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Spectral sensing of foliar water conditions in two co-occurring conifer species: *Pinus edulis* and *Juniperus monosperma*

Hugh C. Stimson[a], David D. Breshears[b,*], Susan L. Ustin[a], Shawn C. Kefauver[a]

[a]Department of Land, Air and Water Resources, University of California, Davis, CA 95616, USA
[b]Earth and Environmental Sciences Division, Mail Stop J495, EES-2, Los Alamos National Laboratory, University of California, Los Alamos, NM 87545, USA

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Abstract

Many fundamental ecosystem properties and dynamics are determined by plant water stress, particularly in dryland ecosystems where water is usually limiting. Indeed, under severe drought, plant water stress and associated insect infestations can produce landscape-scale mortality. Despite the fundamental importance of plant water stress in determining properties and dynamics at ecosystem and landscape scales, approaches for remotely sensing plant water stress are largely lacking, particularly for conifers. We evaluated the remotely sensed detection of foliar drought stress in two conifer species, *Pinus edulis* and *Juniperus monosperma*, which are co-dominants of extensive-juniper woodlands in North America, the first of which experienced extensive mortality in association with a recent drought. Needle spectra were made on these species in the field using an integrating sphere and portable spectrometer. Two indices of foliar water condition, plant water content (% of dry mass) and plant water potential, were compared to five spectral analyses: continuum removal of the 970 and 1200 nm water absorption features, the Normalized Difference Water Index (NDWI), the Normalized Difference Vegetation Index (NDVI), and the red edge wavelength position. For *P. edulis*, plant water content was significantly correlated with four of the five indices: NDVI (R^2=0.71) and NDWI (R^2=0.68) which exhibited stronger relationships than 970 nm continuum removal (R^2=0.57) or red edge position (R^2=0.45). All five indices were significantly correlated with *P. edulis* water content when trees undergoing mortality were included in analyses (R^2=0.60–0.93). Although the correlations were weaker than for plant water content, plant water potential was significantly correlated with NDWI (R^2=0.49), 970 nm (R^2=0.44), NDVI (R^2=0.35), and red edge (R^2=0.34); again all five indices had significant relationships when trees undergoing mortality were included (R^2=0.51–0.86). The relationships were weaker for *J. monosperma*: water content was significantly related to 970 nm (R^2=0.50) and 1200 nm (R^2=0.37) continuums and NDVI (R^2=0.33), while water potential was related only to 1200 nm (R^2=0.40). Our results demonstrate a critical link between plant physiological characteristics tied to water stress and associated spectral signatures for two extensive co-occurring conifer species.

Keywords: *Pinus edulis*; *Juniperus monosperma*; Foliar water content; Water potential; Spectral remote sensing; Drought stress; Spectral indices

1. Introduction

Plant water relations determine many fundamental ecosystem patterns, processes, and dynamics (Lambers et al., 1998; Waring & Running, 1998). In particular, foliar water content and associated water potential is a primary limiting factor for plant transpiration and carbon gain. The constraint imposed by water on these processes is particularly great in dryland ecosystems where water is usually limiting (Ludwig et al., 1997; Noy-Meir, 1973). Foliar water content is temporally and spatially variable in response to high heterogeneity in the distribution of precipitation and associated soil moisture (Breshears et al., 1997b; Loik et al., 2004; Padien & Lajtha, 1992). Variation in foliar water condition is of particular importance during drought, when plant water stress can

* Corresponding author. Current address: School of Natural Resources, Institute for the Study of Planet Earth, and Department of Ecology and Evolutionary Biology, University of Arizona, Biological Sciences East 325, Tucson, AZ 85721-0043, USA.

E-mail address: daveb@ag.arizona.edu (D.D. Breshears).

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cause cavitation, in which embolisms break the water column (Pockman & Sperry, 2000), that can lead to mortality of individual plants, sometimes at landscape scales (Allen & Breshears, 1998).

Ecologists have used field measurements of leaf water content and leaf water potential for several decades as sensitive indicators of water status. Leaf water content and water potential are related to several water status variables and both measures have been reported extensively in the literature. Despite the potential value of these measurements, the requirements for pre-dawn water potential measurements to estimate soil moisture status and minimum plant water stress levels and diurnal measurements to estimate maximum water stress impose severe limits on the number of samples that can be measured. The relationship between water content and water potential has long been used by physiologists to quantify water status by plotting moisture release curves, in which the relative water content (the leaf water weight/leaf turgid weight) is graphed against the reciprocal of water potential, to estimate the water content at zero turgor, the osmotic and matrix potentials, among others. The need to hydrate samples and measure fresh and dry weights to obtain relative water content imposes significant limitations for using this technique over large areas or over extended periods. Both Cohen (1991b) and Hunt (1991) have expressed reservations about the usefulness of a relative water content index for remote sensing applications.

Foliar water status of conifer species is of particular interest to ecologists due to their extensive distribution and frequent dominance in dryland landscapes, where variation in water status is especially important. Nonetheless, it is impractical to obtain the numerous near-simultaneous estimates of plant water status that are needed to assess landscape-scale function and dynamics. The measurement problem becomes impossible when such data are needed to monitor a region over an extended period of time. Consequently, landscape-scale assessments of plant water status are only practically pursued through modeling (Waring & Running, 1998).

Remote sensing offers the potential to estimate foliar water condition, even on a routine basis. Variance in water content of leaves is a primary physical driver for variance in reflectance properties in the infrared region (Gao, 1996; Gao & Goetz, 1994, 1995; Jacquemoud & Ustin, 2003; Ustin & Curtiss, 1990; Ustin & Jacquemoud, 2003; Ustin et al., 1998, 2004). However, assessment of conifer water condition has traditionally been difficult to measure and quantify even in laboratory measurements due to branch and leaf geometry (Brand, 1987) and optical properties (Ustin et al., 2004). Although the potential for assessment of water condition via evaluation of spectral properties of foliage has been demonstrated, previous studies have focused primarily on leaves of broadleaf species grown for this purpose (Adams et al., 1999; Bowman, 1989; Ceccato et al., 2001; Inoue et al., 1993; Penuelas et al., 1993; Peñuelas & Inoue, 1999; Yu et al., 2000) or collected in the field (Blackburn, 1999; Gao, 1996; Gao & Goetz, 1994; Gitelson et al., 1996; Hunt et al., 1987).

Most studies that have investigated detailed spectral properties of conifer needles (Danson et al., 1992; Daughtry et al., 1989; Mesarch et al., 1999; Ustin & Curtiss, 1990) have not focused on water content. However, Cohen (1991a,b) examined relationships between Landsat band indices and relative water content in laboratory experiments on needles of Coulter pine and lodgepole pine, and showed that ratios of red to near infrared (NIR) and NIR to shortwave-infrared (SWIR) were correlated with water content and water potential.

Numerous correlations between spectral bands or band ratios related to water status have been developed (e.g., Datt, 1999; Inoue et al., 1993; Ripple, 1986; Yu et al., 2000). Some spectral indices to assess water content have used Landsat Thematic Mapper (TM) satellite bands, including a pigment index, NDVI (Penuelas et al., 1993); water absorption index, WI (R_{895}/R_{972}; Penuelas et al., 1993); Moisture Stress Index (R_{1599}/R_{819}; Hunt & Rock, 1989); and Normalized Difference Infrared index, NDII ($[R_{819}-R_{1649}]/[R_{819}+R_{1649}]$; Hardisky et al., 1983).

Some landscape-level studies to detect water condition have involved conifers to a greater (Gao & Goetz, 1994, 1995) or lesser extent (Gao, 1996; Serrano et al., 2000; Ustin et al., 1998; Zarco-Tejada et al., 2003). An early hyperspectral study by Riggs and Running (1991) had limited success measuring induced water stress on conifer canopies using the AIS airborne instrument and analysis techniques available at the time. To date, few studies have tested the ability of spectral measurements to detect water condition of conifers at the needle level. Although establishment of needle-level relationships alone is insufficient to detect patterns at larger ecosystem and landscape scales in imagery, it is a necessary component for developing such methods.

Narrow-band spectroscopy measurements like the Equivalent Water Thickness (EWT) that integrate reflectance from R_{867} through R_{1049} (Green et al., 1993) or the water thickness integrating from R_{867} through R_{1068} (Roberts et al., 1998) are obtained by modeling atmospheric water vapor and liquid water in imaging spectrometery data. Serrano et al. (2000) showed in AVIRIS data that pigments, water, and EWT are strongly correlated and show similar relationships to relative water content (RWC), with NDWI providing the best correlation. The continuum removal indices at 970 and 1200 nm integrate responses over water absorption features producing relationships similar to the EWT and WT measures derived from atmospheric calibration of AVIRIS data.

The red edge, a narrow band index that estimates foliar pigment concentration, provides an alternative to the more commonly studied Normalized Difference Vegetation Index (NDVI), which is correlated with water through relationships with leaf area and chlorophyll in foliage. The red edge