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Monitoring water stress and fruit quality in an orange orchard under regulated deficit irrigation using narrow-band structural and physiological remote sensing indices

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ABSTRACT

This paper deals with the monitoring of water status and the assessment of the effect of stress on citrus fruit quality using structural and physiological remote sensing indices. Four flights were conducted over a citrus orchard in 2009 using an unmanned aerial vehicle (UAV) carrying a multispectral camera with six narrow spectral bands in the visible and near infrared. Physiological indices such as the *Photochemical Reflectance Index* (PRI_{570}), a new structurally robust PRI formulation that uses the 515 nm as the reference band (PRI_{515}), and a chlorophyll ratio (R_{700}/R_{670}) were compared against the *Normalized Difference Vegetation Index* (NDVI), *Renormalized Difference Vegetation Index* (RDVI) and *Modified Triangular Vegetation Index* (MTVI) canopy structural indices for their performance in tracking water status and the effects of sustained water stress on fruit quality at harvest. The irrigation setup in the commercial orchard was compared against a treatment scheduled to satisfy full requirements (based on estimated crop evapotranspiration) using two regulated deficit irrigation (RDI) strategies. The water status of the trees throughout the experiment was monitored with frequent field measurements of stem water potential (Ψ_x), while titratable acidity (TA) and total soluble solids (TSS) were measured at harvest on selected trees from each irrigation treatment. The high spatial resolution of the multispectral imagery (30 cm pixel size) enabled identification of pure tree crown components, extracting the tree reflectance from shaded, sunlit and aggregated pixels. The physiological and structural indices were then calculated from each tree at the following levels: (i) pure sunlit tree crown, (ii) entire crown, aggregating the within-crown shadows, and (iii) simulating a lower resolution pixel, including tree crown, sunlit and shaded soil pixels. The resulting analysis demonstrated that both PRI formulations were able to track water status, except when water stress altered canopy structure. In such cases, PRI_{570} was more affected than PRI_{515} by the structural changes caused by sustained water stress throughout the season. Both PRI formulations were proven to serve as pre-visual water stress indicators linked to fruit quality TSS and TA parameters ($r^2 = 0.69$ for PRI_{515} vs TSS; $r^2 = 0.58$ vs TA). In contrast, the chlorophyll (R_{700}/R_{670}) and structural indices (NDVI, RDVI, MTVI) showed poor relationships with fruit quality and water status levels ($r^2 = 0.04$ for NDVI vs TSS; $r^2 = 0.19$ vs TA). The two PRI formulations showed strong relationships with the field-measured fruit quality parameters in September, the beginning of stage III, which appeared to be the period most sensitive to water stress and the most critical for assessing fruit quality in citrus. Both PRI_{515} and PRI_{570} showed similar performance for the two scales assessed (sunlit crown and entire crown), demonstrating that within-crown component separation is not needed in citrus tree crowns where the shaded vegetation component is small. However, the simulation conducted through spatial resampling on tree + soil aggregated pixels revealed that the physiological indices were highly affected by soil reflectance and between-tree shadows, showing that for TSS vs PRI_{515} the relationship dropped from $r^2 = 0.69$ to $r^2 = 0.38$ when aggregating soil + crown components. This work confirms a previous study that demonstrated the link between PRI_{570}, water stress, and fruit quality, while also making progress in assessing the new PRI formulation (PRI_{515}), the within-crown shadow effects on the physiological indices, and the need for high resolution imagery to target individual tree crowns for the purpose of evaluating the effects of water stress on fruit quality in citrus.

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1. Introduction

Water scarcity is a major constraint to irrigated agriculture in many areas of the world. In the Mediterranean region, rainfall is scarce and irregularly distributed throughout the year, and climate change models predict even more arid conditions in the coming decades (Bates et al., 2008). Although citrus are able to withstand considerable drought (Salter and Goode, 1967), they are cultivated widely in semi-arid climates where water resources are becoming the major limiting factor for irrigated agriculture. Therefore, irrigation scheduling needs to be more precise, and this requires the development of methodologies to optimize irrigation water productivity. One technique currently in use is the regulated deficit irrigation (RDI) strategy, where water deficits are imposed only during the crop developmental stages that are least sensitive to water stress (Chalmers et al., 1981). This practice was originally proposed to control vegetative vigor in high-density orchards, to reduce production costs and to improve fruit quality. However, it also saves irrigation water, with the concomitant benefits of reduced drainage losses (Fereres and Soriano, 2007).

The fruit quality of citrus is affected by water stress due to changes in juice properties, such as increases in sugar concentrations and acidity (Chartzoulakis et al., 1999). In some cases, the water stress reduces fruit quality (Mougheith et al., 1977). When water deficits are imposed, as in RDI, yield and fruit size are not generally affected (Girona, 2002), whereas some quality parameters such as total soluble solids and titratable acidity increase (Crisosto et al., 1994; Girona et al., 2003; Mills et al., 1994). Responses to RDI are variable, depending on the timing and severity of the water deficits (Girona et al., 2003; Marsal and Girona, 1997), which in turn depends on orchard management. Although there is increasing knowledge in the application of deficit irrigation strategies and in the relationships between water stress and fruit quality (Baeza et al., 2007; Ginestar and Castel, 1996; Gonzalez-Altozano and Castel, 1999; Myers, 1988), the introduction of these strategies into commercial orchards is being hindered by a lack of reliable indicators of water status that account for the heterogeneity naturally found in orchards. As fruit quality is of paramount importance for harvest strategy and growers' revenues, indicators to depict fruit quality are also desirable. Remote sensing of fruit quality has been attempted by different means, such as determining the vigor or total leaf area in vineyards (Johnson et al., 2001, 2003; Lamb et al., 2004) or relating quality parameters in water-stressed mandarin trees to spectral changes in the red and green channels (Kriston-Vizi et al., 2008). High spatial resolution airborne imagery was also implemented to detect relationships of olive fruit size, weight, and oil content against crown temperature (Sepulcre-Cantó et al., 2007), while the visible part of the spectrum was also used in fruit quality detection of orange, peach and nectarine (Suárez et al., 2010).

Canopy thermal infrared radiation has long been implemented in remote sensing as a method of pre-visual detection of water stress (Cohen et al., 2005; Idso et al., 1981, 1978; Jackson et al., 1977, 1981; Jackson and Pinter Jr., 1981; Leinonen and Jones, 2004; Möller et al., 2007; Sepulcre-Cantó et al., 2006, 2007; Wanjura et al., 2004). Thermal imagery acquired over vegetation is sensitive to canopy instantaneous transpiration rate at the time of image acquisition because temperature rises due to the reduction in evaporative cooling under stress conditions. On the other hand, hyperspectral imagery in the visible and near-infrared (NIR) has been proven capable of accurate estimation of crop physiological status through optical indices related to leaf biochemistry and canopy structure (Haboudane et al., 2004; Zarco-Tejada et al., 2005). However, most of the optical indices track the effects of long-term water stress on plants and thus are not useful in early detection and monitoring of water stress strategies such as RDI. Nevertheless, the visible spectral region has been suggested for pre-visual water stress detection based on indices that use bands located at the specific wavelengths where photosynthetic pigments are affected by stress conditions. The most promising index to track photosynthetic condition is the Photochemical Reflectance Index (PRI) (Gamon et al., 1992), which has been proposed to assess vegetation water stress based on xanthophyll pigment composition changes (Peguero-Pina et al., 2008; Suárez et al., 2008, 2009, 2010; Thenot et al., 2002).

The PRI index is related to the de-epoxidation state of the xanthophyll cycle (Gamon et al., 1990, 1992; Peñuelas et al., 1995) and was initially developed as a method to remotely assess photosynthetic efficiency using narrow-band reflectance (Gamon et al., 1992; Peñuelas et al., 1995). However, the attributes of PRI are more complex since it can also serve as an index of relative chlorophyll:carotenoid levels. Over longer time scales (weeks–months), changes in pigment content and ratios due to leaf development, aging or chronic stress have been reported to play a significant role, along with xanthophyll pigment epoxidation, in the PRI signal (Gamon et al., 2001; Peñuelas et al., 1997; Sims and Gamon, 2002; Stylinski et al., 2002). Together, these responses to the de-epoxidation state of the xanthophyll cycle and to chlorophyll/carotenoid ratios ensure that PRI provides an effective measure of relative photosynthetic rates across a wide range of conditions, species and functional types (Filella et al., 1996; Gamon et al., 1992; Gamon and Qiu, 1999; Peñuelas et al., 1995; Stylinski et al., 2002).

Consequently, PRI can be more descriptive of plant physiology and photosynthetic functioning, and thus the effects of water deficits on yield and vigor, than thermal indicators. In line with this hypothesis, recent work by Suárez et al. (2010) demonstrated that high-resolution PRI time series calculated from pure sunlit vegetation pixels exhibited a good relationship with fruit quality, whereas crown airborne temperature acquired over the same trees did not yield comparable results and did not correlate well with fruit quality. Thus, PRI from pure sunlit tree crowns may be a better estimator of fruit quality than other established water stress indicators that are related directly to transpiration, such as crown temperature, since fruit quality is more closely tied to photosynthesis and carbon metabolism.

However, there are some serious drawbacks that prevent the wide use of PRI at crown or field scale. PRI is affected by a series of parameters such as variability of leaf pigment concentration (due to reflectance overlapping of chlorophyll a + b and carotenoid with xanthophyll pigment de-epoxidation), amount of leaf biomass, canopy structure, viewing-illumination geometry, background reflectance and sensor spectral responses (Barton and North, 2001; Grace et al., 2007; Suárez et al., 2008). The reference band in the formulation of each index is supposed to compensate for a number of unwanted effects. However, in PRI formulation the mechanistic basis for wavelength selection has been fully explored only at the leaf scale (Gamon et al., 1993), and is poorly supported at canopy and larger scales, where a variety of alternate wavebands have been used, often based on statistical correlations (Gamon et al., 1992; Inoue et al., 2008). It is not entirely clear if the best wavelengths for assessing sensitivity to xanthophyll pigments at the leaf scale (531 and 570 nm) are necessarily the best wavelengths at progressively larger scales (canopy level), where multiple scattering due to the canopy structure and background alter the sensitivity of the bands related to the xanthophyll cycle feature. In particular, previous work conducted in forestry used airborne imagery and radiative transfer modeling methods to examine five formulations of PRI (based on 531 nm as a xanthophyll-sensitive spectral band, using five different reference wavelengths) for detecting stress levels, while minimizing the effects of crown architecture and structure. The study proposed a more robust version of PRI, less sensitive to canopy structural and biochemical parameters, that