De la Riva, J., Pérez-Cabello, F. & Chuvieco, E. (Eds) 2005
Proceedings of the 5th International Workshop on Remote Sensing and GIS Applications to Forest Fire Management: Fire Effects Assessment: 85-90
Universidad de Zaragoza. ISBN: 84-96214-52-4

Fine spatial, spectral and temporal characterization of wildfire fuels through the integrated analysis of imaging spectrometry and coarser resolution broad band data

D.A. Roberts[1] , S. Peterson[1], P.E. Dennison[2], J. Rechel[3] & J.W. van Wagtendonk[4]

[1] *Dept. Geography and Institute for Computational Earth System Science, UCSB, Santa Barbara, CA 93106, USA, E-mail: dar@geog.ucsb.edu*

[2] *Dept. Geography University of Utah, Salt Lake City, UT 84112, USA, E-mail: dennison@geog.utah.edu*

[3] *USDA Forest Service, Pacific Southwest Research Station, Forest Fire Laboratory, Riverside, CA, 92506, USA, E-mail: jrechel@fs.fed.us*

[4] *USGS Western Ecological Research Center Yosemite Field Station El Portal, CA 95318-0700, USA, E-mail: jan_van_wagtendonk@usgs.gov*

Keywords: AVIRIS, live fuel moisture, spectral mixture analysis, NDWI, NDVI

ABSTRACT: Wildfire represents one of the most beneficial, yet destructive, forms of disturbance in the western United States. Wildfire danger is a product of weather, fuels and terrain, varying seasonally depending on changes in the amount and condition of fuels (live and dead components) and their moisture content. Recent advances in imaging spectrometry offer the potential of developing improved maps of fuel type, fuel condition (green live to dead fuel ratios) and live fuel moisture. However, airborne data collected by sensors such as the Airborne Visible Infrared Imaging Spectrometer (AVIRIS) are of limited utility because they do not sample a large enough area, nor do they provide adequate seasonal sampling. In this paper, we discuss a multi-scale, multisensor approach, in which relationships derived from AVIRIS are expanded spatially and temporally using the Moderate Resolution Imaging Spectrometer (MODIS). AVIRIS spectra were used to guide the selection of a set of reference endmembers that were used to map fuel condition using AVIRIS and MODIS data. AVIRIS estimates were compared directly to MODIS for the same locations and for the same time period. AVIRIS and MODIS estimates of fuel condition were shown to closely correspond. To quantify seasonal and interannual changes in fuel condition throughout the Western United States, single-date MODIS estimates for NPV and GV were expanded using 16 day composites of 500m MODIS data.

Several AVIRIS measures were also tested to evaluate their relationship to live fuel moisture. AVIRIS measures, including spectral fractions, Modified NDWI, Equivalent Water Thickness (EWT), and NDVI were tested against field measures of live fuel moisture, for select regions in Los Angeles (LA) County using an 8 year time series of AVIRIS data. To test the capability of MODIS for estimating seasonal changes in live fuel moisture, these same remotely sensed measures were tested against the LA County fuel moisture data at 16 day intervals from 2000 to 2003. To evaluate the potential of MODIS as a means for monitoring interannual and seasonal changes in live fuel moisture in other cover types, including coniferous forest, MODIS spectral fractions were calculated at select field sites in the Western States where live fuel moisture had been measured.

AVIRIS analysis showed strong positive correlations between all measures of greenness and moisture and live fuel moisture, with correlations of 0.91 for NDVI and 0.87 for the green vegetation fraction. At MODIS scales, MODIS NDWI was shown to provide improved measures of live fuel moisture relative to the NDVI for (closed canopy) evergreen shrublands, while NDVI was superior for (open canopy) drought deciduous shrublands. Time-series analysis of MODIS data showed clear temporal patterns corresponding to seasonal green up and dry down, but were also subject to errors at high elevation sites due to the presence of snow.

1 INTRODUCTION

Over more than a decade satellite remote sensing has been used to assess the condition of fuels, either by indirect measures of fuel moisture or through measures of relative greenness, typically calculated using the Normalized Difference Vegetation Index (NDVI: Burgan and Hartford, 1996). Recent advances in spaceborne and airborne imaging systems offer the potential of significantly improving our ability to assess fuel condition and moisture. Fuel condition can be assessed using spectral mixture analysis (SMA) to map fractions of green vegetation (GV) and non-photosynthetic vegetation (NPV: Roberts *et al.*, 1993; 2003). Several direct measures of canopy moisture have also been developed, including the Water Band Index (WBI: Penuelas *et al.*, 1997), Normalized Difference Water Index (NDWI: Gao, 1996), and Equivalent Water Thickness (EWT: Roberts *et al.*, 1997). A number of authors have assessed the potential of these indices for estimating fuel moisture in Southern California chaparral, primarily using AVIRIS (Dennison *et al.*, 2003).

While imaging spectrometers have considerable potential for fire danger assessment they are limited by sparse temporal and spatial coverage. For example, we have worked extensively in the Santa Monica Mountains and Santa Barbara area using extensive AVIRIS time series, yet these sites represent only a small portion of the area in southern California subject to fire. Furthermore, even the best temporal coverage only represents a few samples in a fire season, and thus lacks the fine temporal coverage required to monitor seasonal changes in fire danger.

To address these limitations, we evaluate the potential of exporting information extracted at fine spectral and spatial resolutions from AVIRIS and field/lab spectrometers to MODIS time series data covering much of the Western United States. Specifically, we address the following questions:

1) Can reference endmembers, derived from a combination of low altitude AVIRIS data, field spectra and laboratory measurements be ported to MODIS to provide comparable measures of fuel condition?
2) What is the relationship between AVIRIS-derived measures and field measured live fuel moisture (LFM) in chaparral?
3) What is the relationship between MODIS-derived measures and the same field measures?
4) How do spectral fractions, derived from a single set of endmembers vary at select locations in the Western United States seasonally and interannually between 2000 and 2004?

2 MATERIALS AND METHODS

2.1 *Study sites and data*

The study was conducted over three geographic regions, the Santa Monica Mountains, Los Angeles County, California and the Western United States west of the Rocky Mountains. The Santa Monica Mountains are an east-west trending range west of the city of Los Angeles consisting primarily of grasslands, drought deciduous shrublands, evergreen chaparral and oaks. Remotely sensed data include an extensive 8-year fully georectified AVIRIS time-series acquired at a 20 m spatial resolution covering spring/fall pairs through most of the time period. Three of 12 LFM sites monitored by the Los Angeles County Fire Department (LACFD) are located in the region, including Clark Motorway chamise and Ceanothus, Laurel Canyon chamise and Trippet Ranch chamise and black sage. See Dennison *et al.*, 2005 for more details regarding these sites.

The second geographic region includes a diversity of LFM sites distributed throughout the foothills and mountains of Los Angeles County, California. LFM sites included the three sites in the Santa Monica Mountains, and 9 additional sites that sampled primarily chamise, but also included purple sage (Bitter Canyon 1), black sage (Bouquet Canyon), hoary leaf Ceanothus (Sycamore Canyon) and California sagebrush (Bitter Canyon 1). While AVIRIS data were not available over most of this region, MODIS time-series data were available extending from mid-February, 2000 to December, 2004. See Dennison *et al.*, 2005 for more details on the LFM sites.

The final geographic region included five MODIS tiles, covering the entire Western United States extending westward from Kansas. This data set consists of a 16 day composite developed from the 7 channel MOD09GHK Version 4 reflectance product (Dennison *et al.*, 2005). Processing steps included cloud screening using the 1 km MODIS MOD09GST Version 4 product, resampled to 0.5 km resolution, screening to remove extreme off-nadir viewing geometries and the use of median values for each wavelength during the compositing period. Field sites included seven locations distributed across the Western US including Los Padres, Lassen and the Sierra Nevada (California), Rio Grande (Colorado), Gila (New Mexico), Coco (Arizona) and Idaho (Birds of Prey). Land cover types included Great Basin sage brush, Pinyon-juniper woodland, Ponderosa pine, mixed conifer, white fir, gambel oak, coast live oak, several varieties of pines, Douglas fir, chaparral and aspen. See Rechel *et al*. (this issue).

2.2 *Remote sensing analysis*

Analysis was restricted to reflectance data. SMA was accomplished using a simple mixing model consisting of one soil, shade, GV and NPV endmember for all study regions. Candidate endmembers were selected from a reference library consisting of approximately 850 reflectance spectra acquired at a 2 nm spectral interval between 400 and 2500 nm. This spectral library was compiled from several field and lab spectral libraries covering the west-coast of the United States. Reference spectra included a diversity of soils, litter, bark, wood, and vegetation spectra at leaf and branch scales including a large number of chaparral, broadleaf evergreen and conifer dominants. This spectral library was convolved to AVIRIS and MODIS wavelengths.

Candidate endmembers for NPV, GV and soil were selected using Constrained Reference Endmember Selection (CRES), in which field estimates of cover fractions are used to guide the selection of reference endmembers (Roberts *et al.*, 1997; 1998). Candidates were selected from MODIS spectra acquired over several sites with existing AVIRIS coverage and endmembers were constrained to match fractions from prior AVIRIS analysis. Through this approach, one set of GV, NPV and soil spectra was determined that provided reasonable fractions across a diversity of cover types. The shade endmember was set at 0% reflectance.

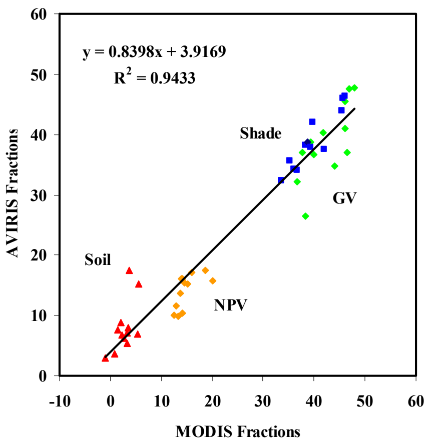
In addition to spectral fractions, other measures included EWT (Roberts *et al.*, 1997), Normalized Difference Water Index (NDWI: Gao, 1996), Modified-NDWI (Roberts *et al.*, 2003) and Normalized Difference Vegetation Index (NDVI). EWT is calculated as the equivalent amount of water required to produce the water absorption feature observed in the 970 nm water absorption region of a reflectance spectrum. NDWI and mNDWI are normalized ratios calculated as NDWI = (ρNIR – ρwater)/(ρNIR+ρwater), where ρNIR and ρwater correspond to 857 and 1241 nm for the NDWI and 1070 and 1200 nm for the mNDWI. The mNDWI is a hyperspectral version of the NDWI that takes advantage of the finer spectral sampling by placing the bands more strategically for water. For AVIRIS, a narrow-band NDVI was calculated as NDVI = (ρ793- ρ677)/(ρ793+ρ677)(Roberts *et al.*, 1997).

3 RESULTS AND DISCUSSION

3.1 *Fuel Condition*

A comparison between AVIRIS-derived and MODIS-derived spectral fractions demonstrated that these two sensors provide comparable measures of fuel condition (Figure 1). Sensor performance was compared by sampling points from the same geographic locations in the Santa Monica Mountains imaged by AVIRIS and MODIS in June, 2000 and 2001. Both sensors quantified chaparral as consisting of a high green vegetation and shade fraction, intermediate NPV and low soil. Given these early dry season images these are reasonable values for NPV.

Figure 1. Spectral fractions from June, 2000 AVIRIS and MODIS from the Santa Monica Mountains.



3.2 Fuel Moisture with AVIRIS

LFM sampled by LACFD showed a strong positive correlation with all remote sensing measures of greenness and moisture and a strongly negative correlation with NPV (Table 1, Figure 2). Contrary to our expectations, the highest correlations were found with the narrow-band NDVI, with an r^2 of 0.9176 and 0.9122 for Clark Motorway and Laurel Canyon, respectively. The second highest correlation was found for the GV Fraction, with an r^2 of 0.8723 for Clark Motorway. Of the two moisture measures evaluated, EWT showed the highest correlations, with an r^2 of 0.86 at Clark Motorway and 0.768 at Trippet Ranch. NPV and Shade were inversely correlated with moisture, with the highest correlation found for NPV at Clark at 0.7685. Soil fractions were poorly correlated in all cases and are excluded from the table.

Table 1. Correlation between live fuel moisture and AVIRIS measures.

	ClarkAdfa	TrippettAdfa	Laurel Canyon	Avg
EWT	0.8603	0.7684	0.6845	0.7711
MNDWI	0.8256	0.6118	0.8655	0.7676
GV	0.8723	0.6635	0.839	0.7916
NPV	0.7685	0.4711	0.2276	0.4891
Shade	0.5708	0.5339	0.6439	0.5829
NDVI	0.9176	0.7174	0.9122	0.8491

Figure 2. Scatterplots of various remotely sensed measures plotted against LFM.

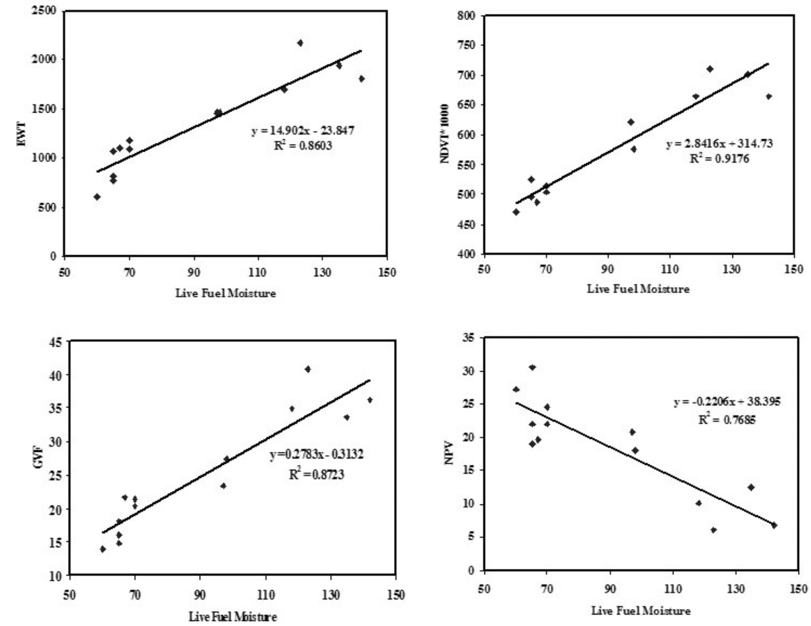


Table 2) Correlations between MODIS measures and LFM at the LACFD sites from 2000 to 2003.

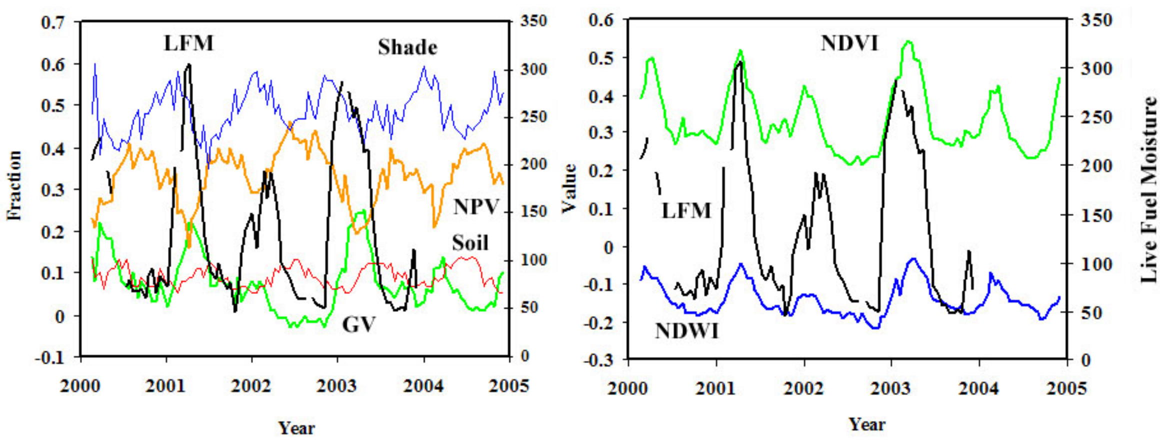
Site	NDVI	NDWI	NPV	GV	Soil	Shade
Bitter Canyon Sagebrush	0.709	0.64	0.644	0.454	0.036	0.024
Bitter Cyn Purple Sage	0.769	0.719	0.707	0.528	0.026	0.012
Bitter Cyn 2 Chamise	0.635	0.715	0.542	0.582	0.021	0.051
Bouquet Canyon Black Sage	0.283	0.556	0.48	0.299	0.001	0.019
Bouquet Cyn Chamise	0.228	0.681	0.572	0.405	0.015	0.138
Clark Mtwy Chamise	0.377	0.589	0.51	0.541	0.071	0.054
Clark Mty Ceme	0.427	0.698	0.561	0.56	0.049	0.041
La Tuna Cyn Chamise	0.499	0.549	0.455	0.477	0.007	0.104
Laurel Cyn Chamise	0.274	0.44	0.144	0.533	0.016	0.254
Pico Cyn Chamise	0.545	0.681	0.623	0.465	0.044	0.093
Placerita Cyn Chamise	0.465	0.696	0.466	0.507	0.194	0.177
Schueren Rd. Chamise	0.08	0.461	0.305	0.224	0.176	0.043
Sycamore Cyn Chamise	0.651	0.737	0.577	0.581	0.018	0.19
Sycamore Cyn Hoaryleaf Ceanothus	0.627	0.737	0.681	0.48	0.012	0.096
Trippet Ranch Black Sage	0.289	0.364	0.334	0.14	0.04	0.002
Trippet Ranch Chamise	0.364	0.481	0.342	0.269	0.07	0.038
Woolsey Cyn Chamise	0.57	0.637	0.322	0.6	0.029	0.143

3.2 *Fuel Moisture with MODIS*

At MODIS scales, the correlation between MODIS-measures and live fuel moisture was generally lower than AVIRIS yet remained high (Table 2). At this scale over four years, the highest correlations were observed at Bitter Canyon and Sycamore Canyon, including 0.769 (NDVI, Bitter Canyon Purple Sage) and 0.737 (NDWI, Sycamore Canyon chamise and Ceanothus). NDWI proved to show the highest correlation with LFM for 14 of 18 LFM samples. NDVI showed the highest correlation at three sites (Bitter Canyon sage brush and purple sage and La Tuna chamise). GVF was the best measure only at one site, Laurel Canyon Chamise.

The relationship between LFM and remotely sensed measures over the entire time series hides considerable interannual variation (Figure 3). For example, in 2001 LFM peaked only a few days in advance of GV, NDVI and NDWI, whereas in 2003 LFM peaked approximately 60 days ahead of these three measures. In 2002, while a modest increase in LFM was observed in the field, remotely sensed measures showed little or no indication of an increase.

Figure 3. Interannual and seasonal changes in spectral fractions, NDVI, NDWI and LFM at the Bitter Canyon purple sage brush.



3.3 *Changes in Spectral fractions in the Western US derived from MODIS*

Spectral fractions derived from MODIS showed the expected patterns of green-up and dry down for all deciduous forests, grasslands and chaparral sites. However spatial, rather than temporal, correlations between LFM measured in the field (see Rechel *et al.*, this issue) and spectral fractions proved to be weaker. The pronounced seasonal patterns in MODIS and weaker spatial correlations highlight the importance of including repeat temporal measurements of LFM in the analysis.

4 CONCLUSIONS

Remote sensing has considerable potential for direct assessment of LFM and fuel condition. In this paper, we compared AVIRIS-derived measures of fuel condition and LFM to MODIS derived measures. While AVIRIS measures showed higher correlations than MODIS, correlations using MODIS remained very high and showed considerable promise over extended time scales and large geographic ranges. However, considerable interannual variability was observed in the relationship between MODIS measures and LFM.

5 REFERENCES

Burgan R.E., Hartford, R.A. 1996. Live vegetation moisture calculated from NDVI and used in fire danger rating. In *Proceedings of the 13th Conference on Fire and Forest Meteorology*, Fairfield, WA: IAWF, 225-231.

Dennison P.E., Roberts, D.A., Thorgusen, S.R., Regelbrugge, J.C., Weise D., Lee, C. 2003. Modeling seasonal changes in live fuel moisture and equivalent water thickness using a cumulative water balance index. *Remote Sensing of Environment* 88: 442-452.

Dennison, P.E., Roberts, D.A., Peterson, S.H., Rechel, J. 2005. Use of normalized difference water index for monitoring live fuel moisture. *International Journal of Remote Sensing* 26: 1035-1042.

Gao, B.C. 1996. NDWI – A normalized difference water index for remote sensing of vegetation liquid water from space. *Remote Sensing of Environment* 58: 257-266.

Penuelas, J., Pinol, J., Ogaya, R., Filella, I. 1997. Estimation of plant water concentration by the reflectance water index WI (R900/R970). *International Journal of Remote Sensing* 58: 257-266.
Rechel, J.L., Peterson, S.H., Roberts, D.A., Van Wagtendonk, J.W. 2005. *Predicting seasonal fuel moisture in the western United States using endmember fractions at multiple spatial and spectral resolutions*. This issue.
Roberts, D.A., Smith, M.O., Adams, J.B. 1993. Green vegetation, nonphotosynthetic vegetation and soils in AVIRIS data. *Remote Sensing of Environment* 44(2-3): 255-269.
Roberts, D.A., Green, R.O., Adams, J.B. 1997. Temporal and spatial patterns in vegetation and atmospheric properties from AVIRIS. *Remote Sensing of Environment* 62: 223-240.
Roberts, D.A., Batista, G., Pereira, J., Waller, E., Nelson, B. 1998, Change Identification using Multitemporal Spectral Mixture Analysis: Applications in Eastern Amazonia. In Elvidge, C., Lunetta, R. (Eds.) *Chapter 9 in Remote Sensing Change Detection: Environmental Monitoring Applications and Method.* Ann Arbor, Ann Arbor Press, Ann Arbor: 137-161
Roberts, D.A., Dennison, P.E., Gardner, M.E., Hetzel, Y., Ustin, S.L., Lee, C.T. 2003. Evaluation of the potential of Hyperion for fire danger assessment by comparison to the Airborne Visible/Infrared Imaging Spectrometer. *IEEE Transactions on Geoscience and Remote Sensing* 41(6): 1297-1310.