Remote Sensing Fire Studies in the Greater Borderlands

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"The road forward is uphill and hard to march. But the higher the hill the finer the view."

—Anonymous

Forest fires place lives, property, and natural resources at risk. Yet fire appears to be a natural ally of a healthy forest and a critical element of sound ecosystem management. These conflicting views impede efforts to define the role of contemporary fire in Borderlands ecosystem management. Forest fires are inevitable, but the slow adoption of pro-fire policy is understandable: Fire behavior complexity and incomplete fuels maps promote uncertainty. Forest managers are unwilling to commit scarce resources to major prescribed burning campaigns without some knowledge of likely outcomes. It is therefore not surprising that a single prescribed burn can take years of planning. This essay surveys recent efforts in pyrogeography, a term introduced here to underscore the spatial complexity of fire, and the mapping mandate for effective fire management.

The geographic information system (GIS) provides the unifying geospatial framework within which to practice contemporary pyrogeography. Although there is no substitute for field work, remote sensing provides a key GIS data resource, enabling mapping at scales impossible purely from the field and required for ecosystem management. I highlight for the Southwestern Borderlands some contributions remote sensing and GIS have made to wildfire management at the ecosystem level. Following the Background, in which I lay out key assumptions and introduce terminology, I review contemporary approaches to fire severity sampling, classification, modeling, and the implications for future fire management in the Borderlands region. Specifically, I describe a strategy for automated sample design, then compare discrete and fuzzy classification of forest fire severity. The essay concludes with my view of "the road ahead" for fire mapping using next-generation remote sensors and modeling of surface fuels.

Background

There are spatial linkages among fire regimes, terrain, and associated fuel complexes. Fire effects and post-fire recovery are tied to firescape properties (fuel complex, topography) and regional climate. A firescape, as defined here, is the collection of fire habitats. The term "fire habitat", introduced here, is defined as the fuels complex, terrain, and fire history at a given site. The fire habitat concept acknowledges that before European settlement, fires were resident in forests. Commercial space-based remote sensing data and GIS techniques can enable exploratory mapping, modeling, and monitoring of fire habitats, but current results are preliminary.

An Orientation to Remote Sensors for Fire Mapping

Remote sensor data collected by the Landsat Thematic Mapper (TM) and the National Oceanic and Atmospheric Administration's Advanced Very High Resolution Radiometer (AVHRR) comprise two primary sources of data for modern wildfire studies. The TM data, which are multi-spectral and carry a nominal spatial resolution of 30 meters, may be used for landscape-scale fire patterns, effects, and recovery studies. The AVHRR data, also multi-spectral with a nominal spatial resolution of 1100 meters at nadir, could provide a broad-scale historical record of precipitation patterns. In addition to providing confirmation of site recovery, the AVHRR data can be used to detect large burn scars and thus monitor regions apparently susceptible to fire. A third data source, the Advanced Visible Infrared Imaging Spectrometer, supplies a rich hyperspectrum of data on the biophysical condition of vegetative fuels. Non-image GIS data, used to model potential fire behavior, include digital elevation models (DEMs), lightning incidence, and fire history data.

Theoretical Framework for Remote Sensing Studies

It is the correlation between the distinctive multi-spectral response patterns produced by similarly distinctive canopy expression that in theory justifies use of remotely sensed data to discriminate forest fuel species and structure. If we assume forest species and structure relate directly to fire behavior, we could claim remote sensing technology provides fire ecologists with spatial information about past and potential fire behavior, and then we could provide forest ecosystem managers data required to assist management decisions. This claim can only be supported partially at this time.

Multi-Spectral Remote Sensing

Multi-spectral remote sensing has been used to assess a variety of forest attributes. These attributes have included species composition, crown/canopy density, tree height, timber volume, forest stand health, and age.

Multi-spectral remote sensing of forest species and structure, and the extension of this technology to forest fuels, remains in fact an open area of research: In rugged areas, variances in spectral response patterns can be produced by topographic shading and by the unequal scattering of reflected light from forested landscapes. Superimposed upon the radiation "ecology" of the firescape are other complicating factors, including atmospheric conditions, pixel size, sunangle differences, and variations in understory material. Pixel size may not, for example, match the "scale of action" of fuels variability. A number of remote sensors have been used over the years for forest inventory and have included efforts to reduce this "noise." Despite the availability of multi-spectral data and results-driven processing techniques the USFS has, for reasons of scale and cost, generally continued to rely on human interpretation of airphotos to perform resource inventories. I wish to suggest here there are management-driven reasons to commit to space-based data and digital analysis methods.

Methods

Digital Image Processing Techniques for Fire Severity Sampling

Spatial patterns of wildfire disturbance are linked to the spatial configuration, or "poses" of terrain. In ecology, and in fire ecology specifically, it is desirable to identify the range and variability of factors that may affect the phenomenon in question. Experimental designs and sampling procedures in fire ecology should thus consider terrain variability and its potential relationship to fire behavior.

Terrain-Based Stratification

Digital image processing supplies effective techniques for analysis of complex fire terrain. These techniques carry the power to analyze large areas while providing spatial information at fine spatial scales and are suited particularly to the study of terrain. Terrain data are often stored in raster format, with each grid-cell representing a small area of the earth. Many digital image-processing techniques are also raster-based and can, therefore, be invoked on digital terrain data. Recent work in this area featured automated digital image processing techniques that stratify terrain into homogenous clusters of elevation, slope, and aspect. These stratifications were then used to guide location of sample plots in a classification of wildfire severity.

Discrete Classification of Fire Severity

The discrete classification model assumes uniform fire severity spans every mapped cell. The fuzzy classification model, discussed below, characterizes fire as a patchy, quasi-random process, representing more than one severity class in any one mapped cell. Remotely sensed images are able to capture the spatial variation of fire severity. Satellites such as the TM are able to record different spectral responses resulting from landscape features experiencing different fire severity.

Enhancing the Fire "Signature"

Information on fire severity can be extracted from the image by examining the signatures within certain portions of the electromagnetic spectrum. Briefly, fire will tend to produce lower spectral responses in the visible and near-infrared TM bands because of the removal of vegetation. In the two middle-infrared TM bands, fire tends to produce higher spectral signatures due to the reduction or removal of moisture from vegetation and soil. The TM spectral data can be transformed, enhancing resolution of fire severity. Two such enhancements, the principal components (PC) and Kauth-Thomas (KT) transforms, are weighted linear combinations of the original spectra that appear sensitive to fire-induced changes in chlorophyll and moisture.

The Principal Components (PC) Transform

The PC transform is used commonly to compress remotely sensed data by reducing redundancy among semi-correlated spectral bands. The first three components, for example, can account for 95 percent of the variance in a typical TM dataset. Transform coefficients are derived from the data and are, therefore, biased toward scene majority characteristics (in this case, unburned areas). Analysis of the factor-loading matrix is used to assign biophysical labels such as brightness and greenness to resulting components. A PC-based classification of fire severity from the July 1994 Rattlesnake Fire (Chiricahua Mountains) produced an overall accuracy of 62% for 3 severity classes.

The Kauth-Thomas (KT) Transform

The KT transform was developed in the 1970s using Landsat Multi-Spectral Scanner data for agricultural applications. Now adapted for the Landsat TM, the first three KT features, produced by the linear transformation of the original TM data, are brightness, greenness and wetness, respectively. Brightness is responsive to biophysical factors such as color and moisture, which affect soil reflectance. Greenness is a function of the amount of vegetation present. (This feature responds to the absorption of visible light and the reflectance of near infrared light.) Wetness is sensitive to the moisture content of soils and vegetation. Fire-induced decreases in vegetation and soil moistures produce changes in the middle infrared bands before and after fire. A KT-based classification of fire severity from the July 1994 Rattlesnake Fire (Chiricahua Mountains) produced an overall accuracy of 73% for 3 severity classes. A multi-temporal KT transform invoked on TM data of the 1996 Baker Canyon Fire (Peloncillo Mountains) produced fire severity map accuracies above 60%, some 10% below accuracies recorded for the Rattlesnake Fire. This disparity underscores performance differences that can be expected in heavily wooded conifer vs. soil-dominated shrubland communities: Background soil can mask the fire signal. It is easier to detect a fire "signature" when vegetation dominates and when spectral distinctions between burned vegetation and soils are large statistically.

A Rationale for KT vs. PC Performance Differences

The KT features outperformed the PC features because the KT features were independent of the post-fire TM scene. The KT wetness feature, for example, coupled directly to the relatively small percentage of "burned" pixels. The PC features were by contrast dependent; they were computed directly from pixels in the post-fire image. Since the majority of pixels were unburned, and the PC coefficients are weighted by the majority of pixels, the PC features appeared less sensitive than the KT features to burned areas.

Fuzzy Classification of Fire Severity

Traditional pattern recognition techniques rely on discrete classification, whereby pixels are assigned to single-label categories. Because of the continuous gradation of burn patterns, discrete classification likely over-simplifies the spatial complexity of wildfire. Accordingly, recent work on fire severity classification has led to fuzzy classification algorithms. Results from fuzzy classifications are intuitively appealing, but depend on the shape of the membership function and resist traditional means of accuracy assessment.

Multi-Dimensional Fuzzy Classification

Improvement in classification accuracy can be expected with more sophisticated multidimensional fuzzy classification algorithms. More sophisticated versions of fuzzy classification define membership functions based on the complete statistical distribution of all the bands of data sets taken together. Some approaches exploit the second order statistics of the training data (variance and covariance). These statistics are then used in a manner similar to a discrete classification. In fuzzy classification, though, the algorithm produces a fuzzy membership value for each pixel that reflects its relative probability of class membership in all categories based on all included data sets. Beyond fuzzy classifiers, another possibility is the application of neural networks.

Digital Terrain Data, Revisited

Whether discrete or fuzzy algorithms are used to classify fire severity, digital terrain data have been used to improve the accuracy of satellite derived fire-induced vegetation mortality classifications. Classification of a large wildfire in New Mexico, for example, showed that combining TM and terrain data provided approximately 40% improvement in accuracy over TM data alone.

The Road Forward

Regional fuel types, including grass, shrub, pine, and mixed conifer have canopies that are typically distinctive. We are thus capable, using current remote sensing technology, of classification accuracies near 80% for regional fuel types. Classifications at the species level usually run 10-15% below regional type classifications. But standing fuels tell only part of the story. Surface structure, including fuel bed properties, is among the least characterized properties of Borderlands or any forests, chiefly because structure is more or less obscured by canopy. This limitation has prompted: a) development of surface spatial models from spectral prediction of species and structural stage; b) spectral mixture modeling to identify spectra contributed by surface materials; and c) exploitation of the synergy of passive and active sensor systems to characterize sub-canopy structures, including surface components. The difficulty with spatial models is the uncertainty associated with databases, including insufficient spatial resolution and inexact or inadequate predictive power. The problems with spectral mixture modeling include: 1) the inability to identify truly pure endmembers; and 2) canopy masking of key endmember spectra. Although fusion of active (i.e., radar) and passive (e.g., TM) remote sensors is promising, there are at this time potential inconsistencies in radar cross sections extracted from rugged terrain.

Geospatial Information and Technology

As fire ecologists ponder what the new millenium will bring, one issue is clear: The Borderlands ecosystem is not more complex than we think; it is more complex than we *can* think. My view is that geospatial information and technology will become increasingly important as we begin to focus together on understanding and managing this fascinating region.