Remote Sensing of Environment 143 (2014) 39–53

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

# Detecting diurnal and seasonal variation in canopy water content of nut tree orchards from airborne imaging spectroscopy data using continuous wavelet analysis

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ARTICLE INFO

*Article history:*
Received 18 August 2013
Received in revised form 19 November 2013
Accepted 19 November 2013
Available online 19 January 2014

*Keywords:*
Canopy water content
Wavelet analysis
Diurnal
Seasonality
Imaging spectroscopy
Spectral index

ABSTRACT

Continuous wavelet analysis (CWA) has recently been applied to leaf-level spectroscopic data for quantifying foliar chemistry, but it is unclear how well or whether CWA can be applied to imaging spectroscopy data under the conditions of higher noise level and more complicating factors. This study evaluates the application of CWA to airborne imaging spectroscopy data for predicting diurnal and seasonal variation in canopy water content (CWC) for nut tree orchards. We collected CWC measurements and concurrent imagery from the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) instrument twice a day (morning and afternoon) in spring and fall of 2011 in California, USA. Several robust wavelet features were determined and compared to four water-sensitive spectral indices, three existing in the literature and one optimized in this study, for the assessment of predictive performance. Results showed that the best prediction using CWA ($R^2 = 0.84$ and root mean square error (RMSE) $= 0.027$ kg/m$^2$) was produced by a combination of three wavelet features and it was considerably better than those by the existing water indices. While the best wavelet feature (1100 nm, scale 6) characterized the water absorption in the near-infrared region, the optimized index $ND_{850,720}$ used a red edge band at 720 nm instead of a direct water absorption band. A bootstrap sampling of the validation data set indicated that $ND_{850,720}$ predicted CWC significantly worse ($p < 0.0001$) and exhibited greater sensitivity to seasonality. Both CWA and $ND_{850,720}$ revealed statistically significant diurnal declines of CWC in two different seasons in the context of a substantial seasonal decline, but the former detected greater declines in diurnal CWC. Our results demonstrated the feasibility of applying CWA to airborne imaging spectroscopy data for CWC mapping and its superiority to spectral indices for improved prediction of CWC and understanding of spectral–chemical relations.

## 1. Introduction

Vegetation water status is a key variable for assessing agricultural water management (El-Shikha, Waller, Hunsaker, Clarke, & Barnes, 2007; Graeff & Claupein, 2007; Kriston-Vizi, Umeda, & Miyamoto, 2008), plant physiological dynamics (Eitel, Gessler, Smith, & Robberecht, 2006; Peñuelas, Filella, Biel, Serrano, & Save, 1993; Peñuelas, Gamon, Fredeen, Merino, & Field, 1994) and wildfire danger (Chuvieco, Riaño, Aguado, & Cocero, 2002; Dennison & Moritz, 2009; Roberts, Dennison, Peterson, Sweeney, & Rechel, 2006). One of the vegetation water measures that can be best estimated through optical remote sensing is canopy water content (CWC), which is defined as the total amount of foliage water per unit ground area. CWC relates to more widely used variables including plant water potential and relative water content for plant stress detection, but they are more difficult to estimate using optical remote sensing (Hunt, Ustin, & Riaño, 2013). Temporal patterns of CWC over the seasonal and diurnal courses contribute significantly to our understanding of vegetation–climate interactions, vegetation phenology, physiological dynamics and ecosystem functioning (Chavez, Clevers, Herold, Ortiz, & Acevedo, 2013; Trombetti, Riaño, Rubio, Cheng, & Ustin, 2008).

A number of methods have been proposed to estimate CWC from remotely sensed reflectance, such as the Normalized Difference Water Index (NDWI) and the Normalized Difference Infrared Index (NDII) (Ceccato, Flasse, & Gregoire, 2002; Cheng, Ustin, Riaño, & Vanderbilt, 2008; Cheng, Zarco-Tejada, Riaño, Rueda, & Ustin, 2006; Cheng et al., 2013; Colombo et al., 2008; Yilmaz, Hunt, Goins, et al., 2008; Yilmaz, Hunt & Jackson, 2008), and inversion of radiative transfer models (Colombo et al., 2008; Trombetti et al., 2008; Zarco-Tejada, Rueda, & Ustin, 2003). These methods are generally developed for multispectral data from broadband, spaceborne instruments but not specifically for imaging spectroscopy data that are available in hundreds of contiguous narrow bands and offer more spectral details on absorption features, *e.g.*, the near infrared (NIR) water absorption features centered at 970 nm and 1200 nm. In contrast, several authors explored other techniques, such as derivative analysis (Clevers, Kooistra, & Schaepman, 2010; Tsai & Philpot, 1998) and spectrally based canopy equivalent

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0034-4257/$ – see front matter © 2014 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.rse.2013.11.018

water thickness (EWT) (Roberts, Green, & Adams, 1997; Ustin et al., 1998), to make use of the detailed information on the NIR water absorption features in spectroscopic data. For example, Clevers, Kooistra, and Schaepman (2008) used derivative analysis of *in situ* and airborne spectroscopy data to estimate CWC and found it to produce higher correlations with CWC than water indices. However, derivative approximations are often derived after spectral smoothing. The performance of derivative spectra is sensitive to the width of derivative operator and the degree of smoothing, which are difficult to be optimized given the factors of smoothing function, absorption features of interest and the characteristics of noise (Bruce & Li, 2001; Rollin & Milton, 1998; Schmidt & Skidmore, 2004). The spectrally based canopy EWT (CWC) is often used as a by-product of atmospheric correction of imaging spectroscopy data and its quality remains to be evaluated with ground truth data to resolve the difference in magnitude when compared to CWC (Cheng et al., 2008; Hunt, Daughtry, Qu, Wang, & Hao, 2011).

Recently, continuous wavelet analysis (CWA) has emerged as a promising spectroscopy tool for quantitative analysis of natural materials, such as vegetation (Blackburn & Ferwerda, 2008), minerals (Rivard, Feng, Gallie, & Sanchez-Azofeifa, 2008) and inland waters (Ampe et al., 2014). It allows us to transform the data into a new representation by decomposing the input signature into various scales (frequencies) (Torrence & Compo, 1998) and is well suited for quantifying compositional constituents from reflectance spectra. In the context of vegetation analysis, Cheng, Rivard, and Sanchez-Azofeifa (2011) applied CWA to spectroscopic measurements for predicting leaf water content and their methodology was further evaluated using leaf-level data sets with a wider variety of species (Cheng et al., 2012) or extended spectral ranges (Ullah, Skidmore, Naeem, & Schlerf, 2012). Those studies also documented the close linkage between foliar chemical absorption and wavelet features, namely spectral features in the wavelet domain. However, previous efforts are limited by applying CWA to leaf reflectance spectra measured in laboratories and simulated with radiative transfer models (Cheng, Rivard, Sanchez-Azofeifa, Feng, & Calvo-Polanco, 2010; Cheng et al., 2011, 2012; Liao et al., 2013; Luo et al., 2013; Ullah et al., 2012; Zhang et al., 2012). It remains unclear as to how well CWA can be applied to airborne or spaceborne canopy reflectance spectra, which are more complex than the reflectance spectra of individual leaves due to a number of complicating factors, such as sensor noise, soil background, canopy structural variation and solar and viewing geometry (Asner & Martin, 2008; Huang, Turner, Dury, Wallis, & Foley, 2004; Ollinger, 2011). Several authors have applied the counterpart of CWA, discrete wavelet analysis (DWA), to airborne imaging spectroscopy data for quantifying forest structural parameters (Pu & Gong, 2004) and identifying plant species (Banskota, Wynne, & Kayastha, 2011; Kalacska, Bohman, Sanchez-Azofeifa, Castro-Esau, & Caelli, 2007; Koger, Bruce, Shaw, & Reddy, 2003; Zhang, Rivard, Sanchez-Azofeifa, & Castro-Esau, 2006), but the length of decomposed components from DWA varies by scale and the wavelet features are more difficult to interpret for band-by-band analysis (Blackburn & Ferwerda, 2008).

While some studies have demonstrated the assessment of CWC with imaging spectroscopy data, most of these have been focused on using single-date imagery (Cheng et al., 2006, 2008; Clevers et al., 2008; Colombo et al., 2008; Serrano, Ustin, Roberts, Gamon, & Peñuelas, 2000) and have not investigated the sensitivity of their methods to the seasonal variation in vegetation spectral reflectance. The use of multi-temporal imaging spectroscopy data was hampered by the high cost of field and image data acquisition within a specific time frame and the effect of solar and viewing geometry on canopy reflectance variation, which is especially the case for the investigation of diurnal vegetation activities (Cheng et al., 2013). A recent study by Cheng et al. (2013) reported on the airborne detection of diurnal variation in CWC over an orchard area using multispectral data acquired from the MODIS/ASTER Airborne Simulator (MASTER) instrument. Although this detection task may be achieved to a higher degree of accuracy with imaging spectroscopy data, we do not know whether, and how well, the diurnal CWC variation can be detected for multiple seasons in a different year.

While previous research in the literature related vegetation dynamics to spectral changes over either the diurnal course (Chavez et al., 2013; Meggio et al., 2008) or the seasonal course (Dzikiti et al., 2011; Stuckens et al., 2011), this study aimed to investigate both diurnal and seasonal variation in CWC using multi-temporal Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) data. Following the methodology in Cheng et al. (2011), we derive here a number of wavelet features from AVIRIS data and compare them to existing and newly calibrated spectral indices in terms of the physical interpretation of selected wavelengths and their predictive capabilities. We apply the best wavelet-based and index-based predictive models to all AVIRIS imagery and assess the diurnal and seasonal variation in CWC in comparison to field measurements. Our ultimate goal is to derive robust wavelet features for predicting CWC for an irrigated agricultural ecosystem and apply them to other agricultural and natural ecosystems. Specifically, we seek to answer these questions: (1) Can we apply CWA to airborne imaging spectroscopy data for quantifying vegetation properties as applied to leaf-level spectroscopic data? (2) Does the wavelet approach outperform the traditional spectral index approach for the estimation of CWC? (3) What is the spectral region most sensitive to CWC in the optical spectral range (400–2500 nm)? (4) Can we detect the diurnal variation in CWC for different seasons using the CWA approach?

## 2. Materials and methods

### 2.1. Study site and field sampling

The study site (35°29′45″ N, 119°40′2.6″ W) is located in the southern end of the California Central Valley, 15 km to the south of Lost Hills, CA with an elevation of 112 m (Fig. 1). It is a flat irrigated nut tree orchard area and encompasses eleven 800 × 800 m blocks. Three of them are cultivated with pistachio (*Pistachio vera* L.) trees and eight are with almond (*Prunus dulcis*) trees. These blocks were chosen to cover variability in tree age, tree variety and irrigation schedule. The tree rows are oriented in the north–south direction. The irrigation was applied by Paramount Farming Company (Bakersfield, CA) either to a whole block or sequentially to three to five sets within a block from west to east (Fig. 1). For sampling purposes, all blocks were divided into three sets and two plots in the same tree row were sampled per set, giving a total of six plots per block. The plots were selected to cover a variety of conditions in vegetation structure and water content using the Normalized Difference Infrared Index (NDII) and the Normalized Difference Vegetation Index (NDVI) images derived from a MODIS/ASTER Airborne Simulator (MASTER) image acquired in 2009. In order to reduce the potential errors in image to plot co-registrations, large homogenous areas encompassed each plot of approximately 18 × 18 m with 3 × 3 trees. The plots were finally located by identifying individual trees on a 1 m USGS Orthophoto Quarter-Quadrangle (DOQQ) image of 2009.

Two field campaigns were conducted at different stages of the crop growth cycle in 2011, one in the green-up season (Spring) and the other one in the senescence season (Fall). The leaf sampling part of each campaign occurred within two consecutive days, the day of diurnal flights and the day before. Diurnal sampling was constrained to two-hour periods twice a day, 0900 h to 1100 h and 1300 h to 1500 h Pacific Standard Time (PST) in May and 0830 h to1030 h and 1230 h to 1430 h PST in November.

Leaves were sampled from the upper-outer canopy of each tree to maximize their possibility of being observed by the aircraft. Leaf sampling was conducted within 2 h before and after solar noon for the east and west side of tree canopies, because the leaves from both east and west sides could be seen from above the canopy and it was difficult to distinguish the sunlit leaves in the east (morning) or west (afternoon)