

Detecting leaf-water content in Mediterranean trees using high-resolution spectrometry

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ABSTRACT

Water content of the vegetation canopy or individual leaves is an important variable in physiological plant processes. In Mediterranean regions where water availability is an important production limiting factor, it is a strong indicator of vegetation stress. Spectroscopic earth-observation techniques in the solar part of the electromagnetic spectrum provide opportunities to determine leaf and canopy-water content due to the presence of water-absorption bands around 970 and 1200 nm. We investigated the possibilities to predict leaf-water content of three dominant tree species in a study area in Mediterranean France using spectral indices. During a field campaign leaf-water content (EWT) was determined and high-resolution spectra were measured of the same leaves. The spectra were measured in two ways: using an optical cable with a field of view of 25° and using a leaf clip with its own artificial illumination source. The spectra were analyzed and related to leaf-water content as original reflectance spectra and as continuum-removed spectra using eight spectral leaf-water indices. Next, reflectance spectra were simulated to explore their sensitivity to environmental conditions like leaf area index and illumination angle using a radiative transfer model. Results show that a good correlation (0.70) exists between leaf-water content and spectral indices using the right slope of the 970 nm water-absorption band. Continuum-removal correction of the spectra improved the relations. The model sensitivity analysis illustrated that from a set of five environmental variables leaf area index has, as may be expected, an important impact on leaf-water estimates. This field and model study illustrates that it is feasible to determine foliar water content on the basis of spectral indices located around the minor water-absorption bands with a limited effect of environmental conditions.

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1. Introduction

Leaf-water content and canopy-water content are important variables in a variety of environmental processes. Foliar water plays a key role in biogeochemical processes such as photosynthesis, evapotranspiration and net primary production (Running and Gower, 1991; Running and Nemani, 1991). Water uptake by roots and evapotranspiration through the stomata of the leaves are driving processes in forest productivity models and controlling respiration and maintenance (Running and Coughlan, 1988). A fast decrease or a lack of leaf-water content is an important early stress indicator (De Jong et al., 2012). Mapping and monitoring of leaf and canopy-water content is relevant for a wide range of applications. Ustin et al. (2004) used it to detect location of environmental stress and Yilmaz et al. (2008) used it to study soil moisture retrievals. In wildfire risk modeling canopy-water content is important to distinguish between dry and wet

fuel (Sow et al., 2013; Maki et al., 2004; Dennison et al., 2003). These applications are especially relevant in arid and semi-arid regions like the Mediterranean area, where water is a major growth limiting factor. Mediterranean climates are characterized by a long hot and dry summer, a wet fall and spring, and mild winters. Especially the summer period and the irregularities in annual precipitation create harsh conditions for plant growth. Plant species growing in the Mediterranean region have developed various mechanisms to cope with periods of water shortage. These sclerophyllous species often have thick and smaller leaves, low rates of photosynthesis, low maximum stomatal conductance (and hence reduced transpiration), reduced evapotranspiration by leaf wax layers, deep and dual root systems, high nutrient-use efficiency, controlled diffuse resistance of stomata, and controlled leaf shedding (Sardans and Peñuelas, 2013; Misson et al., 2011; Lambers et al., 1998; Aerts, 1995; Damesin and Rambal, 1995; Pugnaire et al., 1994). All of which promote efficient water use.

Climate change scenarios predict important changes in the spatial and temporal patterns of temperature, precipitation and hence water availability for crops and plants (IPCC, 2007), which may threaten the existence of the Mediterranean ecosystems. Scenarios

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predict an air temperature increase for the entire Mediterranean area for all months of the year between 2° and 4° by the end of the 21st century (UNEP, 2009; Hertig and Jacobeit, 2008; Fischer and Schär, 2008). Predictions of precipitation for the winter months show a small increase over the northern European Mediterranean area and a small decrease over the southern part. For the summer months, however, the precipitation decrease is estimated between 25% and 50% for the entire area (Gao and Giorgi, 2008). Although the uncertainty of these model predictions is considerable, any temperature change will have an important impact on evaporation rates and thus on water availability for vegetation.

Spectroscopic techniques in the solar part of the spectrum (400–2500 nm) provide possibilities to quantify and to map leaf-water content. Particularly the minor water-absorption bands (around 970 and 1200 nm), rather than the major water-absorption bands (around 1400 and 1900 nm) provide information of leaf-water status (Clevers et al., 2010; Zarco-Tejada et al., 2003; Ceccato et al., 2001; Peñuelas et al., 1997, 1993; Kumar et al., 2002; Gao and Goetz, 1995). Theoretical studies using radiation transfer model simulations like Ceccato et al. (2002) illustrate the physical relation between leaf water and absorption bands, while practical field and laboratory studies like Sims and Gamon (2003) show the value of spectral indices for assessing leaf-water content. Leaf reflectance is, however, not only determined by water content but by many other factors like leaf structure, pigments, air spaces in the leaf, leaf angle, morphology of the leaf, illumination direction, and viewing direction, making it difficult to estimate leaf-water content from reflectance measurements independent of these extraneous factors.

Various algorithms are described in literature to assess leaf-water content from spectral information based on the idea that depth and shape of the water-related absorption band is indicative for leaf-water content (Ceccato et al., 2002). It should be noted that the used water-absorption wavelengths are not always exactly the same for the algorithms indices but studies report slightly different optimal absorption bands. Danson et al. (1992) used six wavebands of maxima and minima of water absorption, centered at 975, 1175, 1450, 1650, 1950 and 2250 nm and first derivative of spectra to determine leaf-water content. Peñuelas et al. (1997, 1993) developed the reflectance water index using a ratio of reflectance at 900 and 970 nm to estimate plant water content. Sims and Gamon (2003) analyzed spectral water indices in three wavelength regions 950–970, 1150–1260 and 1520–1540 nm to estimate vegetation water content from reflectance spectra. Clevers et al. (2010, 2008) used features around the 970 and 1200 nm and investigated derivative spectra, maximum band depth and area under curve algorithms to map leaf-water content.

The objective of this study is to determine the optimal index to estimate leaf-water content (equivalent water thickness, EWT) of Mediterranean tree species from field high-spectral-resolution signatures. The research questions that we formulated are (1) which index provides the best correlation between field-observed EWT and the associated field-measured spectral signatures?, and (2) which part of the spectrum is least sensitive to environmental conditions?

2. Study area

The selected tree locations for this study are situated in the Payne catchment in Mediterranean southern France, approximately 60 km west of the city of Montpellier. The study area is covered by semi-natural vegetation and agricultural crops, i.e. vineyards and pasture. Our tree measurement sites are all located in areas with natural growth. The vegetation mainly consists of evergreen shrubs and trees and is sclerophyll (Sluiter and De Jong,

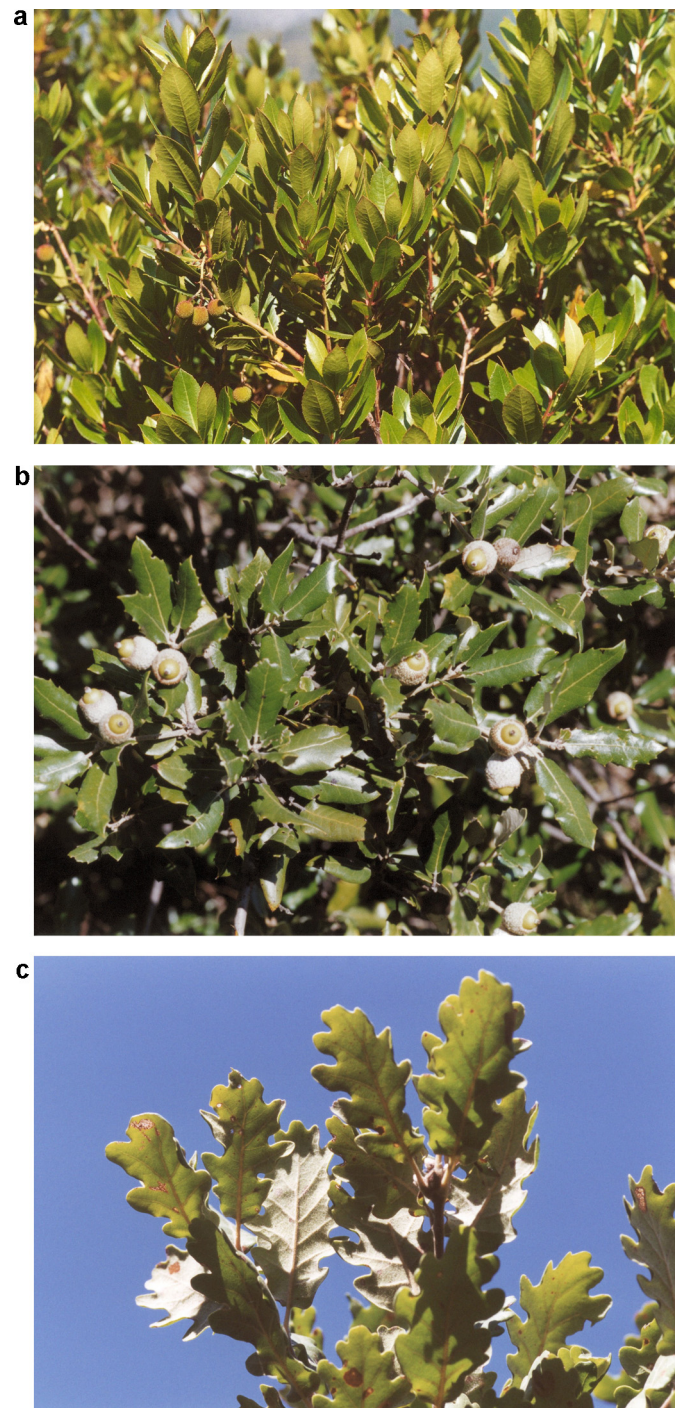


Fig. 1. Field pictures of the three, for this study selected, tree species (a) *Arbutus unedo* (Strawberry tree), (b) *Quercus ilex* (Holm Oak) and (c) *Quercus pubescens* (Downy Oak). The three species are typical and dominant for the Mediterranean region.

Courtesy pictures: Dr. R. Sluiter.

2007). Tree height varies up to 15 m with little or no understory vegetation. Much of the area has been cultivated as coppices (Mather et al., 1999), which has resulted in many small stems sprouting from a shared root system. For our study we made a selection of the dominant tree species and species typical for the Mediterranean area: *Arbutus unedo* (Strawberry tree), *Quercus ilex* (Holm Oak) and *Quercus pubescens* (Downy Oak) (Fig. 1). Their most important characteristics are the following (Polunin and Huxley, 1987):

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