Hyperspectral technologies for wildfire fuel mapping

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ABSTRACT:
Wildfire is one of the most significant forms of natural disturbance, impacting a wide range of ecosystems ranging from boreal forests to Mediterranean shrublands and tropical rainforest. One of the greatest uncertainties in assessing fire danger is our knowledge of fuels. Fuel properties vary at fine spatial scales, change depending on stand age and prior disturbance history and vary seasonally and interannually depending on moisture availability. Remote sensing has the potential of reducing uncertainty in mapping fuels and improving our ability to assess spatially and temporally varying fuel characteristics. One very promising technology for wildfire fuels mapping is hyperspectral remote sensing. Hyperspectral remote sensing systems measure reflected or emitted electromagnetic radiation over a large number of contiguous spectral bands. Detailed spectral information allows researchers to fully characterize atmospheric properties, thereby removing atmospheric contamination to retrieve high quality surface reflectance. Fine spectral information also facilitates mapping of biophysical and chemical information that is directly related to the quality of wildfire fuels, including above ground live biomass, canopy moisture etc.

In this paper, we present examples of mapping wildfire fuel properties derived from Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) data acquired over Southern California. Examples are presented from two chaparral dominated ecosystems, one along the Santa Ynez front range near Santa Barbara, the other the Santa Monica Mountains. Important fuel properties are divided into four broad categories, including fuel type, fuel moisture, green live biomass and fuel condition. Fuel types are mapped using Multiple Endmember Spectral Mixture Analysis, which has the ability to map vegetation to the species level. Live fuel moisture and green live biomass are assessed using remotely sensed measures of canopy moisture, derived from the expression of liquid water in the reflectance spectrum of plants. Fuel condition is mapped using spectral mixture analysis, in which a spectrum composed of a mixture of surface types is decomposed into green vegetation, soil, senesced material (non-photosynthetic vegetation) and shade. Seasonal changes in fuel characteristics, and longer term changes following wildfire are assessed by analysis of time series AVIRIS, acquired between 1994 and 2001.

A hyperspectral system is best used in concert with other data sources, which provide greater temporal and spatial coverage than are currently available from airborne systems, such as AVIRIS. To explore the potential of other sensors, we present results comparing the performance of AVIRIS to Hyperion, a spaceborne hyperspectral system with 242 spectral channels. To explore synergisms with coarser resolution, broad band data we compare AVIRIS measures of fuels to measures provided by ETM and MODIS over the same region in southern California.
INTRODUCTION

Wildfire is one of the most significant forms of global disturbance, impacting community dynamics, biogeochemical cycles and local and regional climate across a wide range of ecosystems ranging from boreal forests to tropical rainforest (Pyne et al., 1996). Within the wildland urban interface, wildfire represents one of the most serious economic and life-threatening natural disasters. For example, in Southern California average annual costs due to home and property loss are estimated at $163 million dollars (California State Board of Forestry, 1996). In these regions, the potential of catastrophic wildfire is exacerbated by extreme weather events (i.e., Santa Ana Winds), more than 70 years of fire suppression, and periods of extended drought (Radtke et al., 1982). Post-fire effects, such as erosion and mud slides from fire-burned slopes often exceed the cost of the original fire in damage (Barro and Conard, 1991).

One of the greatest uncertainties in assessing fire danger is a lack of knowledge of fuels. Fuels vary at fine spatial scales, change depending upon stand age and prior disturbance history and vary seasonally and interannually depending on moisture availability. Remote sensing has the potential of reducing uncertainty in mapping fuels and improving our ability to assess spatially and temporally varying fuel characteristics. Hyperspectral remote sensing is a relatively new technology that has considerable promise for improving our ability to map wildfire fuels. These systems measure reflected or emitted electromagnetic radiation over a large number of contiguous spectral bands. This detailed spectral information allows researchers to fully characterize atmospheric properties, thereby removing atmospheric contamination to retrieve high quality surface reflectance. Subtle spectral differences between plant species also enables improved fuel type mapping, distinguishing land-cover classes with distinct fuel properties. Fine spectral information also facilitates mapping of biophysical and chemical information that are directly related to the quality of wildfire fuels, such as canopy moisture and improved estimates of surface cover (e.g. exposed soils, senesced and live vegetation). In this paper we present research results from two regions in Southern California, in which hyperspectral data from the Airborne Visible Infrared Imaging Spectrometer (AVIRIS) and Hyperion are used to map important fuel properties.

BACKGROUND

Fire behavior is a product of fuels, terrain and weather, which vary in importance depending upon fire regime and season (Pyne et al., 1996). Wildfire fuels, because of high spatial and temporal variability, represent one of the greatest sources of uncertainty in predicting fire danger. Currently, fire danger is most often assessed using broad band sensors such as the Advanced Very High Resolution Radiometer (AVHRR), and Thematic Mapper (TM), through some combination of classification to map fuel types, meteorology and ancillary GIS information such as slope, aspect, elevation and fire history (e.g. Chuvieco and Congalton, 1989; Chuvieco and Salas, 1996). In the United States, fire danger is typically quantified by assigning land-cover to fuel categories described by the National Fire Danger Rating System (Bradshaw et al., 1978), while behavior is predicted using fuels described by Anderson, 1982.

Much of the potential of hyperspectral remote sensing for mapping wildfire fuels is illustrated by plant spectra (Figure 1). In this figure, four spectra are shown, senesced grass, coast live oak (Quercus agrifolia), chamise (Adenostoma fasciculatum) and bigpod Ceanothus (Ceanothus megacarpus). Spectral absorptions by water (1), chlorophyll (2), and ligno-cellulose (4) are numbered and marked by arrows. The strong spectral contrast between high Near-infrared reflectance (3) and strong chlorophyll absorption at 680 nm is the basis for most vegetation indices such as the...
Normalized Difference Vegetation Index (NDVI = \( \frac{\rho_{\text{NIR}} - \rho_{\text{red}}}{\rho_{\text{NIR}} + \rho_{\text{red}}} \)). The depth of liquid water bands at 980, 1200, 1350 and 1900 nm depend upon the number of leaves present in a canopy and the moisture content of leaves, and thus are sensitive to green live biomass and live fuel moisture. Ligno-cellulose bands (4) in the short-wave infrared (SWIR) indicate the presence of dry plant material and are thus a measure of dead fuels. They are particularly important for separating senesced grass from bare soil. Subtle spectral differences between chaparral species make it possible to map them separately when they are dominant within a stand.

Enhanced spectral information available through imaging spectrometry led Dennison et al. (2000) to develop an alternate framework for assessing fuel properties. In this framework, standard mapping of fuel types is augmented with other important fuel properties including: 1) canopy moisture; 2) green live biomass; and 3) measures of live to senesced canopy components, called fuel condition. Canopy moisture and green live biomass can be assessed through expression of the liquid water bands. Indices developed for estimating moisture include equivalent liquid water thickness (EWT; Green et al., 1993; Roberts et al., 1997), the Normalized Difference Water Index (NDWI = \( \frac{\rho_{857} - \rho_{1241}}{\rho_{857} + \rho_{1241}} \); Gao, 1996) and the Water Index (WI = \( \frac{\rho_{895}}{\rho_{972}} \); Penuelas et al., 1993).

EWT is estimated from at sensor radiance or reflectance data using a Beer-Lambert approach in which the spectral expression of liquid water is modeled as the exponential of the absorption coefficient of liquid water modified by the pathlength within the medium (Roberts et al., 1998a). Ustin et al. (1998) evaluated the potential of EWT as a measure of canopy moisture in chaparral ecosystems. Serrano et al. (2001) expanded this analysis to compare the NDWI, EWT and WI as measures of relative water content (RWC) in chaparral, concluding that WI was most sensitive to RWC, while EWT was more sensitive to canopy structure.

Fuel condition can be estimated using Spectral Mixture Analysis (SMA) to map green vegetation (GV) and non-photosynthetic vegetation (NPV) fractions (Roberts et al., 1993). The fractions respond to the relative proportions of live (GV) and senesced (NPV) vegetative land cover. Vegetation communities and species can be mapped using Multiple Endmember Spectral Mixture Analysis (MESMA). MESMA is an extension of SMA, in which the number and types of endmembers are allowed to vary on a per-pixel basis (Roberts et al., 1998b). In many cases it is possible to discrimination vegetation spectra to the species level. For wildfire fuels mapping, vegetation maps produced by MESMA are typically reclassified to standard fuel models such as those presented by Anderson (1982), providing species-specific fuels information otherwise inaccessible through remote sensing.
3 METHODS

3.1 Study Sites
Examples are provided for two regions of Southern California, the Santa Ynez front range (34° N, 120° W) and the Santa Monica Mountains (34° N, 118.7° W). Both regions have Mediterranean climates, characterized by winter precipitation, summer droughts and relatively moderate temperature ranges due to their close proximity to the ocean. Both ranges are approximately east-west oriented, resulting in strong environmental gradients between warm/dry south facing slopes and more mesic, cooler north facing slopes. Vegetation in more xeric locations is dominated by three chaparral species, chamise and big-pod Ceanothus at lower elevations and manzanita (Arctostaphylos sp) at higher elevations. More mesic locations are dominated by coast-live oak and greenbark Ceanothus (Ceanothus spinosus). Senesced grasslands occur primarily on more shallow slopes. Both regions have experienced major fires over the past 12 years, including the Painted Cave Fire (1990: Santa Barbara), Green Meadows (1993: SMM), Old Topanga (1993: SMM) and Calabasas Fires (1996: SMM).

3.2 Remote Sensing Data
Time-series AVIRIS data were acquired over both study sites. AVIRIS is an airborne imaging spectrometer that acquires 224 spectral channels between 350 and 2500 nm at a nominal sampling interval of 10 nm with a ground-instantaneous field of view (GIFOV) of 20 meters and a swath of 12 km when flown on the ER2 at 20 km altitude (Green et al., 1998). Typically AVIRIS data are acquired within 2 hours of solar noon. In the Santa Monica Mountains, 16 AVIRIS flightlines were acquired between 1994 and 2002, including several acquisitions that included both spring and fall. Along the Santa Ynez front range, 5 scenes were acquired between 1998 and 2002, with two scenes acquired in May, one in June and two in September. In addition to AVIRIS, we have analyzed one EO-1 Hyperion scene, acquired on June 12, 2001. Hyperion is a spaceborne imaging spectrometer that samples 242 channels at a nominal sampling interval of 10 nm with a GIFOV of 30 m and a swath of 7 km (Ungar et al., in press). It follows the Landsat Enhanced Thematic Mapper (ETM) in its orbit, and thus acquires data at approximately 10:30 AM DST. AVIRIS data were radiometrically calibrated by the Jet Propulsion Laboratory then georectified by UCSB. Surface reflectance was retrieved using the approach described by Green et al., (1993), in which radiance, modeled using Modtran radiative transfer code for a specific latitude, longitude, date and visibility condition, is fit to radiance measured by AVIRIS. Initial estimates of apparent surface reflectance were further adjusted using homogeneous ground reflectance targets located in each region. Hyperion data were radiometrically calibrated by TRW using Level 1b processing, then corrected using post-launch calibration equal to a 1.08 multiplier applied to radiance for the VNIR and 1.18 multiplier in the SWIR (Green et al., in press). Surface reflectance was retrieved for Hyperion using Atmospheric Correction Now VERSION(3.12) (ACORN:Analytical Imaging & Geophysics, Boulder, CO).

3.3 Image Analysis
Hyperspectral data were processed to map dominant vegetation types, fuel condition, and estimate canopy moisture. Dominant vegetation types were mapped using MESMA, using spectra extracted from relatively pure stands of specific land-cover dominants described in the field. Six land-cover types were described, including: manzanita, chamise, big-pod Ceanothus, coast-live oak, senesced grass and bare soil. Spectra were extracted from over 95 field polygons with uniform cover and composition and a minimum size criterion of 60 by 60 meters. For each polygon, species composition was categorized based on percent of total cover: 0-10%, 10-25%, 25-50%, 50-75%, 75-90%,
90-100%. Several important land-cover categories, including greenbark Ceanothus, could not be mapped at 20 meters resolution because of small spatial extent. Fuel condition was mapped using SMA to map green vegetation (GV; green leaves), non-photosynthetic vegetation (NPV; stems, wood and litter), shade and soil. Reference endmembers used in this study were derived from field and laboratory spectra and are the same as described by Roberts et al. (in press).

A variety of measures can be employed to estimate live fuel moisture and green live biomass. Here we present results based primarily on EWT and the NDWI. EWT is potentially the most viable measure of moisture in that it provides physical units of water thickness (typically in micrometers or millimeters). NDWI, in contrast, is of value because this index can be applied to hyperspectral data and broad-band systems, such as MODIS.

4 EXAMPLES DERIVED FROM AVIRIS

4.1 Live fuel moisture and green live biomass

A subset of examples are presented in this paper. In Figures 2 and 3, applications of EWT are shown. In the first example, EWT is used to estimate leaf area index. The relationship to the left (Fig 2a), was developed by merging data from conifer and broadleaf plants (Roberts et al., 1998a). This example shows a near-linear relationship between LAI and EWT up to LAIs exceeding 10. The example on the right (Fig 2b) shows LAI estimated using this relationship applied to EWT mapped using AVIRIS over the Santa Monica Mountains. LAI estimates are fairly reasonable, including ~3-4 for chamise and up to 6 for Ceanothus. The lowest LAI is estimated for senesced grasslands and drought deciduous soft chaparral.

Figure 2. The relationship between EWT and LAI for conifer and broadleaf deciduous plants (left). Estimates of LAI derived from AVIRIS using this EWT/LAI relationship applied to data acquired over the Santa Monica Mountains.

Figure 3 shows the relationship between EWT and live fuel moisture estimated by the Los Angeles County Fire Department through destructive harvests of chamise. Data points were derived from 16 AVIRIS data sets acquired over the Santa Monica Mountains between 1994 and 2002.
4.2 Fuel Condition

Fuel condition was mapped using SMA and reference endmembers derived from the Santa Monica Mountains applied to the Santa Barbara data sets. An example of how fuel condition changes depending on soil water balance is shown in Figure 4. In this example, soil water balance was estimated as the difference between precipitation and potential evapotranspiration (Dennison and Roberts, 2003). The highest positive soil water balance occurred in May, 1998 during a very strong El Niño. The lowest (most negative) soil water balance was calculated for a September 11, 1999. This example shows a near-linear decrease in the GV fraction and a non-linear increase in NPV as the season progresses from moist to dry conditions.

A. fasciculatum GV and NPV Fractions

5 SCALING UP FROM AVIRIS

A major limitation of a hyperspectral, airborne system such as AVIRIS is its limited temporal and spatial coverage. This limitation can be partially addressed using spaceborne data. One option is to use a spaceborne imaging spectrometer, such as Hyperion. While this sensor has a limited swath width (7 km), it can acquire an image with a down-track length of up to 185 km. More importantly, as an imaging spectrometer it has the potential of providing many of the fuel measures derived from AVIRIS and can do this globally. A second alternative is to use hyperspectral data to improve
the analysis of broad-band data such as ETM and MODIS. For example, AVIRIS can be used to develop spectral libraries needed for the analysis of MODIS or ETM. In addition, AVIRIS can be used to help develop relationships between measures of moisture, such as EWT and measures that can be applied to broad band data, such as SMA used to map GV and NPV fractions. The following examples show some of the capability of Hyperion for mapping important fuel properties including moisture and fuel condition. In these examples, Hyperion data acquired on June 12, 2001 were evaluated by direct comparison to AVIRIS data acquired on June 14, 2001. The last example shows temporal changes in NPV derived from MODIS using the same endmembers used to analyze AVIRIS.

Figure 5 shows plots of moisture estimated from Hyperion (x) plotted against AVIRIS (y). The data points were derived from 79 polygons that occurred in the overlap region between the two scenes (Roberts et al. 2003). Two measures, NDWI and EWT are shown. The latter estimate of moisture was derived from liquid water bands centered at 1200 nm, rather than 980 nm which is more typically used. This became necessary because of the very low Signal to Noise ratio of Hyperion at 980 nm. Both measures show that Hyperion is highly sensitive to canopy moisture. A slope less than one suggests that Hyperion may be more sensitive to moisture, although numerous artefacts in Hyperion may also account for differences in performance.

\[
\text{AV} = 0.8699 \times \text{HYP} - 0.0073 \\
R^2 = 0.7527
\]

\[
\text{AV} = 0.7827 \times \text{HYP} + 101.33 \\
R^2 = 0.6648
\]

Figure 6 shows the relationship between Hyperion and AVIRIS for GV, NPV, soil and shade fractions. The NPV and soil fractions derived from these two sensors show near 1:1 relationships, suggesting that Hyperion has the capability to discriminate senesced vegetation from soils at high accuracy. A slope greater than one for GV, and less than one for the shade fractions is caused by the higher solar zenith angle for the Hyperion data sets. Because the sun was lower in the sky when the Hyperion data were acquired, vertically oriented structures such as plants cast more shadows, resulting in a higher shade fraction, and lower GV fraction relative to AVIRIS. This demonstrates the sensitivity of the shade fraction to canopy structural properties.
Figure 6: Showing the relationship between AVIRIS and Hyperion spectral fractions for NPV, Soil, GV and Shade. Adapted from Roberts et al., 2003.

Figure 7 shows NPV time series data derived by applying SMA to MODIS time series data acquired in 2001 from Southern California. SMA was applied to the MODIS 0.5 km reflectance product using endmembers derived from AVIRIS and convolved to MODIS wavelengths. Grasslands (ecv_l) stand out as having the most pronounced increase in NPV fraction, starting near Julian day 100. Woodlands (ecv_h) show an initial decrease in NPV, followed by a modest increase. All chaparral communities (lpnf_oj, fr and si) show an initial seasonal decrease to Julian day 100-150, followed by a gradual increase.

Figure 7. NPV time series derived from MODIS 0.5 km reflectance data acquired in 2001.
CONCLUSIONS

Hyperspectral data from systems such as AVIRIS provide a diversity of unique wildfire fuel properties including direct measures of live fuel moisture and green live biomass, improved fuel type mapping and improved separation of soils and senesced materials. In this paper, we present examples in which AVIRIS data are used to map live fuel moisture, live green biomass and fuel condition, a measure of live vs senesced material. Examples are provided for time series data acquired over two regions of southern California, the Santa Ynez front range and the Santa Monica Mountains. Some of the potential of scaling up AVIRIS results, is shown using data acquired from the spaceborne imaging spectrometer, Hyperion, and through time series analysis of MODIS.

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REFERENCES CITED IN THE TEXT


California State Board of Forestry, 1996, California Fire Plan : a Framework for Minimizing Costs and Losses from Wildland Fires, the Board, Sacramento, Calif.


