POST-WILDFIRE GROUND COVER MAPPING BY SPECTRAL UNMIXING OF HYPERSPECTRAL DATA

Sarah A. Lewis, Civil Engineer
sarahlewis@fs.fed.us
Andrew T. Hudak, Research Forester
ahudak@fs.fed.us
Peter R. Robichaud, Research Engineer
probichaud@fs.fed.us
USDA Forest Service
Rocky Mountain Research Station
1221 S. Main St., Moscow, ID 83843

Leigh B. Lentile, Fire Ecologist
lentile@uidaho.edu
Penelope Morgan, Fire Ecologist
pmorgan@uidaho.edu
Michael J. Bobbitt, GIS Analyst
mbobbitt@uidaho.edu
University of Idaho, Department of Forest Resources
6th and Line St., Moscow, ID 83844-1133

ABSTRACT

The effects of a wildfire on the ground surface are indicative of the potential for post-fire watershed response. Areas with remaining organic ground cover (green, uncharred, or charred) will likely experience less erosion than areas of complete ground cover combustion (ash) or exposed mineral soil, and may not need post-fire rehabilitation treatments. We collected aerial and field hyperspectral data together with field ground cover measurements after the 2003 Simi Fire in southern California in order to create a map of the remaining ground surface components. Spectral endmembers representing green vegetation, charred vegetation, charred soil, and uncharred soil were used in a constrained linear spectral unmixing process to determine the post-fire fractional ground cover of each surface component. Significant correlations ($r > 0.2$, p-value < 0.0001) were found between the fractional cover interpreted from hyperspectral images and corresponding field measurements indicating that these methods are appropriate for mapping post-fire ground conditions.

INTRODUCTION

The severity of a wildfire is mapped as soon as possible to capture immediate post-fire conditions and to assist rapid-response rehabilitation crews in mitigating immediate and long-term fire effects on the landscape. Standard burn severity mapping methodologies are based upon the classification of spectral indices calculated with multispectral satellite imagery (Key and Benson, 2002; Clark et al., 2003). These burn severity maps are often subjective and are more qualitative than quantitative (Lentile et al., in press). High spatial and spectral resolution airborne hyperspectral data have the potential to provide fine-scale quantitative information about post-fire ground cover and condition. This information may be helpful in guiding post-fire rehabilitation treatments by identifying the effects of the fire on the soil surface.

Post-fire organic ground cover, whether charred or uncharred, can provide protection against soil erosion (Ice et al., 2004). Conversely, areas with exposed mineral soil or ash cover are at an increased risk for erosion. Ash cover is indicative of complete organic combustion; since water repellent soils may be formed when organic material burns on the soil surface, water repellent soils often occur beneath the ash layer (Lewis et al., 2006). Additionally, fire-induced water repellent soil conditions are more common in chaparral vegetation types where waxy chemicals from plant leaves volatilized during burning coat coarse-textured soil particles at or near the soil surface (Barro and Conard, 1991; CDF 2003). Fire can also strengthen and drive a naturally occurring water repellent soil layer deeper

into the soil profile (DeBano, 2000). Fire-induced or enhanced soil water repellency may allow the top 1-5 cm of the soil profile to hold water, but once this wettable layer becomes saturated, erosion is likely.

The chaparral community is a shrubby, sclerophyllous vegetation type that is common in middle elevations throughout much of California (Barro and Conard, 1991). Common chaparral trees and shrub genera include *Adenostoma*, *Arctostaphylos*, *Ceanothus*, *Cercocarpus*, *Prunus*, *Quercus*, and *Rhamnus.* Chaparral vegetation is well adapted to frequent fires that were historically common in the area. Chaparral plant adaptations include rapid post-fire root sprouting, prolific seeding, seed banking, fire-related germination cues, and allelopathy (Hanes, 1977; Keeley, 2006). Ground cover is relatively sparse when shrubs are dominant, and forb (e.g. *Phacelia*, *Penstomen*, *Mimulus* spp.) and grass species are more common in these systems following fire (McAuley, 1996). The presence of native forbs and grasses tend to be ephemeral (< 2 years), although non-native post-fire invaders (e.g., wild oats, rip-gut brome, annual ryegrass, yellow-star thistle, filaree species, and rose clover) may persist longer (Keeley, 2005).

Because many chaparral fires occur near homes and other resources, agencies are often obligated to aggressively pursue fire suppression and rehabilitation activities. Post-fire rehabilitation treatments include seeding and soil stabilization measures to reduce soil erosion and the threat of landslides and flooding. Several studies have shown that these measures do not substantially reduce erosion or flooding (Robichaud et al., 2000), and that native flora may be displaced by non-natives accidentally introduced into seed mixes (Keeley, 2005). A combination of pre-fire vegetation condition, soil texture, fire intensity, and post-fire weather events can complicate post-fire mitigation decisions.

The Simi Fire burn severity map was created from airborne multispectral MASTER imagery (masterweb.jpl.nasa.gov) that was acquired on 1 November 2003 (Clark et al., 2003). Following the Simi Fire, and like many other large wildfires, the highest post-fire priority was to accurately map the extent and severity of water repellent soils and the potential for subsequent erosion and flooding. BAER (Burned Area Emergency Response) teams in the field reported that the burn severity map was overall representative of the conditions observed on the ground (CDF, 2003; Clark et al., 2003). The majority of the area within the fire perimeter was burned at low or moderate severity. However, several watersheds were assessed as having burned at higher severity than indicated on the map and identified as areas at risk for increased post-fire erosion (Cannon et al., 2003; CDF, 2003). Assessment teams also noted the presence of white ash in severely burned areas and the potential link to water repellent soils (CDF, 2003). In a previous study on the Hayman fire, Lewis et al. (2006) explored the potential of hyperspectral data to indirectly detect soil water repellency via detection of an ash signal in the soil. To this end, our objectives were to assess the potential of hyperspectral imagery to provide a better estimate of post-fire soil condition, particularly, the amount of high soil burn severity, than had been achieved with traditional, multispectral imagery.

METHODS

Study Area

The Simi Fire (34° 20' 36" N, 118° 46' 47"W, centroid) was one of several large wildfires that burned throughout southern California during the fall of 2003. These fires threatened thousands of homes and impacted air and water quality throughout the region. The Simi Fire began on 25 October 25 2003, and burned 43,788 ha in Ventura and Los Angeles counties, before being contained on 2 November 2003 (Clark et al., 2003). The fire began when a smaller fire jumped State Highway 126, and driven by erratic Santa Ana winds, burned around the heavily populated towns of Simi Valley, Moorpark and Saticoy, California. The Simi Fire burned in a mix of vegetation types including chaparral (the dominant vegetation type), coastal sage scrub, and annual grasslands across a diversity of topographic conditions including rolling hills and very steep, rocky terrain. Combined effects of frequent human and natural ignitions, hot dry summers, rainfall limited to mostly the winter, and the high flammability of chaparral vegetation, make these ecosystems extremely susceptible to periodic, intense crown fires (Barro and Conard, 1991; Keeley, 2000; Keeley and Fotheringham, 2001).

Field Data Collection

Field data were collected in December 2003 at six sites, which included two low, three moderate and one high burn severity site. Burned sites were classified in the field as low, moderate, or high severity if tree/shrub crowns were predominantly green, brown, or black, respectively. Each site was centered in a random location 80–140 m from the nearest access road, within a consistent stand and burn severity condition. Each site consisted of nine 9 m x 9 m plots and each plot was comprised of fifteen 1 m x 1 m subplots, for a total of 810 subplots. Plot centers were

geolocated with a Trimble GeoExplorer[1] and differentially corrected. Subplot centers were positioned with measurement tape and compass based on systematic distances and bearings from plot center (more details in Hudak et al., 2004).

At the subplot scale, the amount of vegetative cover and percent char of green vegetation, rock, mineral soil, ash, litter (new and old), and any large organics were ocularly estimated. At the plot scale, the depth of new litter (deposited post-fire), old litter, and duff were measured, and a convex spherical densiometer was used to measure canopy cover. At the center of each site, grass, forb, seedling, and low shrub cover was estimated, and tall shrubs, saplings, trees, and snags were inventoried (Hudak et al., 2004).

Hyperspectral Data Collection

Field spectra: Spectra of soil, rock, and green, non-photosynthetic (NPV), and charred vegetation materials were collected in the six months after the Simi Fire using an ASD (Analytical Spectral Devices, Boulder, Colorado, USA) Pro-FR field spectroradiometer. Spectra were collected with the bare tip foreoptic (FOV 22°) pointed at the target material. The ASD Pro-FR reports reflectance in 2151 channels spaced contiguously at 1 nm intervals over the 350 to 2500 nm wavelength range, spanning nearly the same portion of the electromagnetic (EM) spectrum as the Probe I sensor used for airborne imaging. The field spectrometer was calibrated against a Spectralon (Labsphere, North Sutton, New Hampshire, USA) 100% reflective panel immediately before and at frequent intervals during field spectra collection. Spectralon is a bright calibration target with well-documented reflectance in the 400 to 2500 nm region of the EM spectrum, and is used to convert relative reflectance to absolute reflectance. Four representative spectra are shown in Figure 1.

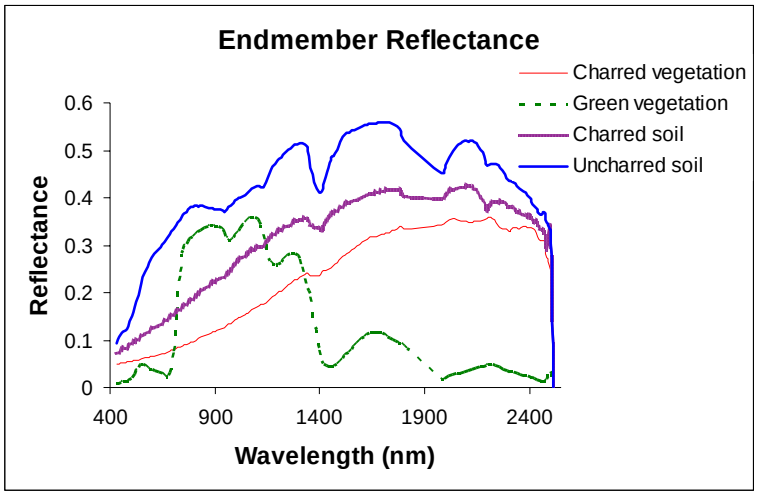


Figure 1. Example field spectra of charred vegetation, green vegetation, charred soil, and uncharred soil field spectra collected from the Simi Fire.

Airborne hyperspectral: One flight line of airborne hyperspectral imagery which covered the range of burn severities observed and included the six field sites was collected in January of 2004. The Probe I whisk-broom sensor (Earth Search Sciences Inc., Lakeside, Montana, USA) was flown at 2100 m AGL and collected data along a track ~28 km long and 2.3 km wide—corresponding to a 512 pixel-wide swath with each pixel 4.2 m by 4.2 m at nadir. Reflected EM energy from the surface was received in 128 contiguous spectral bands that spanned 432 to 2512 nm, with a spectral bandwidth of 11 to 19 nm. An on-board global positioning system (GPS) and inertial measurement unit (IMU) acquired geolocation data that were matched with the spectral data collection. The geolocation data, together with a 30 m digital elevation model, were used to generate Input Geometry (IGM) files, for georeferencing the imagery. Upon delivery, the IGM files were found to be distorted by up to seven pixels (~30 m). Thus, we achieved a more accurate image georegistration by rubber-sheeting the reflectance image to 1 m US Geological Survey Digital Orthophoto Quads. The airborne hyperspectral data were converted to reflectance using

[1] Trade names are included for the benefit of the reader and do not imply endorsement by the US Department of Agriculture or the University of Idaho.

ACORN (Atmospheric CORrection Now) without any additional artifact suppression (Analytical Imaging and Geophysics LLC, Boulder, Colorado, USA). ACORN uses a radiative transfer model to calculate atmospheric gas absorptions and scattering, which are then used to convert at-sensor radiance to apparent surface reflectance. Image reflectance spectra from low, moderate and high burn severity plots are shown in Figure 2.

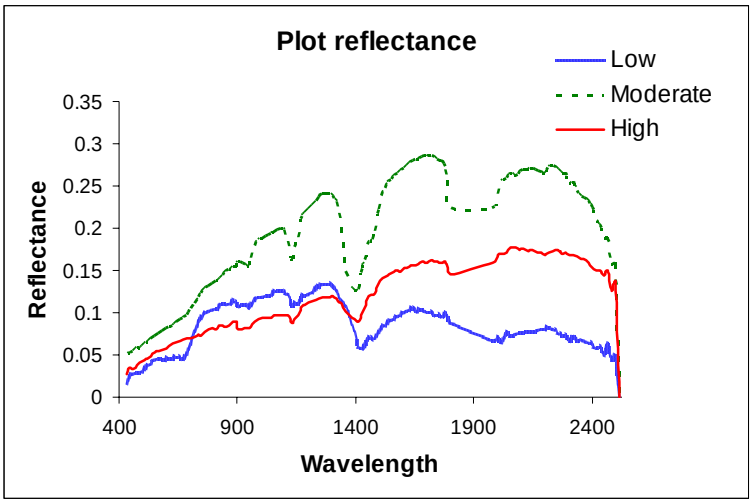


Figure 2. Reflectance spectra from low, moderate and high burn severity plots extracted from the airborne hyperspectral image.

DATA ANALYSIS

Ground Data

The soil and vegetation data were combined into four categories: uncharred organics (e.g., green vegetation and NPV), charred organics (burned shrub stems and needles), uncharred inorganics (rocks and soil), and charred inorganics (rock, soil, and ash) (Table 1). These classes broadly relate to burn severity and erosion potential as post-fire organic ground cover decreases erosion potential by protecting the soil from wind or water. As burn severity increased, inorganic cover increased and organic cover decreased.

Table 1. Means and standard deviations (in parenthesis) of the percent cover of organic and inorganic ground cover components by burn severity class. *N* is the number of plots in each burn severity class.

	Burn severity classes		
Ground cover class	**Low** (*n*=270)	**Moderate** (*n*=405)	**High** (*n*=135)
Uncharred organics (%)	23 (22)	9 (16)	2 (3)
Charred organics (%)	15 (17)	12 (15)	5 (7)
Uncharred inorganics (%)	43 (26)	43 (28)	53 (25)
Charred inorganics (%)	16 (21)	35 (28)	40 (24)

Hyperspectral Image Data

A linear spectral unmixing algorithm was applied to the ACORN reflectance data to determine pixel fractions of green vegetation, charred vegetation, and charred and uncharred inorganic ground cover. The field spectra used as endmembers are shown in Figure 1. A single image pixel is a mixture of the sum of the individual reflectance spectra (endmembers) of the component reflective surface materials (Adams et al., 1985; Smith et al., 1990; Roberts et al., 1993). Once endmember spectra are identified, spectral unmixing of individual image pixels can estimate the fractional component spectra and, in turn, the physical fractional component of the materials (Adams et al., 1985; Roberts et al., 1993; Theseira et al., 2003).

The unmixed image was georeferenced and endmember fractions were extracted from the unmixed image at all subplot locations (i.e., 135 per site). These spectral fractions were compared to the field-measured fractional cover estimates to evaluate how well the image captured the conditions on the ground. Correlations were assessed for each endmember using the Pearson correlation statistic (SAS Institute Inc., 1999) at the subplot and plot scales.

RESULTS AND DISCUSSION

The spectral fractions from the hyperspectral image were significantly correlated to the corresponding ground cover fractions (Table 2). The strongest correlation was between the green vegetation endmember and the field-measured uncharred organic ground cover (r = 0.67). Green vegetation was spectrally distinct in the image and well-matched to the green vegetation field spectrum used as an endmember. The charred vegetation endmember was correlated to the charred inorganics (r = 0.38), suggesting that the field endmember was not spectrally pure, but rather a mix of burned shrub stems reflectance and charred soil background reflectance. Similarly, the charred soil endmember was significantly correlated to uncharred organic (r = 0.54) and inorganic (r = 0.21), and charred organic (r = 0.21) ground cover probably because the charred soil spectral endmember was a mixture of charred organic and inorganic reflectance. The uncharred soil endmember was most strongly correlated to uncharred inorganic ground cover (r = 0.41). This is likely due to the high albedo of uncharred rock and soil inorganics, the brightest components in the scene.

Table 2. Significant Pearson correlation coefficients (p < 0.0001) relating spectral abundance and field-measured ground cover.

	Ground cover components			
Endmember	**Uncharred organic**	**Charred organic**	**Uncharred inorganic**	**Charred inorganic**
Green vegetation	0.67	-	-	-
Charred vegetation	-	-	-	0.38
Charred soil	0.54	0.21	0.21	-
Uncharred soil	-	-	0.41	-
Shade	-	-	-	-

The shade endmember was represented by zero reflectance and was not correlated to any of the individual ground cover components. However, due to topography, much of the image was shaded and the inclusion of the shade endmember in the spectral unmixing improved all correlations. Along with the fractional cover images, the spectral unmixing algorithm also provides a Root Mean Square Error (RMSE) image to help assess the quality of the results. The RMSE was 0.04 or less across the entire image, indicating that these endmembers, while not necessarily pure, captured most of the ground cover types in the image.

All correlations would likely be improved if the ground data and the hyperspectral image data were collected at the same time. Because of logistical and safety concerns and the presence of smoke, ground data and image data are not easily acquired during or immediately after a fire. There was a one-month delay after the ground data were collected before the image was acquired and during this time, burned area assessment teams found that post-fire wind and rain events may have re-distributed white ash, which is characteristic of severe fire effects (CDF, 2003). Hudak et al. (2004) also speculated that poor correlations between field and multispectral satellite data were explained by time since fire and post-fire assessment in southern California.

For comparison, a dNBR (delta normalized burn ratio) image derived from Landsat (acquired 10 November 2003) is shown in Figure 3a. The brightest areas correspond to those changed most by the fire, or burned at the highest severity, while the darkest areas were minimally changed by the fire, or unburned (Key and Benson, 2002). dNBR values can be classified into a Burned Area Reflectance Classification (BARC) map, with dark green representing unburned, light green representing low burn severity, yellow representing moderate-low burn severity, orange representing moderate-high burn severity, and red representing high burn severity (Figure 3b).

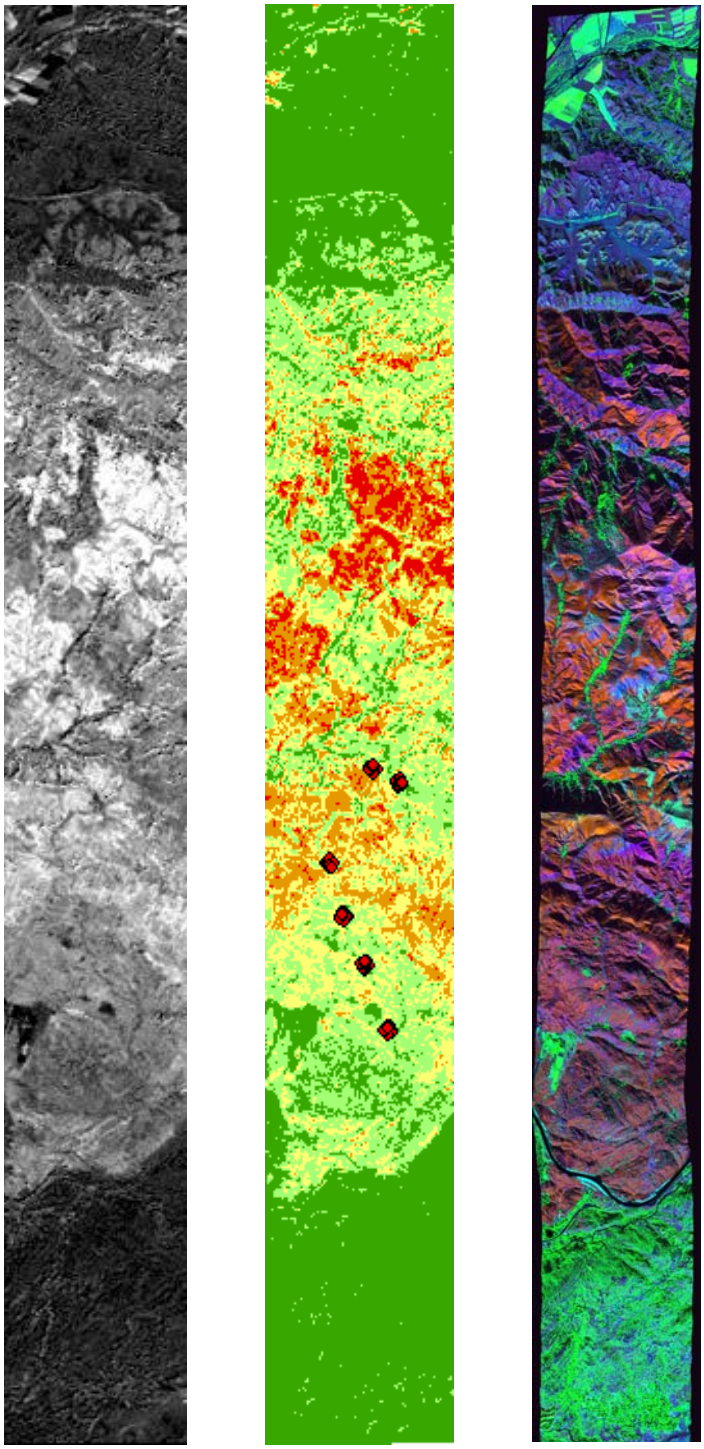
Figure 3c is a Red-Green-Blue (RGB) representation of the unmixed image. Charred vegetation is shown as red, green vegetation as green, soil as blue. The fire perimeter is identifiable on the image where the red/orange/purple colors within the burned area sharply turn to a blue/green color outside of the burned area. Roads are visible within the image (blue) as are some unburned valleys (green). Large patches of bright blue are rocky outcrops and the darkest areas are topographic shadows.

All three images show the same general areas as unburned and as high burn severity; however, unlike the classified BARC map (Figure 3b), the unmixed image (Figure 3c) can be used to discern and quantify the physical ground cover characteristics. The extent to which the ground surface was burned and the amount of remaining organic ground cover are good indicators of the effects of the fire on the soil surface, or soil burn severity. This information could be helpful immediately after a fire when post-fire rehabilitation teams must determine which areas to treat for erosion mitigation. Currently, hyperspectral data collection, pre-processing, and analysis are in research stages, and are not yet appropriate for rapid, operational post-fire response. However, as technology advances and data are made available more quickly, these methods have promise for guiding post-fire rehabilitation efforts.

CONCLUSIONS AND FUTURE RESEARCH

The endmembers used in the spectral unmixing process for the Simi Fire were representative of the burned area. There were significant correlations between spectral abundance in the image and fractional cover measured on the ground for each of the endmembers used in the unmixing. Uncharred organics were the easiest to identify in the imagery, followed by uncharred and charred inorganics. The ability to identify post-fire organic ground cover and the condition of the soil may help to guide rehabilitation efforts. While hyperspectral data are currently time consuming and costly to obtain, these methods will likely be more useful as hyperspectral image acquisition and processing becomes more timely and affordable. The field spectra used as endmembers in the Simi Fire analysis will be useful on future fires in areas with similar vegetation types.

The work presented here is part of a larger research project to identify quantitative indicators of burn severity across multiple landscapes and vegetation types. We have hyperspectral imagery and ground data for five other 2003 fires (one in Califor-



a) b) c)

Figure 3. A comparison of the Landsat-derived dNBR image (a), the classified BARC map (b) and the unmixed hyperspectral image (c). The plot locations within the six field sites are shown on (b) by the red diamonds.

nia, four in Montana) and two 2004 Alaska fires. Our current work includes the creation of a comprehensive spectral library for each vegetation type represented in these images and fractional cover maps for each fire. Comparisons across the different ecosystems will ideally lead to the identification of the most useful and universal indicators of burn severity.

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