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Multi-temporal vegetation canopy water content retrieval and interpretation using artificial neural networks for the continental USA ☆

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Abstract

An inversion of linked radiative transfer models (RTM) through artificial neural networks (ANN) was applied to MODIS data to retrieve vegetation canopy water content (CWC). The estimates were calibrated and validated using water retrievals from AVIRIS data from study sites located around the United States that included a wide range of environmental conditions. The ANN algorithm showed good performance across different vegetation types, with high correlations and consistent determination coefficients. The approach outperformed a multiple linear regression approach used to independently retrieve the same variable. The calibrated algorithm was then applied at the MODIS 500 m scale to follow changes in CWC for the year 2005 across the continental United States, subdivided into three vegetation types (grassland, shrubland, and forest). The ANN estimates of CWC correlated well with rainfall, indicating a strong ecological response. The high correlations suggest that the inversion of RTM through an ANN provide a realistic basis for multi-temporal assessments of CWC over wide areas for continental and global studies.

Keywords: MODIS; AVIRIS; Artificial neural networks; Canopy water content; Radiative transfer model; Ecoregions

1. Introduction

A reliable and repeatable assessment of canopy water content (CWC) is essential for drought assessment of natural vegetation (Peñuelas et al., 1993). Dynamic changes in water status preclude effective field monitoring and require development of remotely sensed monitoring methods. Water stress changes the spectral reflectance and transmittance of leaves (Ceccato et al., 2001; Ustin et al., 2004), reduces leaf area and alters architecture, thus significantly influencing the canopy spectral response (Cohen, 1991). Hence, remote sensing of spectral properties of vegetation can provide a direct method to estimate and comprehensively monitor the spatial and temporal distribution of CWC.

Today, a systematic method to retrieve CWC for wide areas over time does not exist. Estimations of CWC at a national scale and the validation of this biophysical product are challenging. No site network has been established to routinely measure CWC following a common sampling methodology at the appropriate spatial and temporal resolutions. This observational limitation makes it infeasible to obtain CWC at a sufficient number of locations within a short time interval to validate and calibrate satellite data.

Several studies have demonstrated the link between leaf level reflectance across the 0.4 μm–2.5 μm spectral region and the amount of water in the leaf, through optical indexes (Allen et al., 1971; Carter, 1991, 1994; Danson et al., 1992; Hunt & Rock, 1989; Hunt et al., 1987; Sims & Gamon, 2003), regression analysis (Chuvieco et al., 2002) and radiative transfer modeling (RTM) (Aldakheel & Danson, 1997; Ceccato et al., 2002a,b, 2001). In particular, optical reflectance has been related to water

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content, especially in the Shortwave Infrared Region (SWIR) between 1.4 and 2.5 μm (Bowman, 1989; Cohen, 1991; Jackson & Ezra, 1985; Ripple, 1986; Thomas et al., 1971; Tucker, 1980), where reflected energy is negatively related to leaf water content because of strong absorbance at these wavelengths (Gausman et al., 1970; Rohde, 1967).

The spectral information is related to water and dry matter content per unit area (Ceccato et al., 2002a,b; Danson & Bowyer, 2004; Hunt et al., 1987; Peñuelas et al., 1993). Zarco-Tejada et al. (2003) demonstrated the need to control factors such as leaf structure and dry weight and, most importantly, Leaf Area Index (LAI) to successfully retrieve leaf water content from satellite imagery. Hence, in order to derive accurate and consistent estimates in terms of CWC, methods using only vegetation or water indexes do not appear to be sufficiently reliable for quantitative applications.

The application of RTM has been extensively demonstrated in leaf level models such as PROSPECT (Jacquemoud & Baret, 1990) for broadleaf species, LIBERTY (Dawson et al., 1999) for needle-leaf species and LEAFMOD (Ganapol et al., 1998), among others, which enable simulation of leaf water content. Introducing canopy complexity into RTM was first begun by Jacquemoud (1993) and Jacquemoud et al. (1995) who, linking the PROSPECT leaf model and SAIL canopy model, showed successful retrievals of CWC from continuous hyperspectral data (simulated Advanced Visible InfraRed Imaging Spectrometer, AVIRIS) and multispectral data (simulated Landsat Thematic Mapper, TM).

RTM takes into account leaf and canopy variables, soil, and viewing geometry, thereby providing more accurate estimates than a simple spectral index approach (Deshayes & Dauriac, 2003). As shown by Jacquemoud et al. (1996), Fourty and Baret (1997), Zarco-Tejada et al. (2003) and Riaño et al. (2005b), the inversion of RTM provides a physical estimate of CWC. More recently, Cheng et al. (2006) accurately estimated CWC utilizing a RTM applied to simulated AVIRIS-equivalent spectral bands for heterogeneous vegetation conditions.

Because inversion of RTMs requires intensive computational time, it becomes problematic to think of applying them at regional to global scales. Using sample data and working at the leaf level, Riaño et al. (2005a) showed that good estimates of leaf water content are possible from artificial intelligence algorithms such as artificial neural networks (ANN). The same type of approach was shown to give promising results by Rubio et al. (2006) who retrieved CWC estimates from MODIS-based vegetation and water indexes in mixed semi-arid grasslands and shrublands of southern Arizona.

An ANN consists of a system of simple, interconnected neurons, or nodes: it is a model representing a nonlinear mapping between an input vector and an output vector. These were among the first methods developed in data mining and have been shown to be particularly effective in handling the complexities commonly found in remotely sensed data. ANN have been demonstrated to provide a consistent and efficient tool to establish the relationship between simulated reflectance and corresponding biophysical variables (Jin & Liu, 1997; Smith, 1993), and are being widely used in remote sensing for inverse problem resolution. Most work in this field (Abuelgasim et al., 1998; Combal et al., 2003; Gong et al., 1999) has made use of a simulated RTM database, not only for training, but also for validation. A better test would apply training results to sensor-derived reflectance measurements, as demonstrated by Fang and Liang (2003).

This study extends progress in the definition of an algorithm for retrieval of multi-temporal variation in CWC, measured as leaf water content times LAI, at a nationwide scale, combining the use of powerful tools such as ANN to invert a comprehensive RTM and taking advantage of the availability of validated CWC information from an airborne hyperspectral imager, such as AVIRIS, to help fill the validation data gap and improve calibration results.

2. Study area

Four study sites in the USA (Fig. 1), representing a wide range of vegetation types, were selected for calibrating and validating the algorithm to retrieve CWC. The need to analyze different ecosystems was pointed out in the International Geosphere-Biosphere Programme (IGBP) scheme (Belward et al., 1995; Running et al., 1994). Because RTMs function differently with vegetation types, we used the MODIS land cover product (MOD12Q1) to group data into three main growth form types: forest (needleleaf, broadleaf, and mixed), shrublands (closed and open shrublands, and woody savannas) and grasslands (savannas and grasslands). The specific sites were selected on the basis of availability of concurrent AVIRIS and EOS-MODIS data between 2001 and 2005. The distribution of the reference CWC values, as derived by the AVIRIS sensor and the vegetation type are shown for each site in Table 1.

The analysis was conducted for the continental USA for the year 2005. The moisture and nutrient gradients were divided into 19 ecoregions representing homogeneous environmental and climatic conditions, as defined by Bailey (1995) (Fig. 1), to better understand the ecological significance of temporal CWC changes and trends. As described in Ecomap (1993), classifying by ecoregions makes it possible to apply studies and phenomena understood at small scales to sub-regional areas on the basis of their bio-climatic properties (Hargrove & Hoffman, 2004).

3. Data and methods

CWC retrievals from AVIRIS were used to validate and calibrate the MODIS estimates for each vegetation type. The ANN model was run for the year 2005 for the USA and links between variation in multi-temporal patterns of CWC and meteorological variables were made for each ecoregion (Fig. 2).

3.1. AVIRIS and MODIS data

AVIRIS is an airborne, high spatial resolution hyperspectral sensor, having 224 contiguous bands in 0.4 μm to 2.5 μm with approximately 0.01 μm bandwidth. AVIRIS spatial resolution varies from 4 m to 20 m depending on flying altitude. AVIRIS is