Evaluating the performance of xanthophyll, chlorophyll and structural-sensitive spectral indices to detect water stress in five fruit tree species

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Abstract

The performance of several spectral indices sensitive to structural variations and chlorophyll and xanthophyll pigment content was assessed in a commercial farm with five fruit crop species (almond, lemon, orange, apricot and peach). Each species was irrigated differently, which enabled the development of a range of different plant water status. Multispectral and thermal images were acquired from a Remotely Piloted Airborne System (RPAS) while concomitant measurements of stomatal conductance (g_s) and stem water potential (Ψ_s) were taken. Results showed T_c and $PRI_{(570-515)}$ as the first and second most sensitive indicators to water stress in all the crops with the exception of apricot, in which Ψ_s was the most sensitive indicator at midday. PRI_{norm} was the least sensitive index among all the water stress indicators studied. Within the *Prunus* species, Ψ_s yielded the best correlations with PRI_{570} and $PRI_{(570-515)}$ (r^2=0.53) in almond trees, with TCARI/OSAVI (r^2=0.88) in apricot trees and with PRI_{norm}, R_{700}/R_{670} and NDVI (r^2 from 0.72 to 0.88) in peach trees. Weak or no correlations were found for the *Citrus* species due to the low level of water stress reached by the trees. $PRI_{(570-515)}$ and NDVI were the indices that better performed when all the crops were analyzed together. Both were statistically correlated with CWSI, g_s and Ψ_s yielding the best correlations with the latter ($PRI_{(570-515)}$ vs. Ψ_s, r^2=0.61; NDVI vs. Ψ_s, r^2=0.65). This work demonstrates the feasibility of using narrow-band multispectral-derived indices to retrieve water status for a variety of crop species with contrasted phenology and canopy architecture.

Keywords: fruit crops; multispectral imagery; remote sensing; water stress detection

Introduction

Continuous advances in high technology have promoted the use of Remotely Piloted Airborne System (RPAS) for a large range of applications (Anderson and Gaston, 2013). Precision agriculture is one of the most promising applications (Mulla, 2013; Gago et al., 2015) since low-cost RPAS can be equipped with robust sensors, such as miniaturized narrow-band, hyperspectral and thermal cameras, used to remotely monitor vegetation (Bendig et al., 2012). Farm assessment by remote sensing using RPAS enables the monitoring of specific targets from a closer range and a higher frequency than is currently possible with satellites. Inter and intra-field variability of crops can be then assessed in detail providing farmers with crucial information to better optimize farm management, increase farmers' profitability and ultimately enhance the environmental quality (Mulla, 2013).

Drought is becoming the most limiting factor for crop production in much of the world (IPCC, 2014). This fact has increased the emphasis that policy-makers are placing on both demand and supply options to water management. Remote sensing takes on special significance within this context since it enables a better monitoring of large cultivated areas making it easier to assess the proper functioning of irrigation systems (by identifying water-stressed or over-irrigated areas) and the precise management of plants' water stress, which has been extensively pointed out in the literature (Taghvaeian and Neale, 2011) as a key factor to ensure the success of water-saving irrigation strategies based on irrigating plants below their water requirements.

High resolution thermal imagery has been successfully used in a variety of crops to assess the variability in plant water status at the field and farm scales (Bellvert et al., 2013; Berni et al., 2009; Gonzalez-Dugo et al., 2012; Gonzalez-Dugo et al., 2013; Zarco-Tejada et al. 2012). Bellvert et al. (2013) mapped the spatial variability in leaf water potential of different vineyards based on high resolution thermal imagery and then used that information for scheduling irrigation. Similarly, Gonzalez-Dugo et al. (2013) identified water-stressed areas from thermal images in a farm composed of five fruit tree crops and established a crop water stress index (CWSI) threshold. Notwithstanding the suitability of thermal sensing for plant water stress assessment, alternative indices less sensitive to variations in the air vapor pressure deficit and more related to biophysical parameters such as the chlorophyll or xanthophylls pigment content are currently of interest (Zarco-Tejada et al., 2013).

A variety of narrow-band optical indices obtained from remote sensing data have been related to chlorophyll concentration, which is reduced under conditions of water stress (Haboudane et al., 2002; Zarco-Tejada et al., 2004, 2005a, 2005b). Combination of indices such as the Transformed Chlorophyll Absorption in Reflectance Index (TCARI) and the Optimized Soil Adjusted Vegetation Index (OSAVI) to give the TCARI/OSAVI index, have been shown as more robust indices to estimate chlorophyll concentration because of a lower sensitivity to soil background and crop leaf area index variations (Haboudane et al., 2002; Zarco-Tejada et al., 2004).

The narrow-band Photochemical Reflectance Index (PRI) proposed by Gamon et al. (1992), which is based on the xanthophylls cycle activation as a mechanism to dissipate the excess of energy when photosynthesis declines under conditions of stress, has been also successfully tested as a water stress indicator in several studies (Thenot et al., 2002; Suarez et al., 2008, 2009, 2010; Hernández-Clemente et al., 2011; Zarco-Tejada et al., 2012). These authors, however, also pointed out that PRI is highly affected by factors such as canopy structure, viewing and illumination geometry effects, and background, which challenge its widespread use as a water stress indicator. Different formulations of PRI (based on different wavelength references) have been studied in this sense searching to overcome these limitations (Hernández-Clemente et al., 2011). Recently, Zarco-Tejada et al. (2013) proposed a modified PRI-based index (PRI_{norm}) to track the diurnal trends of water stress using a combination of a structural (Renormalized Different Vegetation Index, RDVI) and a sensitive to chlorophyll content ratio index (R_{700}/R_{670}) to normalize PRI. These authors (Zarco-Tejada et al., 2013) tested the PRI_{norm} in an experimental vineyard site in a diurnal setting, yielding higher correlations than PRI with the CWSI and the commonly used water stress indicators leaf water potential and stomatal conductance (g_s).

Spectral indices have been usually evaluated on orchards consisting of a single crop. It is not uncommon for farms to be made up of several crop species with different canopy architectures, nutrient status and even phenological stages. Under these circumstances, the possibility of using a single multispectral index that could provide reliable information regarding the plant water status of all the crops coexisting in the farm would be of great value.

To the best of our knowledge, there are no studies in the literature dealing with the assessment of spectral indices to detect plant water stress in contrasting tree crop species. The aim of the present work was to assess the performance of several xanthophyll (PRI, PRI_{norm} and $PRI_{570-515}$), chlorophyll (TCARI/OSAVI; R_{700}/R_{670}) and structural-sensitive (NDVI) spectral indices and their capability to detect plant water stress in a commercial farm composed of five different tree crop species. The specific objectives were: (i) to assess the sensitivity to water stress of spectral indices in comparison to the established methods based on stem water potential (Ψ_s), g_s and canopy temperature (T_c) measurements; (ii) to explore the relationship between the spectral indices and Ψ_s, g_s and CWSI for each of the fruit tree crop species studied, and; (iii) identify which of the spectral indices performs best when the five tree species are assessed together.

Material and methods

Site characteristics and irrigation treatments

The study was performed in July of 2010 in the same 42-ha commercial farm described in Perez-Sarmiento et al. (2010) and Gonzalez-Dugo et al. (2013), located in the Mula Valley (37º55'N, 1º26'W), Murcia (Spain), where the climate is considered as semi-arid Mediterranean. The annual reference evapotranspiration (ET_o) and rainfall for the experimental season were of 1182 and 445 mm, respectively.

The farm consisted of five orchards planted with almond (*Prunus dulcis* cv. Garrigues and cv. Ramillete), apricot (*Prunus armeniaca* cv. Bulida), peach (*Prunus persica* cv. Catherine), orange (*Citrus sinensis* cv. Lane Late) and lemon (*Citrus x limon* cv. Fino 49) trees. Each orchard was divided into 2-4 irrigation units, which enabled different irrigation managements and the development of contrasted plant water status. The number of irrigation units and other characteristics such as planting space, canopy ground cover and number of emitters per tree used within each orchard are shown in table 1. At the time of the study (July), almond, peach, lemon and orange trees were being daily irrigated. In order to generate different levels of tree water status in these orchards, irrigation was withheld for eight days prior to the measurements in one single irrigation unit in the almond, lemon and orange orchards, and in two irrigation units in the peach orchard. Apricot trees, on the other hand, had already been harvested and water had not been applied since 24 days before the measurements date. Thus, to generate different water status in the apricot orchard, irrigation was resumed in one single unit eight days prior to the measurements.

Airborne imagery and image processing

Multispectral images were acquired on July 7th at 13.00 h (local time; UTC + 1 h) with a 6-band multispectral camera (MCA-6, Tetracam Inc., California, USA) installed on a two-meter wingspan fixed–wing RPAS platform. The image resolution was 1280 x 1024 pixels with 10-bit radiometric resolution and optical focal length of 8.5 mm. The RPAS platform (mX-SIGHT, UAV Services and Systems, Germany) was controlled by an autopilot for autonomous flying (AP04, UAV Navigation, Madrid, Spain) following a flight plan of around 1h at 350 m above the ground and 5.8 kg take-off weight using waypoints to acquire imagery from the entire orchards under study. At this flight altitude, the camera delivered a ground resolution of 20 cm pixel-size. The autopilot had a dual CPU controlling an integrated Attitude Heading Reference System (AHRS) based on a L1 GPS board, 3-axis accelerometers, gyros and a 3-axis magnetometer (Berni et al. 2009). The ground control station and the UAV were radio-linked, transmitting position, altitude and status data at 20 Hz frequency.

The bandset chosen for this study was centered at 515, 530, 570, 670, 700 and 800 nm. The high-resolution of the multispectral imagery enabled the identification of every single crown within the orchard. An algorithm was applied afterwards to restrict the shape of the crowns in order to avoid soil/vegetation mixed pixels. Then, the different indices were calculated at the object level (crown). The average crown reflectance derived from the imagery of well-watered and deficit-irrigated trees for each of the five tree crop species studied is shown in Fig.1. Reflectance values obtained for the six spectral bands enabled the calculation of vegetation indices sensitive to variations in canopy structure, chlorophyll and xanthophyll pigment content (Table 2): the Normalized Difference Vegetation Index (NDVI), which is linked to the leaf area index; the chlorophyll-sensitive indicators R_{670}/R_{700} and Transformed Chlorophyll Absorption in Reflectance Index normalized by the Optimized Soil Adjusted Vegetation Index (TCARI/OSAVI), and different PRI formulations such as the abovementioned PRI and PRI_{norm} as well as $PRI_{(570-515)}$.

The spectral indices were compared with those obtained in a parallel experiment that measured T_c and CWSI in the same trees and was reported by Gonzalez-Dugo et al. (2013). Thermal images were obtained from a thermal camera (MIRICLE 307, Thermoteknix Systems Ldt., Cambridge, UK) also installed on the RPAS during the study.

Field data collection

Concomitant measurements of Ψ_s and g_s were taken during the flight in selected irrigated and non-irrigated trees from each species. Measurements were carried out by five teams composed of 3-5 people each with experience taking in-field determinations.

The Ψ_s determinations were carried out with five Scholander pressure chambers (Model 600 Pressure Chamber, PMS Instrument Company, Albany, USA) in two mature leaves per tree covered with aluminum foil for at least 90 min before measurements. The number of trees used for the Ψ_s and other in-field determinations within each irrigation unit are shown in table 3. The g_s was measured in 2-4 sunny leaves per tree using a diffusion porometer (SC-1 porometer, Decagon, WA, USA) in the lemon, orange and peach orchards, and a portable photosynthesis system (X) in the almond and apricot orchards, which enabled also recording the leaf net CO_2 assimilation (P_n). Additionally, three leaf samples were taken from selected irrigated and non-irrigated trees of all the species with the exception of peach to determine the leaf chlorophyll content (Table 3).

Weather conditions at the time of flights were recorded with a portable weather station (Model WXT510, Vaisala, Finland) placed just outside the orchard. Mean values for the air temperature, vapor pressure deficit and wind speed at the time of flight were 31.9 ºC, 3.76 KPa and 1.9 m s^{-1}, respectively.

Statistical analysis

Performance of all the spectral indices studied was compared to that of Ψ_s, g_s and canopy temperature (T_c) by means of a sensitivity analysis (sensitivity defined as signal to noise ratio) based on that proposed by Goldhamer and Fereres (2001). Thus, when there were significant differences between treatments, the value "signal" for Ψ_s, T_c and the vegetation indices was calculated as the ratio between the average value for the water stressed and control treatments while for g_s it was obtained from the ratio between the average value for the control and water stressed treatments. In all cases the "noise" was defined as the average coefficient of variation (CV) among trees from the same treatments as the signal value.

The relationship between the spectral indices and Ψ_s, g_s or CWSI for each of the crop species studied as well as when data from all the crops were pooled together was explored by correlation analyses.

Results and discussion

Sensitivity analysis

The sensitivity of indicators such as the leaf and Ψ_s, sap flow and trunk diameter fluctuation measurements, g_s or T_c, to water stress has been compared in the past on tree crops of high economic interest (e.g., Goldhamer et al., 1999 in peach Moriana and Fereres, 2002 in olive; Intrigliolo and Castel, 2006 in plum; Ballester et al., 2013 in citrus). From these studies, it is known that higher noise is expected in methods in which measurements at the leaf scale are taken in specific spots around the tree than in methods in which data is averaged from the whole or a large part of the canopy area. That is because of the existence of diverse hydraulic resistances within the tree, particularly under moderate water stress (Gonzalez-Dugo et al., 2012), which may amplify the variability (noise) and notably reduce the sensitivity of indicators relying in measurements taken in specific parts of the trees. In this study, the sensitivity of the Ψ_s (2 leaves/tree) and g_s (2-4 leaves/tree) measurements taken at 13:00 h was compared with that of indices obtained from thermal (T_c) and multispectral images. Data from the orange orchard were not considered in this analysis due to the non-significant differences in plant water status observed between treatments. Results showed that T_c was the indicator with the lowest variability and highest sensitivity to water stress in three out of the four crop species included in the analysis (Table 4). Apricot was the only crop in which Ψ_s resulted the most sensitive indicator to water stress, followed by $PRI_{(570\text{-}515)}$ and T_c. These results were mainly due to the low CV observed in T_c within trees from the same treatment in the almond, lemon and peach orchards, and the low tree to tree variability observed in Ψ_s in apricot trees at 13:00 h compared to the other indicators (Table 4). Gonzalez-Dugo et al. (2013) determined T_c in trees of the same orchards used in this experiment at different times (09:00, 11:00 and 13:00 h). Their results (Gonzalez-Dugo et al., 2013) showed, in fact, that apricot was the species with the highest variability in T_c at any of the three measurement times and that CV within this crop was lowest at 11:00 h. Taking this information into account, the analysis was repeated for this species with Ψ_s, g_s and T_c data obtained at 11:00 h (Table 4). For this time frame, results revealed that T_c was the most sensitive indicator when compared to Ψ_s and g_s (no multispectral data available at 11:00h).

Interestingly, $PRI_{(570\text{-}515)}$ was found the second most sensitive indicator to water stress in all the cases. The good performance of $PRI_{(570\text{-}515)}$ contrasts with the results obtained for PRI_{norm} which, along with g_s, was the indicator with the highest noise and less sensitivity to water stress. The multispectral indices NDVI, TCARI/OSAVI, R_{700}/R_{670} and PRI_{570} had in general intermediate values of sensitivity (Table 4).

Performance of the spectral water stress indicators within each crop

Scaling up observations of plant water status from the leaf to the field or even the farm level requires validation of remote sensing data with ground-truth data. Here, data obtained from the multispectral imagery of selected trees within each orchard were compared with those of in-field measurements of Ψ_s and g_s as well as CWSI, which was already validated for this particular farm by Gonzalez-Dugo et al. (2012).

Within the *Citrus* species, only the sensitive indices to chlorophyll content were significantly correlated with Ψ_s, g_s or CWSI (Table 5). In orange trees, when R_{700}/R_{670} was plotted against g_s yielded a coefficient of determination (r^2) of 0.62 ($p<0.05$). In lemon trees, however, R_{700}/R_{670} and TCARI/OSAVI were significantly correlated respectively with Ψ_s ($r^2=0.41$; $p<0.05$) and CWSI ($r^2=0.64$; $p<0.001$). The structural and photochemical indices did not perform well for the *Citrus* species which could be related to the small variations in water status reached in these orchards compared to the other crops. The performance of structural, xanthophyll and chlorophyll sensitive indices to detect plant water stress in orange trees has been also studied in Zarco-Tejada et al. (2012), who found that in spite of the wide range of Ψ_s reached in that study (from -0.5 to -2.0 MPa) compared to the work presented here, PRI_{570}, TCARI/OSAVI and NDVI although sensitive were weakly related to Ψ_s. The PRI_{515} (band 515 as a reference), proposed by Hernandez-Clemente et al. (2011) and the structural-sensitive indicators RDVI, MTVI1 or TVI were shown in Zarco-Tejada et al. (2012) as more robust water stress indicators for orange trees.

Better correlations than in *Citrus* were obtained for the crops from the genus *Prunus* (Table 5). In almond trees, $PRI_{(570-515)}$, PRI_{570}, NDVI and TCARI/OSAVI indices were statistically correlated with Ψ_s, g_s and CWSI with r^2 ranging from 0.32 to 0.79. The Ψ_s was better correlated with $PRI_{(570-515)}$ and PRI_{570} ($r^2=0.53$ and 0.52, respectively; $p<0.001$). The g_s yielded the highest correlation with TCARI/OSAVI ($r^2=0.65$; $p<0.001$) while CWSI did it with $PRI_{(570-515)}$ and NDVI ($r^2=0.79$ and 0.70, respectively; $p<0.001$). Measurements of photosynthesis taken in almond were highly correlated with TCARI/OSAVI (Fig.2). No correlations however were obtained with the other chlorophyll sensitive indicator, R_{700}/R_{670}. When comparing results from the two almond cultivars used in the study (*cv.* 'Garrigues' and *cv.* 'Ramillete'), the relationships obtained between $PRI_{(570-515)}$ or TCARI/OSAVI and Ψ_s, g_s and CWSI were similar. Nevertheless, PRI and NDVI relationships with Ψ_s, g_s and CWSI were weaker for *cv.* 'Ramillete' (r^2 ranging from 0.13 to 0.68) than for *cv.* 'Garrigues' (r^2 ranging from 0.46 to 0.89).

Apricot trees were in the stage of postharvest when the experiment was performed. Unlike the other crops, these trees were not irrigated before the experiment and irrigation was applied to selected trees to promote variability in water status within the orchard. Contrary to that obtained for almond trees, no correlations were found between Ψ_s, g_s or CWSI and any of the PRI formulations studied. NDVI was significantly correlated with g_s (r^2=0.42; $p<0.05$) and CWSI (r^2=0.69; $p<0.01$) but not with Ψ_s. Among the spectral indices, TCARI/OSAVI was the indicator that yielded the best correlations in apricot trees with Ψ_s, g_s and CWSI (r^2 ranging from 0.77 to 0.88; $p<0.001$). Moreover, as also observed in almond trees, TCARI/OSAVI was highly correlated with Pn (Fig. 2). Differences in the relationship between TCARI/OSAVI and Pn observed between apricot and almond trees may be related to differences in phenological stage between these two crops.

Results obtained in the peach orchard were somewhat different from those reported for almond and apricot trees (Table 5). High correlations were obtained for all the spectral indices with the exception of PRI_{570} and TCARI/OSAVI. $PRI_{(570-515)}$, PRI_{norm}, R_{700}/R_{670} and NDVI yielded similar r^2 when depicted against CWSI (0.61 to 0.68; $p<0.001$). PRI_{norm} and R_{700}/R_{670}, however, were the spectral indices with the highest correlations with Ψ_s and g_s (r^2 from 0.81 to 0.93; $p<0.001$).

Different results were obtained for each crop depending on their particular characteristics. Chlorophyll sensitive indices performed better for *Citrus* and apricot trees; while indices sensitive to changes in the xanthophyll cycle were better for almond trees and both of them (chlorophyll and xanthophyll sensitive indices) performed well in peach. Most of the studies found in the literature assessing the use of spectral information to detect plant water stress have been conducted in one particular crop, generally crops of high economic interest such as olive (Berni et al., 2009; Suarez et al., 2008; Zarco-Tejada et al., 2004) and grapevines (Gago et al., 2015 and references therein). Zarco-Tejada et al. (2013) showed that PRI_{norm} was a more reliable water stress indicator (r^2 = 0.82 when compared against Ψ_s) than PRI_{570} (r^2=0.53) in grapevines.

Here, PRI_{norm} performed better than PRI_{570} in peach trees (Table 5) but the contrary was observed for almond trees.

In the present study multispectral indices were assessed in a farm composed of crops with different canopy architecture, nutrient status and phenology, which made that a specific indicator performed better in some crops than in others. The use of a single multispectral indicator that would be sensitive enough to variations in the plant water status of several crops would facilitate the assessment of irrigation needs at the farm scale and consequently would improve the current options that growers have regarding irrigation decision making

Performance of the spectral water stress indicators for the five fruit crops together

Pooling data from all the fruit tree crops species together, $PRI_{(570-515)}$, PRI_{norm}, R_{700}/R_{670} and NDVI showed a statistically significant correlation with Ψ_s with r^2 ranging between 0.15 and 0.65 (Table 6). Linear relationships were found for $PRI_{(570-515)}$, PRI_{norm} and NDVI while R_{700}/R_{670} was best-fitted by a polynomial curve (Fig.3). Among these indicators, $PRI_{(570-515)}$ and NDVI were those which yielded the highest r^2 (0.61 and 0.65, respectively; $p<0.001$). Although weak, statistically significant correlations were also found between $PRI_{(570-515)}$, PRI_{570} and NDVI with g_s (r^2 of 0.16-0.18; $p<0.01$), and between $PRI_{(570-515)}$, PRI_{norm}, R_{700}/R_{670} and NDVI with CWSI (r^2 ranging from 0.19 to 0.33; $p<0.01$) (Table 6).

Mean chlorophyll content within the farm ranged from 9.51 $\mu g\ cm^{-2}$ in lemon trees to 41.26 $\mu g\ cm^{-2}$ in almond (Table 7). Both, TCARI/OSAVI and R_{700}/R_{670} index were statistically correlated with leaf chlorophyll concentration when data from all the species were pooled together (Fig.4). The red edge ratio, however, yielded the highest r^2 (0.58).

Results showed that $PRI_{(570-515)}$ and NDVI seemed to perform better when contrasting crop species are assessed together. The PRI_{norm}, which was originally formulated to deal with contrasting canopy architecture and pigment content, did not perform as was expected. The non-linear relationship observed between water potential and the red edge ratio (R_{700}/R_{670}) might be responsible for the low performance observed for this index. Future works dealing with new formulations for PRI_{norm} might improve the performance of the index for a wide range of vegetation characteristics, as those observed in the present study.

Conclusions

The work presented here compares the sensitivity to water stress of spectral indices obtained from measurements at leaf and canopy levels. It also explores the relationships between multispectral-derived indices and the established methods for water stress determinations taken in five of the most representative fruit crop species of the area of the study. Finally, it explores which of the multispectral indices tested has the broadest performance for water stress detection when contrasting plants in canopy architecture and phenology are assessed together.

The sensitivity analysis showed $PRI_{(570-515)}$ as the second most sensitive indicator after T_c (and Ψ_s in apricot trees), and the most sensitive indicator among the multispectral indices tested. Within each of the crops studied, chlorophyll-sensitive indices (TCARI/OSAVI) performed better in *Citrus* and apricot trees while indices sensitive to changes in the xanthophyll cycle ($PRI_{(570-515)}$ and PRI_{570}) performed better in almond trees. Most of the multispectral indices (with the exception of PRI_{570} and TCARI/OSAVI), however, were well correlated in peach trees. In spite of these different relationships obtained between the multispectral-derived indices and Ψ_s, g_s or CWSI for each of the fruit crop species, $PRI_{(570-515)}$ and NDVI were sensitive enough (r^2 = 0.61 and 0.65, respectively) to determine the plant water status when all of the fruit crops were analyzed together. These results demonstrate the feasibility of using multispectral narrow-band indices (i.e. 10 nm bandwidths) acquired from miniature cameras on board RPAS platforms to retrieve water status for a variety of crop species with contrasted phenology and canopy architecture.

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Table 1 Planting space, canopy ground cover and number of emitters used per tree within each of the orchards. The number of irrigation units established per orchard is also shown.

Species	**Planting space (m)**	**GC (%)**	**# Emitters tree^{-1} (4 l h^{-1})**	**# Irrigation units**
Almond	6 x 8	40	5	3
Apricot	6 x 8	65	5	2
Peach	4 x 6	48	3	4
Lemon	6 x 8	41	5	2
Orange	4 x 6	51	3	3

Table 2 Formulations used to obtain the vegetation indices Photochemical Reflectance Index (PRI), normalized Photochemical Reflectance Index (PRI_{norm}), $PRI_{(570-515)}$, R_{700}/R_{670}, Normalized DifferenceVegetation Index (NDVI) and Transformed Chlorophyll Absorption in Reflectance Index normalized by the Optimized Soil Adjusted Vegetation Index (TCARI/OSAVI).

Index	**Formulation**	**Reference**
PRI_{570}	$(R_{570} – R_{530}) / (R_{570} + R_{530})$	Gamon et al. (1993)
$PRI_{(570-515)}$	$(R_{570} – R_{515}) / (R_{570} + R_{515})$	Hernandez-Clemente et al., 2011
PRI_{norm}	PRI_{570} / [RDVI (R_{700}/R_{670})]	Zarco-Tejada et al. (2013)
R_{700}/R_{670}	R_{700}/R_{670}	Part of TCARI index
NDVI	$(R_{800} - R_{670}) / (R_{800} + R_{670})$	Rose et al. (1974)
TCARI/OSAVI	$[3[(R_{700} - R_{670}) – 0.2 (R_{700}/R_{550}) (R_{700}/R_{670})]] / [(1 + 0.16) (R_{800} - R_{670}) / (R_{800} + R_{670} + 0.16)] R_{700}/R_{670}$	Haboudane et al. (2002)

Table 3 Number of trees in which measurements of stem water potential (Ψ_s), stomatal conductance (g_s), leaf net CO_2 assimilation (P_n) and leaf chlorophyll content (Chl) were taken within each irrigation treatment.

	Ψ_s		g_s		Pn		Chl	
Species	**WW**	**DI**	**WW**	**DI**	**WW**	**DI**	**WW**	**DI**
Almond	10	12	10	12	10	12	6	6
Apricot	6	4	6	4	6	4	6	4
Peach	5	5	5	5	-	-	3	2
Lemon	5	5	5	5	-	-	4	4
Orange	12	6	5	3	-	-	6	6

Table 4 Sensitivity of the water stress indicators for each species assessed in the experiment. Data obtained from measurements taken at 13:00 h.

	Ψ_s	**g_s**	**T_c**	**NDVI**	**R_{700}/R_{670}**	**TCARI/OSAVI**	**PRI_{570}**	**$PRI_{(570-515)}$**	**PRI_{norm}**
Almond									
Signal	2.04	4.38	1.06	1.12	1.01	1.31	1.66	1.11	1.58
Noise	0.16	0.27	0.02	0.12	0.12	0.11	0.20	0.03	0.45
Sensitivity (signal/noise)	12.66	16.47	**56.06**	9.37	8.29	11.39	8.41	41.97	3.52
Lemon									
Signal	1.18	1.11	1.05	1.02	1.20	1.09	0.98	1.01	0.85
Noise	0.09	0.26	0.01	0.03	0.08	0.04	0.18	0.02	0.36
Sensitivity	13.44	4.36	**124.10**	35.40	14.81	25.43	5.48	65.12	2.38
Apricot									
Signal	1.76	3.90	1.13	1.13	0.94	1.51	0.91	1.07	0.79
Noise	0.02	0.19	0.05	0.07	0.07	0.07	0.07	0.04	0.28
Sensitivity	**77.18**	20.32	24.91	16.21	13.86	21.60	13.59	25.74	2.82
Apricot (11:00)									
Signal	2.11	2.21	1.08						
Noise	0.07	0.40	0.02						
Sensitivity	31.24	5.51	**52.74**						
Peach									
Signal	2.84	2.95	1.17	1.14	0.75	0.92	0.91	1.13	0.51
Noise	0.22	0.59	0.03	0.13	0.19	0.08	0.17	0.08	0.39
Sensitivity	12.76	5.02	**40.47**	9.08	3.96	9.08	5.22	14.30	1.30

Table 5 Coefficients of determination obtained for the relationships between the spectral indices and the more classical water stress indicators: stem water potential (Ψ_s), stomatal conductance (gs) and crop water stress index (CWSI) for each of the crops and cultivars studied.

	PRI_{570}	$PRI_{(570-515)}$	PRI_{norm}	R_{700}/R_{670}	NDVI	TCARI/OSAVI
Almond						
Ψ_s	0.52***	0.53***	0.13	0.01	0.33**	0.39**
gs	0.52***	0.45**	0.14	0.01	0.32*	0.65***
CWSI	0.32**	0.79***	0.01	0.07	0.70***	0.45**
Almond 'Garrigues'						
Ψ_s	0.46*	0.66**	0.21	0.00	0.74***	0.37*
gs	0.75***	0.78***	0.49*	0.10	0.75***	0.72***
CWSI	0.55**	0.77***	0.31	0.03	0.89***	0.57**
Almond 'Ramillete'						
Ψ_s	0.68**	0.72**	0.24	0.00	0.13	0.54*
gs	0.36	0.59**	0.07	0.01	0.51*	0.61**
CWSI	0.37	0.79***	0.07	0.05	0.65**	0.79***
Orange						
Ψ_s	0.16	0.10	0.11	0.02	0.02	0.04
gs	0.25	0.20	0.32	0.62*	0.13	0.00
CWSI	0.08	0.07	0.10	0.06	0.00	0.07
Lemon						
Ψ_s	0.02	0.02	0.10	0.22	0.02	0.41*
gs	0.15	0.38	0.14	0.23	0.00	0.08
CWSI	0.03	0.03	0.19	0.64***	0.14	0.18
Apricot						
Ψ_s	0.00	0.16	0.03	0.04	0.32	0.88***
gs	0.10	0.06	0.23	0.21	0.42*	0.77***
CWSI	0.06	0.18	0.38	0.34	0.69**	0.82***
Peach						
Ψ_s	0.21	0.58*	0.81***	0.88***	0.72**	0.29
gs	0.27	0.56*	0.84***	0.93***	0.71**	0.31
CWSI	0.17	0.61***	0.67***	0.62***	0.68***	0.20

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Table 6 Coefficients of determination obtained for the relationships between the spectral indices and the stem water potential (Ψ_s), stomatal conductance (gs) or crop water stress index (CWSI) when data for all the species were pooled together.

	$PRI_{(570-515)}$	PRI_{570}	PRI_{norm}	R_{700}/R_{670}	NDVI	TCARI/OSAVI
Ψ_s	0.61***	0.01	0.15**	0.42***	0.65***	0.06
gs	0.18**	0.18**	0.02	0.00	0.16**	0.05
CWSI	0.19***	0.06	0.23***	0.27***	0.33***	0.10

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Table 7 Mean total chlorophyll content in well-watered and deficit-irrigated trees of each species. The coefficient of variation (C.V.) within each fruit tree crop studied and the number of measurements (n) taken in each case are also shown.

	Chl (µg cm-2)			
	Control	**Deficit irrigated**	**C.V.**	**n**
Almond	34.61 ± 3.80	28.21 ± 2.32	25.71	12
Almond cv. Ramillete	27.97 ± 4.77	26.98 ± 2.63	23.74	6
Almond cv. Garrigues	41.26 ± 2.29	29.44 ± 4.31	21.80	6
Orange	11.63 ± 3.76	16.61 ± 3.66	28.07	12
Lemon	13.77 ± 2.56	9.51 ± 0.66	35.61	8
Apricot	34.74 ± 4.16	29.29 ± 2.66	26.61	10

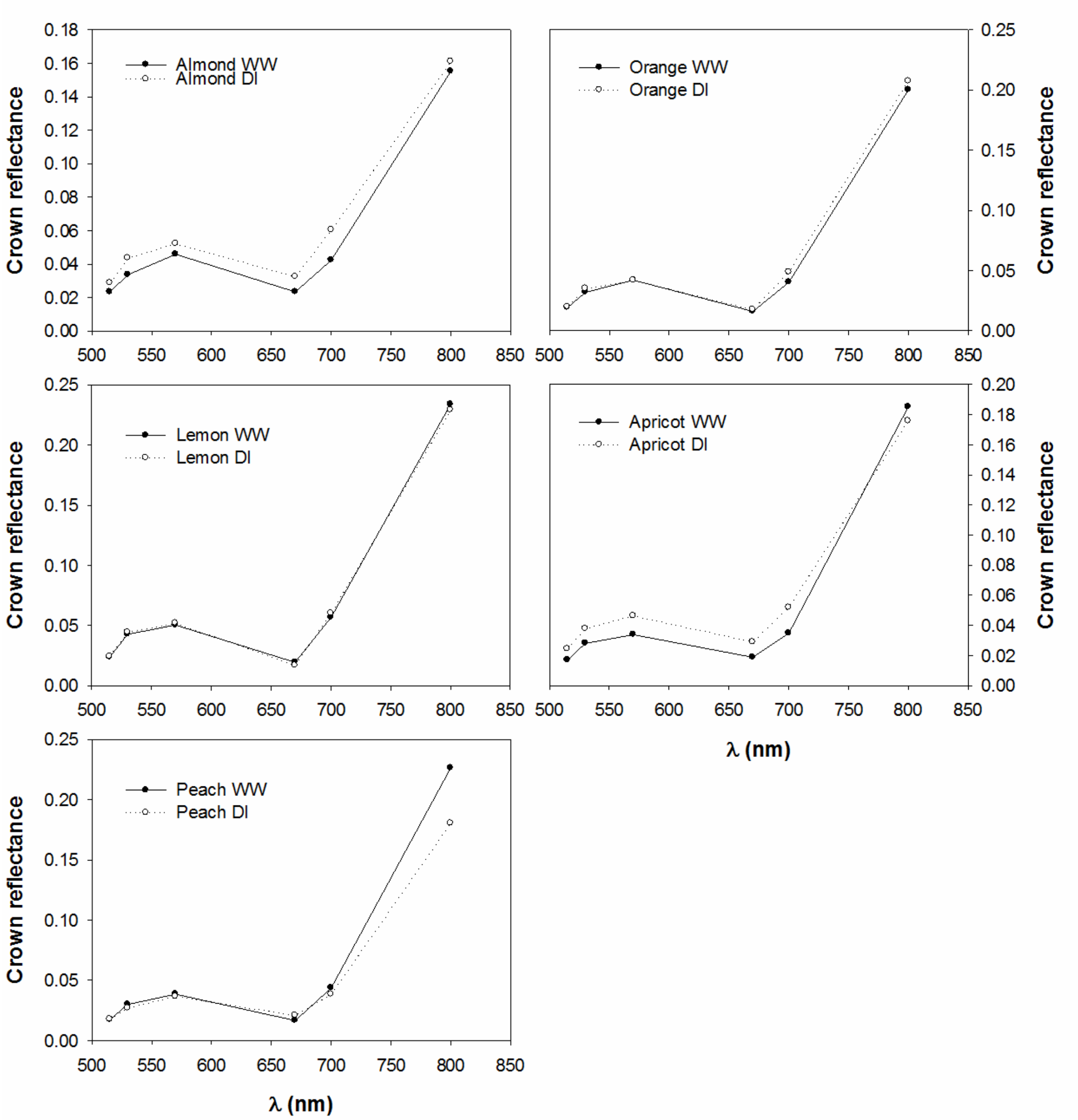

Figure 1 Average crown reflectance derived from the imagery of well-watered and deficit irrigated trees for each of the five species studied.

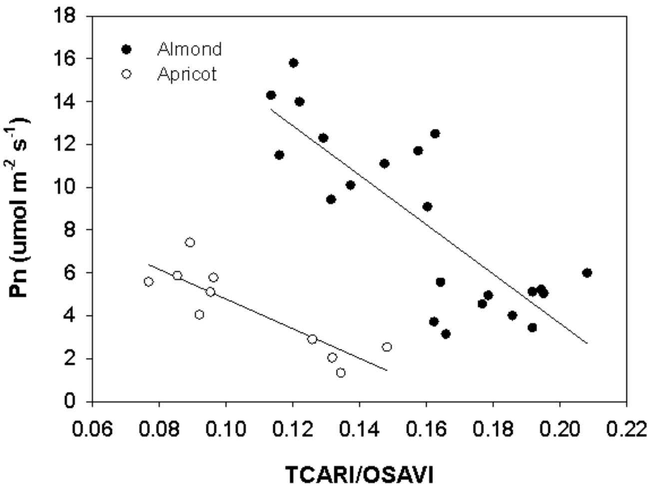

Figure 2 Relationships between photosynthesis (Pn, µmol m^{-2} s^{-1}) and TCARI/OSAVI obtained in almond ($r^2 = 0.67$; $p<0.001$) and apricot ($r^2 = 0.75$; $p<0.001$) trees.

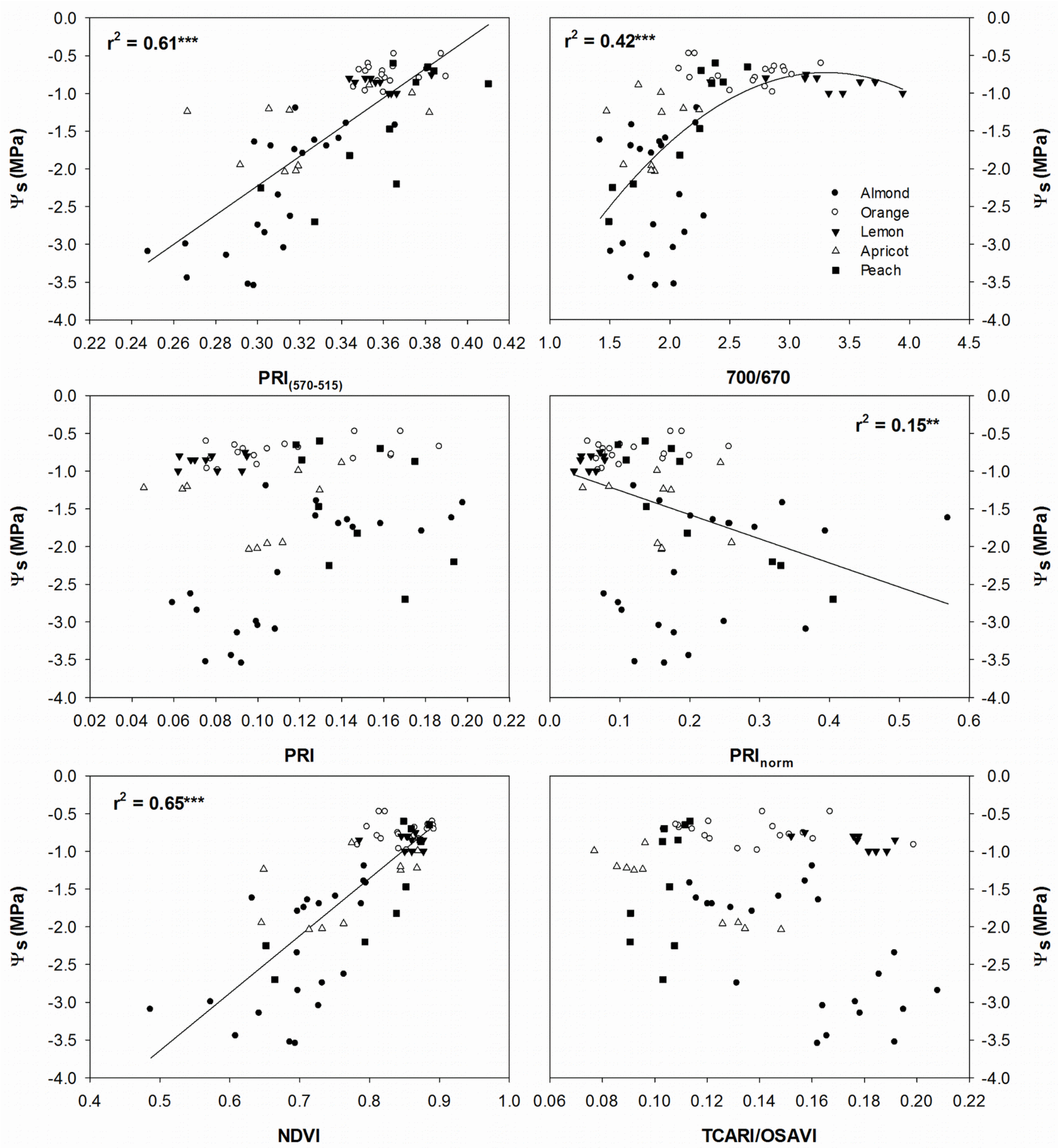

Figure 3 Relationships between stem water potential (Ψ_s) and the multispectral indices studied ($PRI_{(570-515)}$, 700/760, PRI, PRI_{norm}, NDVI and TCARI/OSAVI) for all the fruit species together.

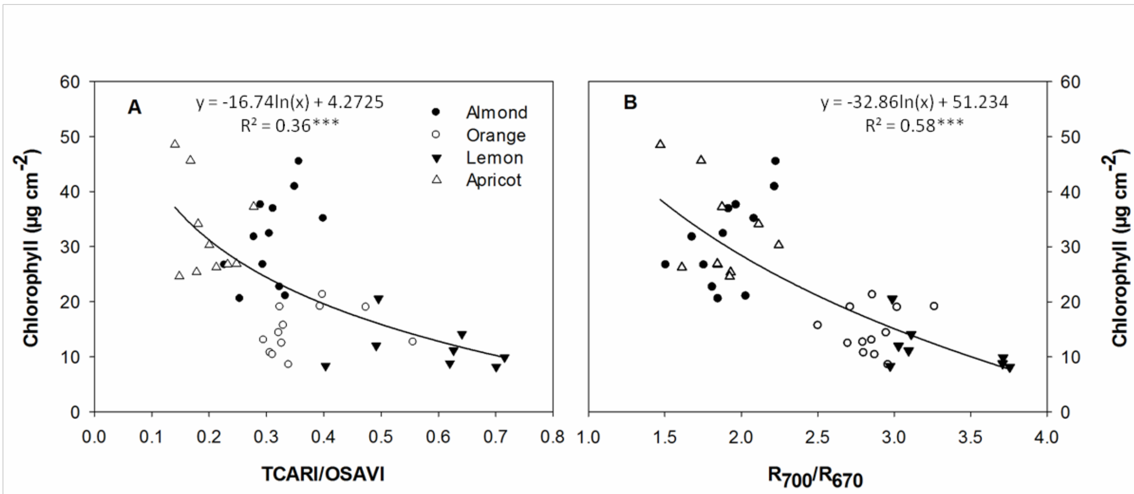

Figure 4 Relationships between leaf chlorophyll content and the ratio TCARI/OSAVI (A) and R_{700}/R_{670} (B) for all the crop species together.