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Characterization of post-fire surface cover, soils, and burn severity at the Cerro Grande Fire, New Mexico, using hyperspectral and multispectral remote sensing

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Abstract

Forest fires leave behind a changed ecosystem with a patchwork of surface cover that includes ash, charred organic matter, soils and soil minerals, and dead, damaged, and living vegetation. The distributions of these materials affect post-fire processes of erosion, nutrient cycling, and vegetation regrowth. We analyzed high spatial resolution (2.4 m pixel size) Airborne Visible and Infrared Imaging Spectrometer (AVIRIS) data collected over the Cerro Grande fire, to map post-fire surface cover into 10 classes, including ash, soil minerals, scorched conifer trees, and green vegetation. The Cerro Grande fire occurred near Los Alamos, New Mexico, in May 2000. The AVIRIS data were collected September 3, 2000. The surface cover map revealed complex patterns of ash, iron oxide minerals, and clay minerals in areas of complete combustion. Scorched conifer trees, which retained dry needles heated by the fire but not fully combusted by the flames, were found to cover much of the post-fire landscape. These scorched trees were found in narrow zones at the edges of completely burned areas. A surface cover map was also made using Landsat Enhanced Thematic Mapper plus (ETM+) data, collected September 5, 2000, and a maximum likelihood, supervised classification. When compared to AVIRIS, the Landsat classification grossly overestimated cover by dry conifer and ash classes and severely underestimated soil and green vegetation cover. In a comparison of AVIRIS surface cover to the Burned Area Emergency Rehabilitation (BAER) map of burn severity, the BAER high burn severity areas did not capture the variable patterns of post-fire surface cover by ash, soil, and scorched conifer trees seen in the AVIRIS map. The BAER map, derived from air photos, also did not capture the distribution of scorched trees that were observed in the AVIRIS map. Similarly, the moderate severity class of Landsat-derived burn severity maps generated from the differenced Normalized Burn Ratio (dNBR) calculation had low agreement with the AVIRIS classes of scorched conifer trees. Burn severity and surface cover images were found to contain complementary information, with the dNBR map presenting an image of degree of change caused by fire and the AVIRIS-derived map showing specific surface cover resulting from fire.
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1. Introduction

As a major disturbance to conifer forest ecosystems in the western United States, wildland fire has long had an impact on ecosystem structure and function. The direct transformation of living and dead organic matter in vegetation and soils to charred organic matter and ash is a clear change wrought by fire. The ecological effects of a specific fire on soils and vegetation, referred to as both "fire severity" and "burn severity", can be more subtle and depend on the degree of combustion of living and dead organic matter, the nature of the soil, and the impact of the fire's heat on the physical and chemical properties of the soil (Neary et al., 2005). Remote sensing is a tool applicable to the characterization of the direct impact of fire on vegetation and soil properties, both of which are important to the understanding of burn severity and post-fire ecosystem processes.

In areas of complete combustion, vegetation growth and successional processes begin anew without the shade cast by overstory and understory vegetation. In conifer forests subject to

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incomplete combustion, scorched needles on trees cast shade and affect post-fire species dynamics (Rowe, 1983). Once dropped, these needles contribute to the soil nutrient pools and can reduce erosion (Pannkuk & Robichaud, 2003). Lightly scorched and unburned forest areas act as seed sources for vegetation regrowth.

Soils are also altered by fire in complex ways. The deposition of ash and charred materials from the combustion of living and dead organic matter increases available nitrogen and phosphorous for uptake by vegetation and microbiota (DeBano et al., 1998; Knoepp et al., 2005). However, an underlying soil of a calcareous nature can immobilize P, making it unavailable for plant growth (Knoepp et al., 2005). The plentiful cations in the ash residue, for example, K, Ca, and Mg, increase the cation exchange between soil and plants; yet, ash deposits are easily removed by water and wind erosion. Soils with clay minerals can better retain the cations, with some forms of clay having greater affinity for cations, such as montmorillonite, compared to others, such as kaolinite (Knoepp et al., 2005; Grim, 1968). In areas greatly heated by the fire, soil structure can be destroyed and water infiltration rates reduced, producing rapid runoff and hillslope erosion (DeBano et al., 1998). The type clays in soils have been shown to have large impacts on erosion, with soils containing clays in the smectite family being associated with less rainfall infiltration and higher rates of soil loss (Ben-Hur & Agassi, 1997; Reichert et al., 1994). In soils heated by fire, iron-bearing minerals in the soil can be oxidized, imparting a reddish color to the soil. This oxidation is often used as a qualitative indicator of burn severity in soils (Neary et al., 2005).

Hyperspectral remote sensing data have been shown to be capable of detecting carbonate, clay, and iron-bearing minerals in soils (Chabrillat et al., 2002; Clark et al., 2003), though no studies targeted at detecting specific soil minerals following wildland fires with hyperspectral data are known to have been conducted. With respect to fire, hyperspectral remote sensing data have been used in estimating “burn severity” (van Wagtendonk et al., 2004) and tracking vegetation regrowth (Riano et al., 2002). Laes et al. (2004) applied partial unmixing to imaging spectrometer data for the mapping of burn severity at the Hayman fire in Colorado. They mapped the distributions of ash, bare ground, scorched vegetation and green vegetation; however, the results varied from one flightline to the next (Laes et al., 2004). Multi-spectral remote sensing (30 m pixel size) has been used to characterize tree canopy mortality (Miller & Yool, 2002), surface and crown fire effects (Turner et al., 1994), and changes in vegetation and soil conditions (Ringleb & Key, 1992; White et al., 1996). Measures of “burn severity” using pre- and post-fire differenced images derived from Landsat ETM+ data are being produced on an operational basis (Key et al., 2002).

While remote sensing is currently being applied to estimate the occurrence, size, and severity of fire, there has not been a detailed study to apply remote sensing to map surface cover and soil characteristics linked to post-fire ecosystem processes, specifically ash and charred matter resulting from combustion, scorched vegetation resulting from the heat of the fire, iron-oxide minerals linked to soil heating, and clay minerals which affect cation exchange between soils and vegetation, rainfall infiltration, and soil loss. In this paper, our objectives are, first, to evaluate the capabilities of hyperspectral and multispectral remote sensing for discriminating between and mapping post-fire surface materials. The second objective is to investigate the relationship between surface materials and burn severity measures and categories. Finally, we compare maps of burn severity developed from hyperspectral and multispectral remote sensing and different analysis methods. The goal of these comparisons is to determine differences in the type and usefulness of information in the maps for understanding post-fire landscape processes. We apply a spectral feature analysis algorithm to high spatial resolution, airborne, hyperspectral remote sensing data from the AVIRIS sensor to map surface cover following the Cerro Grande fire, a large forest fire that occurred in central New Mexico, during the year 2000. We map surface cover from moderate spatial resolution, multispectral, satellite remote sensing data, using a supervised classification method applied to Landsat ETM+ data.

2. The Cerro Grand fire

The Cerro Grande fire started as a prescribed burn at Bandelier National Monument, New Mexico, in May 2000 (Fig. 1). It burned approximately 175 km^2 of forests, including land in the Santa Fe National Forest, parts of the homelands of several Native American tribes including Santa Clara and San Ildephonso, and a portion of the City of Los Alamos. A majority of the forest was mid-elevation ponderosa pine (*Pinus ponderosa*), with some piñon–juniper (*Pinus edulis–Juniperus* spp.) at lower elevations. Douglas fir (*Pseudotsuga menziesii*) and aspen (*Populus tremuloides*) were also components of the burn from mid through high elevations. The fire received enormous publicity and funding for rehabilitation because it affected many private homes, as well as the home of atomic research at Los Alamos National Laboratory.

3. Methods and data

3.1. Field observations of burn severity

Field observations of burn severity were made for 77 field plots in the summer of 2001 (Omi & Martinson, 2002). The dimensions of the plots were 20 m by 50 m. The fire's impact on the vegetation overstory was evaluated by visual evaluation of the fraction of scorched and combusted tree canopies. Each plot was assigned one of five values of “stand damage”: 0 = no damage—all tree crowns unscorched, 1 = spotty damage—partial scorch on at least one tree, but some trees unscorched, 2 = moderate damage—partial scorch on all tree crowns, but few trees completely scorched, 3 = heavy damage—nearly all tree crowns completely scorched, but few crowns fully combusted by flames, and 4 = extreme damage—nearly all tree crowns combusted. Field estimates of soil burn severity were made with ground char ratings in four 30-cm × 60-cm subplots located at 90° angles and 17.85 m from each plot center. Ground char was rated as follows (after Ryan & Noste, 1985): 0 = unburned—no evidence of surface fire, 1 = light—some small twigs or leaves remain, 2 = moderate—all twigs, leaves and standing grasses consumed, mineral soil charred, and 3 = deep-mineral soil altered in color or texture.