Environmental and Experimental Botany 99 (2014) 43–52

Contents lists available at ScienceDirect

Environmental and Experimental Botany

journal homepage: www.elsevier.com/locate/envexpbot

# Assessing gas exchange, sap flow and water relations using tree canopy spectral reflectance indices in irrigated and rainfed *Olea europaea* L.

Giovanni Marino[a,b], Emanuele Pallozzi[c], Claudia Cocozza[b], Roberto Tognetti[b], Alessio Giovannelli[d], Claudio Cantini[d], Mauro Centritto[a,*]

[a] *Institute for Plant Protection, National Research Council, Via Madonna del Piano 10, 50019 Sesto Fiorentino, FI, Italy*
[b] *Dipartimento di Bioscienze e Territorio, Università degli Studi del Molise, Contrada Fonte Lappone, 86090 Pesche, IS, Italy*
[c] *Institute of Agro-Environmental and Forest Biology, National Research Council, Via Salaria km 29.300, 00015 Monterotondo Scalo, RM, Italy*
[d] *Trees and Timber Institute, National Research Council, Via Madonna del Piano 10, 50019 Sesto Fiorentino, FI, Italy*

## ARTICLE INFO

*Article history:*
Received 29 April 2013
Received in revised form 9 October 2013
Accepted 11 October 2013

*Keywords:*
Canopy reflectance
Canopy transpiration
Diurnal course
Drought
Leaf gas exchange
Water status

## ABSTRACT

Diurnal and seasonal trends of leaf photosynthesis ($A$), stomatal conductance to water ($g_s$) and water potential ($\Psi_l$), whole-plant transpiration and tree canopy spectral reflectance indices were evaluated in rainfed and well-watered (control) mature olive (*Olea europaea* L., cv. Leccino) trees. The objective was to evaluate whether photochemical reflectance index (PRI), water index (WI) and normalized difference vegetation index (NDVI) could be used for detecting plant functioning in response to seasonal drought. The measurements were made from March to November, repeated every four weeks during the drought period of the growing season. Rainfed trees were subjected to prolonged water deficit with soil water content ranging between ~30% and 50% than that of control. Consequently, there were significant differences in the diurnal trend of $\Psi_l$, $A$, $g_s$ and sap flux density between treatments. Under severe drought, $\Psi_l$ ranged between $\sim -4.5$ MPa (predawn) and $\sim -6.4$ MPa (midday), $A$ ranged between maximum morning values of $\sim 6\ \mu\text{mol m}^{-2}\ \text{s}^{-1}$ and minimum late afternoon values of $2.5\ \mu\text{mol m}^{-2}\ \text{s}^{-1}$, $g_s$ was lower than $\sim 0.03\ \text{mol m}^{-2}\ \text{s}^{-1}$ for most of the daily courses, whereas stem sap flux density reached maximum peaks of $2.1\ \text{g m}^{-2}\ \text{s}^{-1}$ in rainfed plants. The diurnal trends of all these parameters fully recovered to the control level after autumn rains. PRI, NDVI, and WI of olive tree canopy assessed significantly the effects of drought on rainfed trees and their subsequent recovery. PRI resulted better correlated with $A$ ($r^2 = 0.587$) than with the other measured parameters, pooling together values measured during the whole growing season. In contrast, NDVI showed a stronger relationship with $\Psi_l$ ($r^2 = 0.668$) and $g_s$ ($r^2 = 0.547$) than with $A$ ($r^2 = 0.435$) and whole-plant transpiration ($r^2 = 0.416$). WI scaled linearly as $g_s$ and $\Psi_l$ increased ($r^2 = 0.597$ and $r^2 = 0.576$, respectively) and, even more interestingly, a good correlation was found between WI and whole-plant transpiration ($r^2 = 0.668$) and between WI and $A$ ($r^2 = 0.640$). Overall PRI and WI ranked better than NDVI for tracking photosynthesis, whereas WI was the most accurate predictive index of plant water status and whole-plant transpiration. This study, which is the first to our knowledge that combines diurnal and seasonal trends of leaf gas-exchange, whole-plant transpiration and reflectance indices, clearly shows that PRI and WI measured at the tree canopy can be used for fast, nonintrusive detection of water stress.

## 1. Introduction

Water is the most limiting resource in the Mediterranean region, where the climate is typically characterized by high potential evaporation and low and highly variable rainfall during the growing season. The agricultural sector is the largest water consumer accounting for about 70% of all extracted water (Gilbert, 2012). In the Mediterranean regions, agriculture consumes on average about 65% of total water abstraction (Simonet, 2011). Climate change, which is increasing the chronic water scarcity in the Mediterranean basin (Dai, 2010), together with rapidly growing demand of water for industrial and urban uses, is likely to put under unprecedented pressure the limited water resources for agriculture. Therefore, the major need for development of irrigation is to save substantial water through improved irrigation management and increased water productivity (Fereres et al., 2011).

Optimization of irrigation requires the retrieval of real time crop condition and its sensitivity to water stress, which, in turn, results

---

* Corresponding author at: CNR-IPP, Via Madonna del Piano 10, 50019 Sesto Fiorentino, FI, Italy. Tel.: +39 055 5225585; fax: +39 055 5225666.
*E-mail address:* mauro.centritto@cnr.it (M. Centritto).

0098-8472/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.envexpbot.2013.10.008

from specific physiological status, soil–water availability, climatic conditions (Centritto et al., 2000; Tognetti et al., 2009). Water deficit constraints all the physiological processes involved in plant growth and development. These changes are part of a cascade of responses to drought affecting primary processes including tissue water relations and gas exchange mechanisms (Alvino et al., 1994; Magnani et al., 1996; Aganchich et al., 2009). It is of paramount importance, consequently, to improve non-invasive phenotyping methods to monitor water relations and photosynthetic status in plants experiencing water stress (Loreto and Centritto, 2008; Centritto et al., 2009). Continuous recording of sap flow rate might provide indirect measurements of plant water status, and represent a promising tool for the development of monitoring systems in olive tree plantations to determine irrigation needs in real time, or at least at frequent intervals, and for being integrated with remote sensing techniques in precision irrigation management and control (Fernández et al., 2008).

Major progress has been made with the use of remotely sensed vegetation indices to assess physiological traits associated with plant water status (Peñuelas and Filella, 1998; Sun et al., 2008; Garbulsky et al., 2011). The methodology is based on a number of visible (Vis)- and near infrared (NIR)-based indices as indicators of photosynthetic activity (Gamon et al., 1997) and water status (Sun et al., 2008; Elsayed et al., 2011). The photochemical reflectance index, which was originally developed to estimate rapid changes in the xanthophyll (Gamon et al., 1992), is increasing used to asses changes in the efficiency of photosynthetic activity (Garbulsky et al., 2011) at different plant scale level (Gamon et al., 1997; Garbulsky et al., 2008; Naumann et al., 2008; Suárez et al., 2008). Relationships between photosynthetic parameters and PRI determined at canopy level have been reported in studies performed on grassland, sunflower, grapevine, and olive (see Garbulsky et al., 2011 for a review). Similarly, the NIR-based water index (WI) is increasingly employed for monitoring plant water status (Peñuelas et al., 1993; Peñuelas and Filella, 1998). Whereas, the normalized difference vegetation index (NDVI), which is based on different radiation absorption by green biomass in Red and NIR wavebands (Rouse et al., 1973), is widely used for the assessment of the green plant biomass at ground, airborne and satellite levels (Peñuelas and Filella, 1998). Further indications about the physiological status of plant can be obtained by the evaluation of the photosynthetic pigment composition. For this purpose, Chlorophyll Index (CI) and Structural Independent Pigment Index (SIPI) were developed to assess chlorophyll concentration and carotenoids/chlorophyll ratio, respectively (Gitelson and Merzlyak, 1994; Peñuelas and Filella, 1998).

Olive (*Olea europaea* L.) is a drought tolerant species which has been traditionally cultivated in agricultural rainfed systems in the Mediterranean basin. However, to promote olive fruit production and its economic competitiveness, there has been a large increase in the amount of irrigation water used in olive farming over the past years. To detect water needs, in order to increase water productivity through the management of precision irrigation (Fereres et al., 2011), studies have been recently performed on olive potted plants for remote sensing of water stress using rapid spectral reflectance measurements of leaf water status and photosynthetic limitations (Sun et al., 2008; Sun et al., unpublished data). In the present work, photosynthesis, whole-plant transpiration and spectral reflectance indices were measured in mature olive trees under rainfed conditions and in irrigated control. Furthermore, the effects of water deficit on specific leaf area, pigment and nitrogen concentration were evaluated. The aim of this work was to evaluate whether PRI, WI and NDVI could track rapid changes in plant functioning also in field-grown plants subjected to seasonal drought and if CI and SIPI could detect variations occurred in pigment composition.

## 2. Materials and methods

### 2.1. Field conditions and plant material

The experiment was performed at the "Santa Paolina" experimental station of the CNR-IVALSA, located in Follonica, central Italy (42°55′58″ N, 10°45′51″ E, 17 m a.s.l.). The olive orchard used consisted of 10-year-old trees (*O. europaea* L., cv. Leccino) spaced at 4 × 4 m. The soil is sandy-loam (sand 64.2%, silt 16.9% and clay 18.9%). The soil belongs to the Piane del Pecora system and was developed on recent alluvional deposits of river and river-pond nature. The depth of the soil was 3 m. The climate is of Mediterranean type with hot and dry seasons from April to September and cold winters. In the three growing seasons preceding the experiment, all trees were equally irrigated with microsprayers located 30 cm from the trunk irrigating an area of soil with a ray of 1.25 m to guarantee the uniformity of plant development. Two irrigation treatments (rainfed and well-watered control) were applied starting from Mid-May of 2011. The amount of water supplied to the control trees was estimated weekly by calculating reference evapotranspiration according to the Penman-FAO equation and crop evapotranspiration (Doorenbos and Pruitt, 1977) using a crop coefficient of 0.5 as reported by Gucci (2003) for the same area and plantation. The coefficient of ground cover was 0.8, according to tree size. The volume of the irrigation water was then adjusted in order to keep predawn leaf water potential ($\Psi_1$) around −0.5 MPa. The irrigation period lasted from mid-May to late October 2011; each of the control trees received an average of 3900 L of water. During this period the precipitation was 125 mm with a peak on July (51.6 mm).

### 2.2. Meteorological data

Climate data were recorded every 15 min by a standard meteorological digital station placed at 100 m from the orchard (quality-controlled data were supplied by the Laboratory of monitoring and environmental modeling for the sustainable development, Florence, http://www.lamma.rete.toscana.it/en). The variables measured were air temperature (°C), precipitations (mm) and relative humidity (RH, %).

### 2.3. Soil water content measurements

Volumetric soil moisture content was measured using Terrasense SMT2 soil moisture sensors (model PS-0077-DD, Netsens s.r.l, Florence, Italy) installed in the middle of the irrigation ray at an average distance of 90 cm from the trunk and at 10 cm and 30 cm depths in each plot. Soil moisture content was acquired every 15 min with a Netsens communication platform based on a GPRS integrated main unit, a wireless units and LiveData® software for data storage and elaboration.

### 2.4. Sap flow measurements

Granier-type sensors (Granier, 1985) were inserted radially into 20 mm depth of the stem at the height of ~1.3 m in six plants. These sensors consisted of a pair of copper-constant thermocouples of the same diameter vertically spaced of ~15 cm. The upper probe was continuously heated through a heating wire supplied with a constant power source (120 mA). The temperature difference of the two probes was recorded to obtain the sap flux density, as derived empirically (Granier, 1987; Huang et al., 2009). Sap flux density ($F_d$, $g\,H_2O\,m^{-2}\,s^{-1}$) was monitored using self-made thermal dissipation probes (SF-L sensor) (Granier, 1987):

$$F_d = \alpha K^{\beta}$$