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Detecting crop water status in mature olive groves using vegetation spectral measurements

Giovanni Rallo [a], Mario Minacapilli [a,*], Giuseppe Ciraolo [b], Giuseppe Provenzano [a]

[a] Department of Agricultural and Forest Sciences (SAF), Università degli Studi di Palermo, Viale delle Scienze Ed. 4, 90128, Palermo, Italy

[b] Department of Civil, Environmental and Aerospace Engineering (DICAM), Università degli Studi di Palermo, Viale delle Scienze Ed. 8, 90128, Palermo, Italy

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Full spectral measurements (350–2500 nm) at tree canopy and leaf levels and the corresponding leaf water potentials (LWP) were acquired in an olive grove of Sicily, at different hours of the day, during summer season 2011. The main objective of the work was to assess, on the basis of the experimental data-set, two different approaches to detect crop water status in terms of LWP. Specifically, using existing families of Vegetation Indices (VIs) and applying Partial Least Squares Regression (PLSR) were optimised and tested. The results indicated that a satisfactory estimation of LWP at tree canopy and leaf levels can be obtained using vegetation indices based on the near infrared–shortwave infrared (NIR–SWIR) domain requiring, however, a specific optimisation of the corresponding "centre-bands". At tree canopy level, a good prediction of LWP was obtained by using optimised indices working in the visible domain, like the Normalized Difference Greenness Vegetation Index (NDGI, RMSE = 0.37 and R^2 = 0.57), the Green Index (GI, RMSE = 0.53 and R^2 = 0.39) and the Moisture Spectral Index (MSI, RMSE = 0.41 and R^2 = 0.48). On the other hand, a satisfactory estimation of LWP at leaf level was obtained using indices combining SWIR and NIR wavelengths. The best prediction was specifically found by optimising the MSI (RMSE of 0.72 and R^2 = 0.45) and the Normalized Difference Water Index (NDWI, RMSE = 0.75 and R^2 = 0.45). Even using the PLSR technique, a remarkable prediction of LWP at both tree canopy and leaf levels was obtained. However, this technique requires the availability of full spectra with high resolution, which can only be obtained with handheld spectroradiometers or hyper-spectral remote sensors.

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* *Corresponding author*. Tel.: +39 (0)91 23897075; fax: +39 (0)91 484035.
E-mail address: mario.minacapilli@unipa.it (M. Minacapilli).

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1. Introduction

In typical Mediterranean agro-ecosystems, characterised by long dry seasons and limited water resources, soil-plant water deficit is the main environmental constraint on crop yield. In the last decades, the growing demand for olive tree products has suggested the need to use a precise irrigation scheduling accounting for soil and/or crop water status (Provenzano, Tarquis, & Rodriguez-Sinobas, 2013). Particularly, leaf water potential (LWP) is considered one of the most reliable indicators of crop water status and it can be used as an irrigation scheduling parameter (Jones, 2004). Over large areas, measurements of LWP are labour-intensive and time-consuming, due to the large number of observations necessary to characterise a single plot. As a consequence, non-destructive and fast methodologies to assess crop water status or other related parameters are desirable. In this context, reflectance spectroscopy in the electromagnetic regions of visible (VIS), near infrared (NIR) and shortwave infrared (SWIR) can be applied for indirect evaluations of crop water status across various spatial scales (Gamon & Qiu, 1999).

The theoretical base that justifies the use of spectroradiometric techniques refers to the direct interactions between the VIS, NIR and SWIR vegetation spectral signatures and physiological parameters, photosynthetic activity (Gamon, Serrano, & Surfus, 1997) and leaf water status (Elsayed, Mistele, & Schmidhalter, 2011). In fact, changes in leaf internal structure due to reduced water contents influence reflectance in the red and near infrared spectral regions (Inoue, Morinaga, & Shibayama, 1993). In NIR and SWIR regions, several water spectral absorption bands near 970, 1200, 1450, and 1940 nm can be used to detect crop water status (Curran, 1989). Peñuelas, Filella, Biel, Serrano, & Savé, 1993, Penuelas, Gamon, Fredeen, Merino, and Field (1994), studying the reflectance signature of gerbera, pepper, bean plants and wheat in the NIR domain, proposed the ratio of reflectance at 970 and 900 nm, in order to evaluate a Water Index, WI, to monitor the changes in relative water content, leaf water potential, stomatal conductance, and cell wall elasticity. Tian, Tong, Pu, Guo, and Zhao (2001) obtained a high prediction accuracy for wheat water content from spectral absorption features between 1650 and 1850 nm. In addition, the use of reflectance spectroscopy in the visible region provides information that can be associated with pigments like chlorophyll, carotenoids, anthocyanin and consequently to photosynthetic processes of leaves (Sims & Gamon, 2002), indirectly related to leaf/plant water status.

Another distinctive feature of reflectance spectroscopy is its applicability across various spatial scales, from leaf and tree canopy level, using standard handheld spectroradiometers, to higher levels by means of multispectral and hyperspectral remote sensing technologies. In the past decades, many relationships between spectral data from remote sensing observations and various biophysical and physiological crops parameters (leaf area index, leaf greenness, leaf chlorophyll content, etc.) have been proposed (Liang, 2004, chap. 3). A common and widely used approach to analyse crop spectral signatures acquired from remote sensing platforms is based on the extraction of so-called Vegetation Indices (VIs). These indices can be obtained from multispectral systems able to capture images in a few "broad" spectral bands (with spectral resolution of about 50 nm), usually centred in VIS–NIR regions. For example, the Normalized Difference Vegetation Index (NDVI), based on a simple combination of reflectance values in visible (red or green) and near-infrared regions, has been widely used to map, at various observation scales, crop variables like biomass, Leaf Area Index (LAI), plant coverage and chlorophyll (Aparicio, Villegas, Casadesus, Araus, & Royo, 2000; Christensen & Goudriaan, 1993). Moreover, NDVI or other similar VIs, using average spectral information, have been used to assess the spatial variability of crop variables over large areas (Myneni, Los, & Asrar, 1995; Tucker, Fung, Keeling, & Gammon, 1986). However, this kind of information has to be properly used in order to consider the same observation scale for both VIs and the investigated crop properties. Recently, Marino et al. (2014) collected a large dataset of diurnal and seasonal measurements of leaf gas exchange and plant transpiration, highlighting that the Photochemical Reflectance Index (PRI) and the Water Index (WI), measured at the tree canopy, can be used to detect water stress. However, these authors only considered three indices of the VIS–NIR family, without including the SWIR region.

The recent technological progress in the industrial production of handheld spectroradiometers and hyperspectral sensors, characterised by a high number of contiguous spectral bands (resolution better than 10 nm), has driven scientists to a more accurate analysis aimed at selecting specific wavebands that should be more sensitive to crop-related variables (Blackburn, 1998; Darvishzadeh et al., 2008; Goel, Prasher, Landry, Patel, & Viau, 2003; Maccioni, Agat, & Mazzinghi, 2001). For example, using hyperspectral imagery, Zarco-Tejada et al. (2013) demonstrated the ability of a VI, centred at 570 and 515 nm wavelengths, to assess carotenoid content at canopy level and proposed a new formulation of the PRI, centred at 531 and 570 nm wavelengths, as a water stress indicator.

Moreover, various studies have considered the full spectral information on the basis of multivariate statistical techniques, e.g. Partial Least Squares Regression (PLSR), to take advantages of an increased number of wavebands, to improve the prediction of crop related parameters (Esbensen, 2000, 598 pp.; Hansen & Schjoerring, 2003). However, little research has combined leaf and canopy spectral measurements to assess crop water stress and to exploit the link between physical variables and spectral measurements. Recently, a specific database, containing more than 30 different indices related to "vegetation – water" applications, has been published on-line by the Institute of Crop Science and Resource Conservation (INRES, www.indexdatabase.de) of Bonn University. Unfortunately, the proposed indices are not related to any specific crop or to physical variables. Despite the growing interest in the research topic, demonstrated by the copious literature, only a limited number of investigations have considered the spectral behaviour of Mediterranean crops, like olives, across various scales.

In this context, in the frame of a rational recognition of VIS–NIR and SWIR spectroradiometric techniques, useful to characterise water status of olive crop, the specific objectives of the paper are: i) to assess relation of leaf water potentials (LWP) of a Mediterranean olive grove to high spectral resolution

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