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Leaf and canopy water content estimation in cotton using hyperspectral indices and radiative transfer models

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ABSTRACT

In present study some vegetation indices for estimating leaf EWT and EWTcanopy were investigated using simulations and field measurements. Leaf and canopy spectral reflectance as well as leaf EWT and EWTcanopy were measured in cotton during the growing seasons of 2010 and 2011. The PROSPECT-5 model was coupled with the SAILH model to explore the performance of water-related vegetation indices for leaf EWT and EWTcanopy estimation. The vegetation indices evaluated were published formulations and new simple ratio vegetation indices formulated with wavebands at 1060 nm and 1640 nm. The sensitivities of these indices to leaf internal structural N and LAI effects were assessed. Simulation results indicated that all of the water-related vegetation indices were insensitive to leaf internal structural N, with the highest coefficient of determination $R^2 < 0.15$ and the proposed index SR_{1640} (R_{1060}/R_{1640}) and published index SR2 (R_{1070}/R_{1340}) showed the lowest relationships ($R^2 < 0.35$) with LAI of all the vegetation indices. Furthermore, coefficients of determination between simulated leaf EWT as well as EWTcanopy and vegetation indices tested revealed that the new simple-ratio vegetation indices proposed in this study (SR_{1060}: R_{1640}/R_{1060} and SR_{1640}) were found to be significantly related with leaf EWT ($R^2 > 0.9$; $P < 0.001$) and EWTcanopy ($R^2 > 0.8$; $P < 0.001$). Results obtained with field measurements were in agreement with simulation results, with the coefficient of determination $R^2 = 0.5$ ($P < 0.001$) for leaf EWT and $R^2 = 0.57$ ($P < 0.001$) for EWTcanopy by the new simple ratio indices. This study provides a new candidate for leaf EWT and EWTcanopy estimation using hyperspectral vegetation indices.

Introduction

The knowledge of vegetation water conditions can contribute to detect vegetation physiological status (Carter, 1993; Peñuelas et al., 1994; Stimson et al., 2005), to provide useful information in agriculture for irrigation decisions and drought assessment (Peñuelas et al., 1993, 1994) and it is important in forestry in determining fire susceptibility (Carlson and Burgan, 2003; Chuvieco et al., 2004; Ustin et al., 1998). Several physiological indicators are used to assess plant water conditions, with stomata conductance (g_s), leaf water potential, fuel moisture content (water content express as percent of dry mass or fresh mass (FMC)), vegetation water content (VWC) and equivalent water thickness at leaf and canopy levels (EWT and EWTcanopy), and so on. Remote sensing techniques provide a non-destructive, rapid, and reliable method for assessing water status. Several water condition indicators have been related to spectral reflectance measurements (Cifre et al., 2005; Peñuelas et al., 1993; Serrano et al., 2000; Stimson et al., 2005). At leaf level, investigations revealed that the estimation of leaf water content in terms of equivalent water thickness (EWT) expressed in quantity of water per unit area (g/cm^2) were performed better than water content in terms of moisture content expressed in quantity of water per quantity of fresh or dry matter (%) (Ceccato et al., 2001; Colombo et al., 2008; Datt, 1999; Davidson et al., 2006; Maki et al., 2004). At canopy level, José et al. (2007) also suggested EWTcanopy that expressed in water per unit surface area (g/m^2) may be more appropriate for predicting vine water status at canopy level. EWT and EWTcanopy have been successfully estimated in agricultural crops, forests, Mediterranean shrublands and savannah woodlands (Ceccato et al., 2002b; Gao and Goetz, 1995; Jacquemoud et al., 1995; Serrano et al., 2000; Ustin et al., 1998; Zarco-Tejada et al., 2003). So in present work, EWT and EWTcanopy were adopted for cotton water content estimation. EWT is defined as a hypothetical thickness of a single layer of water average over the whole leaf area (Danson et al., 1992) and EWTcanopy is defined as EWT multiplied by LAI (the leaf area per unit ground surface area, m^2/m^2).

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EWTcanopy represents a quantity of water per unit surface area at canopy level (Ceccato et al., 2002a).

The possibility of estimating water conditions by means of remotely sensed data derives from the fact that water absorbs radiant energy throughout the near-infrared (750–1300 nm) and short-infrared (1300–2500 nm) spectral regions. Leaf and canopy reflectance decreases with increasing tissue water content for wavelengths sensitive to water absorption (Aldakheel and Danson, 1997; Carter, 1991; Ceccato et al., 2001; Hunt and Rock, 1989; Knapp and Carter, 1998; Thomas et al., 1971). Spectral indices have been and are still widely used to retrieve information on vegetation biophysical properties. For wavelengths sensitive to water content (970, 1200, 1450, 1940 and 2500 nm) have been combined in numerous ways to generate vegetation indices related to water status (Gao, 1996; Hardisky et al., 1983; Peñuelas et al., 1993, 1997; Zarco-Tejada et al., 2001). A detailed summary of vegetation indices related to water content can be found in José et al. (2007). A preliminary comparison of several indices from the lecture showed good results in terms of leaf EWT and EWTcanopy retrieval when applied to our experimental dataset. The vegetation indices that were widely used and relatively better related to leaf EWT and EWTcanopy were selected and used in this paper. Adopted indices are summarized in Table 1.

Ceccato et al. (2001) showed that both the shortwave infrared (SWIR) and the near infrared (NIR) wavelength ranges are necessary for retrieving EWT at leaf level. The same authors also showed that in the NIR region, variations in reflectance values are exclusively influenced by leaf internal structure *N* and dry matter content (Cm). Furthermore, in the SWIR region, *N* and Cm factors also significantly affect reflectance values. Several researches have evaluated and quantified the effects of leaf water content on reflectance data (Aldakheel and Danson, 1997; Bowyer and Danson, 2004; Ceccato et al., 2002a; Dawson et al., 1998; Ustin et al., 1998). However, the relationships between leaf internal structure *N* and water-related vegetation indices have not been well illustrated.

Besides, at canopy level, the reflectance is significantly affected by LAI (Zarco-Tejada et al., 2003). A large variability in LAI may cancel out water-related features in spectral reflectance (Cohen, 1991; Riggs and Running, 1991) and therefore complicates the estimation of EWT at the canopy level (Yebra et al., 2013). Jacquemoud et al. (2009) revealed that the SWIR is highly sensitive to LAI between 1000 nm and 1400 nm and suggested that caution should be taken when using these indices for water retrieval. It is necessary to evaluate the effect of LAI on water-related vegetation indices.

Féret et al. (2011) tested the performance of MSI (R_{1600}/R_{820}) for EWT estimation and suggested that other optimal wavelengths could be used to build a better spectral index. The aim of the present study was to evaluate the performance of a set of hyperspectral vegetation indices in EWT and EWTcanopy estimation in cotton using both model simulations and field measurements. The specific objectives were (i) to evaluate the performance of a set of water content related vegetation indices in leaf EWT and EWTcanopy estimation; (ii) to propose a new vegetation indices for EWT and EWTcanopy estimation through sensitive analysis and assess its performance with modeling methods and field measurements.

Materials and methods

Field data collection

Field experiments

The field experiment was conducted in June–September 2010 and 2011 at agricultural belts in Shihezi, Xinjiang, Northwest of China (85°59′ E, 44°19′ N), where cotton is the dominate crop. The study sites were consisted of eight big filed plots (approximately 8–10 ha) and one small water-controlled plot (about 0.1 ha). Every eight big filed plot was consisted of eight small sample sites (about 30 m × 30 m), and other 12 sample sites were set in the water-controlled plot, for a total of 76 sample sites. The continental arid climate of Xinjiang is characterized by aridity, rich sunlight and rare rainfall, with sharply defined seasons, high annual and diurnal fluctuations in air temperature, and low precipitation. Field data collections were conducted in June–September 2010–2011 for six times from seedling stage until boll stage (the actual dates were 12 June, 14 July, and 8 August, 2010; 24 June, 28 July, and 17 August, 2011). This procedure ensured that the normally occurring variation due to growth stage and measurement factors was included in the indices.

Reflectance measurements

Canopy reflectance was obtained using an Analytical Spectral Devices, FieldSpec Full Range (ASD FieldSpec FR, Analytical Spectral Devices, Inc., Boulder, CO, USA) that acquires continuous spectra from 350 to 2500 nm. All canopy spectral measurements were taken on clear days with no visible cloud cover between 10:00 am and 14:00 pm (Beijing local time). In each sample site, representative plants were selected for canopy spectral measurement.

Leaf reflectance was measured over the spectral region between 350 nm and 2500 nm by coupling a leaf clip (ASD, Inc., Boulder, CO, USA) with the ASD FieldSpec FR. The reflectance was measured in the "reflectance" mode against a black background. Leaves healthy were used for leaf reflectance measurements, for a total of 481 leaf samples.

The reflectance of a white Spectralon panel ($BaSO_4$) was measured before every reflectance was taken, then the reflectance was calculated as the ratio between energy reflected by the leaf or the canopy and energy incident on the leaf or the canopy. Every reflectance was an average of ten repeated scans that were automatically acquired by the FieldSpec.

Leaf sampling and water content measurements

Three average-looking plants per plot were pulled out with their roots, placed and sealed in a plastic bag, and then placed in a cool dark container to avoid water loss as much as possible. Upon return to the laboratory, fresh weight (FW) of leaves was recorded immediately using an analytical balance, after which optical properties were measured and leaf photos were taken. Fresh leaves were then put into oven to dry with 105 °C for half an hour and 70 °C till the constant weight were acquired (Saura-Mas and Lioret, 2007). In order to make all measurement simultaneous, four groups worked like a line operation for leaf sampling, weighting, leaf spectra measurement and leaf photo taken. Leaf EWT was calculated for each leaf sample using Eq. (1):

$$\mathrm{EWT} = \frac{FW - DW}{A} \quad (\mathrm{g/cm^2}) \tag{1}$$

where *FW* is the leaf fresh weight and *DW* is the dry leaf weight of all the leaves in the same sample plant, *A* is the area of fresh leaf (cm^2), which was obtained by scanning.

By multiplying leaf EWT with LAI the canopy water content (EWTcanopy) is obtained:

$$\mathrm{EWTcanopy} = \frac{\mathrm{LAI} \times \mathrm{EWT}}{10} \quad (\mathrm{kg/m^2}) \tag{2}$$

LAI was obtained using Li-Cor Plant Canopy Analyzer (model LAI-2000) on the field before collecting. Since the instrument requires diffuse conditions for accurate readings, the measurements were typically collected in the late afternoon hours and an umbrella was used to block the direct solar beam. Five below canopy readings were taken between two above-canopy readings, for a total of 353 valid LAI measurements.