Evaluate Sensitivities of Burn-Severity Mapping Algorithms for Different Ecosystems and Fire Histories in the United States

Final Report to the Joint Fire Science Program

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OVERVIEW

This project sought to evaluate the performance of two indices of burn severity, one a remote sensing index called the differenced Normalized Burn Ratio (dNBR) based on 30-meter Landsat data, and the other a field plot-based measure called the Composite Burn Index or CBI (Key and Benson 2006). The evaluation intended to cover the prominent fire regimes of the U.S. The specific purpose was to support a scientific basis for broad-scale implementation of standardized national burn severity mapping that could routinely quantify the general, multi-faceted ecological effects from fire.

When this project was proposed in 2001, there had been a large number of investigations by Federal and university scientists concerning various aspects of burned area remote sensing (Chuvieco 1997; Patterson and Yool 1998; Coppin et al. 2004; Lu et al. 2004; Lentile et al. 2006). These studies were somewhat related to, though not to be confused with, activities that concerned the remote sensing of fire detection and active fire behavior (Giglio et al. 1999; Rauste et al. 1997; Cahoon et al. 2000; Li et al. 2000). At the time, however, there was no consistent approach within the U.S. Federal Government to quantify burned area on a national level, and in particular, to describe the character of ecological effects within burned areas. With perceived dramatic increases in the size and severity of wildfires through the 1990's and into the twenty-first century (Keane et al. 2002), the need to establish some standard measures and mapping technology became obvious.

There were ongoing efforts within the U.S. Forest Service (USFS) and Department of Interior (DOI) to produce rapid post-fire assessments to support emergency response, typically on the larger, more socially impacting fires (e.g. Hardwick et al. 1997; Bobbe et al. 2001; Lachowski et al. 2001; and work conducted by the USGS on the 2000 Jasper Fire[1] in the Black Hills, SD). These were not yet fully standardized, and the information told only part of the national fire-effects story, being limited by real-world circumstances of timing, resources and data availability, as well as methods used to estimate burn severity. The emergency assessment focused mostly on needs for urgent treatment, such as soil effects leading to erosion and impacts to transportation or utilities. At the same time, a joint project with the U.S. Geological Survey (USGS) and National Park Service (NPS) was underway to nationally map the severity of all NPS fires over 300 ac (http://burnseverity.cr.usgs.gov/). This was not designed to aid emergency response; rather emphasis was on broad and complete assessment of fire effects that could serve longer-term management and science. Protocols focused solely on Landsat data and standard processing, waiting for the best available data on each burn, in terms of timing, sun angle, phenology, and atmospheric conditions. Images were acquired when fires were completely out, and included some delayed responses that were not apparent immediately post fire (Key 2005).

The approach proposed in this study was based largely on experiences drawn from the joint USGS/NPS project, using methods developed by Key and Benson in the mid-to-late 1990's (Key and Benson 1999; Key and Benson 2002). The project relied on Landsat TM or ETM+ data, which provided archived, contiguous 30-meter coverage from pre- and post-fire reference dates to cover potentially all fires in the nation at reasonable cost. A central theme was to integrate the burn severity definition, field measures and remote sensing in a context compatible with the resolution and a landscape perspective on post-fire conditions. Common threads running through

[1] www.fs.fed.us/r2/blackhills/fire/history/jasper/00_11-09_jrapid_text.pdf

the concept of burn severity, the field methodology and remote sensing index were temporal differencing, change detection, the magnitude of change, and the aggregation of effects detected at moderate resolution. A goal was to link these in a framework for testing and understanding the relationships between fire severity and remote sensing, while not losing sight of constraints imposed by national implementation. A second goal was to incorporate broader ecological factors in the definition of severity than were necessary for emergency response. The approach and methodology has been described in FIREMON (Lutes et al. 2006) within the chapter on landscape assessment (Key and Benson 2006).

Since 2001, several investigations and projects have used the methods defined in FIREMON, or some derivation thereof, to map burns and test results. For example, we provided technology and data transfer to the USFS. Their follow-up investigations led to implementation of similar methods based on the dNBR when feasible to support Burned Area Emergency Response (BAER) teams (Gmelin and Brewer 2002; Orlemann et al. 2002; Bobbe et al. 2001. The DOI also adopted the same rapid assessment routines for BAER teams working on DOI lands. Other approaches using other sensors were needed, however, when suitable Landsat data were not available in time for BAER planning, so these methods were not always directly applicable to emergency applications.

Recently, the Wildland Fire Leadership Council (WFLC) adopted a strategy to monitor the effectiveness of the National Fire Plan and the Healthy Forests Restoration Act. One component was to assess the environmental impacts of large wildland fires and identify trends in burn severity across the United States. The USGS, NPS and USFS provided the leadership to develop Monitoring Trends in Burn Severity (MTBS) in support of the WFLC monitoring strategy. This JFSP project formed a scientific basis for MTBS, which will rely on Landsat satellite imagery and the dNBR algorithm to assess burn severity in the United States, covering fires greater than 500 acres in the east and greater than 1000 acres in the west that have occurred since 1982. The MTBS project is designed for two primary applications: 1) local-to-regional planning, management and research using dNBR-based fire assessment products imported into land-unit-based GIS, and 2) national policies such as the National Fire Plan to analyze effects and effectiveness of fire management practices across large geographic regions. The MTBS project represents perhaps the most significant technology transfer of this JFSP sponsored study.

Aside from those direct operational applications, a considerable amount of interest, discussion, and research has followed that centered on the approaches originally proposed in this project. Some have been based on relatively few observations and/or on only one to a few burns (Cocke et al. 2005; van Wagtendonk et al. 2004, Chuvieco et al. *in press*; Finney et al. 2005; Miller and Yool 2002; Rogan and Franklin 2001; Lieberman and Rogan 2002; Brewer et al. 2005; Kokaly et al. *in press*). Others have been more regional in scope or spanned more than one fire season (Bigler et al. 2005; Roy et al. 2006; Thode 2005; Miller and Thode *in press*; Hudak 2004a, 2004b; Epting et al. 2005; Epting and Verbyla 2005). While it is beyond this report to address all these studies, suffice it to say there have been a variety of results, including a few reporting mediocre performance of dNBR or difficulties with the CBI. Some of those are addressed in the summary of findings that follows, including the relative dNBR (RdNBR) proposed by Miller and Thode (*in press*) from California, which tends to reflect the way severity can be manifested and classified particularly in sparsely vegetated areas.

As these and other studies were completed and discussions continued, we proceeded to process burns and collect plot data. The present work represents considerably more field data from more burns and different areas of the country than previous studies.

Burn severity or fire severity is difficult to define and quantify; it continues to be the source of much discussion (Jain 2004). We agree that the definition of fire severity varies depending on the characteristics of interest and how they are measured (Albert Simard, in Jain 2004). Severity depends on one's point of view and the application at hand. It may focus on either select individual effects, or encompass a holistic combination of effects (Lentile et al. 2006). It has been a question of how one chooses to view severity. In reference to Landsat detection capabilities, we believe the main issues surrounding burn severity remote sensing as undertaken by this project chiefly concern: 1) the 30-meter resolution of mapping, which aggregates effects and includes non-burnable surfaces; 2) timing and whether or not vegetation survivorship and delayed mortality factor into the severity equation; and 3) the emphasis or exclusion of certain effects, which have variable significance in different ecotypes and may selectively be used to define particular classifications of severity.

Based on Landsat spectral and spatial resolution, the concept of burn severity applied in this project represents the average condition of the pixel, or site, including all potential first-order effects. First-order effects are considered to be the evidence of burning, the condition or response soon after burning of biophysical components or processes that were present before fire. This can include considerable within-site heterogeneity. In addition, the measure corresponds with a magnitude of change, either spectrally or ecologically, which is a continuum and the primary variable of analysis. Moreover, we consider two time intervals for assessment of first-order effects. The first is an Initial Assessment, done as soon as good quality Landsat data is available within about six weeks of the fire. The second is an Extended Assessment, done during the first growth period after fire when latent first-order responses can be detected. These assessments are in contrast to Rapid Assessment, which has not been the focus of this project. Distinctions of timing and the implications for gauging severity are discussed in more detail below.

PROJECT GOALS AND OBJECTIVES

The overall goal of the project was to develop a scientific foundation for national, long-term and operational post-fire remote sensing and mapping of wildland fire burn severity. The purpose was to guide production of a common data reference to wildland fires on federally managed lands, so that compatible and consistent burn mapping occurred across ecological regions. The goal was envisioned to take a step beyond emergency response, to augment that information with more fires geographically, and make updated assessments at appropriate times after active burning. A condition to achieve the goal was that processes and products needed to be relatively simple, inexpensive, and able to be implemented nationally. As such, the proposed research was designed to answer a central hypothesis that a burn area-mapping algorithm can perform consistently and sufficiently well for different ecosystems and under different burning conditions within the U.S.

As proposed, the project sought to address several objectives:

- Compare a burn-severity mapping algorithm called dNBR with other algorithms (e.g. differenced normalized difference vegetation index, dNDVI) at several test sites representing different fire characteristics. National Park Service (NPS) lands are targeted for expediency due to ongoing cooperation with NPS.

- Conduct field sampling to test the CBI for field rating of burn severity at the above sites.

- In some of the study areas, conduct the above mapping and field sampling for two successive years.

- Compare field CBI data with dNBR and other mapping algorithms; conduct statistical analysis for sensitivity of dNBR to different ecosystems, different pre-fire vegetation or fuel conditions, different burn characteristics and, in some areas, for two successive years following fire.

STUDY AREAS

We proposed to conduct research on recent burns in 13 National Parks or National Forests throughout the conterminous United States and Alaska. As the project developed and new fires burned near NPS fire effects monitoring crews, opportunities arose for more extensive analysis, and additional study areas were included. Study area selection emphasized broad coverage of the ecosystems and prominent fire regimes of the United States, along with the availability of trained personnel to collect field data. Only the Montana Valley and Sadler Complexes were not included as originally proposed (due to timing and logistical issues). However, by pursuing the opportunities for new study areas we were able to double the number of land management units and increase the number of fire regimes represented in the project (Table 1). We more than tripled the number of fires sampled, which significantly increased the number of plots over what was originally proposed. Appendix Table 3 contains an expanded breakdown of field sampling and remote sensing effort by fires.

Table 1. General breakdown of study area locations and numbers of field plots collected.

Region	State	Land Management Unit	Number of Fires	Number of Plots
Alaska, tundra and boreal forests	AK	Alaska BLM	1	53
	AK	Denali National Park & Preserve	4	84
	AK	Noatak National Preserve	2	40
	AK	Yukon Charley Rivers National Preserve	3	119
California, conifer forests and woodland/ chaparral	CA	Sequoia & Inyo National Forests	1	38
	CA	Sequoia & Kings Canyon National Parks	4	66
	CA	Whiskeytown National Recreation Area	1	32
	CA	Yosemite National Park	7	278
Central, ponderosa pine woodland /grasslands	SD	Badlands Natonal Park	1	54
	SD	Black Hills National Forest	1	72
	SD	Wind Cave	1	13
North Central, deciduous & conifer forest	MN	Voyageurs National Park	1	9
N. Rockies, conifer forests /sagebrush-grasslands/ aspen parklands	MT	Flathead National Forest	1	4
	MT	Glacier National Park	10	493
	WY	Bridger-Teton National Forest	7	122
	WY	Grand Teton National Park	6	405
	WY	Yellowstone National Park	7	128
Southeast, deciduous & conifer forests /wet & dry prairies	AR	Buffalo River National River	1	14
	FL	Big Cypress National Preserve	1	12
	FL	Everglades National Park	1	3
	KY/TN	Big South Fork National River & Recreation Area	3	9
	TN	Great Smoky Mountains National Park	1	37
	VA	Shenandoah National Park	3	50
Southwest, pinion-juniper woodlands/ sagebrush-grasslands/ conifer forests	AZ	Grand Canyon National Park	5	305
	CO	Mesa Verde National Park	2	31
	NM	Bandelier National Monument	1	23
	NM	Santa Fe National Forest	1	5
	UT	Dixie National Forest	1	33
	UT	Zion National Park	4	25
	UT/CO	Dinosaur National Monument	1	55
Total	**15**	**30**	**83**	**2612**

METHODS

The project was based on FIREMON Landscape Assessment protocols for field validation and Landsat processing for dNBR (Lutes et al. 2006). Each dNBR was calibrated by subtracting the mean unburned bias, determined by sampling unchanged pixels outside the burn. The differenced

NDVI (dNDVI) followed the NDVI of Tucker (1979), and relative dNBR (RdNBR) calculation followed Miller and Thode (*in press*). Field sampling design was stratified random, using accessibility and proximity, as well as within-burn dNBR frequency and local homogeneity as site selection factors. The latter was based on range of dNBR values within a 3x3 neighborhood of each pixel. Data processing and analysis was done at the USGS Center for EROS and the USGS Northern Rocky Mountain Science Center. Fieldwork was conducted with significant contributions from local NPS fire monitoring personnel and others, who were trained on-site in the various field environments of the project. To extract remote sensing data for field plots, we used a 5-point sampling technique that yielded the plot-center pixel value and the average of, at most, the four closest pixels to plot center. This resulted in an average with the center pixel weighted by 2/5 (i.e. counted twice) and the neighboring 3 pixels weighted by 1/5. Generally the 5-point pixel average remote sensing value was used for comparison with CBI.

Statistical analysis was conducted to explore relationships and characteristics of remote sensing indices and CBI field data. Conventional correlations, regressions, and scatter plots were used to explore the complex interrelationships and differences between these datasets. From our present and past research, the typical relationship between CBI and dNBR was clearly nonlinear. This was due in part to field rating factors of the CBI tending to change more rapidly from unburned to moderate levels of dNBR, than from moderate to highest levels. Also, CBI scores became asymptotic near 3.0, often before the highest dNBR values were reached. Evidently, dNBR responded to changes not estimated by CBI above highest perceived levels of severity on the ground. Further, CBI did not gauge post-fire increased greenness or enhanced productivity, though dNBR did when it took on strongly negative values. A number of algorithms possibly could model the relationship; however for simplicity we usually applied a cubic polynomial, which seemed adequate for comparing different sets of burns or conditions. We considered CBI as the dependent variable when used in regression, because in practice, a common application was to predict burn severity on the ground, given the continuous dNBR derived from remote sensing. The dNBR (or other Landsat index), then, represented the independent variable.

SUMMARY OF FINDINGS TO DATE

Many aspects affecting dNBR performance, such as timing, geographic location, fire seasonality, pre-fire fuel and vegetation are closely interrelated, and many combinations of these factors could be discussed in a national context. A thorough comparison of dNBR with other remote sensing indices becomes very complex when viewed from all angles. Therefore, some overlap exists between the subheadings below, and only highlights of findings are discussed.

There are three basic temporal reference points in practice for gauging the severity of first-order fire effects. We define these as rapid, initial and extended assessments, as discussed in the introduction. Assessments done beyond the time of extended assessment incorporate aspects of long-term severity and recovery. This project primarily focused on the initial and extended assessment time frames, based on 0-6 week and 4-12 month post-fire Landsat acquisitions, respectively. The goal for initial assessment was to map the burn as soon as the fire was out, and when relatively high quality Landsat data became available. The goal for extended assessment was to incorporate the best quality Landsat data at a time when survivorship and mortality was detectable in burned-vegetation. Because not all plants die at the time of burning, some may remain viable even after above ground foliage is consumed, while others may die over time from heat-induced stress. The appropriate time for extended assessment varied from region to region, depending on climate and rates of resprouting or mortality.

Table 1 summarizes CBI plot data. Of the 2612 total plots, 17 plots were not included in analysis due to poor quality Landsat coverage. Of the remaining 2595 plots, 2570 linked to at least one Extended Assessment dNBR and RdNBR covering 79 burns. Initial Assessment dNBR and RdNBR was applicable to 1329 plots on 35 burns. The number of plots used in dNDVI analysis totaled 602 across 14 burns. In addition, remote sensing assessments (dNBR, RdNBR and dNDVI) were produced for approximately 50 fires from which no CBI data were collected. The combination of remote sensing assessments with and without CBI field data made up the overall basis of findings reported.

We would like to emphasize, correlations with plot data are only part of the story. Simple correlations to small plot samples can be inherently misleading in terms of evaluating performance or comparing assessments nationally. The CBI relied on interpretation and judgment, which can vary substantially from individual to individual. Burn severity estimation in the field could be perplexing, especially as it often must be done without complete familiarity of pre-burn conditions or post-burn responses. It required a forensic approach to understanding what happened on a site and why. In addition, the scope of the project demanded relatively quick plot evaluation in order to obtain sufficient coverage and sample sizes. Although field training attempted to standardize and inform crews on the approach, there was a wide range of experience and perception influencing data collection. In some instances, CBI procedures were modified slightly by local preferences, such as altering the plot size or the choice of rating factors.

Moreover, the sampling design was not intended to represent the whole burn, rather only to provide the correlation of ground conditions to the remote sensing index. Plots were not strictly randomly located, and represented very few points in relation to the total area burned. They could not possibly represent the spatial complexity or range of conditions within a full burn. It would be invalid, therefore, to draw firm conclusions about the correctness of the derived spatial representation of a whole burn, based on such distribution and relatively low number of plots.

As a result, other qualities of remote-sensing derived burn models were considered in the evaluation, including: image correspondence to ground patterns observed in aerial photos or while driving or walking through burns; clarity and differentiation of burn patterns represented in the image; distinction between burned and unburned areas, and correspondence to boundaries or small patches observed on the ground; the range of values represented by burned pixels and how plainly that differentiated levels of fire effects; the visual contrast within the burn indicating spatial pattern and variation of effects; the uniformity of unburned areas outside the burn and the degree of confusion between the burn and other disturbance factors; occurrence of aberrant spikes in the data that detracted from image clarity; the level of geographic and seasonal consistency between burn images; and finally the feasibility to produce, deliver and describe burn images to users on a national basis.

Fire Effects Inference and CBI Relations to dNBR

As a field estimate of burn severity, the CBI was designed to complement the Landsat-based dNBR, which integrates the overall magnitude of change across a 30-meter pixel. Thus, the CBI is not a precise measure of a specific fire effect. Rather, it is a composite of effects averaged over the area and the strata of the site. In practice, the individual CBI rating factors (or fire effects) are assessed generally over a 30-meter diameter plot. The effects include a number of contrasting responses that on balance attempt to arrive at an average overall condition of the site. For example, the amount of charring and consumption is considered, along with the amount of unburned, and resprouting from burned but surviving plants.

The CBI values are hierarchical in derivation, and allow dissection into factors contributing to a site's post-fire condition, starting with individual effects, then average conditions of each stratum, followed by integration of responses separately for the understory and overstory, and finally the overall average for the whole site. This organization of field observations was intended to facilitate testing multiple dimensions of the relationships between CBI and dNBR.

If CBI performs as designed while dNBR integrates multiple types and degrees of change into each pixel value, then one would expect a general increase in correspondence of CBI to dNBR as the field estimate of burn severity progressively incorporates more fire effects. Similarly, one would expect individual rating factors of the CBI to be less correlated to dNBR than the average scores of the strata and total plot. That was exactly the case supported by extended assessment data aggregated over many burns within regions. From region to region, extended assessment dNBR tended to correspond best with the total plot CBI (R-square .691 to .777), followed sequentially by the overstory (R-square .685 to .747), then the understory (R-square .575 to .715), and then the separate scores of the 5 strata from substrates to big trees (.373 to .756).

Although understory composite scores usually corresponded less to dNBR than the overstory scores, differences tended to be slight. This indicated that inference to understory conditions can be made with dNBR, and the overstory does not necessarily dominate the dNBR signal, as might be assumed. If the upper canopy was impacted to some degree, understory conditions such as resprouting or newly exposed soil were detected in the post-fire acquisition, where variations could contribute significantly to the dNBR in spite of dense pre-fire tree canopy.

It follows that individual strata of the understory (substrates, vegetation < 1 m, and vegetation 1 to 5 m) tended to correspond less to dNBR than the individual strata of the overstory, when overstory trees were present before fire. The range of R-square typically was from .500 to .630 for separate understory strata, and between .650 and .750 for the discrete overstory strata.

The poorest direct correlations with dNBR (R-square typically .400 to .650) occurred at the level of individual rating factors (or fire effects). Some of the best-correlated single effects, however, included the amount of black (charring) and green (not dead) within tree crowns, changes to low vegetation foliage cover and species composition, and litter and duff consumption. Some individual rating factors, such as litter and small fuels consumption, saturated near 3.0 before the highest average CBI severity levels were reached, and long before maximum levels of dNBR were attained. The implication was that those factors did not contribute a great deal to defining severity above a certain level.

For initial assessment, the CBI understory and overstory composite scores showed better correlations to dNBR than either the individual stratum scores or the individual rating factor (fire effects) scores that comprised the composite scores. However, stronger disparity in correlation appeared between overstory and understory strata composite scores in initial assessment than was evident in extended assessment. In other words, the overstory components (R-square .750 to .850) were more strongly correlated with initial assessment dNBR than understory components (R-square .500 to .750), when compared to extended assessment. Moreover, overstory scores could exceed the total plot score in correlation with initial assessment dNBR, which was not typically the case for extended assessment dNBR. Thus, overstory correlation to initial assessment dNBR can be expected to be among the highest of all correlations to dNBR.

Regional results suggest initial assessment dNBR is more strongly influenced by overstory effects, while understory effects collectively play less of a role, in contrast to extended assessment. This may be a consequence of timing, as initial assessment dNBR may not record delayed responses, such as vegetation survivorship, and may be more affected by undesirable late-season remote sensing conditions such as low sun angle or senescent unburned vegetation. On an individual fire basis, however, overstory CBI may not be as highly correlated with initial assessment dNBR if there is a strong influence from delayed tree mortality, which does not show up until the extended assessment. Thus, it is important to recognize the differences between initial assessment and extended assessment timing for application purposes.

These results reinforce the notion that dNBR integrates multiple effects representing a synthesis of burn severity conditions on a site, and the CBI composite scores are usually the most useful variables to relate to dNBR. Results also imply that it is important to maintain the balance of rating factors contributing to CBI in field applications. Poorer results may be incurred if some portion of the overall balance of CBI rating factors is altered, or if some factors are ignored. That is not to say that exactly the same rating factors need be considered in all applications. Rather, the number of factors assessed should represent the whole structure of the site, and factors should encompass the variety of fire effects that may occur across strata. Moreover, users can expect relatively lower correlation when dNBR alone is used to model individual effects, such as a soil condition (R-square .430 to .550), without incorporating ancillary data.

Initial and Extended Assessment Differences

Almost universally, the initial assessment dNBR provided good delineation of fire perimeters, the areas burned and unburned. Problems mapping fire scars arose mainly as a result of poor remote sensing conditions, such as low sun angle, shadow on north slopes, regional smoke from other fires, bad weather, and snow or clouds. Under those conditions (perhaps 30-60% of the time), a satisfactory initial assessment simply could not be developed. The limitations seemed increasingly prevalent at latitudes above 40^o (roughly the latitude of Denver, CO) or in areas generally cloudy and moist after a dry fire season. These conditions often occurred in areas with only one fire season, typically in late summer through fall, as in the northern Rocky Mountains. Fires in the southeast that occurred in October through December were also problematic.

We found fire perimeters based on initial assessment dNBR could differ from those derived from extended assessment data, and both often differed markedly from the incident perimeter. Reasons for this included the variable objectives and source information that were often used to derive the incident perimeter, and burning often continued after the time of fire management or initial assessment. That aside, perimeter quality was mixed depending on regional circumstances.

Extended assessment perimeters were judged to be better where illumination, phenology or delayed mortality factors hampered initial assessment. Conversely, initial assessment perimeters were often better where regrowth was rapid. In most circumstances, one or the other assessments resulted in acceptably accurate perimeters. Highest confidence, however, generally resulted when the perimeter was developed from both assessments.

In terms of burn severity, extended assessment dNBR generally correlated better with CBI than initial assessment dNBR (Table 2). Complications in initial assessment mapping arose due to both ground and remote sensing factors. Low sun angle, in particular, tended to diminish the quality of the dNBR. Difficulties in matching the phenology of pre- and post-fire scenes were also more frequent than with extended assessment. This occurred because of inter-annual variations in snow and vegetation senescence, coupled with the short window of time following fire from which to select suitable Landsat scenes for initial assessment. In some cases, differences in greenness (or dryness) between pre- and post-fire acquisitions identified levels of change detected by the dNBR that were not the result of fire. For example, greener pre-fire conditions matched with drier post-fire conditions could result in less contrast and distinction between burned and unburned areas. Notably, many of the preceding factors would negatively affect remote sensing results no matter what approach or index was used. In addition, some factors at times can be avoided by proper selection of Landsat scenes. It is important, therefore, that analysts base their findings on the best quality data available.

In many cases, sub-optimal remote sensing acquisitions still were found to be useful for initial assessment. There were instances where some portions of the burn were occluded in the imagery, but significant portions remained clear. Although incomplete, the initial assessment could still provide valuable information about the acreage burned by large fires, or about burns in remote locations where little other information existed.

Table 2. CBI Plot correlations (R-squared) to valid initial assessment (IA) dNBR and RdNBR by major geographic regions, and correlations of those subsets of plots to valid extended assessment (EA) dNBR. Polynomial regression as noted.

Regions	**IA dNBR R-square (N)**	**IA RdNBR R-square (N)**	**EA dNBR R-square (N)**	**Polynomial**
Northern Rockies	.651 (436)	.604 (436)	.706 (398)	cubic
Southwest [1]	.727 (484)	.607 (484)	.735 (477)	cubic
California	.790 (156)	.752 (151)	.816 (157)	cubic
Alaska	.838 (42)	.811 (42)	.896 (25)	cubic
Southeast	.747 (94)	.479 (94)	.776 (96)	quadratic
All Regions	.674 (1212)	.597 (1207)	.714 (1153)	cubic

[1] (includes South Dakota: West Sage fire.)

Relatively high quality initial assessments were obtained when remote sensing conditions were good and relatively stable for one-two months after fire. We obtained especially good assessments from the southern to central Rockies and the Southwest. In these areas, fire seasons were sometimes early, so there was ample opportunity to obtain high quality imagery during the months following the fires. In other cases, fires ended before mid-September and the weather cooperated for acquiring imagery. We also experienced success in the grassland areas of the central plains, especially when grasses "cured out" early for mid-summer fire seasons.

Initial assessment dNBR values for most burned areas tended to be higher than extended assessment values. Thus, burned-area initial assessment dNBR images were generally brighter than dNBR images generated for extended assessment. The initial assessment dNBR images also showed somewhat less variation, with histograms being skewed more to the right (i.e., skewed towards higher dNBR values) than extended assessment. Soon after a fire, when initial assessments were conducted, burns were very fresh, with maximum difference occurring between scorched, charred, ash-covered and consumed components compared to the pre-fire state. These effects became less pronounced by time of extended assessment due to weathering and resprouting from surviving burned plants. In some areas, such as western conifer forest, the frequency distribution of initial assessment dNBR was relatively lower (more left-shifted in the histograms) than extended assessment. This was especially true if trees remained green soon after fire, but eventually died from heat stress by the time of extended assessment. Thus, the final relationship between initial and extended assessment was a balance between these two responses.

The majority of initial assessments we tested tended to be from high quality source data (Table 2), so regional correlations to CBI were relatively good (R-square .650 to .840, N=42 to 1212 plots). In general however, the total plot CBI was better correlated with extended assessment dNBR (R-square .710-.900), when comparing the same plots with initial assessment. This should not be surprising because the CBI incorporates survivorship and mortality factors, which often take time to develop. Moreover, CBI crews were typically in the field during the growing season after fire, around the time when the extended assessment post-fire Landsat scenes were acquired. Both CBI timing and extended assessment dNBR, then, tended to capture similar delayed first-order effects from fire. Again, on an individual fire basis, results can vary.

A set of CBI plots was measured in the field both during the initial assessment time frame, and again later during the extended assessment period (N=284). For those plots, the relationship between total plot CBI and initial assessment dNBR was better using the earlier plot data (R-square .703) than using the later CBI data set (R-square .640). Similarly, plots measured at the later time correlated slightly better with extended assessment dNBR (R-square .776) than plot data collected at the earlier time (R-square .768). Overall, however, extended assessment correlations for those plots were somewhat better than initial.

In most cases, extended assessment dNBR provided high quality, useful information on burn severity. Good quality images had unburned mean dNBR values near zero (± 50, on a scale of –2000 to +2000), low dNBR variation within unburned areas (std. dev. <50), good contrast between burned and unburned areas, a large range of within-burn dNBR (potentially -500 to +1300), and spatial variation indicating a high degree of complexity to the severity pattern and distribution resulting from fire. When these characteristics are not evident, users should be informed that the dNBR might not be optimal. Complications with extended assessment are discussed below under the context of regional and pre-fire ecological differences.

Regional Differences

Regional distinctions largely reflected differences in climate, ecosystems, and remote-sensing factors, which are also discussed in other sections. In grouping study assessments by region, however, we were able to combine relatively similar types of burns and achieve larger sample sizes for general comparison.

After combining all valid plots over all fires, correlation to extended assessment dNBR was found to be fairly good (R-square .657, N=2355), but lower than plots grouped individually by region (Table 3). Obviously, the combined relationship contained all the variation encountered nationally, which was expected to be greater than variation within more consistent regional groupings. Results suggest better inference of burn severity from dNBR was achieved when mapping applies regional relationships, rather than a single national rule set. Results from neighboring fires within smaller geographical contexts potentially can improve relationships even further.

Table 3. CBI plot correlations (R-squared) to valid extended assessment dNBR and RdNBR by major geographic regions. Summarized using cubic polynomial regression.

Regions	**N**	**dNBR R-square**	**RdNBR R-square**
Northern Rockies [1]	1,000	.721	.687
Southwest [2]	580	.728	.763
California	407	.691	.676
Alaska	262	.799	.764
Southeast	106	.760	.760
All Regions	2,355	.657	.663

[1] (includes Minnesota: Section 33 fire.)
[2] (includes South Dakota: Jasper, Highland Creek, and West Sage fires.)

Extended assessment dNBR was judged effective and operationally comparable in all regions, although perhaps marginally so in South Florida. On an individual fire basis, however, there were some differences in consistency among regions. Alaska, for example proved problematic due to recently discontinued coverage from Landsat 5 and exclusive reliance on Landsat 7 SLC-off data. Even though correlations with CBI severity can be quite high there, gaps from missing scan lines resulted in incomplete burn information. Cloud cover continued to be an issue in some regions, particularly Alaska, the Northwest and the Southeast, especially Florida.

As mentioned, portions of the Southeast had fire seasons in October through December, and therefore initial assessment was hampered by low sun angles. Low severity burns that occurred during deciduous leaf-off conditions were generally marginally detectable in extended assessment, after trees leafed out the following spring. It was difficult to delineate perimeters solely from the dNBR in several cases. Unlike fire in western conifers, such burns did not seem to transfer much detectable stress to the canopy. Where burns did stress or kill the canopy, however, the impacts were detectable in the conventional way. South Florida and other wet swampy areas were influenced by frequent, large fluctuations in soil moisture or flooding, which degraded burn mapping potential. If comparable pre- and post-fire Landsat scenes could be found that were not excessively influenced by surface moisture, then results could be acceptable. Rapid regrowth, however, still made assessments difficult due to timing issues. Such regrowth led to low detection of fire effects after one to three months, which actually turned out to be a valid assessment of low severity in many cases.

Suitable timing of imagery was also an issue in drier regions where green-up occurred and disappeared fairly quickly, given irregular rainfall year to year. Included were areas of the Southwest and California, as well as the large interior western basins and the Great Plains. Difficulties arose because of subtle phenological differences between pre- and post-fire imagery, coupled with sparse pre-fire vegetation and fuels. Landsat scene selection was somewhat more difficult when conditions were dry and growth was ephemeral, such that we needed to rely on phenological similarities rather than the acquisition date only. In general, fire seasons came early and weather was cloud free outside of brief monsoons in these regions, so availability of suitable Landsat scenes was usually adequate. The per-pixel inclusion of large proportions of non-burnable surface (soil and rock) was also an issue, which diminished detected magnitudes of change. Such factors contributed to relatively narrow ranges of detected severity, or just subtle contrasts in dNBR between severity levels on the ground. Although all available vegetation and fuel may have burned, the per-pixel area was small. Discussion continues on what that means in terms of defining severity on a pixel-by-pixel basis – either in absolute or relative terms.

The Northern Rockies had perhaps the most consistent fire-to-fire results. Large portions of burns were coniferous forest, where detectable effects contrasted well with pre-fire conditions, and persisted through the extended assessment time frame. Most burns occurred in relatively high vegetation cover, and regrowth potential was strong in low-to-moderately severe burn areas. Delayed mortality in conifers was also commonly detected in extended assessment. All these factors contributed to meaningful representation of a large range of severity conditions. Generally similar trends applied in portions of other regions occupied by conifer forest.

Pre-fire Cover and Vegetation Type Differences

Pre-fire cover and vegetation type information was obtained from two independent sources. The first relied on plot photos to identify general vegetation (Tables 4-5) and canopy cover classes (Table 6), which was possible on about 70% of plots. The second extracted existing vegetation type and percent cover (EVT and cover class) from the LANDFIRE and National Land Cover Data (NLCD) data sets. Because about half of the plots were not covered by the more-detailed LANDFIRE data, EVT types were grouped into the more-general NLCD types, which included all plots except those in Alaska (Tables 7-8). Plots that were mapped with LANDFIRE percent cover were compared in Table 9. Problems with EVT and NLCD class assignments were noted, and were corrected with interpretation from the field photos when possible.

Since not all plots had pre-fire cover or vegetation type information, different sets of plots were represented in the various categories of Tables 4 through 9. To compare dNBR to RdNBR, the reader should use Table 4 and the top half of Table 6 for pre-fire conditions interpreted from plot photos, and Table 7 and the top half of Table 9 for pre-fire conditions extracted from LANDFIRE and NLCD datasets. To compare dNDVI to the other two indices, the reader should use Table 5 and the bottom half of Table 6 for pre-fire conditions interpreted from plot photos, and Table 8 and the bottom half of Table 9 for pre-fire conditions extracted from LANDFIRE and NLCD datasets.

In general, results from the two different sources for pre-fire vegetation type or percent canopy cover indicated similar patterns, and insight into performance of the remote sensing indices was consistent between CBI plots stratified by the two sources of pre-fire vegetation. This finding reinforced the operational potential for assessing burn severity trends nationally when stratified by available pre-fire vegetation information.

Results generally showed small differences among the three remote sensing indices (dNBR, RdNBR, and dNDVI) as measured by correlations (R-square) to shared CBI plots with similar pre-fire conditions. The dNBR and RdNBR trended similarly across different vegetation types and canopy cover classes. This was not surprising given that RdNBR was essentially a proportional transformation of dNBR. In comparison, dNDVI was somewhat weaker than either dNBR or RdNBR in estimating CBI-based burn severity, but had similar trends in relation to pre-fire conditions.

There was a regular difference in CBI correlations to remote sensing indices between forest and grassland fires. Extended assessment tables showed both dNBR and RdNBR had stronger CBI correlations in forest fires than grassland fires. Severity was relatively uniform and low across grassland burns, which were often masked by strong and fast regrowth by the time of extended assessment. Remote sensing of grassland burns should perform well in initial assessments, however, because variations in actual severity tend to be slight and the assessment simply defines the area burned, which is often the main management concern in that ecosystem. Because of the lack of national vegetation type data (limited by the LANDFIRE schedule), sample sizes were deemed too small to conduct further analysis of differences between specific vegetation types, such as comparing Rocky Mountains and Cascade-Sierra conifer forest types, or comparing the deciduous forests of western versus eastern states.

Is estimation of burn severity related to pre-fire forest canopy density? Is pre-fire forest canopy density related to the severity of fires? Our results provided some information to the first question. In Tables 6 and 9, there is a consistent pre-fire canopy density difference in estimating CBI burn severity. However, the difference is approximately the same for all the indices tested. Closed canopy forests tend to yield stronger CBI correlations with each of the three indices (dNBR, RdNBR, and dNDVI) than open canopy forests. It may be noted that even though there was a consistent trend in terms of forest canopy, the difference is not necessarily significant in statistical terms. This is likely a regional pattern, which is beyond the scope of this analysis.

The non-linear relationships between CBI and each of the remote sensing indices also should be noted. We used non-linear regression models to estimate the correlation values, which improved the correlations. The non-linearity nature of the relationships was probably related to vegetation canopy cover and other factors (as discussed above).

Table 4. Extended assessment comparisons of total-plot CBI correlations (R-square) with dNBR and RdNBR, using all plots (N) summarized by general pre-fire vegetation types determined from plot photos.

Pre-fire vegetation	**N**	**dNBR**	**RdNBR**	**Reg. model**
Conifer Forest	947	.696	.673	Cubic
Deciduous Forest	39	.723	.631	Cubic
Conifer/Deciduous Mixed	195	.744	.760	Cubic
Non-Forest/Forest Mixed	308	.495	.590	Cubic
Grassland	52	.500	.437	Quadratic
Non-Forest Mixed (grass/shrub)	73	.613	.644	Quadratic
All Non-Forest	142	.579	.589	Quadratic

Table 5. Extended assessment comparisons of total-plot CBI correlations (R-square) with dNBR, RdNBR, and dNDVI, using plots from dNDVI-mapped fires (N) and summarized by pre-fire general vegetation types determined from plot photos. Note that sample sizes for deciduous forest and grassland plots on dNDVI-mapped fires were judged to be too small for analysis, and plots from dNDVI-mapped fires were only a subset of those available for dNBR and RdNBR analysis.

Pre-fire vegetation types	**dNBR (N)**	**RdNBR (N)**	**dNDVI (N)**	**Reg. model**
Conifer Forest	.782 (253)	.716 (253)	.781 (253)	cubic
Deciduous Forest	N/A	N/A	N/A	cubic
Conifer/Deciduous Mixed	.736 (38)	.741 (38)	.604 (34)	cubic
Non-Forest/Forest Mixed	.594 (97)	.781 (97)	.453 (97)	cubic
Grassland	N/A	N/A	N/A	quadratic
Non-Forest Mixed (grass/shrub)	.613 (73)	.644 (73)	.609 (20)	quadratic
All Non-Forest	.579 (142)	.589 (142)	.562 (25)	quadratic

Table 6. Extended assessment comparisons of total-plot CBI correlations (R-square) with dNBR, RdNBR, and dNDVI using shared plots (N) summarized by pre-fire vegetation canopy cover derived from plot photos. All regression models are cubic. Two sets of shared plots were used, one comparing dNBR and RdNBR, the other comparing plots where all three indices were available.

Canopy cover using all plots with dNBR and RdNBR	**N**	**dNBR**	**RdNBR**	**dNDVI**
Canopy cover < 25%	68	.649	.711	
Canopy cover = 25-70%	1,067	.620	.610	
Canopy cover > 70%	496	.788	.771	
Canopy cover using the subset of plots with dNDVI				
Canopy cover < 25%	30	.734	.863	.699
Canopy cover = 25-70%	300	.679	.702	.621
Canopy cover > 70%	94	.841	.832	.774

Table 7. Extended assessment comparisons of total-plot CBI correlations (R-square) with dNBR and RdNBR, using all plots (N) summarized by general pre-fire vegetation types extracted from available LANDFIRE and NLCD datasets.

Pre-fire vegetation types	**N**	**dNBR**	**RdNBR**	**Reg. model**
Evergreen Forest	1,528	.722	.709	Cubic
Deciduous Forest	150	.602	.633	Cubic
Evergreen/Deciduous Mixed	198	.721	.689	Cubic
Shrubland	160	.757	.795	Cubic
Dry Grassland/Sage	123	.433	.488	Quadratic

Table 8. Extended assessment comparisons of total plot CBI correlations (R-square) with dNBR, RdNBR, and dNDVI, using plots from dNDVI-mapped fires (N) and summarized by general pre-fire vegetation types extracted from available LANDFIRE and NLCD datasets. Note, sample sizes for dry grassland/sage plots on dNDVI-mapped fires were judged to be too small for analysis, and plots from dNDVI-mapped fires were only a subset of those available for dNBR and RdNBR analysis.

Pre-fire vegetation types	**N**	**dNBR**	**RdNBR**	**dNDVI**	**Reg. model**
Evergreen Forest	407	.747	.728	.726	Cubic
Deciduous Forest	45	.727	.733	.672	Quadratic
Evergreen/Deciduous Mixed	57	.805	.781	.831	Quadratic
Shrubland	41	.846	.870	.792	Cubic
Dry Grassland/Sage	N/A	N/A	N/A	N/A	
All Non-evergreen Forest	166	.706	.797	.593	Cubic

Table 9. Extended assessment comparisons of total-plot CBI correlations (R-square) with dNBR, RdNBR, and dNDVI using only shared plots (N) summarized by pre-fire vegetation canopy cover extracted from available LANDFIRE and NLCD datasets. All regression models are cubic. Two sets of shared plots were used, one comparing dNBR and RdNBR, the other comparing plots where all three indices were available.

Canopy cover using all plots with dNBR and RdNBR	**N**	**dNBR**	**RdNBR**	**dNDVI**
Canopy cover < 30%	166	.769	.739	
Canopy cover = 30-70%	478	.732	.761	
Canopy cover > 70%	584	.756	.759	
Canopy cover using the subset of plots with dNDVI				
Canopy cover < 30%	45	.813	.735	.738
Canopy cover = 30-70%	174	.721	.754	.682
Canopy cover > 70%	116	.830	.845	.801

Remote Sensing Index Differences

Based on plot data alone, we found little difference in correlations between extended assessment dNBR and RdNBR across most regions, and results over all plots combined were very similar (Table 3). The CBI plots appeared to be slightly better correlated with dNBR in the Northern Rockies, California and Alaska, while plots appeared to be slightly better correlated with RdNBR in the Southwest. The regional CBI results, however, depended a great deal on site-selection and plot representation of cover types within regions. Results in the former three regions probably responded to proportionately more samples from more densely vegetated sites, while the Southwest tended to be represented by less vegetated pre-fire conditions than elsewhere. Had there been greater representation from sparsely vegetated sites in some regions, such as California for example, the correlation with RdNBR may have been greater. Also, some regional differences were noted in the way CBI was interpreted.

The dNBR and RdNBR were fundamentally different in terms of how they defined severity. If either definition were applied consistently in the way CBI ratings were interpreted, then plot data would tend to be more highly correlated with the corresponding index. We found it was generally easier for field personnel to interpret severity on sparsely vegetated sites, by discounting the contribution or relevance of non-burnable areas in the plot to the total average score. Indeed, that may be desirable for many applications, but it represented a departure from how spectral differences on the site were recorded by Landsat. As such, absolute values of dNBR would tend to be less correlated with that interpretation of CBI. Thus, regional trends were influenced by the ecotypes represented, as well as the CBI rating factor definitions applied.

On a fire-by-fire basis, results were mixed, apparently depending on proportions of sparse or dry vegetation, fuels and non-burnable surfaces within a particular burn. Three general situations seemed to emerge that require continued investigation. First, if NBR and green vegetative cover were relatively high in the burn before fire, the relationship of CBI with both dNBR and RdNBR was similarly good across the range of severity. Also, there was little difference in the appearance of imagery, in terms of the magnitude gradient and spatial pattern of the burn. They differed mainly in that the RdNBR values were somewhat higher.

On the other hand, if pre-fire green vegetative cover and NBR were both quite low before the fire, the CBI values could be quite high while the dNBR was low. These were plots scored with high CBI interpreted largely from the burnable portions of the plot. In that situation, RdNBR tended to improve the relationship by yielding significantly higher values than dNBR. RdNBR tended to pull such plots far over to the right, and more in proximity of the regression trend line. RdNBR imagery tended to appear significantly brighter in those areas, indicating high severity, compared with much lower severity indicated by dNBR imagery. These conditions were more common in some Southwest and California ecotypes, and in some more northerly grassland.

A third situation existed, however, which on balance influenced regional results. Under the same pre-fire conditions as the preceding, or when pre-fire NBR was quite low but vegetative cover was moderate to high and perhaps senescent, CBI values could be low while the dNBR was also low. These plots were scored with low CBI interpreted from the whole area of the plot, including non-burnable portions, and fell near lower portions of the trend line on CBI vs dNBR scattergrams. Due to low pre-fire NBR, however, RdNBR tended to worsen the relationship by yielding significantly higher values than dNBR. Again, RdNBR would tend to pull such plots far over the right, but away from the trend line in the lower right region of the scattergram. The RdNBR imagery appeared brighter than dNBR in areas that seemed to exhibit low severity on the ground. Such plots were more common in more highly vegetated regions where conditions supported good resprouting after burning, such as Alaska and the Northwest.

Though correlations may have been slightly lower in some regions, extended assessment RdNBR tended to produce regionally consistent regression curves. In other words, regional curves followed similar trajectories and tended to closely overlie each other. Conversely, regression curves for extended assessment dNBR differed slightly from region to region, even though correlations with those individual curves were slightly better in some instances than regional RdNBR. Results supported the notion that RdNBR may provide a more nationally consistent single relationship with burn severity (Miller and Thode, *in press*), while national use of dNBR would benefit by application of regionally adjusted curves, that is, regional definition of the relationship between dNBR and burn severity.

Under initial assessment, plot CBI was better correlated with dNBR than RdNBR in every region and over all samples (Table 2). Initial assessment RdNBR performance may have suffered in some cases by conditions at the time of Landsat acquisition that yielded very low pre-fire NBR due to vegetation senescence or low sun angle. These influences could cause unwarranted magnification of the value, not necessarily related to burn severity based on sparse cover or inclusion of non-burnable surfaces. Also, on some burns there was improvement in the initial assessment dNBR over extended assessment dNBR, which was comparable to the improvement in extended assessment RdNBR over extended assessment dNBR. In those cases, higher initial assessment dNBR was more in line with the higher CBI ratings based largely on the burnable portions of sparsely vegetated plots (cases where extended assessment RdNBR tended to do a better job), or where CBI ratings may have down played the significance of regrowth.

Concerning image characteristics, dNBR and RdNBR appeared similar when areas were densely vegetated prior to burning and the vegetation was relatively productive (not senescent), although RdNBR was stretched to higher values. Such areas typically exhibited relatively high pre-fire NBR. Perhaps the most notable difference between indices occurred where areas had either sparse or non-productive (senescent) vegetation before fire, or within fairly recent previous burns. There the RdNBR was significantly higher, due to very low pre-fire NBR, and could equal or exceed the highest dNBR or RdNBR values observed in densely-vegetated burned conifer forest. In some cases, such boost in the remote sensing index may be appropriate, depending on objectives and definition of severity. In other cases, however, such areas produced RdNBR values that seemed unreasonable and out of proportion to the potential severity on the ground.

Negative values were affected in similar ways, signifying a degree of increased greenness or enhanced productivity in the post-fire environment. In other words, negative dNBR was amplified in RdNBR when, as above, pre-fire conditions yielded very low NBR. Generally the increase was significant and led to greater contrast with dark areas intensified. Negative RdNBR values appeared to be most extreme on previous burns undergoing recovery or when older burns reburned, compared to dNBR.

Where vegetation was very sparse before fire or in previous burns, pre-fire NBR values near zero (±50) could yield unrealistically high positive or negative RdNBR values, whether the area burned or not. Such spikes in the data produced salt and pepper aberrations in some images when conditions extended over large enough areas, such as in desert environments. Under sparse cover conditions, RdNBR beneficially enhanced the contrast between burned and unburned in many areas, but could confuse the distinction in other areas due to such spikes. Extended assessment dNBR, on the other hand, could remain relatively uniform under these conditions, but provided generally less contrast between burned and unburned. Initial assessment under these conditions generally improved the dNBR contrast, provided remote sensing conditions were good.

The disproportionately high RdNBR values were influential when dealing with continuous data and image interpretation. These anomalies within a burn may be inconsequential, however, if the data were classified into discrete levels of severity (e.g., low, medium and high). In that case, all extreme high values would simply be grouped with other high values in a single category, and their presence would disappear from the classified burn image.

More research is needed about ground characteristics that influence single-date NBR, in terms of Landsat Band 4 and Band 7 relationships, to help clarify further distinctions between dNBR and RdNBR.

Plot relationships to extended assessment dNDVI were similar to dNBR, with somewhat higher correlations to dNBR overall and especially in the Southwest and Southeast (Table 10). The dNDVI images, however, contained about half the within-burn range of values as dNBR. The dNDVI signal was not as strong, and correspondingly provided less contrast and variation within the burn. The dNDVI performed best during extended assessment under good remote sensing conditions as most of the test data represented. That was not the case at other times, however. Smoke or hazy conditions adversely affected dNDVI to a greater extent than dNBR, due to elevated potential of atmospheric scattering in the dNDVI Band 3. Moreover, the dNDVI signal seemed to dissipate more quickly as vegetation senesced. Thus late season dNDVI was found to be less effective than late season dNBR, even for extended assessments, while initial assessment dNDVI was frequently found to be poor.

Table 10. Extended assessment index correlations (R-squared) to total plot CBI, polynomial regression as noted, using plots that had dNDVI coverage.

Regions	**N**	**dNBR**	**dNDVI**	**Reg. model**
Northern Rockies	179	.804	.797	cubic
Southwest [1]	188	.714	.621	cubic
California	133	.762	.767	cubic
Southeast	73	.732	.689	quadratic
All Regions	573	.721	.680	cubic

[2] (includes South Dakota: West Sage fire.)

As part of the project, (Nelson 2005) examined 30-m Landsat TM/ETM+ and 500-m MODIS reflectance data in mapping burn severity for 16 fires. The CBI was obtained for 8 of the 16 fires and compared to maps of three indices generated from each data set. The comparison of CBI data to 30-m Landsat dNBR data produced an average linear R-square value of 0.54, which was greater than the average linear R-square between CBI and either dNDVI or the differenced Enhanced Vegetation Index, dEVI (Miura et al. 2001; Huete et al. 2002). Correlations between CBI and 500-m MODIS and Landsat data resampled to 500-m were weak, with average linear R-square values less than 0.25. Estimates of burned area were, on average, 34% greater from MODIS data than 30-m Landsat data, with the percent difference much greater for smaller fires < 2,000 ha (<5,000 ac) than for larger fires. Fires greater than 25,000 ha (62,000 ac) yielded similar sizes between both sensors. Compared to Landsat data, MODIS data tended to underestimate the burn severity of relatively smaller fires, and overestimate the area burned. For the 16 burns, dNBR was a robust and scalable index useful for mapping burn severity and it performed better than dNDVI and dEVI. Ground based CBI estimates of burn severity were significantly related to TM based burn maps, but the MODIS data were too coarse to be validated with the current CBI sampling strategy.

Conclusion:

In summary, there are pros and cons to both dNBR and RdNBR, and their use depends in large measure on how one wants to define burn severity. RdNBR may be favored in ecosystems with sparse vegetation when the amount of non-burnable surface is not considered a factor of the severity per-unit-area. RdNBR may also be useful towards facilitating national standardization in mapping discrete categories of severity. The dNBR may be favored when absolute quantities related to burning are important, such as biomass consumption or per-unit-area generation of heat, or when continuous data are used and include surrounding areas, such as previous burns. Users need to understand the strengths and implications of each measure. Information from both can be improved and become more specific as analyses move from national to regional and into local-area contexts. We believe both measures can provide consistent measures within a given context, and can be comparable between regions and ecotypes. Both can be used to explore spatial pattern and landscape characteristics of fire, and both can produce cost-effective and relatively efficient national coverage. Meanwhile, dNDVI can be useful to mapping burn scars and severity when dNBR is not an option due to sensor characteristics. In any case, time of year, time since burn, vegetation and fuel conditions, and factors affecting the integrity of the spectral signal all contribute to understanding the data provided by the remote sensing index of burn severity. Regardless of the index, remote sensing applications that quantify burned areas need to account for the timing and radiometric quality of the data, especially when evaluating performance and comparing burns at different times and places.

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Appendix. JFSP DELIVERABLE CROSS WALK TABLE

Appendix Table 1 – Summary table for major deliverables

Proposed	Delivered	Status
Methodology analysis and implementation: summary	- Number of study sites (management units) where research activities were conducted: proposed 13 sites, actually studied 28 (includes 80 fires in 14 different states). - Project objectives studied and completed: 100% - Partnerships formed: the Fish & Wildlife Service, National Park Service, U.S. Forest Service, U.S. Geological Survey, and several universities - Outcome of the research: Better understanding of usefulness and limitations of mapping burn severity in support of fire management and scientific applications - Implementation of the methodology: 1. Monitoring Trends in Burn Severity – a national interagency fire monitoring project sponsored by the Wildland Fire Leadership Council 2. NPS/USGS National Burn Severity Mapping Project 3. FIREMON protocol - Technology transfer conducted: extensive training workshops, technical sessions, publications, presentations, briefing sessions, GIS data and maps, etc.	Done
Web site	- URL: http://burnseverity.cr.usgs.gov/ - Functions: data distribution, information dissemination, training information, technical discussion. - Downloads and visits continue to be provided to Federal Agencies, State Agencies, Universities, and the general public.	Ongoing
Tech transfer sessions	- Number of training sessions conducted: 23 - Number of training attendees: over 200 - Technical and data support to graduate students: 20 PhD and MS students	Done
Composite Burn Index field plots	- Number of CBI plots collected: 2,595	Done
Burn severity assessments	- Number of assessments completed: 88 with field data, about 50 without field data	Done
Publications	- Two (2) papers published - One graduate (Master of Science) thesis	Ongoing
Presentations, posters and briefings	- 29 conference presentations - Two conference special sessions - 10 conference posters - Briefings to DOI, Congressional staff, and GAO and Wildland Fire Leadership Council.	Done

Appendix Table 2 – Detailed data about deliverables

Proposed	**Delivered**	**Status**
Validation of a burn severity mapping method: analysis activities	- NPS/USGS Remote Sensing Training: Quantifying Burn Severity Data, Sioux Falls SD, 8/7-9/01. - Burn Severity Mapping Workshop– USDA Forest Service Remote Sensing Applications Center (RSAC), USGS NMD and BRD, US National Park Service, and US Bureau of Land Management. Salt Lake City, UT, 12/09/2002 – 12/13/2002. - Overview, remote sensing and field validation methods were revised and updated in 2005 and are available on the FIREMON and FRAMES-NBII web sites: http://fire.org/firemon/, http://frames.nbii.gov/.	Done
Web site	http://burnseverity.cr.usgs.gov/ The website will remain active.	Ongoing
Publications	Key, C.H. 2005. Remote sensing sensitivity to fire severity and fire recovery. In J. de la Riva and E. Chuvieco, eds. 2005. *Proceedings of the 5th International Workshop on remote sensing and GIS applications to forest fire management: fire effects assessment*. Universidad de Zaragoza, Spain, 16-18 June 2005. ISBN 84-96214-52-4: 29-39. Key, C.H. and N.C. Benson. 2005. Landscape Assessment: Ground measure of severity, the Composite Burn Index; and Remote sensing of severity, the Normalized Burn Ratio. *In* D.C. Lutes; R.E. Keane; J.F. Caratti; C.H. Key; N.C. Benson; and L.J. Gangi. 2005. *FIREMON: Fire Effects Monitoring and Inventory System*. USDA Forest Service, Rocky Mountain Research Station, Ogden, UT. Gen. Tech. Rep. RMRS-GTR-164-CD: LA1-LA51.	Ongoing
Posters	- Key, C.H. and N.C. Benson, 2002. *Measuring and Remote sensing of burn severity.* In J.L. Coffelt and R.K. Livingston, 2nd U.S. Geological Survey Wildland Fire Workshop, Los Alamos, NM. October 31-November 3, 2000. USGS Open-File Report 02-11:55. - Key, C.H. and N.C. Benson, 2002. *Post-fire assessment by remote sensing on National Park Service Lands.* In J.L. Coffelt and R.K. Livingston, 2nd U.S. Geological Survey Wildland Fire Workshop, Los Alamos, NM. October 31-November 3, 2000. USGS Open-File Report 02-11: 56.	Done

Proposed	**Delivered**	**Status**
	- Key, C.H., 2002. *2000 Wildfires of Western Montana and Northern Idaho*. In J.L. Coffelt and R.K. Livingston, 2nd U.S. Geological Survey Wildland Fire Workshop, Los Alamos, NM. October 31-November 3, 2000. USGS Open-File Report 02-11: 57. - *Post-Fire Mapping and Analysis Using Satellite Data*. The Joint Florida Prescribed Burning Council, Ocala, FL, 11/14/02. - *Monitoring How Fire Changes the Landscape*. National Fire Plan Conference and Wildland Fire 2004 Surviving in the Interface Danger Zone. March, 2004, Reno, Nevada. - Key, C.; N. Benson; B. Sorbel; Z. Zhu; D. Ohlen; S. Howard; and B. Clement. 2003. *A national burn severity project: from concept to reality*. Poster abstract. In R. K. Livingston, 3rd U.S. Geological Survey Wildland Fire-Science Workshop. November 12-15, 2002 Denver, CO. USGS Scientific Investigations Report 2004-5005: 34. - Howard, S.M.; D.O. Ohlen; R.A. McKinley; Z. Zhu. 2003. *Historical Fire-Severity Mapping from Landsat Data.* In, Livingston, R.K., 2003, 3rd U.S. Geological Survey Wildland Fire-Science Workshop, Denver, Colorado, November 12–15, 2002: U.S. Geological Survey Scientific Investigations Report 2004–5005: 33 p. - *Evaluate sensitivities of burn-severity mapping algorithms for different ecosystems and fire histories in the United States.* Joint Fire Sciences Principle Investigators Conference, San Diego, CA. 11/01/2005 – 11/03/2005. - Zhu, Zhiliang, S. Howard, D. Brownlie. 2005. *Landsat – Based Fire Atlas: Okefenokee National Wildlife Refuge and Surrounding Areas*. East Fire Conference, May 2005, George Mason University, Fairfax, VA. - Ohlen, Donald, *S.* Howard, and Z. Zhu. 2005. *Landsat-Based Fire Atlases for Land Management*. Pecora 16: Global priorities in land remote sensing. October 2005, Sioux Falls, SD.	
Presentations/briefings	- Key, C.H. *Mesoscale Burn Severity and the Normalized Burn Ratio: ecology, remote sensing and implementation.* Missoula, MT. USFS Rocky Mountain Research Station, Fire Sciences Lab., 03/27/2002 – 03/29/2002	Done

Proposed	Delivered	Status

	- Key, C.H.; Z. Zhu; D. Ohlen; S. Howard; R. McKinley; and N. Benson, 2002. *The normalized burn ratio and relationships to burn severity: ecology, remote sensing and implementation*. In J.D. Greer, ed. Rapid Delivery of Remote Sensing Products. Proceedings of the Ninth Forest Service Remote Sensing Applications Conference, San Diego, CA 8-12 April 2002. American Society for Photogrammetry and Remote Sensing, Bethesda, MD.
	- Zhu, Z.; C.H. Key; D. Ohlen; S. Howard; R. McKinley; and N. Benson, 2002. *Landscape-Level Post-Fire Mapping and Analysis Using Satellite Data.* In J.D. Greer, ed. Rapid Delivery of Remote Sensing Products. Proceedings of the Ninth Forest Service Remote Sensing Applications Conference, San Diego, CA 8-12 April 2002. American Society for Photogrammetry and Remote Sensing, Bethesda, MD.
	- Briefing for Department of Interior and Congressional Staff on burn severity mapping, Washington DC 08/05/2002-08/06/2002.
	- Briefing for NPS Fire Ecology Steering Committee on burn severity mapping program, Philadelphia, PA, 10/22/2002.
	- Briefing to NPS Fire Management Leadership Board on NPS-USGS National Burn Severity Mapping Program, Boise, ID. 01/09/2003.
	- Briefing for Government Accounting Office on burn severity mapping, Sioux Falls, SD. 02/11/2003.
	- *Evaluate sensitivities of burn-severity mapping algorithms for different ecosystems and fire histories in the United States.* Joint Fire Sciences Principle Investigators Conference, Phoenix, AZ. 03/10/2003 – 03/14/2003.
	- 2nd International Wildland Fire Ecology and Fire Management Congress and the 5th Symposium on Fire and Forest Meteorology. Joint Session 7G Wildfire Burn Severity Mapping (Special Session), Orlando, FL, November 18-20, 2003:
	  - *Evaluating Fire Impacts with Landsat Data: A Comparison of Two Methodologies.*
	  - *Data acquisition timing for burned area remote sensing and relationships to measures of burn severity*.
	  - *Using the Composite Burn Index to field validation meso-scale burn severity assessment.*	

Proposed	Delivered	Status
	- *Burn Mapping of Wildland Fires within Different Ecosystems Using Field Verified.* - *Evaluate sensitivities of burn-severity mapping algorithms for different ecosystems and fire histories in the United States.* Joint Fire Sciences Principle Investigators Conference, Phoenix, AZ. 04/06–08/2004. - *Initial assessment of the 2003 fires in the greater Glacier region.* Fire in the Crown Workshop, Glacier National Park, MT, April 15, 2004. - Ohlen, Donald, C. H. Key, N. Benson, 2004, *Burn Severity Mapping with Satellite Data: Effectiveness and Variations*. Proceedings of the ASPRS 2004 Annual Conference, Denver, CO May 2004. American Society for Photogrammetry and Remote Sensing, Bethesda, MD. - *Burn Mapping on Different Ecosystems Using Field Verified Landsat Normalized Burn Ratio Data*. 2004 Great Plains/Rocky Mountain AAG Annual Meeting, Sioux Falls, SD. September 2004. - *Remote sensing of burn severity.* Universidad de Alcalá, Departamento de Geografía, Alcalá, Spain. June 13, 2005. - *Remote sensing sensitivity to fire severity and fire recovery*. 5th International Workshop on remote sensing and GIS applications to forest fire management: fire effects assessment. The Global Observation of Forest and Land Cover Dynamics (GOFC-GOLD), the European Association of Remote Sensing Laboratories (EARSeL) Special Interest Group on Forest Fires (FF-SIG), and the European Commission (Joint Research Centre), Universidad de Zaragoza, Spain. June 16-18, 2005. - *Landscape Assessment of Burn Severity*, Fire in Ecosystem Management. National Fire Institute (NAFRI), Tucson AZ. 03/08/2005. - Zhu, Zhiliang, D. Ohlen, Stephen Howard, Carl Key and Nate Benson *Mapping burn severity with satellite data: an analysis of ecosystem differences and time lapse since fire.* Pecora 16: Global priorities in land remote sensing. October 2005, Sioux Falls, SD. - *Burn Severity Mapping and Linkages to LANDFIRE*. LANDFIRE Executive Oversight Committee Meeting, Sioux Falls, SD. 08/18/2005 - 4th USGS Wildland Fire Science Workshop, Tucson,	

Proposed	Delivered	Status
	AZ. 12/06/2005 – 12/09/2005. - *Assessing and Mapping Burn Severity – Science Basis and Implementation.* - *Development of Fire Effects Monitoring Frameworks and Tools.* - *Overview of fire effects and remote sensing*. Station biologique de la Tour du Valat, Le Sambuc, France. June 20, 2005. - *Burn severity, remote sensing and project overview*. Wildland Fire Leadership Council (WFLC), Proposed Project to Track Burn Severity Trends, Coeur d'Alene, ID. 05/12/2005. - *The Interagency Fire Community: Available Tools, Data, and Collaborative Opportunities,* Fifth I&M Program "Meeting of the Networks", San Diego, CA. 2/07/2006 – 02/10/2006. - *Landscape Assessment of Burn Severity*. Fire in Ecosystem Management, National Fire Institute (NAFRI), Tucson AZ. 02/27/2006. - *Landscape Assessment of Burn Severity*. NPS decision support on fire management activities and invasive plant species control using the Invasive Species Forecasting System (Joint NASA, NPS, Colorado State research project), Yellowstone National Park, WY. 07/18/2006. - *Mapping Burn Severity from 1982 to 2010, the MTBS Project*, seminar at the Firelab, Rocky Mountain Research Station, Missoula, MT. January 19, 2006.	
Education activities supported (including direct participation in research and cooperation through discussion and exchange of materials)	- Kurtis Nelson, MS thesis, South Dakota School of Mines and Technology - Provided technical and data assistance to 20 graduate students.	Done
Collection of CBI field reference plots	2595 Plots in 14 States and 28 different Management units.	Done
Soft- and hard-copies of burn severity maps	Soft copies of burn severity data were provided to the Management units. Data are available for download on web site. Hard copies were provided upon request.	Done
CBI training workshops	Over 200 interagency and university personnel attended	Done

Proposed	**Delivered**	**Status**

	over 20 training sessions in field methods and remote sensing data processing.
	- NPS Fire GIS Workshop, Primm Valley, NV, Dec. 9-11, 2001.
	- Methods in CBI and field data collection at:
	  - Glacier National Park, Sept. 2000, 2001, 2003
	  - Glacier National Park, Aug. 2004
	  - Los Alamos, NM, Aug. 2001, 2002
	  - Great Smokey Mtns. National Park, Sept. 2002
	  - Shenandoah National Park, Sept. 2002
	  - Black Hills, SD, May 2002
	  - Mesa Verde National Monument, Oct., 2001
	  - Kern River, CA, Aug. 2003
	  - Southern UT, Northwest CO, May-June 2003
	  - Las Vegas, NV, March 2006
	- FIREMON, Missoula, MT, May 2003, Oct. 2004	

Burn Remote Sensing workshops	- NPS Fire GIS Workshop, Primm Valley, NV, Dec. 9-11, 2001. - Yellowstone National Park, Oct. 2003 - Interagency Monitoring Workshop – *Burn Severity, integrating dNBR index of burn severity with FRCC and LANDFIRE*. Included USFS, TNC, USNPS, USGS, BLM, University of Idaho, DOI, and USFWS. Tucson, AZ. December 15-17, 2004. - *Monitoring Landscape Scale Changes with Remote Sensing*, Rx510 – Advanced Fire Effects, National Advanced Resource Technology Center (NARTC), Tucson AZ. 02/27/2004. - *Landscape Assessment of Burn Severity*, Rx310 – Intermediate Fire Effects , Boise, ID. 01/09/2005. - *Monitoring Landscape Scale Changes with Remote Sensing*, Rx510 – Advanced Fire Effects, National Fire Institute (NAFRI), Tucson AZ. 04/06/2005. - *Monitoring Landscape Scale Changes with Remote Sensing*, Rx510 – Advanced Fire Effects, National Fire Institute (NAFRI), Tucson AZ. 02/15/2006. - FIREMON, Missoula, MT, May 2003, Oct. 2004 *Fire perimeter mapping and burn severity classification from dNBR*. USFS RSAC, Salt Lake, UT, May 2006	Done
Implementation of the validated burn severity	The burn severity mapping method validated through	Done

Proposed	Delivered	Status
method	this project has been implemented for two operational burn severity project nationwide: the National Park Service burn severity project and the interagency Monitoring Trends in Burn Severity (MTBS) project	

Appendix Table 3. Listing of fires analyzed, study areas, number of field plots, and remote sensing assessments. IA = Initial Assessment; EA = Extended Assessment; * = where more than one IA or EA was done; << = where CBI data was collected but not used in analysis.

Regional Eco-Types	State	Unit	Fires	Fire Year	CBI Data Sampling	N Plots	Timing	Approx. Acres
Southeast	TN	GRSM	Green Mountain	2001	2002-2003	37	IA EA	2360
Deciduous Hardwood	VA	SHEN	Shenandoah Complex	2000	2002	11	EA	16120
Pine forest	VA	SHEN	Fultz Run-Rocky Top	2002	2002-2003	39	IA EA*	5750
	KY/TN	BISO	Schoolhse-Cmp Branch-Darrow Rdg	2000	2001	9	IA EA	5430
	AR	BURI	Lower Wilderness	2004	2004	14	IA EA	10750
	FL	BICY	Bear Island <<	2001	2001	12	EA	25000
	FL	EVER	Squawk Creek <<	2001	2001	3	IA EA	4300
SubTotals:	**5**	**6**	**10**			**125**	**13**	**69710**
Southwest	UT	ZION	Langston	2001	2003	5	EA*	680
Pinyon / Juniper	UT	ZION	Timber Top <<	2003	2003	2	no imager	365
Sage / Grass	UT	ZION/DIXIE	Blue Creek-Sequoia (Dixie NF)	2002	2003	18	IA EA*	8436
Pine / Fir	UT	DIXIE	Sanford	2002	2003	33	IA EA*	81161
	UT/CO	DINO	Bear Creek	2002	2003	55	IA EA	4600
	CO	MEVE	Bircher-Pony	2000	2001	31	IA EA	27140
	NM	BAND/SFNF	Cerro Grande-Viveash (Santa Fe NF)	2000	2001-2002	28	IA* EA*	65882
	AZ	GRCA	Outlet	2000	2001-2002	68	IA EA	11870
	AZ	GRCA	Vista-Tower-Swamp Ridge	2001	2002	128	IA EA	11040
	AZ	GRCA	Poplar Complex	2003	2004	109	IA EA	7400
Central	SD	BADL	West Sage	2001	2002	54	IA EA	3710
Pine / Grassland	SD	WICA/BHNF	Jasper-Highland (Black Hills NF)	2000	2002	85	EA*	83120
SubTotals:	**5**	**10**	**18**			**616**	**26**	**305404**
California	CA	WHIS	Sunshine	2001	2002-2003	32	EA	670
Chaparral	CA	YOSE	Dark-Lost Bear	1999	2000	79	EA*	2679
Sierra Mixed Conifer	CA	YOSE	Hoover	2001	2002	63	IA EA*	7230
	CA	YOSE	PW3-Wolf	2002	2003	79	EA	3360
	CA	YOSE	Tuolomne-Whiskey	2003	2004	57	IA EA	4715
	CA	SNF/INF	McNally (Sequoia-Inyo NF)	2002	2003	38	IA EA	145300
	CA	SEKI	Highway-Tar Gap-Palisade-Sherman	2002	2003	66	EA	2710
SubTotals:	**1**	**4**	**13**			**414**	**12**	**166664**
Northern Rockies	MT	GLAC	Adair-Starvation	1994	1996	88	EA*	16993
Conifer forest	MT	FNF	Challenge (Flathead NF)	1998	2001	4	EA*	7311
Shrub / Herbaceous	MT	GLAC	Anaconda	1999	2000-2002	29	EA*	9657
Sage / Grass	MT	GLAC	Sharon	2000	2001	5	EA*	380
	MT	GLAC/FNF	Moose01	2001	2002	98	IA EA	66686
	MT	GLAC/FNF	Robert-Wedge-Trapper	2003	2003-2004	224	IA* EA*	126200
	MT	GLAC	Middle Fork-Rampage	2003	2003-2004	49	IA* EA*	35240
	WY	YELL	Boundary-Moose00	2000	2001	25	EA	1470
	WY	YELL	Falcon-Arthur-Little-Little Joe-Stone	2001	2002	103	EA	6840
	WY	GRTE/BRTE	Boulder-Glade-Upper Slide	2000	2001	98	EA	6449
	WY	BRTE	Enos-Blind Trail (Bridger-Teton NF)	2000	2001-2002	137	EA*	15715
	WY	BRTE	Green Knoll	2001	2002	54	EA	3790
	WY	GRTE/BRTE	Wolff Ridge-Elbo-Kelly	2002	2003	24	EA	1780
	WY	BRTE	Mule-Divide	2002	2003	107	IA EA	5980
	WY	BRTE	Blacktail-East Table	2003	2004	107	IA EA	5860
North Central Conifer	MN	VOYA	Section 33	2004	2005	9	EA	1500
SubTotals:	**3**	**6**	**32**			**1161**	**31**	**311851**
Alaska	AK	YUCH	242Witch-248Beverly-260Jessica	1999	2001	119	EA*	115000
Boreal Forest	AK	DENA	Foraker-Otter Creek-Chitsia	2000	2002	59	EA*	34780
Tundra	AK	DENA	Herron River	2001	2002	25	IA EA	6260
	AK	BLM	Milepost85	2002	2003	53	EA	21530
	AK	NOAT	Cottonwood Bar-Uyon Lakes	2002	2002-2003	40	IA EA	13986
SubTotals:	**1**	**4**	**10**			**296**	**9**	**191556**
TOTALS:	**15**	**30**	**83**			**2612**	**91**	**1045185**