Using Remote Sensing to Monitor Post-fire Watershed Recovery as a Tool for Management

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Abstract—*Post-fire watershed recovery is influenced by numerous variables but one of the most important factors is the rate of re-establishment of vegetative cover. Burned Area Emergency Response (BAER) teams, along with other agencies (Natural Resource Conservation Service, state, counties, cities, etc.), prescribe temporary post-fire mitigation treatments based on expected post-fire responses of watersheds to fire-caused damage and based on threats to life, property, and resources associated with watershed damage. The objective of this project was to develop tools to more accurately assess the rate of vegetation regeneration after wildfire that will help managers decide if there is a continued need for mitigation measures. We develop a decision support tool to aid land managers and emergency response personnel in their evaluation of continued risks posed by recovering watersheds.*

Introduction

In the last decade wildfires have increased in both size and severity (Westerling and others 2006; Snider and others 2007; Westerling and Bryant 2008). The effects of wildfires potentially impact property within and adjacent to burn areas several years post-fire via their adverse effects on watersheds (Jung and others 2009; Kinoshita and Hogue 2011). As a result, land managers are constantly seeking ways to assess post-fire watershed responses and their potential impacts (e.g., flooding, erosion, sedimentation) to federal and non-federal lands. After a significant wildfire, federal land managers restore and rehabilitate burn areas in three ways: suppression repair, emergency response (within 1-3 years after fire), and long-term rehabilitation (3-10 years after fire). Treatments implemented as part of Burned Area Emergency Response (BAER) are designed to reduce post-fire watershed impacts to life, property, and natural and cultural resources. These treatments, however, are viewed as temporary and are monitored, maintained or even retreated for up to three years after fire containment (U.S. Department of Agriculture Forest Service 2012).

The type and duration of treatments in the aftermath of a fire is directly related to the degree of watershed impairment. A primary rehabilitation objective is restoration of vegetation cover to stabilize slopes and erodible soils, and reduce overland flow. Hillslope erosion is inversely related to plant cover and is considered minimal when plant cover is ≥ 60% (Noble 1965; Orr 1970). For example, treatments such as straw mulching are most effective at reducing rill development and sediment transport when cover is >60% (Robichaud and others 2010). Cover is especially critical in the first year after the fire when the risk of erosion is highest (DeBano and others 1998).

Remote sensing and geospatial technologies are frequently used by land managers to guide resource management decisions. Moderate resolution satellite imagery, most notably Landsat, has proven to be a valuable information source for mapping fire severity and its effects on vegetation (Clark and Bobbe 2006) and monitoring post-fire vegetation recovery (Diaz-Delgado and others 1998; Clark and Kuyumjian 2006; Wittenberg and others 2007). Three well-known Landsat image derivatives used in fire effects mapping are the normalized difference vegetation index (NDVI) (Tucker 1979),

$$\mathrm{NDVI} = (B4 - B3) / (B4 + B3),$$

the enhanced vegetation index (EVI) (Huete and others 2002),

$$\mathrm{EVI} = 2.5 * ((B4 - B3) / (B4 + 6 * B3 - 7.5 * B1 + 1)),$$

and the normalized burn ratio (NBR) (Lòpez Garcia and Caselles 1991),

$$\mathrm{NBR} = (B4 - B7) / (B4 + B7).$$

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where *B* is the top of atmosphere (TOA) reflectance of the specified Landsat band. Vegetation indices are common remote sensing products that are used to highlight a particular vegetation property.

While both NDVI and EVI measure the photosynthetic activity and chlorophyll content in plants, the EVI was developed to correct for soil background signals as well as atmospheric influences (Huete and others 2002). The NBR is influenced by chlorophyll activity, but it is influenced more by moisture content of vegetation and soils (presence or absence of dry, bare soil and healthy vegetation) (Key and Benson 2006).

BAER teams, and those charged with long-term monitoring of watershed recovery, utilize these vegetation indices to ensure that stabilization plans remain on schedule. Since severely burned watersheds often require > 3 years (limit of BAER program's stewardship) to return to pre-fire conditions, managers need a method to monitor their condition (U.S. General Accounting Office 2003). Currently, however, managers lack a cost-effective way to evaluate watershed recovery that could help decide when to end temporary protective treatments. Thus, the objective of this project was to use remote sensing to monitor post-fire vegetation recovery and to develop a decision support tool that assists managers in their assessment of risks posed by the watershed to resource values.

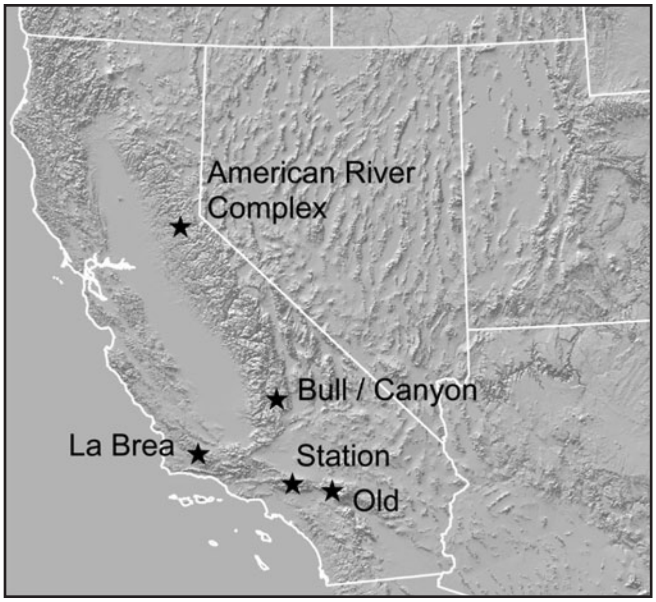

Figure 1—The six fires sampled (burn date) included Old (2003), American River Complex (2008), La Brea (2009), Station (2009), Bull (2010), and Canyon (2010).

Methods

The study area included six fires that burned between 2003 and 2010 and included a variety of elevations, soil burn severities, and stages of recovery (table 1, fig. 1). The six fires burned in predominately chaparral and mixed conifer cover types.

Data on percent vegetative cover were collected at several locations within the burn areas. We utilized pole-mast photography, that is, down-looking camera attached to the top of a telescoping monopod (fig. 2) to measure ground cover from heights ranging from 25-30 feet (Gilbert and others 2009; Smith and others 2000; Vanha-Majamaa and others 2000). Plots were chosen for ease of access, internal homogeneity, and soil burn severity. We took between four and ten photos per plot depending on the size of the homogeneous patch. Photos were spaced approximately 15 meters apart and interpreted with custom-built tools within Esri's ArcGIS ArcMap© using a random dot grid sampling of 600 points per plot. Plant cover was termed either present or absent at each point and cover was based only on living plants (both healthy and dormant/senesced vegetation). Plots were given a single percent cover value using the count of covered points.

A remote sensing data analysis was conducted to relate the photo-interpreted field plots to the maximum greenness observed from satellite imagery during the growing season. To accomplish this, we compiled all available cloud-free Landsat imagery acquired for each growing season after the fire. For each Landsat image, we created an NDVI, EVI, and NBR vegetation index layer. The vegetation index data for each growing season were further analyzed on a per-pixel basis to derive maximum observed vegetation index value during the growing season (Sousa and others 2003). The annual maximum vegetation index value results capture the spatial and temporal distribution of annuals and other vegetation that green up in the spring and those whose peak green-up is later in the season.

Each plot intersected between 2 and 5 Landsat pixels depending on the plot size and orientation. The mean value of the annual maximum vegetation index pixels intersecting the plots were calculated for each year. We then performed regression analysis between ground cover derived from pole-mast photography and the mean vegetation index value computed from the three vegetation indices for each growing season.

Table 1—We analyzed vegetation recovery on 6 burned areas and applied our models to fires in the Madrean Archipelago.

Fire name	Year burned	Location	Acres	Elevation range	Soil burn severity percentages[a]	Project application[b]
Old	2003	San Bernardino, CA	91,281	2,000-7,600'	24, 20, 46, 10	Sample
American River Complex	2008	Foresthill, CA	20,541	2,500-6,700'	27, 35, 26, 12	Sample
La Brea	2009	Santa Maria, CA	89,489	1,100-5,000'	13, 24, 53, 10	Sample
Station	2009	La Cańada, CA	160,577	2,000-6,500'	12, 16, 62, 10	Sample
Bull	2010	Kernville, CA	16,442	2,700-7,400'	13, 37, 49, 1	Sample
Canyon	2010	Lake Isabella, CA	9,860	2,000-6,000'	18, 35, 43, 4	Sample
Monument	2011	Sierra Vista, AZ	32,837	4,400-9,500'	9, 42, 39, 10	Modeled
Horseshoe2	2011	Portal, AZ	222,694	4,500-9,800'	18, 42, 36, 4	Modeled

[a] Percentage of area classified as unburned, low, moderate, and high as estimated from the Burned Area Reflectance Classification (BARC).
[b] Field data was gathered on "sample" fires; models were applied to create predicted cover maps on the "modeled" fires.

Figure 2—Field sampling included an innovative use of pole-mast photography. We took multiple photos in a homogeneous plot; percent ground cover was interpreted using a random dot grid overlayed on photos in Esri's ArcGIS ArcMap.

Results

Regression models produced an acceptable fit for NDVI (N = 53, $R^2 = 0.65$, $p = 0.038$) and EVI (N = 53, $R^2 = 0.63$, $p = 0.019$) but not for NBR (N = 53, $R^2 = 0.17$, $p = 0.004$). Fitting a simple linear model resulted in a "reasonably good" relationship between ground-observed cover and the NDVI index.

$$\text{Percent cover} = 221.18*\text{MaxNDVI}–26.273$$

The relationship between ground cover and EVI was best represented by a polynomial model (fig. 3).

$$\text{Percent cover} = -455.22*\text{MaxEVI}^2 + 519.99*\text{MaxEVI} – 47.508$$

Discussion

Despite the utility of NBR for burn severity mapping (Chen and others 2011), it did not correlate well with field-measured ground cover (fig. 3). The NBR is best suited for densely forested areas and, in general, does not perform as well in sparsely vegetated areas (Miller and Thode 2007). Our data show considerable confusion of NBR values in the 0-30% observed cover range (fig. 3). This confusion is probably due to the influence of Landsat band 7 in the NBR algorithm since similar results were not found in the NDVI or EVI correlations, neither of which use Landsat band 7. Conversely, the NDVI and EVI had significantly better correlations than NBR. These results have operational significance in providing user flexibility to apply multiple available remote sensing assets for post-fire recovery monitoring. Specifically, a limited number of satellite sensors collect data in the 2.1 μm band which is necessary for generating the NBR. However, several moderate resolution sensors collect data in the visible/near infrared which is required for generating EVI/NDVI.

Initial results indicated correlations between EVI and NDVI with plant cover on the six different fires sampled. Nevertheless, we had to confine our sampling to chaparral and mixed conifer forests in California because of project timelines and budget constraints. There is an obvious need to continue testing in other vegetation types. Furthermore, we sampled each fire only once which created a single snapshot in time of the vegetation. To some extent we addressed this problem by leveraging annual time series satellite imagery and field photo interpretation that inventoried all living vegetation material (green and brown).

Additionally, the procedure and models developed through this initial effort can be enhanced by conducting field observations at permanent plots on a regular interval in the years following a fire. This supports multi-temporal assessments of post-fire vegetation conditions at intervals defined by land managers and facilitate the ability to assess and quantify rates of vegetation cover change. To this end, permanent plots have been established on the Bull and Canyon Fires (fig. 1), the two fires we sampled in this project, for long-term monitoring. As we obtain additional samples, we will improve the modeling to better correspond to observed ground cover.

There was one impediment to using pole-mast photography—interference by the overstory tree canopy. We found this technique did not work well in plots with a living overstory canopy (higher than 30 feet) that had little or no live understory. This situation resulted in high vegetation index values because the satellite sees the top of the living canopy but low cover values because the photo was captured beneath the canopy. This is not important when the overstory consists of burned snags because the understory ground cover is viewable by both the satellite and photography.

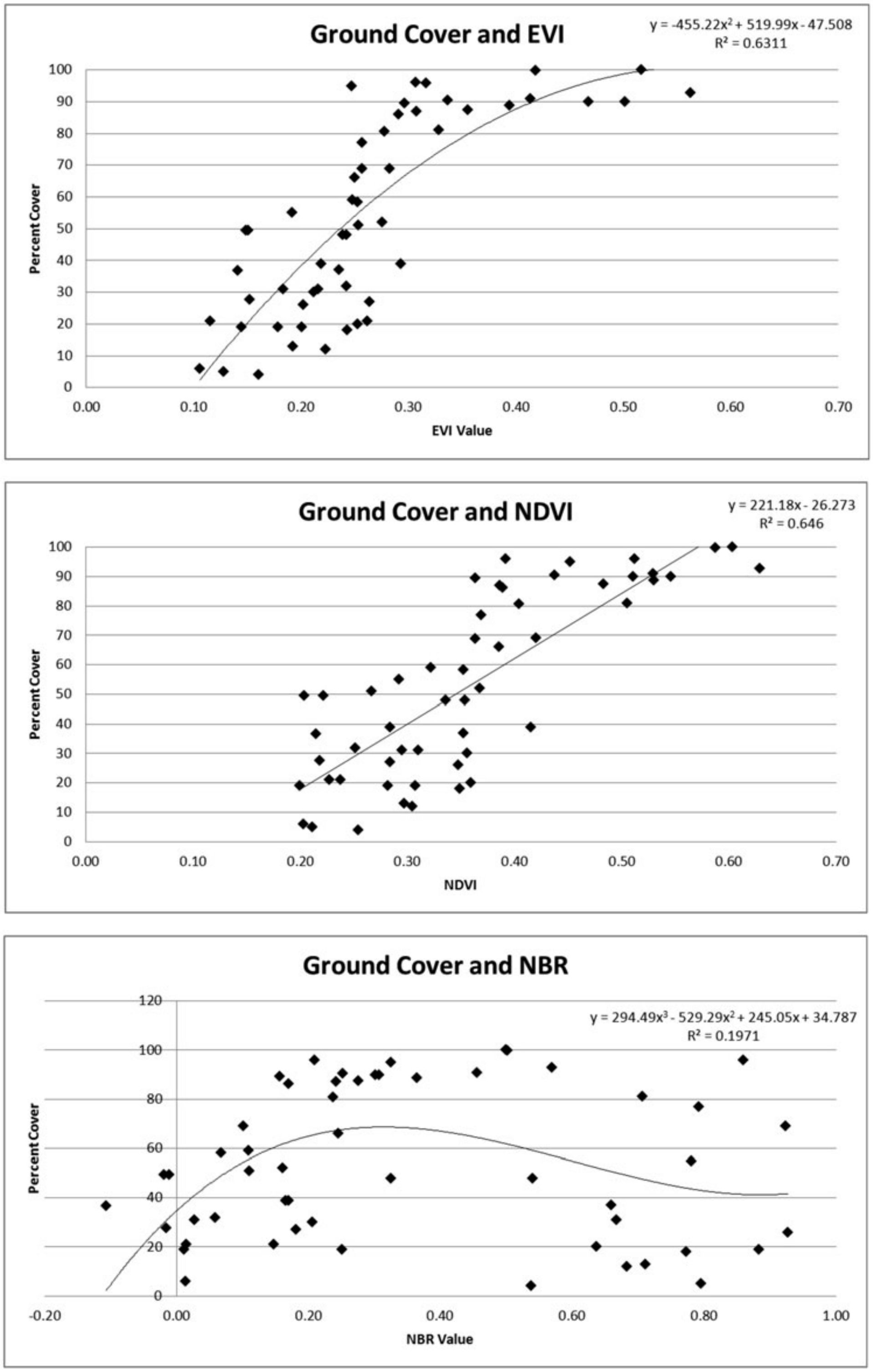

Figure 3—Both EVI and NDVI were well correlated with photo-interpreted ground cover although NBR performed poorly.

Application

To test our model, we applied it to the Monument and Horseshoe 2 Fires that burned in the Madrean Archipelago of Southern Arizona during 2011. We compiled maximum NDVI/EVI composite layers to create a continuous raster layer where every output pixel represents a predicted ground cover value. Broad classes of vegetation cover (e.g., 0-30%, 30-60%, 60-100%) were applied to the continuous data for easier interpretation (fig. 4). An initial validation of the classification for the Monument Fire was encouraging and it appeared to be a potentially useful layer for predicting ground cover in the semi-arid Southwest. Acquisition of field observation data for model validation and further assessment of this methodology is planned for other fires in the region. Also, class thresholds can be adjusted by managers based on their resource needs and to identify high risk areas.

Decision Support Tool

Results from the described methodology can be integrated into a larger decision support tool. The decision support process (fig. 5) is a new tool developed by combining the Fuels Treatment Planning Decision Support Process (2009, Fire Science Digest, JFSP, Issue 7), Forest Service Manual 2520 (2523.1), Calculated Risk: a Tool for Improving Design Decisions by Larry Schmidt (October, 1998 STREAM NOTES), and Assessing Post-Fire Values-At-Risk with a New Calculation Tool. This tool is intended to be used by managers to utilize satellite imagery (vegetation indices), to follow watershed recovery and evaluate potential impacts to values at risk identified during the BAER assessment.

The process described above utilizes composite satellite imagery to generate percent cover from NDVI values. By factoring in percent soil cover, soil depth, and type of vegetation cover, land managers

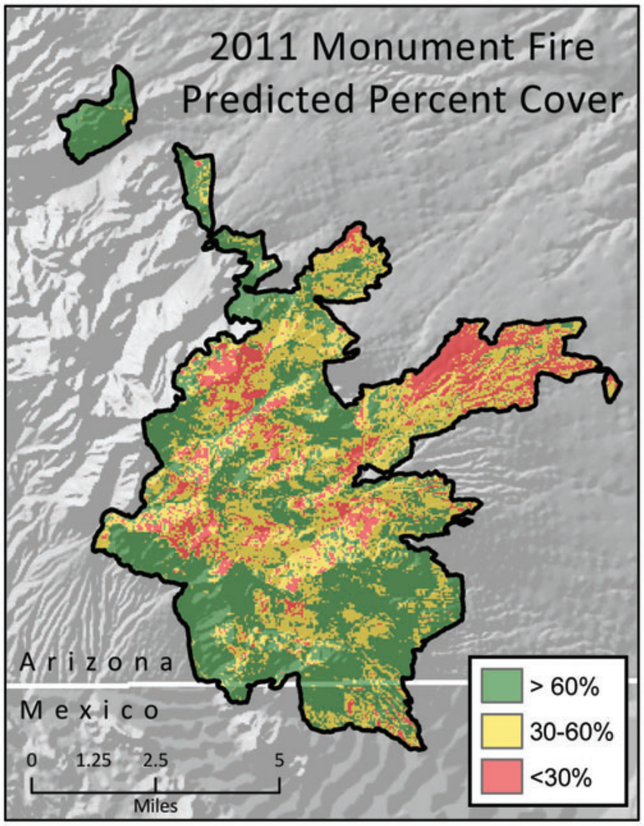

Figure 4—The Monument Fire burned near the town of Sierra Vista, Arizona, in June 2011. This map shows the predicted ground cover in three cover classes: 0-30% (red), 30-60% (yellow), and 60-100% (green).

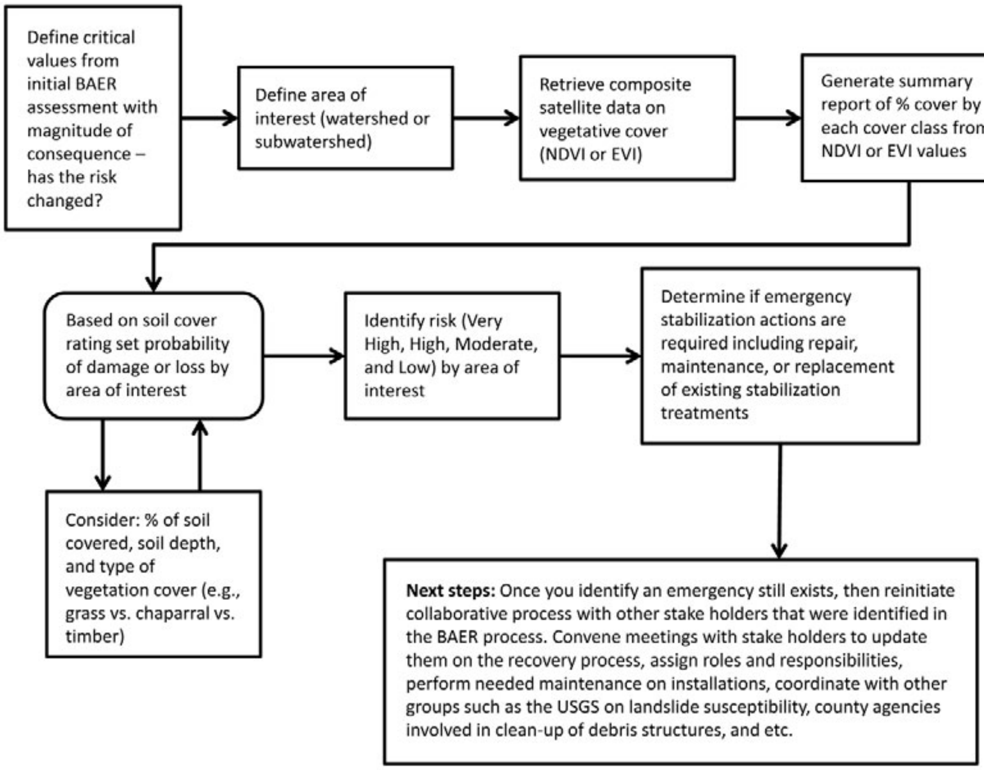

Figure 5—Flow chart for the decision support tool.

may identify potential risks at the watershed scale using departures from pre-fire conditions. Managers know that ≥60% cover typically reduces the potential for rill development and hillslope erosion (Noble 1965; Orr 1970; Robichaud and others 2010). Therefore, if the watershed has recovered to ≥60% cover, the associated risk of erosion in those areas drops to low or moderate, determinations which could trigger the removal of temporary protective treatments. If, however, the analysis shows < 60% cover then removal of treatments may increase the risk to high or very high. Determinations of high or very high might prompt management agencies to re-initiate a collaborative process with stake holders identified in the BAER process which might include the National Weather Service (NWS), government-based Offices of Emergency Services (OES), Natural Resources Conservation Service (NRCS), U.S. Geological Survey (USGS), local flood control districts, and private landowners.

Conclusions and Recommendatons

Our model appears to predict the post-fire recovery of ground cover well. We believe the cover class maps can be used in concert with our developed decision support tool, on-the-ground observations, and good communication between cooperating agencies to help land managers make better informed decisions regarding existing protective treatments and burned watersheds upslope. The cover class maps and decision support tool proposed in this project represent a step toward a more efficient monitoring approach as well as provide a standard and repeatable protocol for managers throughout the nation. Finally, we plan to strengthen the model by applying it to other fires to test its robustness.

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