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Predicting seasonal fuel moisture in the western United States using endmember fractions at multiple spatial and spectral resolutions

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ABSTRACT: Fuel moisture is one of the major components of fire risk assessment in the western United States. Regional and landscape fuel moisture estimates are currently derived from coarse resolution remotely sensed imagery without ground measurements to validate the estimates. Additionally, these estimates are determined using the Normalized Difference Vegetation Index (NDVI) which typically results in low R^2 values indicating a poor relationship between NDVI and the actual live biomass fuel moisture. We collected above ground standing live biomass fuel moisture for coniferous and deciduous forested and mixed forest/shrublands at seven sites in the western United States during early season (leaf-out) and late season (senescence) to detect changes in fuel moisture over a fire season. Spectral mixture analysis (SMA) expresses pixel reflectance as endmember (EM) fractions; typically green vegetation (GV), nonphotosynthetic vegetation (NPV), soil, and shade. We linked the ground % fuel moisture values with the following MODIS image products: NDVI, Normalized Difference Water Index (NDWI), Normailzed Difference Infrared Index (NDII), Normalized Difference Green Red Index (NDRGI), Visible Atmospherically Resident Index (VARI) and GV, NPV, soil, and shade endmember fractions. R^2 values for live fuel moisture and the image products during the high risk (hot and dry) fire season for a particular study site ranged from 0.4 to 0.7, during wetter periods R^2 values were lower, ranging from 0.2 to 0.4. NDVI, NDII, and GV endmember fractions performed best, with NDWI having lower values. NDVI and GV are sensitive to vegetation cover, whereas NDWI is sensitive to vegetation condition, and works best when a pixel has complete canopy cover, which may not be the case for a 500m pixel. Soil fraction was important only for the most sparsely vegetated site. Imagery-based live fuel moisture predictions improve regional fire severity modeling by increasing the temporal resolution and spatial coverage of ground-based % live fuel moisture values.

1 INTRODUCTION

Wildland fires are a dominant factor in shaping the structure of forests and shrublands in the western United States. Since the 1900s and more recently the 1950s, fire suppression have led to (unnaturally) large accumulations of fuel (Skinner and Chang, 1996; Arno, 2000), thereby increasing fire danger. Fire danger is estimated using multiple physical and biological factors. The primary factor in estimating fire danger is fuel moisture. Fuel moisture varies seasonally and must be measured over an entire fire season from the early (low risk) to the late (high risk) periods to provide more accurate estimates of fuel moisture to improve fire severity models and fire danger rating systems.

Current fuel maps are not accurate at the landscape scale. They are derived from coarse resolution remotely sensed data, with limited image processing using only Normalized Difference Vegetation Index (NDVI) (Burgan *et al.*, 1998). Those data represented only a single point in time with one or no field data to verify the NDVI analysis. The objective of this research is to develop products from remotely sensed data that provide accurate, fine spatial resolution fuel maps for the dominant forested and shrubland fire-prone ecosystems of the western United States. The general approach is to link ground-based vegetation measurements of potential fuel, including live fuel moisture content of trees and shrubs with remotely sensed data products, primarily endmember (EM) fractions, of varying spatial and spectral resolutions.

2 STUDY AREAS

Seven study areas were selected in the western United States. The areas were chosen based on the importance of the dominant vegetation types to fire severity and the absence of data on fuels. All study sites were located on public lands administered by the Federal government. The study sites were: 1) Sierra National Forest, California; 2) Lassen National Forest, California; 3) Los Padres National Forest, California; 4) Coconino and Kaibab National Forests, Arizona; 5) Gila National Forest, New Mexico; 6) Rio Grande National Forest, Colorado; and 7) Birds of Prey Conservation Area, Idaho.

Major vegetation communities sampled were aspen (*Populus tremuliodes*), mixed fir (*Pseudotsuga menziesii*, *Abies lasiocarpa*), mixed pine (*Pinus jeffreyi, Pinus ponderosa, Pinus coulteri*), mixed oak woodlands (*Quercus agrifolia, Quercus chrysolepis, Quercus douglasii*), mixed chaparral (*Adenostema fasiculatum, Ceonouthus sp., Arctostaphylus sp.*), and mixed Great Basin sage (*Artemsia tridentata, Eriogonum sp., Atriplex sp.*), and pinyon-juniper (*Juniperus sp., Pinus edulis*).

3 METHODS

3.1 *Field Data Collection*

Above ground standing live biomass was collected in 15-33 plots for each of the dominant vegetation types. Tree plots were 400 m^2 and shrub plots were 100m^2 . At each plot up to 6 samples were clipped from individual trees and shrubs and stored in moisture proof polypropylene bottles. We used a fuel gauge to collect samples that consisted of less than 10 hour fuel size classes. Each fuel bottle was weighed with the live (wet) fuel and then oven dried for at least 96 hours at 95º F/35º C. Percent fuel moisture was calculated as the difference between the wet and dry fuel weights, divided by dry weight.

All plots were located on a map and with a Global Positioning System (GPS). Samples were collected at each site in the early (low risk) fire season and again at the same plots in the late (high risk) fire season.

3.2 *Remotely Sensed Data*

Three remotely sensed data sets were utilized in this study, 463m MODIS data consist of 7 bands, centered at 469, 555, 645, 857, 1240, 1640, and 2130 nms. The sensor covers the entire earth day. Hyperspectral data from AVIRIS of approximately 4m to 20m pixel resolution, consisting of 224 bands from 374 to 2508 nm and an Analytical Spectral Devices (ASD) spectrometer consisting of 1076 bands from 350 to 2500 nm were also utilized.

The AVIRIS data were processed to surface reflectance using Atmospheric CORrection Now (ACORN) software. Atmospheric water vapor and canopy liquid water maps are also produced when AVIRIS data is processed to reflectance. MODIS data are released in reflectance and ASD data are readily converted to reflectance by normalizing using a Spectralon panel of known reflectance. Daily MODIS data for the entire western US are online at the University of California Santa Barbara. However, due to look angle distortions, approximately every other day is useful for any given location.

The AVIRIS and ASD data were used to build an EM library. The EMs were derived from hyperspectral data for a number of reasons. First, the spectral resolution allows for greater confidence that a pixel is "pure." Second, having hyperspectral spectra allows for convolution to the bands of any lower spectral resolution sensor. Convolution is essentially the process of determining which hyperspectral bands (and how much of each one) make up each broad-band sensor band.

Multiple EM SMA (MESMA) was run for the study sites, and a count-based (COB) method was used to reduce the pool of available EMs. The EMs used include one each of conifer and broadleaf GV spectra; douglas fir bark, dry stems and senesced grass NPV spectra; and two sandy soil spectra. Three EM MESMA was performed for all study sites except the Idaho site where a 4 EM model was required.

The vegetation indices are of the form ($band_1$-$band_2$)/($band_1$+$band_2$) except for VARI where the denominator contains three bands. For bands 1 and 2 NDVI uses 4 and 3, NDWI 4 and 5, NDII6 4 and 6, NDII7 4 and 7, NDGRI 2 and 3, and VARI 2 and 3 with 1 used in the denominator.

4 RESULTS AND DISCUSSION

4.1 *Fuel Moisture*

Differences among early and late season mean percent fuel moisture are listed in Table 1. The most notable differences were in oak woodlands (-23% and --68%), ceonothus sp. (35%), firs (36%), and junipers (31%). Generally, mean percent fuel moisture was similar or increased for most of the vegetation types for each study area. For the Gila National Forest, New Mexico, the late season % fuel is lower than the early season. This is expected due to August and September monsoon weather patterns that bring more precipitation to southern New Mexico.

Table 1. % change in fuel moisture from early season to late season samples.

	minimum # sampled	%change
Boise		
rabbit brush	11	-14,25
sage brush	68	-6,44
salt bush	7	15,41
Gila		
aspen	4	-6,35
douglas fir	7	14,50
firs	3	5,09
junipers	11	24,85
oaks	9	-23,06
pines	32	16,42
Kaib/Coco		
aspen	16	-7,76
firs	2	-21,07
junipers	10	12,87
oaks	15	68,73
pines	42	-14,88
Lassen		
firs	21	10,41
pines	38	12,10

	minimum # sampled	%change
LosPadres		
ceaothus	8	-34,82
douglas fir	2	-15,10
firs	2	-7,49
oaks	29	-32,45
pines	8	-16,24
RioGrande		
aspen		-11,39
douglas fir		9,36
firs		36,31
junipers		-31,14
pines		1,17
spruce		4,02
Sierra		
firs	34	-2,79
incense cedar	17	-10,14
oaks	8	-11,47
pines	21	-13,54

4.2 *Vegetation Indices*

Relationships between fuel moisture and a number of normalized indices as well as EM fractions were examined. Table 2 contains R^2 for the relationships. Figure 1 contains example plots of fuel moisture versus NDVI for Coconino-Kaibab NF and GV and NPV for Lassen NF. A number of interesting patterns are present. The strength of the relationship between fuel moisture and image products appears to be a function of fire risk. For each study site, the season having the stronger relation between fuel moisture and image products was the season having higher fire risk. In the spring, study sites in California are still quite wet due to winter rainfall associated with the Mediterranean climate. The Colorado site is at high elevation so elevated soil moisture associated with snow melt reduces fire danger. Only the Arizona and New Mexico study sites experience high fire danger during the spring. During August and September, monsoonal rainfall has lowered fire danger in the southwest, but the other sites have dried out.

NDVI was the overall best vegetation index for both seasons. NDII7 was second best for spring; there was no clear pattern for the fall. NDWI has been shown to track temporal changes in fuel moisture better than NDVI (Dennison *et al.*, 2005), but it did not prove useful in this spatial fuel moisture study.

For the EM fractions, GV and NPV proved to be about equally useful, and R^2 were similar to those for the vegetation indices. EM fractions have an advantage, however, in that they decompose the remote sensing signal into a live and dead vegetation component, and thus are more readily interpretable than vegetation indices.

For fall, an interesting finding was that shade normalized fractions performed better than “raw” ones. Shade normalizing is a process designed to reduce noise associated with differences in topographic shading. The spring data was acquired within a month of the summer solstice, the fall data 3 months from summer solstice. Thus, spring remotely sensed data was more illuminated, minimizing topographic shading.

The Idaho site is unique in this study because vegetation cover is much lower. It was the only site on which a 4 EM model (GV, NPV, and soil) was required to model pixel reflectance. The NPV fraction showed the strongest relationship with fuel moisture, with soil having less of a relationship and GV having no relationship.

Table 2. R^2 between fuel moisture content and MODIS products.

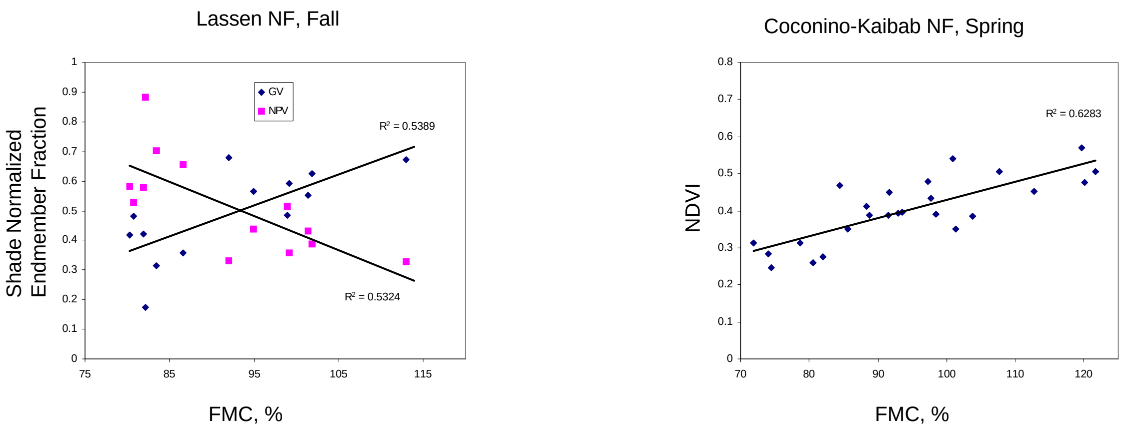
Spring

	NDVI	NDWI	NDII6	NDII7	NDGRI	VARI	GV	GVN	NPV	NPVN	SOIL	SOILN
C-K NF	0.628	0.253	0.458	0.526	0.504	0.511	0.569	0.537	0.518	0.529		
GNF	0.757	0.594	0.649	0.712	0.672	0.683	0.576	0.601	0.613	0.573		
LPNF	0.173	0.098	0.128	0.207	0.002	0.002	0.457	0.344	0.147	0.386		
LNF	0.454	0.038	0.062	0.04	0.06	0.056	0.249	0.361	0.469	0.36		
SNF	0.084	0.004	0.018	0.064	0.039	0.039	0.094	0.076	0.02	0.062		
ID	0.308	0.112	0.407	0.471	0.346	0.365	0.263	0.37	0	0	0.19	0.07
RGNF	0.15	0.183	0.189	0.149	0.116	0.115	0.389	0.216	0.037	0.227		

Fall

	NDVI	NDWI	NDII6	NDII7	NDGRI	VARI	GV	GVN	NPV	NPVN	SOIL	SOILN
C-K NF	0.619	0.173	0.563	0.659	0.633	0.643	0.759	0.76	0.798	0.803		
GNF	0.035	0.048	0.015	0.019	0.052	0.052	0.001	0.007	0.05	0.02		
LPNF	0.625	0.583	0.639	0.619	0.409	0.417	0.575	0.697	0.657	0.718		
LNF	0.409	0.393	0.398	0.389	0.511	0.503	0.369	0.539	0.544	0.532		
SNF	0.535	0.582	0.562	0.493	0.405	0.416	0.548	0.395	0.3	0.423		
ID	0.606	0.261	0.141	0.081	0.572	0.568	0.08	0.03	0.589	0.57	0.392	0.56
RGNF	0.53	0.318	0.577	0.583	0.427	0.423	0.263	0.39	0.329	0.445		

Figure 1. Select plots of fuel moisture and image products.



5 CONCLUSIONS

Ground based fuel moisture measurements are important to analyze vegetation indices that are then used to estimate and predict fire danger. The fuel moisture data improved fire danger estimates using remotely sensed data and vegetation indices.

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