EXAMINING SEASONAL CHANGES IN CANOPY MOISTURE USING AVIRIS TIME SERIES DATA

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1. Introduction

Canopy moisture content has both ecological importance as indicator of vegetation response to drought stress and importance in terms of fire danger, as canopy moisture is a major determinant of the ability of fire to propagate through vegetation canopies. Imaging spectrometer data are well-suited to measuring canopy water moisture using water absorption features in the near- and shortwave- infrared. This paper examines the use of Airborne Visible Infrared Imaging Spectrometer (AVIRIS) and Moderate Resolution Imaging Spectrometer (MODIS) data for mapping and monitoring canopy moisture content in chaparral in the Santa Monica Mountains of Southern California.

2. Background

Canopy water content is measured as live fuel moisture for fire danger assessment (Countryman and Dean, 1979). Live fuel moisture is the mass of liquid water divided by the mass of dry vegetation:

$$M = \frac{m_w - m_d}{m_d} \tag{1}$$

where M is the live fuel moisture, m_w is the measured mass of a fresh, undried sample, and m_d is the measured mass of a dried sample. Live fuel moisture in chaparral typically follows a seasonal trend, with high live fuel moisture in the winter and spring and low fuel moisture in summer and fall (Figure 1). Live fuel moisture peaks between 130-160% in chamise (*A. fasciculatum*), a species common in Southern California chaparral. Live fuel moisture declines through the summer and fall to reach approximately 60%, a level that is referred to as the "critical" live fuel moisture. At this level, fire will readily propagate through chamise canopies by the combustion of live fuels. The ability to monitor changes in live fuel moisture and identify the onset of critical live fuel moisture could permit more efficient allocation of personnel and resources in fire prone areas.

Canopy water content measures in the near-infrared are based on weak water absorption features centered around 970 nm and 1200 nm wavelength. Equivalent water thickness (EWT) is a measure of canopy water content that can be easily derived from hyperspectral data (Gao and Goetz, 1995). EWT models reflectance (ρ_λ) as a linear function of wavelength (λ) multiplied by an absorption function:

$$\rho_\lambda = (m\lambda + b)e^{-t\alpha_\lambda} \tag{2}$$

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where m and b are coefficients that determine the slope and intercept of the linear function, α_λ is the absorption coefficient of liquid water, and t is the equivalent water thickness (Gao and Goetz, 1995; Green, 2003). Thus EWT is the equivalent amount of water that would be necessary to reproduce the water absorption feature in the reflectance spectrum. An alternative measure of canopy water absorption, normalized difference water index (NDWI) is portable to multispectral data. NDWI (Gao, 1996) uses a normalized difference index to compared the reflectance measured in the 1200 nm water absorption feature and reflectance measured in a reference band. For MODIS data, NDWI is calculated as:

$$\text{NDWI} = \frac{\rho_{857} - \rho_{1241}}{\rho_{857} + \rho_{1241}} \tag{3}$$

where ρ_{857} is the reflectance in a near infrared reference band and ρ_{1241} is the reflectance at the edge of the 1200 nm water absorption band (Gao, 1996).

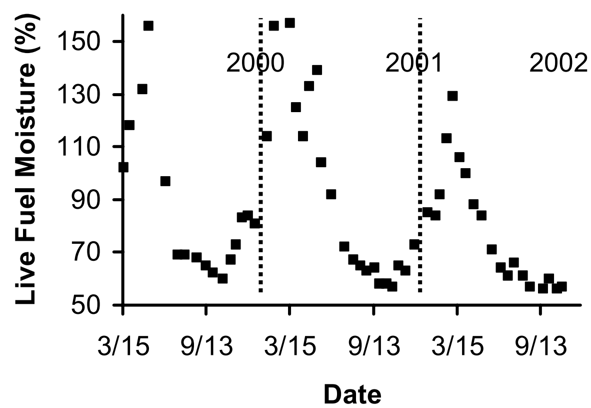

Figure 1. Seasonal trends in chamise live fuel moisture as measured by the Los Angeles County Fire Department at Clark Motorway, March 2000-October 2002.

Several studies have demonstrated relationships between spectral measures of water absorption and canopy moisture. Sims and Gamon (2003) compared the ability of water indices to estimate vegetation water content. They found indices based on the 970 nm and 1200 nm water absorption bands to be the best predictors of canopy water content. Serrano et al. (2000) compared water index (WI), NDWI, and EWT calculated from AVIRIS data to relative water content in chaparral. WI and NDWI accounted for most of the variation in canopy relative water content, but the relationship between these indices and relative water content was found to be species dependent. Roberts et al. (1997) and Ustin et al. (1998) identified seasonal changes in EWT that were dependent on changes in canopy moisture in chaparral. Peñuelas et al. (1997) used time series field spectrometer data to relate WI to the relative water content of Mediterranean plant seedlings. Zarco-Tejada et al. (2003) modeled EWT from a Moderate Resolution Imaging Spectrometer (MODIS) time series and found a good correlation with field-measured relative water content.

3. Methods

Two methods were used to demonstrate remote sensing retrieval of canopy water content in chaparral: 1) EWT was calculated for an AVIRIS time series, and then compared to live fuel moisture sampled by the Los Angeles County Fire Department (LACFD) and to cumulative water balance index (CWBI), a relative measure of drought stress; and 2) NDWI was calculated for an MODIS time series, and was compared live fuel moisture sampled by the LACFD.

AVIRIS Time Series

Fifteen high-altitude AVIRIS images acquired over the Santa Monica Mountains, California between 1994 and 2002 were used to construct a time series. AVIRIS data were corrected to apparent surface reflectance using MODTRAN (Green et al., 1993). Images were registered to an orthorectified SPOT image sampled to a resolution of 20 meters. EWT was calculated for each pixel by fitting equation (2) to the 850-1100 nm spectral region using non-linear least squares. CWBI was calculated for each date by cumulatively summing precipitation and reference evapotranspiration measured by a California Irrigation Management Information System (CIMIS) station in Santa Monica, California (Dennison et al., 2003).

EWT and live fuel moisture from the LACFD Clark Motorway site were compared using linear regression. A mean EWT value was determined for the site by extracting EWT values from a polygon containing homogeneous vegetation cover around the coordinates of the site. Homogeneity was determined using a 1 meter resolution orthophotograph. A sigmoidal function was used to compared EWT for each pixel within the time series and CWBI:

$$EWT = a + \frac{b}{1 + e^{-(c + d \cdot CWBI)}} \tag{4}$$

where *a* is the minimum EWT, *b* is the range in EWT, and *c* and *d* control the slope and timing of the sigmoidal function. Four AVIRIS dates were excluded from the time series fit with equation (4), with three dates excluded due to registration errors and one date excluded due to extremely high precipitation during the winter of 1998, which skewed the CWBI calculated for that date.

MODIS Time Series

Terra MODIS data acquired between March 2000 and October 2002 were used to construct a time series for Southern California. The MODIS 500-meter resolution daily surface reflectance product (MOD09GHK version 4; Vermote et al., 1997) was used to create 10-day cloud masked composites. Median reflectance within the masked 10-day window was calculated for each band and for each pixel in the time series. NDWI was calculated for each 10-day composite using equation (3). NDWI was extracted for a single pixel containing the Clark Motorway live fuel moisture site. Since LACFD does not report actual sampling dates, the date of the actual report was used to determine the date of the composite used for comparison.

4. Results

EWT demonstrated a strong, linear relationship with live fuel moisture measured at the Clark Motorway site (Figure 2). A linear regression of live fuel moisture against EWT produced a R^2 of 0.83. NDWI calculated from MODIS data was also positively correlated with live fuel moisture measured at the Clark Motorway site (Figure 3). A linear regression of live fuel moisture against NDWI produced a R^2 of 0.73.

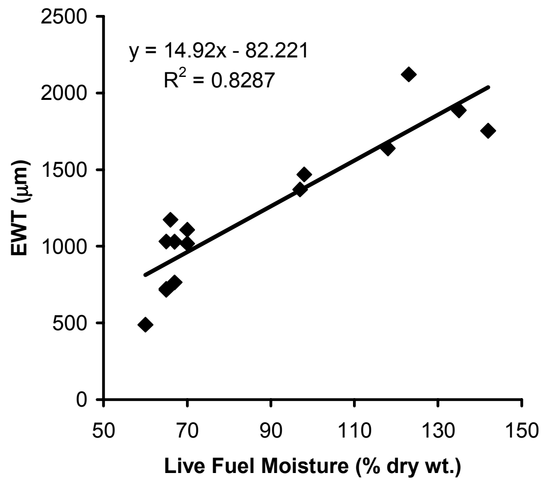

Figure 2. Live fuel moisture vs. EWT for the Clark Motorway chamise site.

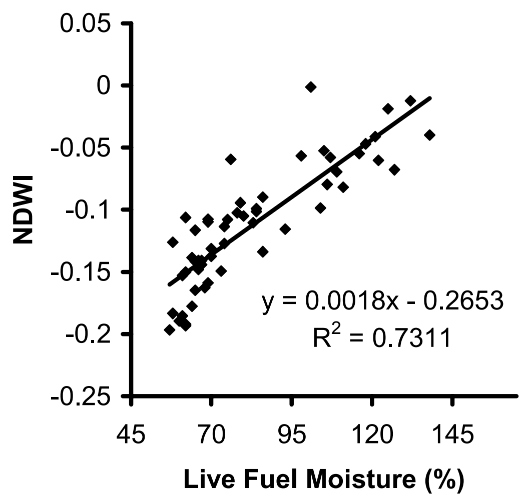

Figure 3. Live fuel moisture vs. MODIS NDWI for the Clark Motorway chamise site.

Fit parameters derived from Equation 4 for CWBI and EWT are shown in Figure 4. RMSE of the model fits was below 0.3mm in most naturally vegetated areas, and higher in residential and agricultural areas surrounding the Santa Monica Mountains (Figure 4a). RMSE was highest in pixels with temporal vegetation disturbances such as wildfire or human activity. Fire scars from the 1993 Green Meadow Fire (G), 1996 Calabasas Fire (C), and 1993 Topanga Fire are clearly visible in Figure 4a. Minimum EWT (Figure 4b) and maximum EWT (Figure 4c) define the baseline and upper limit canopy water absorption. The minimum and maximum EWT values are highest in high elevation areas outside of the fire scars. The modeled inflection points demonstrated several important spatial trends (Figure 4d). The most rapid change in EWT occurred at small negative CWBI values in lower elevation grassland and chaparral areas in the northern and eastern Santa Monica Mountains (Figure 4d). Inflection points occurred at more negative CWBI values in higher elevation, inland areas of the Santa Monica Mountains.

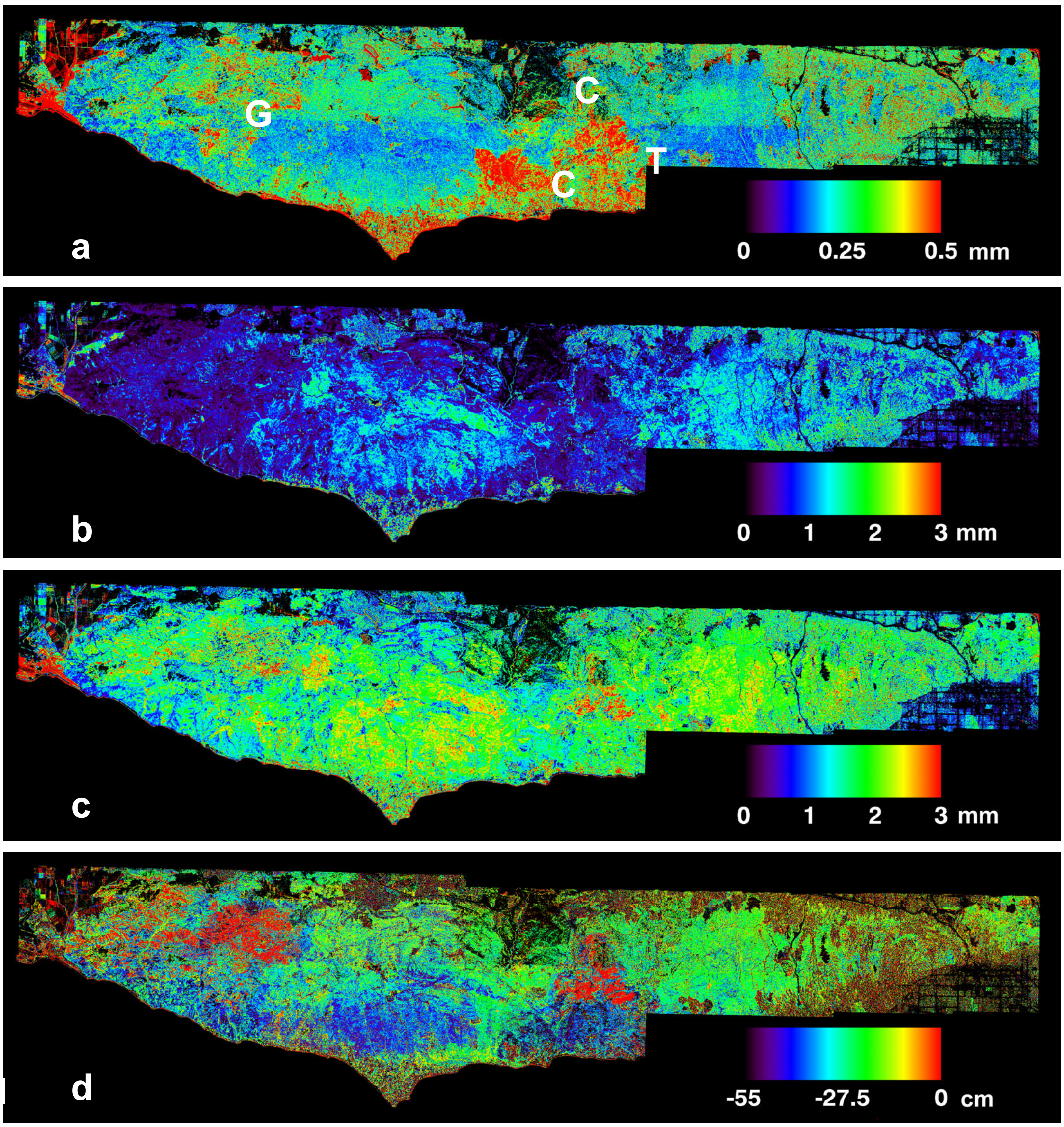

Figure 4. Sigmoidal model fit parameters for the time series: a) root mean square error, b) minimum EWT, c) maximum EWT, and d) inflection point. Fire scars are marked in the RMSE image as the 1993 Green Meadow Fire (G), the 1993 Topanga Fire (T), and the northern and southern halves of the 1996 Calabasas Fire (C).

Both the minimum and maximum EWT were closely related to aboveground biomass (Figure 5). Minimum and maximum EWT were compared to biomass measured at seven chaparral sites in the Santa Monica Mountains (Regelbrugge and Conard, 1997; Dennison et al., 2003). The two linear regressions between biomass and EWT had similar slopes, but the intercept term for maximum EWT possessed an intercept 0.87 mm higher than the intercept for minimum EWT. Minimum EWT had the strongest correlation with biomass, with an R^2 of 0.88 (Figure 5).

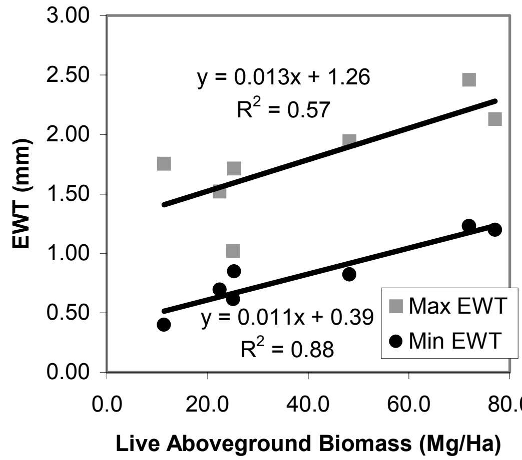

Figure 5. Live aboveground biomass versus the minimum and maximum EWT.

5. Discussion

Both AVIRIS EWT and MODIS NDWI demonstrate strong relationships with live fuel moisture measured at a single sample site. The correlation between NDWI and live fuel moisture is somewhat weaker than the correlation between EWT and live fuel moisture. Differences in the strengths of the two relationships may be due to difference in spatial resolution. While the actual size of the sample site is unknown, Countryman and Dean (1979) recommended that frequently sampled sites possess a size of approximately 3-4 hectares. In contrast, a 500 meter MODIS pixel contains 25 hectares, within which significant variation in land cover type and topography can occur. Twenty-meter AVIRIS data were averaged for the comparison of live fuel moisture and EWT, which may have reduced spatial variation in spectral characteristics.

Both Figures 2 and 3 show higher variability in EWT and NDWI at the critical live fuel moisture of 60%. While live fuel moisture does not drop below 60% in live chaparral, extreme drought stress may lead to a reduction in leaf area or partial die-back of chaparral canopies. Changes in canopy biomass are difficult to discriminate from changes in canopy moisture using any method of quantifying spectral water absorption (Gao, 1996). Where reduction in canopy biomass occurs, EWT and NDWI may underestimate live fuel moisture. An index with greater range at high drought stress, such as CWBI, may be more appropriate for characterizing changes in canopy moisture during periods of extreme drought.

Time series EWT modeled by CWBI reveals spatial differences in EWT minima, maxima, and inflection points. Conditions that may cause spatial variation in drought stress may include the prevalence of vegetation species, soil depth and water capacity, and topographic variability of solar insolation and precipitation. Higher elevation areas in the Santa Monica Mountains receive higher precipitation, and portions of the range closer to the Pacific Ocean may receive reduced evapotranspiration and additional moisture from marine fog. These factors may delay the onset of drought stress at higher elevation and coastal sites.

6. Conclusions

Both EWT calculated from AVIRIS data and NDWI calculated from MODIS data were found to be related to chaparral live fuel moisture measured in the Santa Monica Mountains. Using CWBI, spatial trends in the minimum and maximum EWT values and the CWBI inflection point were observed. The results of this work point to different roles for a high resolution hyperspectral sensor such as AVIRIS and a coarse resolution multispectral instrument such as MODIS. AVIRIS data can best be used for the detailed spatial analysis of vegetation response to drought stress. A small number of well-timed data acquisitions could reasonably characterize seasonal changes in canopy moisture, as shown with the Santa Monica Mountains time series. An airborne hyperspectral sensor can not provide a means for active monitoring of changes in canopy moisture. This is a role better suited to MODIS, which allows frequent (daily-to-weekly) retrieval of vegetation response to drought stress.

7. Acknowledgements

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