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Remote sensing of grassland–shrubland vegetation water content in the shortwave domain

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Abstract

This study compares the ability of spectral approaches operating in the shortwave optical domain to predict absolute and relative vegetation water content (AWC and RWC, respectively) across northern prairie grassland–shrubland. We collected vegetation water content and spectral radiometer data over plots of comparable ground resolution (0.5 m) at seven field sites in the Canadian mixed grass prairie in June 2004. We then aggregated observations to scale these data ‘‘up’’ to an observational scale consistent with that of Landsat-TM satellite imagery (30 m). This allowed us to assess abilities of three spectral approaches to predict AWC and RWC at both observational scales. These approaches were: individual vegetation indices, a combination of spectral bands and a combination of spectral derivatives. Our results showed that (a) the band-combination approach provides the most accurate and precise estimates of AWC and RWC at both 0.5 and 30 m sampling resolutions; (b) the combination of bands providing the greatest predictive abilities are those that emphasize the contrast in reflectance between the NIR and SWIR spectral regions; (c) the band-combination approach predicts AWC with much greater accuracy and precision than RWC and (d) the predictive ability of the band-combination approach decreases only slightly when plot-level data are aggregated to a 30 m sampling resolution. These results are generally consistent with the results of other studies and with theory. While our results suggest that simple spectral methods (e.g. linear band-combinations or indices) are good predictors of AWC over grazed and ungrazed grassland–shrubland landscapes at plot- and Landsat spatial resolutions, they are less encouraging for the estimation of RWC. Despite their good predictive abilities, the temporal and geographical portabilities of the spectral approaches for estimating AWC must be further assessed before they can be considered reliable and robust predictive tools. Thus, the further testing of these techniques over larger geographical extents is required.

Keywords: Absolute water content; Relative water content; Spectral vegetation indices; Grasslands; Shortwave infrared

1. Introduction

The measurement of vegetation water content is important for determining the physiological status of plants (Datt, 1999), and for evaluating drought and wildfire risk in natural plant communities (Peñuelas et al., 1997) and for estimating land surface albedo which is an important parameter in climate and climate change studies (Wang, in press; Wang and Davidson, in

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press). These assessments are particularly important in environments that frequently experience extreme water stress. The northern portion of the North American mixed grass prairie is an example of such a region. Here, relatively little summer precipitation (150–225 mm), high summer temperatures (often >20 °C) and strong and dry prevailing winds frequently combine to create a severely water-limited landscape during much of the growing season (Bryson and Hare, 1974; Loveridge and Potyondi, 1983; Coupland, 1992). However, the sheer vastness of this landscape means that in situ observations are rarely sufficiently dense to accurately characterize its regional variation in vegetation water content. Thus, other measurement approaches must instead be utilized. One possible approach is the use of satellite remote sensing systems.

Remote sensing has the potential to overcome the present limitations of traditional methods of large-scale vegetation assessment by offering a non-destructive and instantaneous monitoring approach at various landscape scales. However, the first step towards establishing an operational technique to retrieve vegetation water content using remote sensing is to clearly identify where the potential lies (Ceccato et al., 2001). Attempts to estimate vegetation water content using spectral data have been carried out using sensors operating in three portions of the electromagnetic spectrum. These are (a) the visible (VIS) to shortwave infrared region (blue (B; $\lambda \approx 0.45$–$0.52\ \mu$m); green (G; $\lambda = 0.52$–$0.6\ \mu$m), red (R; $\lambda \approx 0.62$–$0.69\ \mu$m), near infrared (NIR; $\lambda \approx 0.7$–$0.90\ \mu$m), shortwave infrared (SWIR; $\lambda \approx 0.9$–$2.5\ \mu$m)); (b) the thermal–infrared region (TIR; $\lambda \approx 6.0$–$15.0\ \mu$m) and (c) the microwave region (MW; $\lambda \approx 0.1$–100 cm). Observations in the VIS-to-SWIR wavelengths have received particular attention because they contain the wavelengths most heavily influenced by tissue water content (Tucker, 1980; Bowman, 1989; Cohen, 1991). Studies operating in these wavelengths have been carried out using simulated spectra (e.g. Danson and Bowyer, 2004), ground-based radiometers in the laboratory (e.g. Hunt et al., 1987; Hunt and Rock, 1989; Datt, 1999; Ceccato et al., 2001; Tian et al., 2001) and in the field (e.g. Peñuelas et al., 1997; Piñol et al., 1998; Rollin and Milton, 1998; Peñuelas and Inoue, 1999; Liu et al., 2004), and multi-spectral scanning systems mounted on aircraft (e.g. Ustin et al., 1998; Serrano et al., 2000) and satellites (e.g. Paltridge and Barber, 1988; Ceccato et al., 2002a; Chuvieco et al., 2003; Maki et al., 2004). A number of these studies have focused their attentions on grassland–shrubland ecosystems (e.g. Paltridge and Barber, 1988; Peñuelas et al., 1996; Rollin and Milton, 1998; Serrano et al., 2000; Ceccato et al., 2002a; Chuvieco et al., 2002; Ustin et al., 2004).

Two approaches have commonly been used to estimate vegetation water content in visible-to-shortwave infrared wavelengths. The indirect approach does not measure vegetation water content directly. Rather, it usually uses spectral vegetation indices based on reflectances in the R and NIR wavelengths – such as the Normalized Difference Vegetation Index (NDVI), the Structural Independent Pigment Index (SIPI), Modified Vegetation Index (MVI) and Simple Ratio (SR) (Table 1) – to estimate leaf chlorophyll content, which is assumed to correlate well with leaf moisture content, and hence, the drought stress experienced by plants (see Tucker, 1977; Paltridge and Barber, 1988; Illera et al., 1996). However, while this assumption may be correct for some species, it cannot be generalized for all ecosystems because variations in chlorophyll content can also be caused by plant nutrient deficiency, disease, stress, toxicity and phenological stage (Larcher, 1995; Ceccato et al., 2001). As a result, such techniques are only valid in regions where the correlations between leaf chlorophyll and water contents have been established (Ceccato et al., 2001). The direct approach usually uses spectral vegetation indices based on reflectances in the NIR and SWIR wavelengths – such as the Normalized Difference Infrared Index (NDII), Moisture Stress Index (MSI), Global Vegetation Moisture Index (GVMI) and NIR–SWIR derivative ($DER_{4.5}$) (Table 1) – to directly estimate vegetation water content. However, the integral method is also a direct approach, and it is based on reflectances in the VIS–SWIR spectral regions (Table 1). Studies have shown that plant water content strongly influences SWIR, particularly at $\lambda = 1.53$ and $1.72\ \mu$m (Tucker, 1980; Jackson and Ezra, 1985; Hunt et al., 1987; Bowman, 1989; Fourty and Baret, 1997).

In this study, we compare the ability of three spectral approaches to predict vegetation water content across northern prairie grassland–shrubland communities. Specifically, we assess whether vegetation water content is best predicted by (i) a single vegetation index, (ii) a combination of spectral bands or (iii) a combination of spectral derivatives. This "best" spectral approach should satisfy three criteria: it should have good predictive abilities, it should work equally well over grazed and ungrazed grassland and shrubland targets, and it should be simple. To achieve these goals, we collected vegetation water content and spectral radiometer data over plots of comparable ground resolution (0.5 m) at seven field sites in the Canadian