FINAL REPORT, JOINT FIRE SCIENCE PROGRAM AFP2-2003

Project Title: Assessing the Causes, Consequences and Spatial Variability of Burn Severity: A Rapid Response Proposal

JFSP Project Number: 03-2-1-02

Project Locations: We collected data on 4 fires in Montana on 2 national forests and private industrial forest lands, on 2 fires in southern California on one national forest and local government lands, and on 3 fires in interior Alaska on federal lands. Research analysis and interpretation were conducted at University of Idaho, Latah County, Moscow, ID, First Congressional District (Idaho); the Forestry Sciences Laboratory, Rocky Mountain Research Station, USDA Forest Service, Moscow, ID, First Congressional District (Idaho); and Fire Science Laboratory, Rocky Mountain Research Station, USDA Forest Service, Missoula, MT, First Congressional District (Montana).

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EXECUTIVE SUMMARY

The main goals of this rapid response research project were to identify quantitative indicators of burn severity that could be rapidly assessed on the ground and mapped remotely, and to explore alternative remote sensing tools to Landsat-derived NBR and dNBR indices. Nine wildfires in four different ecological and geographical regions were selected as study areas. Extensive vegetation and soils field data and satellite and airborne hyperspectral imagery were collected immediately after each fire, and field sites were revisited one year post-fire. We coordinated sampling, analysis, and publication of results with two other rapid response teams in order to more efficiently and effectively provide decision support for fire managers.

From the perspective of both field and remotely sensed measures, low proportions of green vegetation and high proportions of black charred vegetation and soil are perhaps the best indicators of high severity (in terms of vegetation response) in all systems. High proportions of green vegetation are the best indicators of low burn severity. However, we found that no one field indicator, class break or threshold for burn severity was applicable in all four ecosystems, ranging from Alaska to southern California. When mapping burn severity rapidly and remotely, there will likely always be an oversimplification of the natural variation – this may be a necessary and acceptable tradeoff for managers tasked with making time-sensitive decisions. Much of the variability in post-fire effects measured in the field occurred at fine scales, or less than the 30 m size of Landsat pixels. We found evidence that spectral mixture modeling of multispectral or hyperspectral imagery can produce useful estimates of char, ash, soil, litter, green vegetation cover fractions at subpixel scales. However, more research and development is required to

speed the more complex data processing and analysis required to facilitate applications for rapid response.

We were able to improve the scale and accuracy of mapping soil surface and understory features using post-fire hyperspectral imagery. The fire effects on the soil surface are highly indicative of potential post-fire watershed response. However, at present, for both logistical and financial reasons hyperspectral imagery is not highly feasible for rapid response. Landsat and NBR/dNBR, as long as they are available, seem to be the most practical current technologies for rapid remote mapping of fire effects. Local expertise and local threshold calibration should be applied whenever possible for improved mapping and for the prescription of post-fire rehabilitation treatments.

Comparison of results between this project and related rapid response projects funded by JFSP remains preliminary but is beginning to yield useful insights into the interactions between pre-fire fuels, active fire behavior, and post-fire effects. In Alaska, the deep fuel layer in the forest floor extends fire duration, while at the other end of the fire duration spectrum in California, fuel is nearly exclusive to the chaparral vegetation and burns quickly. Intermediate on the fire duration spectrum in western Montana, multitemporal thermal imagery was collected and definitively suggests that cumulative heat yield may be an important driver of burn severity. However, fire duration is difficult to measure using current research methods that revolve around field or remote data collected at only one or maybe two points in time. We recommend further strengthening cooperative relationships between research and active fire management personnel, to broaden the duration of measurements pre-fire, during the fire, and post-fire. Such research will in turn improve pre-fire fuel treatments, fire management, and post-fire rehabilitation.

Lastly, we were tasked to synthesize the state of the knowledge of existing and potential remote sensing tools and methodologies, including the results of this project, and to widely share what we have learned with land managers and others. We have accomplished this via 7 peer-reviewed publications with 4 more in review, 9 published proceedings from national meetings, 21 oral presentations at national meetings, 7 BAER and IMT training sessions, 2 RSAC workshops, and 8 poster presentations. These technology transfer products, including a spectral library, are available on our project website and linked to FRAMES.

SUMMARY OF FINDINGS

Quantitative indicators of burn severity from field and remote post-fire measurements

Our first objective was to develop and validate quantitative indicators of burn severity, including both overstory and soil surface effects, from field and remote post-fire measurements in a variety of sites (e.g. vegetation, topography, soils, parent material) and burning conditions. These quantitative indicators of burn severity that can be mapped in the field, and remotely from airplanes and satellites are needed to encompass fire effects on both the overstory and the soil surface across a broad range of site conditions. Indicators of burn severity, and thus potential ecosystem recovery, are used post-fire by planners tasked with strategically rehabilitating areas likely to recover slowly or in undesirable ways (Hudak et al. 2004b; Lentile et al. 2006b).

We measured or calculated fire effects at 418 plots, nested in 50 field sites, located across the full range of burn severities observed at the 2003 Black Mountain II, Cooney Ridge, Robert, and Wedge Canyon wildfires in western Montana, the 2003 Old and Simi wildfires in southern California, and the 2004 Porcupine, Chicken, and Wall Street wildfires in interior Alaska (Hudak et al. *in review*; Lentile et al. *in review,a*; Lewis et al. *in review*). We also report results from related analyses on the 2002 Hayman fire in Colorado (Lewis et al. 2007; Robichaud et al. 2007), and the 2000 Jasper fire in South Dakota (Smith et al. *in press*; Lentile et al. *in review,b*).

We generated the Normalized Burn Ratio (NBR), delta Normalized Burn Ratio (dNBR), Relative dNBR (RdNBR), Normalized Difference Vegetation Index (NDVI), and delta NDVI (dNDVI) burn severity indices from Landsat 5 Thematic Mapper (TM) imagery across these nine wildfires, and from SPOT imagery in Montana, MODIS, ASTER, and MASTER imagery in California, and Landsat 7 ETM+ imagery in Alaska (Hudak et al. 2004a; Hudak et al. 2004b; Hudak et al. 2006; Hudak et al. *in review*).

- Compared to other indices, the NBR correlated best with the fire effects we measured in the field, but insignificantly so—meaning other indices could act as suitable substitutes. The overstory (trees in Montana and Alaska, shrubs in California) measures appear to have more influence on the image variables, followed by understory and surface cover measures. The degree of exposed mineral soil and soil water repellency were poorly correlated with the image variables, while the abundance of green vegetation was highly correlated and therefore more readily interpreted from satellite imagery (Hudak et al. 2004b; Hudak et al. 2006; Hudak et al. *in review*).

- We recommend that BAER teams consider BARC products much more indicative of post-fire vegetation condition than soil condition and use caution when interpreting BARC maps as a measure of soil burn severity for prescribing post-fire soil rehabilitation treatments. Image acquisition date, in relation to time of field data collection and time since fire, appears to be more important than type of imagery or index used (Hudak et al. 2004a).

- We recommend that BAER teams use the continuous BARC-Adjustable (BARC-A) data product (and assign their own severity thresholds as needed) instead of the classified BARC product, which oversimplifies the highly heterogeneous nature of burn severity on the ground. Furthermore, preserving the raw NBR or dNBR values in an archived map product enables remote monitoring of post-fire vegetation recovery in subsequent post-fire years (Hudak et al. 2004a).

- We collected hyperspectral imagery across nine fires in 2003-2004 and used spectral mixture analysis (SMA) to estimate the abundance of green and nonphotosynthetic (senesced or charred) vegetation and litter, soil, and ash fractions directly from the imagery. The discrimination power of hyperspectral imagery allowed these postfire materials to be characterized within a 5-m pixel, so we can quantify their abundance on the ground. Quantifying ground cover characteristics, rather than classifying NBR values derived from satellite imagery, provided a better evaluation of the condition of the soil surface and its variation at the fine scales important to vegetation recovery and fire effects on the soil (Lewis et al. 2006a; Lewis et al. 2006b; Lewis et al. 2007; Lewis et al, *in review*).

- Compared to Landsat data which is currently used for postfire assessment, the additional information provided by fine-scale hyperspectral imagery makes it possible to more accurately assess the effects of the fire on the soil surface and to predict water repellent soil conditions which are indicative of potential hydrologic response. However, there is yet no standard protocol for processing hyperspectral imagery; processing is time consuming, especially because of the very large data sets that result from the high resolution and hyperspectral measures (Lewis et al. 2006a; Lewis et al. 2006b; Lewis et al. 2007; Lewis et al, *in review*).

- Immediate post-fire measurements of ground cover and water repellency indicated that ash cover, both measured on the ground and remotely, was the variable most significantly correlated to strong water repellency (as we found in the Hayman Fire). Greater than 49% ash cover measured on the ground and 33% detected in the remotely sensed image indicated strongly water repellent soil conditions. These results emphasize the potential of hyperspectral imagery for detecting or monitoring fine-scale soil conditions and surface attributes (Lewis et al. 2007).

- Vegetation response was examined following nine wildfires in four very different geographical regions. Immediately following fire, plant cover and species richness were low, while exposed soil, ash, and rock cover were high. For all fires, plant canopy cover and species richness remained low and were highly variable one year post-burn. We found a greater number of forbs when compared to other plant life forms, independent of burn severity. Plant cover was dominated by grasses in chaparral systems, forbs in mixed-conifer forests, and shrubs in boreal forests. Most species observed after the fires were present before the fires. On all sites, with the exception of burned sites in southern California, where one year post-burn vegetation was dominated by non-native grasses and forbs, vegetation recovery was dominated by native species (Lentile et al. 2006c; Lentile et al. *in review*).

Accuracy of dNBR and other remote measures of burn severity

Our second objective was to assess the accuracy of dNBR and other remote measures of burn severity across a range of fire severities. Multi-temporal remote sensing techniques have been effectively employed to assess and monitor landscape change in a rapid and cost-effective manner. Remotely sensed data give researchers a means to quantify patterns of variation in space and time. Remote sensing has great potential for studying fine-scale heterogeneity in fire effects across large areas, to understand causal relationships, to document rates of recovery, and to prioritize areas for fuels reduction and post-fire rehabilitation (Lentile et al. 2006b).

Burn severity indices calculated from pre- and post-fire multispectral imagery were differenced (i.e., dNBR) to highlight fire-induced changes in soil and vegetation (Hudak et al. 2004b; Hudak et al. 2006; Hudak et al. *in review*).Field fractional cover data were compared to the image pixel data used to produce Burned Area Reflectance Classification (BARC) maps (Hudak et al. 2004a; Hudak et al 2004b).

- Correlations between 32 fire effects we measured in the field and the eight image variables were highly variable when compared across the nine fires. No fire effects were consistently highly correlated to any of the image variables across all fires due to major vegetation differences from Alaska to California. The overstory measures of canopy closure, green and charred tree crowns in Montana and Alaska and green and charred shrubs in CA, were most highly correlated to the image variables, while understory measures had less influence. Litter depth was more highly correlated to the image variables than other surface or subsurface measures, which varied widely in correlation strength (Hudak et al. 2004b; Hudak et al. 2006; Hudak et al. *in review*).

- Green vegetation fraction was significantly and more highly correlated to NBR than to any of the other image band ratio indices in Montana ($r = 0.82$), California ($r = 0.63$), and Alaska ($r = 0.86$). Green vegetation fraction also correlated with 32 post-fire effects measured on the ground better than NBR or other image indices. Although the improvement over NBR was insignificant, green vegetation fraction (and other fractional cover variables) is a biophysical measure and more directly interpretable (Hudak et al. 2004b; Hudak et al. 2006; Hudak et al. *in review*).

- We compared and evaluated the applicability of immediate post-fire estimates of percentage char and vegetation fractions, in addition to ΔNBR derived from Landsat ETM+ imagery, to remotely assess 1-yr post-fire ecological effects following the 2000 Jasper fire in ponderosa pine forests of the South Dakota Black Hills. The measure of immediate char cover fraction either equaled or outperformed all other immediate measures in predicting 1-yr post-fire effects. Application of ΔNBR only provided a significant increase in regression performance for predicting percentage live tree when applied to 1-yr post fire imagery, as might be expected since the imagery better represents vegetation canopy condition measured during fieldwork. Fractional brown vegetation cover was a poor predictor of all effects ($r^2<0.30$) and each remote measure produced only poor predictions of crown scorch ($r^2<0.20$) (Smith et al. *in press*; Lentile et al. *in review,b*).

- In our analysis of the 2003 Simi and Old Fires in southern California, we have compared results from multispectral and hyperspectral imagery to see which product best indicates

fire-induced changes in soil and vegetation. Aerial and field hyperspectral data were also collected together with field ground cover measurements on portions of these two large wildfires. Spectral endmembers representing charred and uncharred soil and rock, and green, non-photosynthetic, and charred vegetation were used in a constrained linear spectral unmixing process to determine the post-fire fractional ground cover of each surface component. The spectral unmixing results, dNBR, and Relative dNBR (RdNBR) were validated using fractional ground cover estimates from the field to see which product best represented the conditions on the ground (Lewis et al. 2006a; Lewis et al. 2006b).

The spectral unmixing results were significantly correlated to all classes of charred and uncharred organics and inorganics, and the dNBR was the best indicator of charred soil and green vegetation. The RdNBR had several significant correlations with the ground data, yet did not consistently correlate well with any specific ground cover types. A map of post-wildfire ground cover and condition, especially soil and remaining vegetative cover, is a good indicator of the fire's effect on the ground surface and the resulting potential for hydrologic response (Lewis et al. 2006a; Lewis et al. 2006b).

- The fires sampled in southern California presented unique opportunities for exploring alternative methods for burn severity mapping. The chaparral vegetation on both fires was sparse pre-and post-fire, and the Old Fire burned in mixed chaparral and woodland vegetation types, creating conditions shown to be incompatible with the dNBR and RdNBR change indices. Overall, the results of the spectral mixture analysis were slightly better than the dNBR and RdNBR at mapping quantitative ground cover conditions rather than burn severity classes (Lewis et al. 2006a; Lewis et al. 2006b).

- Mixture Tuned Matched Filtering (MTMF), a partial spectral unmixing algorithm, was used to identify the spectral abundance of ash, soil, and scorched and green vegetation in the Hayman fire, Colorado (Robichaud, JFSP 01C-2-1-02). The overall performance of the MTMF for predicting the ground cover components was satisfactory (R^2 = 0.21 to 0.48) based on a comparison to fractional ash, soil, and vegetation cover measured on ground validation plots. The relationship between Landsat-derived differenced Normalized Burn Ratio (dNBR) values and the ground data was also evaluated (R^2 = 0.20 to 0.58) and found to be comparable to the MTMF (Lewis et al. 2007; Robichaud et al. 2007).

- The quantitative information provided by the fine-scale hyperspectral imagery makes it possible to more accurately assess the effects of the fire on the soil surface by identifying discrete ground cover characteristics. These surface effects, especially soil and ash cover and the lack of any remaining vegetative cover, relate to potential postfire watershed response processes, as runoff and soil erosion are directly related to the amount of exposed, disturbed soil after a fire (Lewis et al. 2006a; Lewis et al. 2006b; Lewis et al. 2007; Robichaud et al. 2007; Lewis et al. *in review*).

- The burn severity interpreted from dNBR varied among and within the nine fires sampled. Fire effects at the landscape scale were quite different in Alaska than in the other region. In the California and Montana fires, less than 5% of the area within the fire perimeter burned at high burn severity, while in Alaska more than 50% burned with high severity. In the California and Montana fires, from 14 to 43% of the landscape was unburned, while 7% of the Alaska fires were unburned. Patch sizes were significantly different in low, moderate, and high burn severity in individual fires and across all fires.

In general, unburned patches were the smallest in size. The mean size of low severity patches was consistent across all regions, while the mean size of moderate severity patches in Alaska was anomalously lower than in the other regions. Conversely, the mean size of high severity patches was much larger in Alaska than in the other two regions (Lentile et al. 2006c; Lentile et al. *in review*).

- The unusually high proportion of the high burn severity class in Alaska is not evidence that dNBR is an unsuitable metric in this region. These fires did burn with high severity effects across much of their area, and it is possible that the current threshold used to separate moderate from high burn severity should be different for Alaska. Whether absolute thresholds have utility across the widely different ecosystems sampled in this study, or the many other ecosystems to which they might be applied in North America and elsewhere, is debatable (Lentile et al. 2006c; Lentile et al. *in review*).

- The proportion, pattern and size of patches burned at different burn severities (as indicated by delta Normalized Burn Ratio, dNBR) were dissimilar across sites located in southern CA, western and northwestern MT, and in AK. As others have done, we suggest that dNBR is a reasonable, but imperfect indicator of both the immediate and one-year post-fire ecological effects (Lentile et al. 2006c; Lentile et al. *in review*).

- Our results show that the NBR and dNBR burn severity indices, as currently used in BARC maps of large wildfires in the United States, are sound choices for rapid, preliminary assessment of immediate post-fire burn severity across different ecosystems. We recommend that RSAC and EROS continue their current practice of archiving the continuous NBR and dNBR layers upon which BARC maps are based, for future retrospective studies. The correlations of NDVI and dNDVI to the same suite of 32 fire effects measures generally were not significantly different, so these indices could serve as suitable substitutes for NBR and dNBR (Hudak et al. 2004a; Hudak et al. 2006; Hudak et al. *in review*).

Spatial variation in burn severity from field and remotely post-fire measures

Our third objective was to quantify spatial variability in burn severity (both in the field and remotely) in terms of tree mortality and other overstory effects, soil surface effects, and combined effects, across a range of fuel and site conditions. Burn severity varies greatly at fine scales, but the causes and consequences of that spatial variability in terms of post-fire effects are poorly understood. Recent developments in remote sensing and vegetation pattern analysis allow the evaluation of variation in burn severity (e.g. patch sizes and interspersion), which influences subsequent vegetation recovery (Lentile et al. 2006b).

We used remote sensing and geographic information systems (GIS) tools to characterize and compare the patch characteristics of stand-replacing harvest and fire disturbance processes in a coniferous forest landscape where both disturbances were known to have recently occurred. The degree to which prior timber harvest and other vegetation conditions have influenced fire effects across landscapes is little understood, yet has tremendous implications for the efficacy of fuels management designed to moderate fire effects (Hudak et al. 2007).

- Analysis of fire effects data from two western MT fires indicated that most field variables, with the notable exception of ash, tended to vary more at low and moderate burn severity sites than at high burn severity sites. Semivariograms of the field variables revealed spatial autocorrelation across the fine spatial scales sampled (2 – 130 m), which the 20 m or 30 m resolution satellite imagery only weakly detected (Hudak et al. 2004b).

- Fire effects on the soil surface may vary at finer scales than fire effects on the tree overstory. In general, high severity burn sites had significantly more exposed soil/rock and less surface organic matter on the surface than less severely burned sites. Thus, even within areas with relatively uniform fire effects on the overstory (e.g. across a site we classified as moderate severity) the highly variable post-burn soil surface likely contributes to the high variation in vegetation response (Hudak et al. *in review*; Lentile et al. *in review*).

- Based on a geostatistical analysis, spatial autocorrelation between ash cover and water repellency field measurements were found to exist on the scale of 15 to 40 m, which allowed for additional predictions between and beyond field plot locations. Remotely sensed ash cover was used as a continuous variable across the entire Hayman Fire to map patches of ash with at least 33% cover including areas within 15 m of these patches. The significant correlation between ash cover and soil water repellency allowed for mapping highly water repellent soil conditions (Lewis et al. 2007; Robichaud et al. 2007).

- These results, combined with other information typically available in a post-fire situation, such as a map of burn severity, soil characteristics, and slope, increase the ability to examine the potential for post-fire runoff and erosion than previously possible (Lewis et al. 2007; Robichaud et al. 2007). Although ash appeared to be an important correlate with soil water repellency at the Hayman Fire, we have not found significant ash cover on other sites (and soil types), and thus we are looking for different field indicators (e.g., char) that can be identified in the remotely sensed imagery. We found some degree of soil water repellency on the fires we sampled in MT and CA, but the absence of prevalent ash on our sites prevented us from measuring strong correlations between the variables.

Influences of fuel, topography and weather on fire behavior and effects

Our fourth objective was to model how spatial variation in fuel, topography and weather influences fire behavior across a variety of fire-adapted ecosystems. Linking ecological effects of fires with fire behavior and fuels requires data that can only be collected during and soon after ongoing wildland fires. These data provide an improved understanding of the role of fire in creating conditions that drive post-fire ecosystem processes, structures, and functions (Lentile et al. 2007a; Lentile et al. 2007b).

In addition to the sampling described above for all fires, we coordinated with Hardy (JFSP 03-S-01) and Ottmar (JFSP 03-1-3-08) to collect data before, during, and after fire events on the same field sites in one fire in MT and one fire in AK. Small crews of research technicians were sent into areas before they burned to collect pre-fire measurements of soil, fuels, and vegetation condition and to install fire-proofed video systems and instrumentation for measuring heat flux, fire behavior, and local weather. We subsequently sampled fire effects on these same points immediately and one year after the fire (Lentile et al. 2007a; Lentile et al. 2007b; Hudak et al. *in prep*).

- Variation among sites, fine-scale variability in post-fire effects on soils, and diversity of prefire vegetation likely explain the high variation observed in post-fire vegetation responses across burn severity in the nine fires we sampled. On most low and moderate burn severity sites, >30% of the soil surface was covered with organic material immediately post-fire, and one year later, the canopy cover of understory vegetation averaged 10% or more, suggesting low risk to post-fire erosion (Lentile et al. *in review*).

- Fire may result in very different ecological responses depending on location (climate and topography), pre-fire vegetation and spatial patterns. The term *burn severity* can be misleading given that vegetation response is rapid even in large, severely burned patches in ecosystems where such fires were characteristic and vegetation is well adapted to such fires (Lentile et al. 2006b). Vegetation response was rapid in all ecosystems that we sampled, and post-fire vegetation cover and species richness was highest in the moist forests of northwestern Montana relative to wildfires burned in the other three ecosystems (Lentile et al. 2006c; Lentile et al. *in review*).

- Most of the areas mapped as severely burned in our analysis of the Cooney Ridge fire, MT were on steep, upper slopes adjacent to and above clearcuts (stand-replacing harvests). Extremely low fuel moistures in the exposed slash remaining in clearcuts downslope and upwind of standing timber can contribute to fire ignition and/or fast fire spread into the valuable standing timber (Hudak et al. 2007).

- In Montana, a thermal image (FireMapper) active fire snapshot collected by Hardy, Riggan, and others (JFSP 03-S-01) was useful for mapping our discrete post-fire measures of exposed mineral soil across an entire hillslope, using universal kriging with the active fire image serving as an auxiliary variable. We are prepared to expand upon this preliminary result once we have the entire time series of thermal imagery processed into a cumulative map of heat yield, as measured by both the airborne FireMapper sensor (Riggan) and an oblique-viewing thermal IR camera recording the active fire behavior from across the drainage (Hardy). In summary, this should allow more comprehensive and robust analysis of the spatial and temporal variability in both active fire

characteristics and post-fire effects, and their relationship as described using both statistical and geostatistical models.

- We are leading analyses in Alaska to compare pre- and post-fire measures of fuel moisture, moss, surface material, and duff depth, and forest floor consumption collected by Ottmar, Cronan, and others (JFSP 03-1-3-08), with our measures of post-fire effects (Hudak et al. *in prep*). All nine of these coincident field sites occurred in high or moderate burn severities. We added pre-fire measurements collected by Mathews and Hood (JFSP 03-S-01) at six additional sites coincident with our own, including two at the lower end of the burn severity gradient. Preliminary results indicate that fuel load as indicated mainly by pre-fire forest floor depth is directly correlated with post-fire % organic cover fraction (moss, litter, downed woody debris, duff, etc.), and inversely correlated with post-fire % inorganic cover fraction (exposed soil and rock). Pre-fire fuel indicators do not correlate as well with post-fire char or ash cover fractions. Duff depth appears to be a better pre-fire indicator of burn severity than duff fuel moisture. We will also consider active fire information (e.g., flame heights) that can be quantified from videos collected by Huffman (JFSP 03-1-3-08). In summary, this should provide more comprehensive and robust results at the massive Taylor Fire Complex in Alaska (Porcupine, Chicken, and Wall Street fires), where three rapid response research teams funded by JFSP worked together to better understand the linkages between pre-fire, active fire, and post-fire characteristics (Hudak et al. *in prep*).

- We are in the process of analyzing our post-fire effects data with the weather and fuel conditions at each of our sites (Morgan et al. *in prep*). In many cases, detailed weather information was unavailable, but we are working with weather information from adjacent RAWS (remote area weather stations). Where our partners were unable to collect these fire weather data, we may opt to substitute available weather, recorded at the nearest location to the fire perimeter. Fires burn 24 hours each day with certain behaviors more commonly associated with specific time periods. The sensitivity of fire behavior to immediate weather conditions, particularly localized winds and relative humidity, is such that fire managers are mandated to base fire planning on “spot” weather forecasts created by the National Weather Service for a specific time and location; fire managers who have used off-site or untimely weather forecasts have been subjected to disciplinary action. Firefighters are mandated to collect weather data at their own locations on the fireline throughout their shifts, usually doing so at least hourly and often more frequently. We will use these “spot forecasts” and local weather recordings when available. Thus, where our partners were unable to sample or these spot forecasts are unavailable, our weather data may not accurately represent the accumulation of fire behaviors and effects that occur over each 24-hour burning period in the forest (Morgan et al. *in prep*).

Efficient sampling and remote sensing methods for rapid assessment of fire effects

Our fifth objective was to identify and widely share efficient sampling and remote sensing methods for rapid assessment of fire effects to assist strategic fire management before (e.g., fuels management) during and after (e.g., rehabilitation) wildfires. We shared data, expertise, personnel, and results among several ongoing research projects to facilitate interpretation and utility of the results to land managers and others.

We collected field-based and remotely sensed data on post-fire effects from nine large fires that burned in 2003 and 2004. On two of these fires, we collaborated with teams led by Colin Hardy and Phil Riggan (JFSP 03-S-01) to characterize pre-fire fuels and vegetation and to explore alternative image acquisition and analysis methods for remote sensing of burn severity. Hardy and Riggan's rapid response projects were designed to collect heat flux and other fire behavior information at several fires, and we subsequently collected fire effects information in 2003 at the same experimental site at the Cooney Ridge fire.

- We participated in two database design workshops held in July 2003 and March 2004 to coordinate data sharing between our rapid response project and others, including Hardy et al. (JFSP 03-S-01) and Finney et al. (JFSP 03-2-1-04). As a component of this research, a common geodatabase was assembled to facilitate data sharing and analysis (http://firecenter.cfc.umt.edu/RapidResponse).

- Our project is also closely linked with three ongoing research projects focused on burn severity and remote sensing. Terrie Jain and others are quantifying burn severity as a function of pre-wildfire forest structures for many 2000, 2001 and 2002 wildfires. We have collaborated with Jain to disseminate information to BAER teams, at two professional conferences, and via two manuscripts in preparation.

- Pete Robichaud, Sarah Lewis, and others have explored the utility of hyperspectral imagery for evaluating post-fire erosion potential on the Hayman Fire (Lewis et al. 2007; Robichaud et al. 2007) and we are applying these same techniques and methodologies on the nine fires that we sampled.

- For the nine fires sampled in this project, it took ~2 years to obtain the hyperspectral data that was collected shortly after each fire. We also learned that these data often require significant rectification and pre-processing before analysis can begin. We learned the benefits of collecting spatial coordinates of prominent ground features to assist in image rectification.

- Hyperspectral data show promise, but logistical challenges associated with acquisition, pre-processing, and rectification may limit their utility for time-sensitive decision support, such as that needed by most BAER teams (Lewis et al. 2006a; Lewis et al. 2006b; Lewis et al. 2007; Lewis et al. *in review*).

- We have also collaborated with Carl Key, Nate Benson and others to synthesize the state of the knowledge of existing and potential remote sensing tools and methodologies for mapping post-burn severity (Lentile et al. 2006a; Lentile et al. 2006b). Results from the data we collected across four broad ecological regions support the assertions made by Key and others that Landsat data and NBR and dNBR burn severity indices are sound

choices for rapid, preliminary assessment of immediate post-fire burn severity (Hudak et al. *in review*).

- Based on our findings, we recommend that the Monitoring Trends in Burn Severity project should consider extending their historical scope and apply NDVI or dNDVI to map burn severity on fires preceding the availability of Landsat TM imagery, or from the 1972-84 Landsat Multispectral Scanner (MSS) image record, since MSS images lack the SWIR band needed to calculate NBR. The RdNBR only produced better correlations to fire effects at one of the nine wildfires sampled; thus, its broad-scale utility may be more limited (Hudak et al. *in review*).

- During the summer of 2004 in Alaska, we collaborated with teams led by Roger Ottmar (JFSP 03-1-3-08) and David Sandberg of the USDA Forest Service, and teams from Colorado State University and Yale University to jointly sample and characterize fuels, vegetation, fire consumption, and smoke production from the same sample points before, during, and after fires (Hudak et al. *in prep*).

- We have organized two panel discussions, attended many fire manager meetings, and produced three publications highlighting the values and challenges of conducting rapid response research on wildland fires (Lentile et al. 2006a; Lentile et al. 2007a; Lentile et al. 2007b). In these three publications, we have provided recommendations to scientists for conducting safer and less obtrusive research and improved extension techniques. We have also integrated manager feedback on rapid response and recommendations for research needs. In summary, we have offered the following recommendations for consideration by any research team:

    - Be aware that the Incident Management Team's primary responsibility is to manage the fire safely and not to support research.
    - Be prepared when arriving at fire camp. Do not depend on the fire organization to provide the necessary equipment or data.
    - Have a current red card and demonstrate the knowledge and language of safe operations.
    - Develop and follow an operations plan.
    - Use a liaison to bridge the communication gap between the research and fire management teams. An effective liaison helps research teams fit into the fire management system and allows research team leaders to focus on ongoing and time-sensitive research with full confidence that the operations side is under control.
    - Build relationships by communicating early and often with fire managers. Careful pre-work before the fire season and coordination with the local land management unit is essential.
    - Share what was learned. Rapid Response Research can provide valuable information, but it must be communicated. Technology transfer should be synonymous with a good communications plan
    - Work together to take advantage of research opportunities, as appropriate.
    - Rapid Response team leaders must acknowledge that they likely will have limited control over where and when their crews can sample during actively burning fires. Research teams that focus on strategic operations and preseason organization are more likely to integrate and effectively coordinate with fire management teams.

DELIVERABLES

All proposed products are complete, unless stated otherwise as ***in review*** or ***in prep*** at the end of the citation. A hardcopy of each publication and an electronic copy (on CD-ROM) are enclosed.

Proposed	***Delivered/Status***
Annual progress reports Oral progress report RJVA Final reports	Progress reports were completed each year from 2003 through 2006. Oral progress report and two project posters presented at the JFSP PI Meeting, Nov. 2005, San Diego, CA. Annual reports for RJVA between USDA Forest Service and University of Idaho. Final report Assessing the Causes, Consequences and Spatial Variability of Burn Severity: A Rapid Response Proposal (03-2-1-02) Final report from a pilot study Evaluating High Resolution Hyperspectral Images for Determining Postfire Burn Severity (01C-2-1-02)
We proposed to collect fire behavior, fire effects and fuels data from two 2003 and four 2004 wildfires across the US.	We have field and remotely sensed data on six 2003 and three 2004 fires: Detailed sampling of burn severity immediately post-fire and one year later on the Porcupine, Chicken, Wall Street (in AK, 2004-2005), Roberts, Wedge, Cooney Ridge, Black Mountain (in MT, 2003-2004), Simi and Old (in CA, 2003-2004) and Flannigan (ID, 2003-2004) fires. Besides Landsat 5 on all fires, we also obtained postfire SPOT imagery on all of the MT fires, ASTER on the Old Fire (CA), MASTER on the Simi Fire (CA), MODIS on both CA fires, and Landsat 7 on the AK fires. We collected hyperspectral data on portions of all fires—we did not collect lidar on any fires. We collaborated with Phil Riggan and Colin Hardy's teams at the Cooney Ridge Fire, MT, collecting post-fire field measurements to complement their real-time thermal and IR imagery collected as the site burned. We have extensive pre-burn data from Roger Ottmar and Jim Cronan on the 2004

	Alaska fires—we sampled the same sites they did on most of our sites in Alaska. The only pre-burn data we have from our collaborators are the pre-fire fuels measurements that Sharon Hood and Helen Smith made. Pre-fire data was also collected by Ed Mathews and Sharon Hood in Alaska. We presented a preliminary result correlating a field-based fractional cover map of soil to one thermal image snapshot at the 2005 JFSP meeting. This analysis is on hold until Hardy/Riggan's group produces a map of cumulative radiative heat flux across the entire duration of the experiment. We have stand-level fuels data from the three national Forests we sampled (Lolo, Flathead, and San Bernardino).
Project website	http://www.cnrhome.uidaho.edu/burnseverity also linked at FRAMES: http://frames.nbii.gov
Four different manuscripts will be submitted to refereed journals. • In one, we will review burn severity concepts and measures, the degree to which these are linked to fire behavior and fuels, and quantitative indicators of burn severity that can be rapidly assessed in the field and mapped remotely.	Publications have been produced in several formats for each of the topic areas: • Lentile LB, Holden ZA, Smith AMS, Falkowski MJ, Hudak AT, Morgan P, Lewis SA, Gessler PE, Benson NC. 2006. Remote sensing techniques to assess active fire characteristics and post-fire effects. *International Journal of Wildland Fire* 15: 319-345. • Smith AMS, Lentile LB, Hudak AT, Morgan P. 2007. Evaluation of linear spectral unmixing and dNBR for predicting post-fire recovery in a North American ponderosa pine forest. *International Journal of Remote Sensing* ***in press***. • Smith, A.M.S., L.B. Lentile and A.T. Hudak. (2006) Potential of char fraction maps for evaluating burned area and post-fire effects: Bridging the immediate to long-term divide. 3rd International Fire Ecology and Management Congress Proceedings, CD-ROM, 3 p. • Lentile, L.B., P. Morgan, M. J. Bobbitt, S.A. Lewis, A.T. Hudak and P.R. Robichaud. (2006) Fire effects on vegetation recovery following eight large western wildfires. 3rd International Fire Ecology and Management Congress Proceedings, CD-ROM, 3 p. • Lentile LB, Morgan P, Hudak AT, Bobbitt MJ, Lewis SA, Smith AMS,

	Robichaud PR. Post-fire burn severity and vegetation response following eight large wildfires across the western US. *Fire Ecology* ***in review.*** • Lentile LB, Smith AMS, Hudak AT, Morgan P, Bobbitt MJ. Remote sensing for prediction of 1-year post-fire ecosystem condition**.** *International Journal of Wildland Fire* ***in review*****.**
• In a second paper, we will present the accuracy assessment of dNBR and alternative analyses of Landsat data.	• Hudak, A, Evans J, Robichaud P, Clark J, Lannom K, Morgan P, Stone C. 2004. Field validation of burned area remote classification (BARC) products for the purpose of rapid response. USFS Remote Sensing Workshop, Salt Lake City, UT, 5-9 April 2004. 13 p., CD-ROM. • Hudak A, Robichaud P, Jain T, Morgan P, Stone C, Clark J. 2004. The relationship of field burn severity measures to satellite-derived burned area reflectance classification (BARC) maps. Proceedings, ASPRS Annual Meeting. • Lewis SA, Hudak AT, Robichaud PR, Lentile LB, Morgan P, and Bobbitt MJ. 2006. Post-wildfire ground cover mapping by spectral unmixing of hyperspectral data. Proceedings of the 11th Biennial USDA Forest Service RSAC, Salt Lake City, Utah, 24-28 April 2006. • Lewis, S.A., A.T. Hudak, P.R. Robichaud, L.B. Lentile, P. Morgan and M. Bobbitt. (2006) Mapping post-wildfire ground cover after two 2003 California wildfires. 3rd International Fire Ecology and Management Congress Proceedings, CD-ROM, 3 p. • Hudak, A.T., S. Lewis, P. Robichaud, P. Morgan, M. Bobbitt, L. Lentile, A. Smith, Z. Holden, J. Clark and R. McKinley. (2006) Sensitivity of Landsat image-derived burn severity indices to immediate post-fire effects. 3rd International Fire Ecology and Management Congress Proceedings, CD-ROM, 3 p. http://treesearch.fs.fed.us/pubs/26200 • Hudak AT, Morgan P, Bobbitt MJ, Smith AMS, Lewis SA, Lentile LB, Robichaud PR, Clark JT, McKinley RA. The relationship of multispectral satellite imagery to immediate fire effects. *Fire Ecology* ***in review.*** • Lewis SA, Lentile LB, Hudak AT, Robichaud PR, Morgan P, Bobbitt MJ. Mapping post-wildfire ground cover after the 2003 Simi and Old wildfires in southern California. *Fire Ecology* ***in review.***

• In a third, we will evaluate the agreement between spatial variability of vegetation, heat flux, fuels and fuels consumption, topography, burn severity and satellite images. • In a fourth, we will assess the degree to which post-burn effects are correlated with and predictable from fire behavior, preburn forest structure, terrain and weather.	• Robichaud, P.R., Lewis, S.A., Laes, D.Y.M., Hudak, A.T., Kokaly, R.F., and Zamudio, J.A. 2007. Postfire soil burn severity mapping with hyperspectral image unmixing. *Remote Sensing of Environment* 108: 467-480. • Lewis SA, Robichaud PR, Frazier BE, Wu JQ, Laes DYM. 2007. Using hyperspectral imagery to predict post-wildfire soil water repellency. *Geomorphology*, doi:10.1016/j.geomorph.2007.06.002. • Morgan P, Hudak AT, Lentile LB, Lewis SA, Robichaud PR. Relationship between pre-fire forest structure, topography, and weather and burn severity following the Cooney Ridge, Black Mountain II, and Fish Creek Fires, MT, 2003, ***in prep***. • Stone C, Hudak A, Morgan P. 2004. Forest harvest can increase subsequent forest fire severity. In: International Symposium on Fire Economics, Policy & Planning: A Global Vision, Spain, April 2004. • Hudak, AT, Morgan P, Bobbitt M, Lentile LB. 2007. Characterizing stand-replacing harvest and fire disturbance patches in a forested landscape: A case study from Cooney Ridge, Montana. In: Ch. 8; *Understanding Forest Disturbance and Spatial Patterns: Remote Sensing and GIS Approaches* (M.A. Wulder and S.E. Franklin, eds.), Taylor & Francis, London, 246 p. • Hudak, AT, Lentile LB, Morgan P, Lewis SA, Robichaud, PR, Ottmar R, Sandberg D, Cronan J, Hood S, Hardy C. Relating post-fire effects to pre-fire conditions across a range of burn severities in Alaska. *International Journal of Wildland Fire*, ***in prep***.
Spectral library available online	Available on http://frames.nbii.gov
Technology transfer was an integral part of our project. • We presented results, solicited feedback and provided recommendations at BAER trainings, Fire Use, and Incident Commander Meetings. During the past 4 years, over 350 BAER and other fire personnel were educated about our latest findings at meetings across the country.	• Robichaud PR. 2005. BAER: New information, latest methods, what's effective, where? Region 4 Soil Science Meeting, 25-27 May 2005, Grangeville, ID. • Robichaud PR, Hudak AT. 2006. BARC-burn severity evaluation—relationship of NBR and dNBR to surface organic, soil, and vegetation cover. Joint Department of Interior-Department of Agriculture-Forest Service Burned Area Emergency Response Meeting, 31 January – 2 February 2006, San Diego,

	CA. • Robichaud PR. Latest findings on the effectiveness of various postfire rehabilitation treatments. DOI Interagency BAER Pre-season Meeting, 9-14 April 2006, Las Vegas, NV. • Robichaud PR. Remote sensing of burn severity using hyperspectral imagery. Presented at the National BAER Coordinator's Meeting, 29 Jan-1 Feb 2007, Spokane, WA. • Robichaud PR. 2006. Latest findings on effectiveness of various postfire rehabilitation treatments. BAER Refresher Workshop, 6-8 June 2006, La Grande, OR. • Jain TB, Pilliod D, Graham R, Evans J, Seavy N, Lentile LB, Alexander J. 2006. Soil Burn Severity Within the Fire-Disturbance Continuum. Rocky Mountain Regional BAER Team Meeting, January 2006. Fort Collins, CO and Region 3, Southwestern Regional Meeting, Watershed and Soils Session, March 2006, Albuquerque, NM. • Coordinated with Hardy (JFSP 03-S-01) and Butler (JFSP 03-2-1-03) to present rapid response project objectives, protocols, and results in an oral session and two posters at the Northern Rockies Geographic Area Incident Management Team Meeting in Missoula, MT, 10-12 April 2006. • We have had several “exchanges” with Henry Shovic, BAER team leader. In 2004, we held a two day “workshop”(including seminar and round-table discussion) with students, researchers and Henry Shovic to discuss BAER team needs, research direction, and collaborative opportunities. • Lentile LB, Holden ZA, Smith AMS, Falkowski MJ, Hudak AT, Morgan P, Gessler PE and Benson NC (2006) Challenges and Recommendations for the Mapping of Active Fire and Post-fire Effects. Proceedings of the 11th Biennial USDA Forest Service RSAC, Salt Lake City, Utah, 24-28 April 2006. • Lentile LB, Morgan P, Hardy C, Hudak A, Means R, Ottmar R, Robichaud P, Sutherland E, Way F, Lewis S. 2007. The Value of Rapid Response Research to Wildland Fire Management. *Fire Management Today* 67 (1): 24-31. • Lentile LB, Morgan P, Hardy C, Hudak A, Means R, Ottmar R, Robichaud P, Sutherland E, Szymoniak J, Way F, Fites-Kaufman J, Lewis S, Mathews E, Shovic H, Ryan K. 2000. Value and Challenges of Conducting Rapid Response

	Research on Wildland Fires. USDA Forest Service General Technical Report. GTR 193. Fort Collins, CO, 16 p. • Organized RRR panel discussion at JFSP PI workshop, San Diego, Dec. 2005, invited three managers and five scientists to share their perspectives on RRR
• Where our field assessment and remote sensing procedures were an improvement on existing protocols, we provided them to FIREMON	• Nothing to report. While our field protocols were suited for our research objectives, they are not suited for the more general needs of FIREMON.
• We worked closely with RSAC personnel to improve their procedures for mapping fire effects	• We held the "Improved Procedures for Mapping Fire Effects" break-out session at the BARC mapping workshop, USFS Remote Sensing Applications Conference, Salt Lake City, UT, 5-9 April 2004. • We continued collaborative work with RSAC doing hyperspectral image analysis after the conclusion of a pilot study (Robichaud, JFSP 01C-2-1-02) via direct contracts with RSAC personnel. • We organized a panel discussion with six invited managers "Recommendations and Research Needs for the Mapping of Active Fire and Post-fire Effects". 11th Biennial USDA Forest Service RSAC, Salt Lake City, Utah, 24-28 April 2006.
• We organized two workshops	• We participated in two database design workshops held in July 2003 and March 2004 to coordinate data sharing between our rapid response project and others, including Hardy et al. (JFSP 03-S-01) and Finney et al. (JFSP 03-2-1-04).
• We organized two special sessions on burn severity mapping and presented results via oral papers and/or posters at 15 national, professional conferences.	• Lentile LB, Lewis SA, Morgan P, Robichaud P, Hudak A, Stone C, Ryan K, Mathews E, Hood S, and Smith H (2004). Rapid Response Research: Lessons from Assessing Burn Severity on Active Wildfires. Mixed Severity Fire Regimes: Fire Ecology & Management Congress, 17-19 Nov. 2004, Spokane, WA. (participation and poster presentation) • L. Lentile, S. Lewis, A. Hudak, P. Morgan, P. Robichaud, C. Stone, and K. Ryan (2004). Consequences and Spatial Variability of Burn Severity for Four 2003 Montana Wildfires. Mixed Severity Fire Regimes: Fire Ecology &

	Management Congress, 17-19 Nov. 2004, Spokane, WA. (participation and poster presentation) ***Above posters also presented at the Tri-State Society of American Foresters 13-15 April 2005, Lewiston, ID, and at the Association of American Geographers Annual Meeting, Denver, Colorado, 5-9 Apr 2005.* • Hudak, A., S. Lewis, P. Robichaud, L. Lentile and P. Morgan. Relationships between field and remotely sensed indicators of burn severity. In: Geosystems, Ecosystems, and Wildfires: Remote Sensing and Geospatial Approaches to Wildfire Hazards and Effects, Special Session at the Association of American Geographers Annual Meeting, Denver, Colorado, 5-9 Apr 2005. (oral presentation, published abstract). • Lewis SA, Robichaud PR, Hudak AT, Laes DYM, Lentile LB, Morgan P. 2004 Comparing remotely sensed burn severity with fire-induced soil water repellency. In: Geosystems, Ecosystems, and Wildfires: Soil Factors and Time, Special Session at the Association of American Geographers Annual Meeting, Denver, Colorado, 5-9 Apr 2005. (oral presentation, published abstract). • Lentile LB, Lewis SA, Robichaud PR, Morgan P, Hudak AT, Smith FW, Shepperd WD. Fire Effects and Recovery Following Mixed Severity Fire in Ponderosa Pine Forests of the South Dakota Black Hills and Colorado Front Range. In: Geosystems, Ecosystems, and Wildfires: Biotic Effects and Responses, Special Session at the Association of American Geographers Annual Meeting, Denver, Colorado, 5-9 Apr 2005. (oral presentation, published abstract). • Smith AMS, Chair, Special Session on Mapping Burn Severity, 10 presenters, RSAC 2006. • Smith AMS, Lentile LB, Holden ZA, Falkowski M, Hudak AT, Morgan P, Gessler P, Benson N. 2006. Remote Sensing Techniques to Assess Active Fire and Postfire Effects: Clarification of Terminology. (oral paper) • Special session on burn severity mapping at the International Fire Ecology and Management Congress in 2006 organized by Thode, Hudak and others; papers currently in review for a special issue of *Fire Ecology*. • Robichaud PR, Lewis SA, Laes DYM. 2004. Evaluating hyperspectral images for burn severity classification and water repellent conditions. US Geological

	Survey, Collaborative Investigation of Wildfire, 18-26 June 2004. Boulder, CO. • Robichaud PR. 2005. Influence of fire induced water repellency on runoff and erosion. European Geoscience Union General Assembly, 24-29 April 2005, Vienna, Austria. • Robichaud PR. 2005. Tools, treatment effectiveness: what managers need to know. BC Ministry of Forestry and Okanagan University, 7-9 June 2005, Okanagan University, Kelowna, BC. • Robichaud PR. Postfire treatment effectiveness—the latest findings. Department of Agriculture, Forest Service, Region 3, Watershed, Soil, and Air Regional Meeting, 22-24 February 2006, Albuquerque, NM. • Robichaud, PR. Postfire burn severity. Technical Fire Management (TFM-21) Fire Ecology Module, 1-14 May 2006 and 7-18 May 2007, Washington Institute, Bothel, Washington, participation and oral presentation. • Robichaud, PR. New tools to assess post-fire water repellent soil conditions. Bouyoucos Conference "On the Origin of Water Repellency in Soils", 29 Apr-3 May 2007, Sanibel Island, FL, participation, oral presentation.
• Our data will be shared with local land managers for each site and the general public.	• In hindsight, it was beyond the scope of what we could do. Because we collected data on 9 fires instead of the proposed 6 spanning Alaska to southern California, it was too much data to provide local feedback to all areas. • Fire Symposium, University of Idaho, Moscow, ID, September 25, 2004 participation and discussion of project.
• We will assess the ability of remote sensing data to monitor post-fire rehabilitation treatments, such as estimating changes in percent mulch cover over time, or distinguishing native from non-native vegetation regrowth.	• In hindsight, we discovered extensive post-fire monitoring was beyond the scope of this project due to the extra time, money, and data required to observe many sites over several years. However, in a related project, we are currently investigating the use of Quickbird satellite imagery (high spatial resolution) to monitor post-fire rehabilitation treatments and monitor non-native vegetation after the 2005 School Fire.

APPENDIX 1: PROJECT LOCATIONS

State	Fire	Landowner	Type of Data		
			Multispectral Satellite	**Hyperspectral**	**Fire Mapper**
Montana	Black Mountain II	Lolo National Forest	X	X	X
Montana	Cooney Ridge		X	X	X
Montana	Robert	Flathead National Forest	X	X	
Montana	Wedge Canyon		X	X	
California	Simi	Mountains Recreation & Conservation Authority	X	X	
California	Old	San Bernardino National Forest	X	X	X
Alaska	Porcupine	Bureau of Land Management	X	X	
Alaska	Chicken		X	X	
Alaska	Wall Street		X	X	