

HYPERSPECTRAL REMOTE SENSING OF POSTFIRE SOIL PROPERTIES

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ABSTRACT

Forest fires may induce changes in soil organic properties that often lead to water repellent conditions within the soil profile that decrease soil infiltration capacity. The remote detection of water repellent soils after forest fires would lead to quicker and more accurate assessment of erosion potential. An airborne hyperspectral image was acquired over the Hayman Fire in the summer of 2002. A supervised classification was performed in an attempt to identify soils that were highly water repellent. The classification was not accurate in determining water repellency severity, but it was nearly 80 percent accurate for identifying the presence of surface water repellency. According to the classified image, nearly 20 percent of the Hayman Fire had water repellent soils.

INTRODUCTION

The intermountain west has recently experienced several severe fire seasons. Forest fires render soils susceptible to increased erosion due to the disturbed soil structure and the formation of fire-induced water repellent soils (DeBano, 2000; Letey 2001; Shakesby et al., 2000). Millions of dollars have been spent on emergency postfire treatments attempting to minimize postfire erosion and the effects of the fire on surrounding resources (Robichaud et al., 2000). The recent application of remote sensing technology to map postfire burn severity is tied to postfire erosion mitigation efforts (Remote Sensing Applications Center, 2004). Postfire burn severity maps serve as a rapid indicator of the hydrologic response of the burned area by estimating the effects of the fire on the soils (Parsons, 2003, unpublished report).

Increasing fire burn severity is often assumed to be directly related to an increase in soil water repellency (DeBano, 2000; Doerr et al., 2000). The combustion of organic matter and litter on the soil surface during the fire generally results in a water repellent soil layer at or below the soil surface (Clothier et al., 2000; DeBano et al., 1976). Post-fire water repellency is highly variable both laterally and vertically within the soil profile (Dekker and Ritsema, 2000; Doerr et al., 2000; Doerr and Moody, 2004). The temperature reached at the soil surface as well as the depth of the pre-fire litter and duff influence the degree of water repellency. Temperatures up to 280 degrees C contribute to the formation of water repellency, while temperatures above this point destroy the hydrophobic compounds (DeBano, 2000; Letey, 2001). Therefore, the water repellency may not be present at the soil surface, while it still exists in the deeper soil layers that did not reach as high of a temperature. Because of this phenomenon, it is difficult to predict soil water repellency from fire burn severity alone; the relationship is not consistent or well-defined (Doerr et al., 2000).

The correlation between soil organic matter (OM) and soil water repellency has been examined in other studies and the relationship is not consistent (Mataix-Solera and Doerr, 2004; Doerr et al., 2000). OM is neither always higher in water repellent soils nor is it lower; however, OM and soil water repellency are often statistically correlated (Mataix-Solera and Doerr, 2004; Doerr et al., 2000). The hydrophobic compounds that are found in water repellent soils are organic in nature, specifically aliphatic hydrocarbons (Schmid et al., 2001; Almendros et al., 1990; Savage et al., 1972). An abundance of aliphatic functional groups in a burned soil may suggest water repellent soil conditions due to the quantity of OM combusted during the fire. The aliphatic hydrocarbons in burned soil may be detectable using the hyperspectral sensors in the laboratory and in the field. The region from 1400 to 2100 nm (near-infrared and short wave infrared) experiences significant absorption by many organic compounds (Fidencio et al., 2002; Hummel et al., 2001; Ben-Dor and Banin, 1995; Henderson et al., 1992).

The 2002 Hayman Fire burned nearly 55,000 ha on the Colorado Front Range, and over half of the burned area was classified as a moderate or high severity burn by the BAER burn severity map. Based on the BAER map, millions of dollars in rehabilitation treatments were prescribed. Lewis et al., 2004 (in review) found that the Hayman Fire BAER map likely under classified some areas as low or moderate severity burns while they actually exhibited high severity burn attributes. They also found that moderate or strong water repellency existed at nearly 70 percent of the sample plots from the same study, the majority of which were classified as low and moderate burn severity by the BAER map.

The objectives of this study were to: (1) compare soil burn severity to soil water repellency on the Hayman Fire; and (2) attempt to remotely sense water repellent soils from hyperspectral imagery collected after the Hayman Fire. The results are needed to examine whether areas at-risk for postfire erosion may be better identified by remotely identifying water repellent soils rather than soils burned at a high severity.

METHODS

Study Area

The study was conducted immediately following the 55,000 ha Hayman Fire in the Pike-San Isabelle National Forest located in the Front Range of central Colorado (Figure 1) that burned in June and July, 2002. From the BAER burn severity map, 31 percent of the total area was classified as low soil burn severity, 20 percent as moderate, 32 percent as high, and 17 percent was unburned (Graham et al., 2003). The fire burned primarily in ponderosa pine (*Pinus ponderosa*) and Douglas fir (*Pseudotsuga menziesii*) forest. In the higher elevations, the vegetation shifts to a sub-alpine forest: lodgepole pine (*Pinus contorta* var. *latifolia*), limber pine (*Pinus flexilis*), aspen (*Populus tremuloides*), subalpine fir (*Abies lasiocarpa*), and Englemann spruce (*Picea engelmannii*) (Romme et al., 2003). The region is underlain by the Pikes Peak batholith, with frequent rocky outcroppings. The two dominant soil types are of the Sphinx and Legault series, which are coarse-textured, gravelly, and often excessively drained (Robichaud et al., 2003).

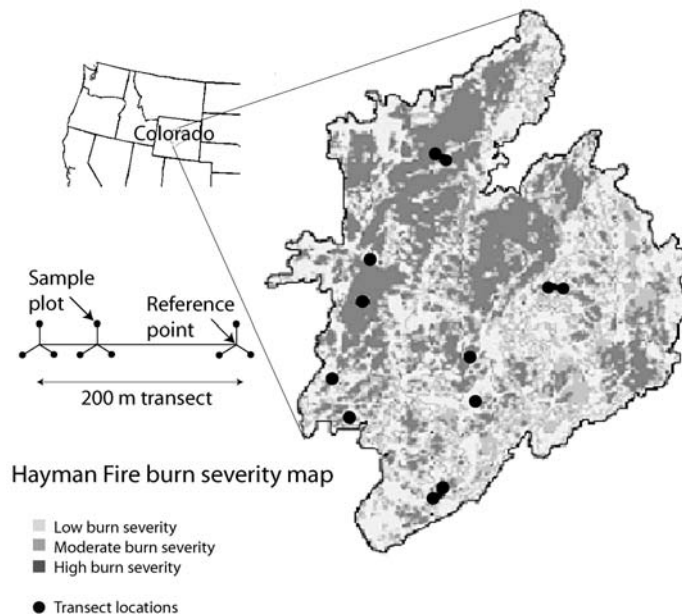


Figure 1. Hayman Fire map showing burn severity, plot locations, and the sampling scheme.

Burn Severity Assessment

Approximately sixty sample points were selected in each of the three burn severity classes (low, moderate, and high) as delineated by the BAER burn severity map for a total of 182 sample points. Ocular classification of 24 selected variables indicating soil and vegetation conditions was performed at each sample point which were 12.5 m² circles (4-m diameter). The burn severity assessment was intended to be used for ground truth validation of the

BAER burn severity map. The details of the sampling scheme and burn severity assessment can be found in Lewis et al., 2004 (in review).

Water Repellency Tests

Soils at each plot were tested for surface water repellency only with two tests, water drop penetration time (WDPT) and the mini-disk infiltrometer (MDI). The WDPT was conducted at 11 evenly spaced points along a 0.5-m line transect within each 4-m circle. The surface ash and litter were swept aside to expose the mineral soil. At each point, a water drop was placed on the soil surface and the time to infiltration was measured. If the water drop remained on the soil surface for longer than five seconds, the soil was considered water repellent (DeBano, 2000; Letey et al., 2000). MDI tests were performed on a line parallel to and within 200 mm directly above or below the WDPT test line. The field-portable MDI had a constant pressure head of five mm with a 310 mm diameter porous disk. The graduated cylinder body of the MDI allowed a measurement of cumulative infiltration per time to be read directly. The MDI was filled with water and placed on the exposed soil surface at four evenly spaced locations along the line. The time to the start of infiltration was noted (MDI_{time}), as well as the volume of water that infiltrated into the soil within the first minute of infiltration (MDI_{rate}).

Organic Matter Determination

A laboratory dry combustion procedure (loss on ignition) was performed on soil samples taken from all 182 sampling points in order to determine the organic matter content (Smith and Atkinson, 1975). Soil samples were dried at 105°C for 24 hours to remove moisture. The dried samples were placed in a muffle furnace at 375°C for 16 hours to incinerate all organic matter. Upon cooling to room temperature, the percent organic matter was calculated by mass.

Aerial Image Acquisition

A Probe-1 hyperspectral sensor (Earth Search Sciences Inc., Kalispell, MT) was mounted to a fixed-wing aircraft for hyperspectral data collection over the Hayman Fire in August 2002. Fourteen flight lines were flown for continuous coverage of the fire area with a mean sensor altitude of 7000 m above the ground. The sensor measures reflectance at an average 15 nm spectral resolution over the range of 400–2500 nm, resulting in 128 bands of data. The spatial resolution of the processed data was 5.1 m. As each of the study plots was a 4-m circle, each plot was considered one pixel in the image analysis.

Image Pre-processing

Pre-processing of the image data was primarily completed prior to our receiving the data. The Hayman image data was converted to reflectance using the atmospheric modeling algorithm ACORN (Atmospheric CORrection Now). Geo-rectification was performed within Environment for Visualizing Images (ENVI, 2002) software using input geometry (IGM) files provided with the reflectance data and the data were projected into UTM coordinates, zone 13N. Finally, the ground truth plots were located on the image using the GPS coordinates that were collected at each site. A spectral library was built within ENVI from the 182 plots where water repellency and burn severity data were collected. Due to the exploratory nature of this study, image analysis was focused on one flight line only, flight line 7 (FL7).

Statistical Analysis

Confusion matrix analysis was used to determine whether surface soil water repellency increased with soil burn severity. The confusion matrix presents a comparison of two spatial classifications where the frequency of occurrence a_{ij} , where class i of one variable coincides with class j of another variable. The agreement between the classifications is calculated by the number of times i is equal to j , which is along the diagonal of the matrix (Congalton and Green, 1999).

A principal component (PC) transform was performed on the reflectance data in order to identify the major source(s) of variance in the image as well as to reduce the dimensionality of the data (Richards and Jia, 1999; Jensen, 1996). In order to identify the most useful NIR and SWIR data, the PC transform was performed on reflectance data between 1482 and 2451 nm, and 20 output PC bands were generated. On FL7, PC bands 1–3 contained 99.9 percent of the variance and bands 1–10 contained nearly 100 percent of the variance. PC bands 11–20 appeared very noisy and not especially informative; therefore, subsequent image analysis was focused on the first 10

PC bands. On FL7, PC1 was correlated highest with SWIR bands 2183–2235 nm. PC2 was correlated highest with bands 1697 and 1564 nm. PC3 was correlated highest with bands 1717 and 1537 nm.

Supervised Classification

Regions of interest (ROIs) were built to separate strong, moderate and slight water repellency plots, which allowed for distinct spectral regions to be separated as training classes (endmembers) for supervised classification (Figure 2). For validation, 20 to 50 percent of the plots were reserved for classification validation. These endmembers were used as training classes within the PC images for a supervised classification. Spectral Angle Mapper (SAM) calculates the spectral angle in n-dimensional space between spectra to compute a match to reference spectra or endmembers (ENVI, 2000). The smaller the angle between two spectra, the better the match. Due to the high spatial variability of soil water repellency, adjacent pixels (a 3 by 3 window) were examined for the presence of water repellency as well as water repellency severity (Figure 3). The pixel error from the georectification was not known exactly, however it is thought to be up to 30 m, depending on the horizontal position within the flight line (errors are greater on the edges). Therefore, examining surrounding pixels for water repellency seemed to be a reasonable approach. A classification matrix was created to assess the accuracy of the classification.

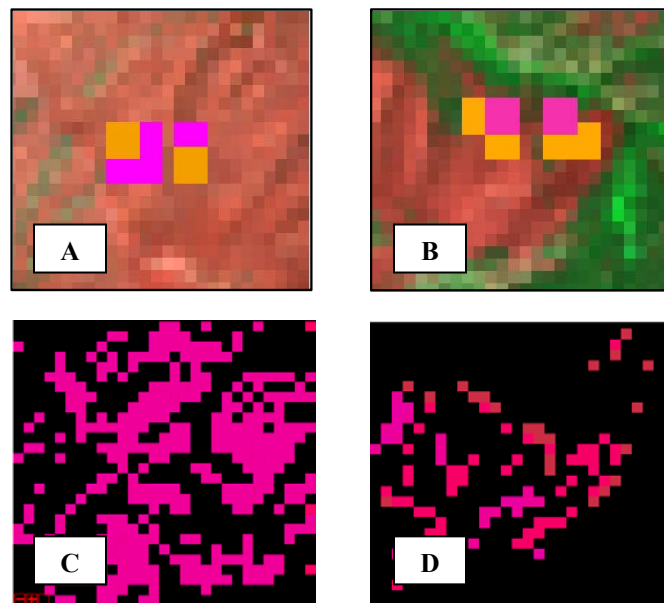


Figure 2. Regions of strongly (pink) and moderately (orange/yellow) water repellent pixels/plots used to create water repellency endmembers. Background postfire RGB image (on A and B) shows burned soils and green live vegetation. Images C and D are classified images of A and B, respectively. Black pixels are unclassified and pink/red pixels are classified as strongly water repellent.

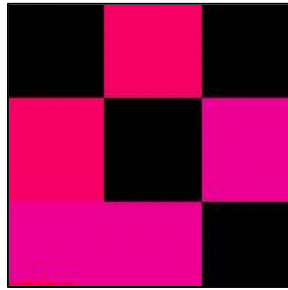


Figure 3. An example of the 3 x 3 pixel window that was used to assess the accuracy of the water repellency classification. The center pixel is the validation pixel, which was unclassified, however it was adjacent to 5 pixels that were classified as strongly water repellent.

RESULTS

Soil Burn Severity Compared to Soil Water Repellency

Soil burn severity and surface soil water repellency do not increase concurrently, regardless of which method is used to test for soil water repellency. The confusion matrices (Table 1) that compare water repellency and burn severity show a 26 percent agreement when the WDPT is used. Most of the error comes from the high burn severity plots exhibiting slight surface water repellency. When the MDI test is used to test for water repellency, there is a somewhat higher agreement, 37 percent; again, a significant amount of the error comes from the high burn severity plots having slightly or only moderately water repellent soils (Table 2). Lewis et al., 2004, found similar results, using different statistical methods. Surface soil water repellency was not strong in the highly burned sites. The most likely explanation is that a deeper water repellent layer exists within the soil profile and it was not detected with our surface tests.

Table 1. Confusion matrix comparing surface water repellency classes as determined by the WDPT to burn severity classes. Sum of the plots along the diagonal divided by the total plots ($n=182$) is the percent agreement between the two classifications.

Water Repellency Class	Burn Severity Class		
	Low	Moderate	High
Slight			
WDPT 6 to 60 s	10	20	30
Moderate			
WDPT 61 to 180 s	17	24	24
Strong			
WDPT 181 to 300 s	14	29	14

Table 2. Confusion matrix comparing surface water repellency classes as determined by the MDI to burn severity classes. Sum of the plots along the diagonal divided by the total plots ($n=182$) is the percent agreement between the two classifications.

Water Repellency Class	Burn Severity Class		
	Low	Moderate	High
Slight MDI > 6 ml min ⁻¹	13	14	23
Moderate MDI 3 to 6 ml min ⁻¹	11	29	20
Strong MDI < 3 ml min ⁻¹	17	30	25

A comparison of the characteristics of the different burn severity classes and the different water repellency classes (Tables 3, 4) shows again that these classes are very different on the ground. Mineral soil exposure increases as burn severity increases, yet decreases with increasing surface soil water repellency. The percent litter cover and ash both decrease with increasing burn severity and increase with increasing water repellency. Soil organic matter has an overall decrease with increasing burn severity and an overall increase with increasing surface water repellency.

Table 3. ground characteristics of burn severity classes.

Burn Severity Class	Exposed mineral soil (%)	Litter cover (%)	Ash (%)	Soil organic matter (%)
Low	4	66	22	5.6
Moderate	36	40	18	6.0
High	71	8	16	3.9

Table 4; ground characteristics of water repellency classes (by WDPT).

Water Repellency Class	Exposed mineral soil (%)	Litter cover (%)	Ash (%)	Soil organic matter (%)
Slight	53	30	11	4.1
Moderate	41	36	18	5.6
Strong	31	37	26	5.7

Remote Sensing of Water Repellent Soils

On FL7 no more than one pixel was correctly classified into any of the water repellency classes when 20 percent of the plots were used for validation (data not shown). When 50 percent of the plots were reserved for validation, four out of 26 plots (1 slight, 3 moderate, 0 strong), 15 percent, were correctly classified into water repellency classes (Table 5) and more than 50 percent of the overall area was unclassified (Figure 4). The slight water repellency predictability increased from 17 percent (1 out of 6 pixels correctly classified) to 67 percent (4 out of 6 pixels were adjacent to a slightly water repellent pixel) when adjacent pixels were considered and the moderate water repellency predictability increased from 27 percent (3 out of 11) to 55 percent (6 out of 11). The high water repellency predictability increased from 0 percent (0 out of 9) to 45 percent (4 out of 9) and the overall accuracy of identifying the severity of soil water repellency was 54 percent (14 out of 26) (Table 5). When examining the validation pixels for adjacency to a pixel classified at any severity of soil water repellency, the overall accuracy went up to 81 percent (21 out of 26).

Table 5. Classification matrix for FL7 with half of the pixels used as validation pixels.

Classified Pixels	Validation Pixels			Row total sample size $n=26$
	Slight WR $n=6$	Moderate WR $n=11$	Strong WR $n=9$	
Slightly water repellent (WR)	1	1	3	5
Moderately WR	1	3	0	4
Strongly WR	0	1	0	1
Unclassified	4	6	6	16
Number of pixels adjacent to same severity WR pixel	4	6	4	14
Number of pixels adjacent to any severity WR pixel	5	8	8	21

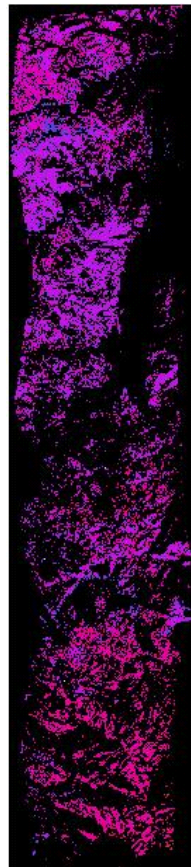


Figure 4. A subset of the FL7 water repellency classification. Black pixels are unclassified, pink/red pixels are strongly water repellent, purple pixels are moderately water repellent and blue pixels are slightly water repellent.

DISCUSSION

The ground cover components of plots with strong surface soil water repellency are more similar to plots burned at a low severity and plots with slight surface soil water repellency have similar ground cover characteristics to the high burn severity plots. Thus, the identification (in situ or remote) of burn severity is not necessarily related to the identification of surface soil water repellency. These results increase justification for attempting to remotely map soil water repellency as opposed to burn severity alone.

The plots in this study were highly susceptible to misclassification. The ground cover varies greatly between water repellency plots and between different burn severities (Tables 3, 4). The soil that was tested for water repellency was often surrounded or covered (on the image) by ash, charred organics, postfire needlecast, rock and green and black canopy. It was a combination of these organic and inorganic components that created the spectral signature associated with each of the water repellency classes. Many of the plots were misclassified (Table 5) because of an overriding spectral signature different than the mean signatures of the three water repellency severities.

CONCLUSION

Areas burned at a high severity often have very different ground characteristics than areas with strong surface soil water repellency. We have shown attempted to remotely sense water repellent soils after forest fires in addition to the more traditional burn severity mapping. The SAM classification does a better job of identifying the presence or absence of water repellent soils than predicting the water repellency severity. As seen on the images, soil water repellency occurred in fairly distinct regions (Figure 4). These would be the regions to consider for erosion mitigation. The identification of water repellent soils is likely more important than distinguishing between water repellency severity.

In order to improve results, future work should focus areas that have sparse canopy cover or canopy characteristics should be more carefully measured, e.g. densiometer measurements over plot centers. Increased soil exposure on the image would likely improve the chances of identifying a spectral signature unique to water repellent soils. The collection of water repellency endmembers in the field with a hand-held spectrometer would also improve image classification results. With some technique modifications, remote sensing of water repellent soils may be a useful addition to postfire assessment of erosion.

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