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Estimation of leaf water content in cotton by means of hyperspectral indices

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ABSTRACT

The knowledge of vegetation water conditions can contribute to drought assessment. Remote sensing has a proven ability to assess vegetation properties. In this study, all two-band combinations (350–2500 nm) in the ratio type of vegetation index (RVI) and the normalized difference type of vegetation index (NDVI) were performed on cotton leaf raw spectral reflectance (*R*) and the first derivative reflectance (DR). The correlation coefficient (*r*) between all two-band combinations and two leaf water parameters (EWT: equivalent water thickness, and FMC: fuel moisture content) were determined, and the results of this comprehensive analysis were presented by matrix plots. Band centers (λ_1 and λ_2) and band widths ($\Delta\lambda_1$ and $\Delta\lambda_2$) that combine to form the best indices were identified for EWT and FMC through matrix plots. Then the evaluation of the predictive power of three predictors, i.e. single narrow band reflectance, the widely used published water indices and the best band combination indices, were performed. The results shown that the new indices DR1647/DR1133 and DR1653/DR1687, proposed by two-band combinations, were considered as the optimal indices for EWT and FMC estimation, respectively. The models based on these two best combination indices could explain 58% and 67% variability in EWT and FMC, respectively. Besides, bands with center wavelengths in region from 950 nm to 1100 nm, and 1650 nm to 1750 nm were represented almost all selected bands. The study should further our understanding of the relationships between leaf water content and hyperspectral reflectance.

1. Introduction

The knowledge of vegetation water conditions can in fact 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). Remote sensing offers an important opportunity for quantitative assessment of vegetation properties at different scales. Together with other parameters, vegetation water content is an important property that can be investigated by using remotely sensed data. With the development of hyperspectral remote sensing technique, direct detection approaches of vegetation water content have been proposed and further used to evaluate crop drought condition.

The main parameters describing the amount of water in vegetation that are usually investigated by remote sensing are fuel moisture content (FMC, %) and leaf equivalent water thickness (EWT, cm). FMC defined as the proportion of water over the vegetation dry mass (Burgan, 1996), and EWT is the ratio between the quantity of water and leaf area (Danson et al., 1992). EWT and FMC provide information on the amount of water present in vegetation. The possibility of estimating FMC and EWT 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. Depending on tissue water content, reflectance is thus reduced to a varying extent within the water absorption features centered on 970, 1200, 1450, 1940, and 2500 nm (Knipling, 1970; Thomas et al., 1971; Tucker, 1980) and these changes can be recognized and quantified as water content variations. Our study investigates the potential of retrieving both of these measurements via leaf reflectance.

Several hyperspectral indices such as the Normalized Difference Infrared Index (NDII), the Water Index (WI) have been established based on hyperspectral remote sensing data. The most widely used ratio type of vegetation index and normalized difference type of vegetation index at leaf level were summarized in Table 1. The results obtained in these studies indicate that knowledge of connection between the investigated variable and the spectral data can improve the performance of the vegetation indices (Thenkabail et al., 2000). Further improvement in indices is generally possible through use of spectral data from distinct narrow bands or through corrections for soil background effects, and further, through different band combinations. Selection of new wavebands in hyperspectral data has been performed in some cases, mainly focusing on how to increase the sensitivity of the vegetation indices to

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Table 1
Correlation analysis between published water indices and water content ($n = 113$).

Water indices	Name	Formula	Reference	EWT	FMC
NDII	Normalized different infrared index	$(\rho850 - \rho1650)/(\rho850 + \rho1650)$	Hardisky et al. (1983), Kimes et al. (1981)	0.341**	0.231*
NDII1	Normalized different infrared index	$(\rho835 - \rho1650)/(\rho835 + \rho1650)$	Hardisky et al. (1983), Van Niel et al. (2003)	0.331**	0.247*
NDWI2130	Normalized different water index	$(\rho858 - \rho2130)/(\rho858 + \rho2130)$	Chen et al. (2005)	−0.020	0.370*
NDWI1240	Normalized different water index	$(\rho860 - \rho1240)/(\rho860 + \rho1240)$	Gao (1996)	0.539**	0.163
NDWI1260	Normalized different water index	$(\rho870 - \rho1260)/(\rho870 + \rho1260)$	José et al. (2007)	0.600**	0.099
NDVI	Normalized different vegetation index	$(\rho858 - \rho648)/(\rho858 + \rho648)$	Rouse et al. (1974)	−0.472**	0.313**
WI	Water index	$\rho900/\rho970$	Peñuelas et al. (1993), (1997)	0.647**	0.082
WBI	Water band index	$\rho970/\rho900$	Peñuelas et al. (1993)	−0.647**	−0.079
FWBI	Floating position water band	$\rho900/\min(\rho930–980)$	Strachan et al. (2002)	0.659**	0.058
SRWI1	Simple ratio water index	$\rho858/\rho1240$	Zarco-Tejada et al. (2001), (2003)	0.527**	0.173
SRWI2	Simple ratio water index	$\rho1070/\rho1340$	José et al. (2007)	0.258**	0.299**
SRWI3	Simple ratio water index	$\rho678/\rho1070$	José et al. (2007)	0.498**	−0.160
SRWI4	Simple ratio water index	$\rho880/\rho1265$	José et al. (2007)	0.618**	0.078
MSI	Moisture stress index	$\rho1600/\rho820$	Rock et al. (1986), Hunt (1991)	−0.262**	−0.294**
MSI1	Moisture stress index	$\rho870/\rho1350$	Rock et al. (1986), Hunt (1991)	0.374**	0.296**
MSI1	Moisture stress index	$\rho1650/\rho835$	Rock et al. (1986), Hunt (1991)	−0.336**	−0.248*
SIWSI	Shortwave infrared water stress	$(\rho858 - \rho1640)/(\rho858 + \rho1640)$	Fensholt and Sandholt (2003)	0.332**	0.233*

* Indicates significant differences at 95% confidence level ($r = 0.195$).
** Indicates significant difference at 99% confidence level ($r = 0.254$).

chlorophyll and other pigments (Thenkabail et al., 2000; Blackburn, 1998; Hansen and Schjoerring, 2003). These investigations have mainly been performed on other crop variables but not water parameters or on vegetation very distinct from cotton. As a consequence of the different measurement conditions and the different crop variables, some degree of disagreement exists in the selection of wavebands. Several studies successfully exploited empirical relationships to estimate leaf water content (Peñuelas et al., 1993; Ceccato et al., 2001; Datt, 1999), first derivative reflectance spectra (Danson et al., 1992), continuum removed spectra analysis (Curran et al., 2001; Pu et al., 2003; Tian et al., 2001) and artificial neural networks (Dawson et al., 1998). To date, however, relationships between leaf water content (EWT and FMC) and the narrow band ratio type of vegetation index (RVI) and normalized difference type of vegetation index (NDVI) involving all possible two-band combinations of 2150 bands (from 350 nm to 2500 nm) have not been well investigated.

Based on the above background, the objective of the present investigation was to (i) exploit the relationships between leaf water content (EWT and FMC) and all possible two-band combinations indices, which based on raw reflectance spectra and first derivative reflectance spectra; (ii) identify the best combinations of narrow wavebands for ratio type of vegetation indices and normalized difference type of indices for EWT and FMC estimation and (iii) evaluate the performance of various types of hyperspectral vegetation indices in characterizing leaf water content. The final goal is to determine and recommend an optimal number of hyperspectral bands, their centers and widths, thus reducing the redundancy in hyperspectral data.

2. Materials and methods

2.1. Study area

The field experiment was conducted in June–October 2010 at agricultural belts in Shihezi, Xinjiang, Northwest of China (85°59′E, 44°19′N), where cotton is the dominate crop. 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. The total annual precipitation for the whole study area is about 193 mm, and the total precipitation of whole cotton growth stage from April to October is about 108 mm. Sites of cotton were selected for the experiment. Cotton is generally planted in April–May, and harvested in September–October. The whole growth period is about 180 days. The medium loam soil at the experiment area had the following properties: the field moisture capacity at depth of 10 cm is 0.33 g cm^{-3}, the volumetric water content at depth of 10 cm is 1.59 g cm^{-3}, and the saturation moisture content is 0.44 g cm^{-3}. Besides, field sampling was complemented by a water-controlled experiment in order to obtain very low vegetation water content that could not be obtained in the field, except in very extreme situations.

2.2. Plant sampling and water content measurements

Leaf spectral readings and corresponding water status measurements were performed four times from seedling stage until boll stage (dates are 9–12 June, 14–18 July, 4–8 August, and 8–12 September, 2011, respectively). This procedure ensured that the normally occurring variation due to growth stage and measurement factors was included in the models giving a more realistic basis for model development.

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, leaf sampling was conducted near the tops, middle and bottom of every sampling plant, for a total of 113 leaf samples. 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. 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 FWC and EWT were calculated for each leaf sample using Eqs. (1) and (2), respectively.

$$FMC = \frac{FW - DW}{DW} \times 100\% \quad (1)$$

$$EWT = \frac{FW - DW}{dw * A} \quad (2)$$

where FW is the leaf fresh weight and DW is the dry leaf weight of the same sample, A is the area of fresh leaf (cm^2), dw is the density of water (1 g cm^{-3}).