leaf area index (LAI). The simulation work demonstrates that canopy PRI is affected by structural parameters such as LAI, Cab, leaf structure, background effects, viewing angle and sun position. The modelling work accounts for such leaf biochemical and canopy structural inputs to simulate the PRI-based water stress thresholds for non-stress conditions. Water stress levels are quantified by comparing the image-derived PRI and the simulated non-stress PRI (sPRI) obtained through radiative transfer. PRI simulation was conducted using the coupled PROSPECT-SAILH models for the corn field, and the PROSPECT leaf model coupled with FLIGHT 3D radiative transfer model for the olive and peach orchards. Results obtained confirm that PRI is a pre-visual indicator of water stress, yielding good relationships for the three crops studied with canopy temperature, an indicator of stomatal conductance (r^2=0.65 for olive, r^2=0.8 for peach, and r^2=0.72 for maize). PRI values of deficit irrigation treatments in olive and peach were consistently higher than the modelled PRI for the study sites, yielding relationships with water potential (r^2=0.84) that enabled the identification of stressed crowns accounting for within-field LAI and Cab variability. The methodology presented here for water stress detection is based on the visible part of the spectrum, and therefore it has important implications for remote sensing applications in agriculture. This method may be a better alternative to using the thermal region, which has limitations to acquire operationally high spatial resolution thermal imagery.

1. Introduction

The *Photochemical Reflectance Index* (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 is based on a normalized difference of the 530 nm band where xanthophyll pigment absorption occurs, and a reference band located at 570 nm. As the xanthophyll pigments are related to light absorption mechanisms, the PRI index has been extensively linked to light use efficiency (LUE) at the leaf scale (Guo & Trotter, 2004; Nakaji et al., 2006; Serrano & Peñuelas, 2005; Sims et al., 2006), at canopy scale using field spectrometers (Nichol et al., 2000, 2002; Strachan et al., 2002; Trotter et al., 2002) and using satellite imagery such as EO-1 Hyperion (Asner et al., 2005), MODIS (Drolet et al., 2005) and AVIRIS (Fuentes et al., 2006). The estimation of LUE through the remote sensing PRI index has shown a direct link to photosynthesis rate assessment (Guo & Trotter, 2004; Nichol et al., 2000, 2006; Sims et al., 2006). In addition, photosynthesis has also been related to PRI through chlorophyll fluorescence and non-photochemical quenching (Evain et al., 2004; Nichol et al., 2006).

The early detection of water stress is a key issue to avoid yield loss, which can be affected even by short-term water deficits (Hsiao et al., 1976). The pre-visual detection of water stress has been successfully achieved with remote sensing data using thermal infrared radiation since long ago (Cohen et al., 2005; Idso et al., 1978; 1981; Jackson et al., 1977, 1981; Jackson & Pinter, 1981; Leinonen & Jones, 2004; Möller et al., 2007; Sepulcre-Cantó et al., 2006, 2007; Wanjura et al., 2004), and more recently being suggested the visible spectral region with the PRI index as an indicator of stress (Peguero-Pina et al., 2008; Suárez et al., 2008; Thenot et al., 2002). Alternatively, thermal imagery acquired over vegetation is sensitive to canopy transpiration because temperature is raised due to the reduction in evaporative cooling under stress conditions. Thermal remote sensing of water stress has

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been accomplished using spectrometers at ground level (Idso et al., 1981; Jackson et al., 1977, 1981), thermal sensors at image level (Cohen et al., 2005; Leinonen & Jones, 2004; Sepulcre-Cantó et al., 2007) and using satellite thermal information (Sepulcre-Cantó et al., in press).

It is well known that severe water deficits affect many physiological processes and have a strong impact on yield (Hsiao et al., 1976). However, even moderate water deficits, which are not easy to detect, can also have important negative effects on yield (Hsiao & Bradford, 1983). It is important to be able to assess the level of stress through some pertinent indicators. This is the case of the xanthophyll cycle response to stress tracked by the PRI index, which is suggested as a pre-visual indicator of water stress and is the aim of this study. PRI has been used to assess pre-visual water stress in the work by Thenot et al. (2002) and Winkel et al. (2002) at leaf level, at canopy level (Dobrowsky et al., 2005; Evain et al., 2004; Peguero-Pina et al., 2008; Sun et al., 2008) and using airborne imaging spectroscopy (Suárez et al., 2008). Both indicators, canopy temperature and PRI, are complementary; they provide physiological information related to plant water status, transpiration and photosynthesis. High spatial resolution imagery in the visible and near infrared region is relatively easy to acquire with current airborne and satellite sensors, such as AHS, Hymap, CASI, AVIRIS, and Hyperion, among others. On the contrary, high-resolution thermal sensors are not common due to technical limitations of microbolometer technology. Moreover, high resolution thermal imagers onboard satellite platforms are restricted due to technical limitations. Current thermal medium resolution sensors on satellite platforms are limited to ASTER and LANDSAT sensors, offering spatial resolutions limited to the 60–120 m pixel-size range. These current technical limitations for acquiring high-spatial resolution thermal imagery emphasize the need for developing pre-visual water stress indicators in the VIS/NIR region for agricultural and precision farming methods. Technically, CMOS and CCD VIS/NIR imaging sensors based on silicon detectors provide very high spatial resolution with pixel sizes at the centimetre level and cost-effective for precision agriculture imagers and future satellite platforms. Thus, attention must be placed on VIS/NIR narrow-band indicators of pre-visual stress, such as PRI, as well as chlorophyll fluorescence for stress-detection methods (Dobrowsky et al., 2005; Pérez-Priego et al., 2005; Suárez et al., 2008; Thenot et al., 2002). Nevertheless, the PRI index cannot be readily used to map vegetation stress without considering leaf and canopy structural effects on the index. PRI bands at 531 and 570 nm are affected by both leaf and canopy parameters such as chlorophyll content (Cab), dry matter (Cm), leaf thickness, leaf area index (LAI), and leaf angle distribution function (LADF), among others (Barton & North, 2001; Suárez et al., 2008). Thus, PRI maps obtained over canopies with variable LAI mask the sensitivity of the index to stress, mostly tracking the spatial variation of the canopy leaf area density and structure (Barton & North, 2001; Suárez et al., 2008). Consequently, modelling work at leaf and canopy scale is needed to enable an operational application of PRI to map water stress in non-homogeneous canopies where structural changes 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

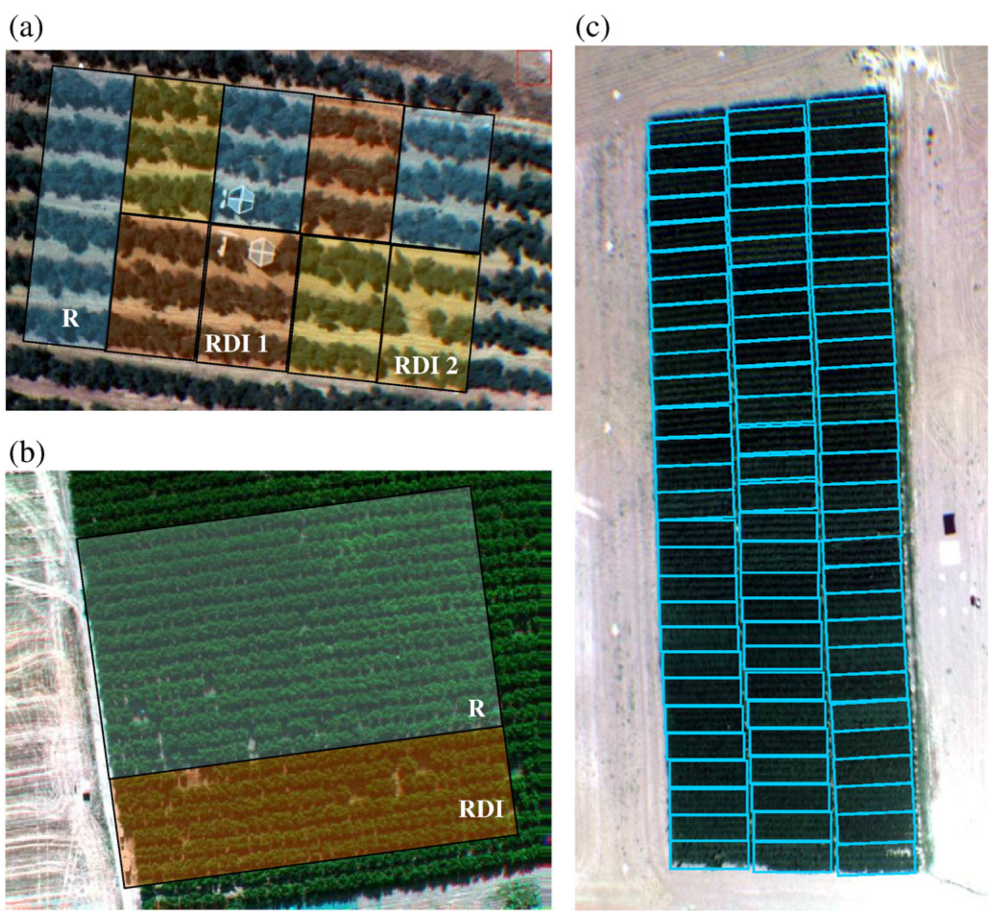

Fig. 1. Overview of the field experiments presented in this study: (a) olive orchard and the three irrigation treatments applied: Full irrigation (R), and two regulated deficit irrigation treatments (RDI1, RDI2); (b) peach orchard with one full irrigation treatment (R) and a regulated deficit irrigation treatment (RDI); and (c) corn field with 24 different cultivars replicated three times.